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The cover illustration is an artist's view of the NA49 detector, used for studying ultrarelativistic heavy-ion collisions at the CERN Laboratory in Geneva, Switzerland. Collisions of very-high-energy nuclei are the best means of producing very hot and dense matter, in an attempt to understand the conditions that existed in the universe a microsecond after the big bang. The CERN SPS accelerator was upgraded this year to accelerate lead ions to 160 GeV/nucleon. NA49 was designed to measure simultaneously the thousand or more particles produced in these lead-lead collisions, which are of unprecedented complexity for nuclear and high-energy physics experiments. The main components of NA49 are two large analyzing magnets, each containing a Time Projection Chamber (TPC), followed by two large TPCs on either side of the beam pipe. The lead beam arrives from the upper right and interacts with a lead target upstream of the first magnet. First results from NA49 are given in this annual report.

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NUCLEAR SCIENCE DIVISION

1994
ANNUAL REPORT

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Division Deputy
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Editor
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June 1995

Lawrence Berkeley National Laboratory
University of California
Berkeley, California

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INTRODUCTION
June 12, 1995
Introduction

T.J.M. Symons

This report describes the activities of the Nuclear Science Division for the period of January 1, 1994, to December 31, 1994. This was a time of significant accomplishment for all of the programs in the Division.

Assembly of the solar neutrino detector at the Sudbury Neutrino Observatory is well under way. All of the components fabricated by LBL were shipped to Sudbury early in the year and our efforts are now divided between assisting the assembly of the detector and preparing software for data analysis once the detector is operational in 1996.

Much of the activity at the 88-Inch Cyclotron centered on Gammasphere. The "early implementation" phase of the detector ended in September. This phase was extremely successful, involving over 60 experiments with nearly 200 users from 37 institutions worldwide. The mechanical structure was installed and the final electronic system is expected to operate in March 1995. The Division concurrently hosted a conference on physics for large γ-ray detector arrays at the Clark Kerr Campus at UC Berkeley in August. This was a very successful meeting, reflecting the enthusiasm for this field worldwide.

Also at the Cyclotron, the progress toward weak interaction experiments using ultra-thin sources passed a major milestone with the trapping of radioactive $^{21}\text{Na}$ atoms. We are now engaged in a major upgrade of the experimental area and the outlook is very promising for these novel experiments. Another highlight of research at the Cyclotron was the confirmation of element 106. This development allowed the original LLNL/LBL discovery team to move forward with their proposal to name this element seaborgium.
In the relativistic heavy-ion area, the biggest accomplishment came with the start of research using Pb beams at the CERN Super-Proton Synchrotron. The Division had devoted substantial effort to construction of the electronic system for the NA49 time projection chamber. We are now working hard on the analysis of this exciting experiment. During the year, construction of the STAR experiment made excellent progress toward operation of the detector in 1999.

Several other experimental groups made good progress during the year. The results from the medium energy group working at Michigan State University were very striking. It was also pleasing to see the first results published on flow and fragmentation from data taken using the EOS detector at the Bevalac.

During the year, a substantial effort went into long-range planning for the Division, culminating in a retreat meeting with the Division’s scientific staff. This retreat was very valuable in clarifying the Division’s position on several topics that were discussed widely in the NSAC long-range planning process.

Finally, we are evaluating the effectiveness of the various publications issued by the Division. This is a time of change with the explosion of information available on the internet. The Division now has a home page on the World Wide Web, as do most of our programs and research groups. For now, we believe that this annual report is useful in its current form, although our readers tell us that it will be even more so if we publish it more quickly. However, the future for documents of this kind is less clear. Any comments and suggestions should be sent to our Editor, Bill Myers (WDMyers@lbl.gov), who has, once again, put together a fine document.
OVERVIEWS
Nuclear Structure and Reactions Program

F.S. Stephens

The Nuclear Structure and Reactions Program at LBL addresses a variety of current problems in nuclear physics. The aim is to understand the nuclear system and develop new ways of probing basic physical concepts. This program focuses on studying nuclear systems at extremes of angular momentum, isospin, \( Z \) and \( A \), and temperature. During the last year, many exciting results have emerged from our work. A brief overview and highlights of the programs are given here. A more detailed accounting of specific activities is given in the "Nuclear Structure and Reactions" section of technical reports in this volume.

The 88-Inch Cyclotron is the center of most of this program's activity. The Cyclotron is operated as a national facility and is equipped with two state-of-the-art Electron Cyclotron Resonance (ECR) ion sources capable of producing high-charge-state ions of most elements. Beams of ions from helium to neon are available with energies up to 32.5 MeV/nucleon. For heavier ions, the maximum energy per nucleon decreases with increasing mass approaching the Coulomb barrier in the lead region. In addition, intense (and polarized) light-ion beams of isotopes of hydrogen and helium are available. The high reliability and ease of changing beam species make the 88-Inch Cyclotron ideally suited for nuclear structure and reactions studies.

Gammasphere is a National \( \gamma \)-Ray Facility consisting of a 4\( \pi \) array of 110 Compton-suppressed high-purity germanium detectors. Completion of this system is scheduled for October 1995; however, it was recognized several years ago that even a modest fraction of the full system would be very powerful. Thus,
an Early Implementation phase of operation was planned, which began in April 1993 and ended in January 1995. A total of 60 runs were completed, using about 50% of the 88-Inch Cyclotron research time. A total of 176 users came from 24 U.S. and 14 foreign institutions to use this phase of Gammasphere.

The new Building 88 office addition was completed in the spring of 1994. This addition increased the office space in the building, allowing the Nuclear Structure and the Reactions groups to locate at the Cyclotron, as well as providing office space for outside users.

**Nuclear Structure**

The Nuclear Structure Group has two main focuses: one is to construct and operate Gammasphere, and the other is to pursue a physics program mainly centered on high-spin studies of the atomic nucleus. During the year this group organized a very successful international meeting, the Conference on Physics from Large Gamma-ray Detector Arrays. This conference was held in the Clark Kerr Campus at Berkeley, California, on August 2-6, 1994, and was attended by about 200 scientists. The physics developed with large arrays like Gammasphere's were discussed and detector developments were also reported. The Nuclear Structure Group has played the leading role in the construction and operation of Gammasphere. Both the Director and the Deputy Director of Gammasphere are members of the Nuclear Structure Group, and other members support the operation of the array, as well as contribute to its construction and maintenance.

This group is interested in the structure of the nucleus, mostly at high angular momentum. One of the main goals is to understand nuclear behavior in terms of the characteristics of a few-body quantal system. Persistent themes reflecting these interests have been identical bands and the C₄ symmetry suggested for the nuclear shape. Progress on these as yet unresolved issues is described below. In the last 2-3 years the group has been involved in discovering about 25 new superdeformed bands. These investigations extend the mass-190 and mass-150 regions of superdeformed nuclei, provide an unexpected view of the decay of a superdeformed band, generate new questions in the ongoing problem of pairing in nuclei at high spins, and contribute other new information of various kinds. Measuring lifetimes in superdeformed (and other) nuclei is also of considerable interest. Recently the group demonstrated that the slowing down of nuclei in thin targets may be used to deduce lifetimes of short-lived states, notably those at the top of superdeformed bands. This method was subsequently applied in the mass-80 region, where it is even more spectacular and important.

In the future, one of the most tantalizing goals is to find hyperdeformed nuclei; i.e., nuclei even more elongated and probably better rotors than superdeformed nuclei. There is already some evidence that such shapes may exist. Also, it would be very interesting to study the neutron-rich nuclei. The group has begun to study these nuclei using deep inelastic reactions. A first study, completed this year with a relatively light projectile (⁴⁸Ca), produced nuclei several neutrons richer than any β-stable ones at spins up to 20 ℓ. This program will continue
using heavier projectiles. Finally, the group is engaged in a collaboration with S. Freedman and his group to measure the branching ratio of the superallowed \((0^+ \rightarrow 0^+)\) \(\beta^+\) decay of \(^{10}\text{C}\). This work is expected to provide the best determination to date of the electroweak vector coupling constant.

The group is also developing a new Gamma-Ray Energy Tracking Array (GRETA), which would have a resolving power a thousand times that of Gammasphere. This array would consist of a solid shell of highly segmented Ge detectors. The technology has already been developed in part (encapsulated Ge detectors for Euroball and segmented Ge detectors for Gammasphere), but feasibility has not yet been established. A gas-filled recoil separator is also under study as an auxiliary detector for Gammasphere. With a high efficiency and reasonable mass resolution, such a solenoid-dipole system appears quite attractive.

Recently, a group led by John Rasmussen has conducted a successful off-line study of nuclear structure following the spontaneous fission of \(^{252}\text{Cf}\). The group has accumulated a very large data set and is searching for weak transitions feeding into known rotational bands, as well as other features.

**Structure of Nuclei Far from Stability**

**Proton-Rich Nuclei**

Studies near the proton drip line throughout the nuclidic chart can provide excellent tests of the limitations of nuclear models and stimulate improvements. For nuclides beyond the drip line, searches for new ground-state proton emitters are of interest to compare reduced widths to nuclear structure theory, as are searches for the quantum mechanically interesting decay mode of ground-state two-proton emission \((^2\text{He})\). For nuclides near the drip line, the large available \(\beta\)-decay energies open up new decay modes (such as \(\beta\)-delayed two-proton emission).

This group has developed a new low-threshold proton ball, consisting of six \(\Delta E\)(gas), \(\Delta E\)(gas), Si(E) triple telescopes, each with a 200-keV proton threshold. Recent experiments have led to the discovery of a \(\beta\)-delayed low-energy proton group in \(^{23}\text{Al}\) decay that proceeds via the isobaric analog state in \(^{23}\text{Mg}\). This nucleus, \(^{23}\text{Al}\), is the lightest particle-stable member of the \(A = 4n + 3, T_z = -3/2\) mass series and the only member of this series for which \(\beta\)-delayed proton emission through the isobaric analog state is possible. The proton strength from the isobaric analog state indicates a much stronger isospin mixing than expected. Preliminary results for \(^{27}\text{P}\) and \(^{31}\text{Cl}\) also indicate low-energy proton groups, but these do not proceed via the isobaric analog state. This group has also observed an unexpected low-energy (around 800 keV) \(\alpha\) group arising from the \(\beta\)-delayed \(\alpha\) decay of \(^{20}\text{Na}\). In addition, the group obtained tentative evidence for the two-proton decay from \(^{46}\text{Mn}\) to an excited state in \(^{44}\text{Ti}\).

Future plans include searches both for ground-state two-proton radioactivities (with emphasis on observing \(^2\text{He}\) emission) and for (single) proton
radioactivities in the mass-80 region. In addition, β-strength measurements will be started in the 1f7/2 shell.

**Heavy Nuclei**

This group uses the LBL 88-Inch Cyclotron to produce and characterize new elements and isotopes, to study nuclear reaction mechanisms, and to train students in modern nuclear and radiochemical techniques. Currently, research using both radiochemical and physical techniques is focused in the following areas: (1) the synthesis and identification of new isotopes and elements in the actinide and transactinide region; (2) the study of nuclear decay and nuclear properties of the actinide and transactinide isotopes; and (3) the use of new chemical separation techniques to prepare sufficient quantities of high-purity actinide and transactinide isotopes for more complex studies of both chemical and nuclear properties.

The group has completed measurements of the 2.1-s spontaneous fission activity produced by the bombardment of a 244Pu target with 22Ne ions. Because of the excitation function for production of this activity it was assigned to 262Rf. Over 200 pairs of coincident fission fragments have been recorded, allowing a determination of a symmetric mass distribution and a high total kinetic energy (TKE) distribution. Fission events with such high TKE have been observed in the fission of nuclides with N and Z approaching that of 264Fm and this has been explained in terms of the strong influence of spherical shells Z = 50 and N = 82 in the fission fragments. The high-TKE events seen in the fission of 262Rf indicate that the influence of these spherical shells persists to 262Rf (four protons and six neutrons from 264Fm). A search was also made for the α-decay of 262Rf, but this branch was found to be less than 1.2%. With this limit, the α-decay systematics indicate that the α-decay energy is less than 8.1 MeV, which is very close to the predicted value.

Future plans include a study of the properties of 260No and searches for new isotopes of elements 105 and 106. In addition, the group is undertaking a design study for a compound-nucleus separator with capabilities that surpass any of those previously used. As presently envisioned, this would be a superconducting gas-filled magnetic separator with a high efficiency, allowing complete isolation of compound-nucleus products from other interfering activities. Together with the ongoing development of higher intensity beams at the LBL 88-Inch Cyclotron, this separator should allow a broad experimental program.

**Radioactive Beams R&D**

The first generation of radioactive beam facilities generated new interest in nuclear structure studies of nuclei far from stability. A classic example is the deluge of experimental data and theoretical predictions for the very weakly bound 11Li nucleus. However, these experimental efforts have been severely handicapped by the low beam intensity and poor beam quality of the present first-generation facilities. The large improvements in both beam intensity and
beam quality that would result from a second-generation facility like the IsoSpin Laboratory (ISL) would open up many new physics opportunities. This group has made several important technical contributions to the design of a high-intensity radioactive beam facility. These contributions have been in the following areas: a cost-effective proton driver, high-power gas-cooled targets, a very-low-velocity post-accelerator, multiple beam use, and techniques for minimizing losses during stripping.

Magnetic Moments

An Osaka University–LBL collaboration is conducting a magnetic moment and nuclear polarization program at the 88-Inch Cyclotron. The cross-section and polarization of \(^{39}\)Ca was measured following the \(^{181}\)Ta(\(^{40}\)Ca, \(^{39}\)Ca)\(^{182}\)Ta reaction at about 10 MeV/A. The group plans to measure the quadrupole moment of \(^{39}\)Ca by implanting it in a MgF\(_2\) crystal that has a well-defined electric field gradient. The measurement will then be made using NMR techniques. This measurement is important to determine the deformation of the \(^{40}\)Ca core.

Heavy-Ion Reactions

At low energies complex fragment emission is a very rare process. Increasing the excitation energy brings the emission of these fragments to the forefront, until they dominate the reaction scene. The goal of the Nuclear Reactions Group is to characterize the physics of this emission process, both theoretically and experimentally, from its onset as binary compound nucleus decay to its full deployment as multifragmentation. The understanding of this process appears to be reaching a rather satisfying state. On the one hand, the thermal features observed in the fragment emission probabilities strengthen the hypothesis of phase space dominance in multifragmentation. On the other hand, the reducibility of the multiplicity distributions to a single binary event probability highlights the near independence of individual fragment emission.

The recent low-energy work has demonstrated the compound nucleus emission of complex fragments and characterized it to be a generalized fission process controlled by a set of conditional barriers each of which is applicable to a given mass asymmetry. For several systems near \(A \sim 100\), excitation functions have been measured and conditional barriers extracted. These barriers compare favorably with those calculated. In addition, over seventy excitation functions for different asymmetries from four different compound nuclei can be collapsed into a single universal straight line that is consistent with predictions. Once the phase space associated with each asymmetry at the conditional saddle point is removed, the reduced rates are identical for all fragments. In other studies at higher energies, experimental intermediate-mass-fragment multiplicity distributions for the \(E/A = 80\) and \(110\) MeV \(^{36}\)Ar + \(^{197}\)Au reactions have been shown to be binomial at all excitation energies. From these distributions a single binary event probability can be extracted that has a thermal-like dependence. Thus, it is inferred that multifragmentation is reducible to a combination of nearly independent emission processes.
In the future, the group plans to continue the program on multifragmentation. The observation that multifragmentation is reducible to single-fragment emission is very striking and the group is interested in determining whether this reducibility occurs in other intermediate-energy heavy-ion reactions. Also, at extremely high excitations, the vaporization region, the probability for light charged-particle emission should increase dramatically and one should observe a decrease in the IMF emission probability. The plan is to search for such an effect in Kr-induced reactions at higher bombarding energies. The group is also examining the charge distributions associated with multifragmentation for evidence of reducibility and thermal scaling.

A new program has also been started to reexamine the physics of the deep-inelastic scattering process (N/Z equilibration, energy equilibration, angular momentum transfer and alignment) by taking advantage of recently constructed fragment, light charged particle, and γ-ray detector arrays. The group has recently completed an experiment using a Si-strip fragment detector in Gammasphere together with neutron-deficient/rich $^{76}$Kr and $^{86}$Kr projectiles and $^{112}$Sn and $^{124}$Sn targets. These data are under analysis.
Activities of the Institute for Nuclear and Particle Physics (INPA) include research in nuclear astrophysics, weak interactions, high-energy nuclear astrophysics, cosmic background radiation, supernovae searches, direct detection of dark matter, and geoastrophysics. The researchers are members of the Nuclear Science Division, Physics Division, the UC Berkeley Physics Department, and the UC Space Sciences Laboratory. The Institute is an interdivisional organization sponsored by the Nuclear Science Division and the Physics Division.

Two main goals of the Institute are to promote communication and interaction among participants working in different areas of astrophysics and to foster the development of new initiatives. Moving the experimental groups close together, which was completed by the summer of 1994, has been very important in meeting these goals. A common room, centrally located, has been established and is used for the weekly seminar, group meetings, workshops, impromptu discussions, and a daily gathering for tea. A visitor program has been initiated and has arranged short-term visits for five theorists and one experimentalist so far. New initiatives under development include (1) data evaluation and compilation in nuclear and particle astrophysics, and (2) R&D toward the next-generation cosmic neutrino detector. Additional information on the Institute and its activities can be found on the World Wide Web under the URL http://www-inpa.lbl.gov/.
Within the Nuclear Science Division, the major research activity in nuclear astrophysics is the Sudbury Neutrino Observatory (SNO), a 1,000-ton heavy-water Cerenkov detector under construction in a nickel mine in Canada. Major milestones for LBL achieved during this past year have been the assembly of the upper part of the geodesic sphere that will hold the phototubes and the beginning of the installation of the phototubes themselves. Concurrent with this has been the establishment of clean conditions within the underground laboratory. The LBL/SNO group's involvement in preparing for the acquisition and analysis of data has increased substantially in the last year. Monte Carlo analyses of background contributions, development of tagged neutron sources, a study of neutron poisons, and software development for acquisition and analysis have proceeded at a rapid pace. A mock-up of the SNO phototube assembly (mini-SNO) containing about one hundred phototubes has been constructed and shipped to Seattle where it will be used for testing equipment for Sudbury. Finally, the LBL/SNO group has joined the Neutral Current Detector project. The proposal to build strings of $^3$He proportional counters for direct detection of neutrons liberated by neutrinos in heavy water was first developed at Los Alamos and has since been approved for funding by the DOE.

Other research in astrophysics and fundamental symmetries uses the 88-Inch Cyclotron (a search for excited states in $^{180}$Ta that could explain the natural abundance of this rare isotope) and the low-background counting facility in Oroville (a search for double beta decay to excited states in the daughter nucleus).

The Weak Interactions group conducts a number of precision decay studies of nuclei and atoms. Following their initial success in trapping $^{21}$Na atoms (22-s half-life), they have made a number of improvements in their trapping apparatus at the 88-Inch Cyclotron. The entire system has been moved to a new dedicated location, a new high-temperature oven has been designed, and new schemes for laser trapping have been developed. All together, an order of magnitude improvement in performance is expected. Experiments on $^{21}$Na and on isotopes of Fr are planned.

Two other high-precision experiments are a measurement of the weak vector coupling constant and a study of time-reversal invariance. The former uses Gammasphere to measure a branching ratio in the decay of $^{10}$C, which is essential for the experimental determination of the partial half-life for the Fermi decay of $^{10}$C. The latter, called EMIT, is a triple correlation experiment on the beta decay of polarized free neutrons. The Weak Interactions group is building the detector, electronics, and data-acquisition system, which will be installed at the NIST Cold Neutron Research Facility. With this new apparatus they expect to achieve a sensitivity to a time-reversal-violating correlation that is an order of magnitude better than previous experiments. Moving the experiment to a higher flux reactor (ILL in Grenoble) could produce an additional order of magnitude in sensitivity.

New limits on dark matter in the form of Weakly Interacting Massive Particles (WIMPS) have been set by searching for the tracks of scattered recoil nuclei in ancient mica. Scanning a total area of about $0.3 \times 0.3$ mm$^2$ with an atomic force
microscope enables limits to be set on the mass and cross-section of WIMPS that are comparable to limits set with Ge detectors.

Earlier searches for dark matter using Ge detectors have made use of the low-background counting laboratory at the Oroville Dam. The capabilities of this facility continue to find wide application, from semiconductor research to space radiation effects.
Relativistic Nuclear Collisions Program

A.M. Poskanzer

The Relativistic Nuclear Collisions Program (RNC) conducts experiments studying the collision of heavy ions in four energy regimes: (1) the Bevalac, where nuclear matter is compressed sufficiently to study its equation of state; (2) the AGS at Brookhaven National Laboratory (BNL), extending the studies of the Bevalac to an energy range where the maximum pressure from the baryons is likely to occur; (3) the SPS at CERN, where the energy density of the nucleons in the collision of very heavy nuclei may be sufficient to produce a phase transition to a plasma of free quarks and gluons; and (4) RHIC, where the energy density of the produced particles will be sufficiently high that production of the quark-gluon plasma is expected to occur. Understanding the reaction dynamics in these energy regimes and the nuclear matter equation of state is of fundamental interest.

The major efforts at the Bevalac have been the Dilepton Spectrometer (DLS) and the EOS Time Projection Chamber (TPC). Because of the shutdown of the Bevalac in January 1993, the extensive local activities are now in the analysis stage. The EOS TPC has been moved to the AGS to continue its studies at higher energies as experiment E895. The various experiments at CERN with LBL participants finished data-taking with $^{32}$S beams and have been consolidated into one experiment, NA49, for the Pb beams program, which started in November 1994. However, the main focus of the future high-energy heavy-ion research program at LBL is the STAR experiment at RHIC, which will begin data-taking in 1999.
CERN/RHIC Physics

At CERN, two large acceptance experiments measuring hadrons were carried out. The main goal of the NA36 TPC experiment was to determine if the trends in strange particle production indicate a signature of the quark gluon plasma, while the NA35 experiment covered a wide region of phase space with both a streamer chamber and a TPC, addressing several experimental topics.

The collisions of the heaviest nuclei at the highest energies (Pb ions at the SPS, Au ions at RHIC) are expected to create systems whose space-time dynamics are qualitatively different from those of the colliding light ions studied up to now. The heavy systems have significantly higher energy densities over longer time scales. The extremely large number of produced hadrons in such collisions (several thousand in a central Au-Au event at RHIC) presents a real technical challenge and a unique opportunity: nontrivial, statistically significant signals can be extracted from single events, a technique known as “event-by-event” analysis. The correlation of extreme values of several observables sensitive to the quark-gluon plasma phase transition in a single event is a powerful tool for selecting ensembles of interesting events for detailed study. An event-by-event measurement of the produced particles provides the opportunity to select events with extreme values of temperature (particle spectrum), flavor (strangeness content), shape of the flow (particle momenta), and size (two-particle correlations). This technique requires a large acceptance detector that can determine the momentum and identify a large fraction of the particles emitted in the collision.

NA49 is a fixed-target experiment at the SPS designed to study Pb-Pb collisions at 160 GeV/nucleon ($\sqrt{s_{\text{nn}}} = 17$ GeV). Its goal is to simultaneously measure many hadronic signals that are thought to be sensitive to the quark-gluon plasma. To perform event-by-event analysis, it will measure and identify almost all charged particles in the forward half of phase space and will carry out detailed ensemble measurements of all the single-event observables as well as strange particle decays, two-particle correlation functions, and other hadronic observables.

STAR is a collider experiment at RHIC designed to study Au-Au collisions at $\sqrt{s_{\text{nn}}} = 200$ GeV. Its goal is similar to NA49's, to simultaneously measure many hadronic signals. To perform event-by-event analysis, it will measure and identify almost all charged particles over two units of rapidity, centered at midrapidity. At RHIC there is a high rate of hard processes. Hard-scattered partons (the precursors of high pt particles and jets) are predicted to be sensitive to the medium through which they propagate and are directly calculable in perturbative quantum chromodynamics. The study of high pt particles and jets as a function of energy and mass of the colliding system may also be an attractive experimental approach to identify the presence of quark matter, and STAR is being planned with this capability.
Bevalac/AGS Physics

Due to the relatively weak interaction of dileptons with matter, they provide a unique tool for probing the early phase of the hot, condensed system created in central A-A collisions. Theoretical calculations indicate that the yield of dileptons is sensitive to the density and temperature of this early phase of the collision, providing information on the nuclear matter equation of state. These indications formed the basis of the experimental program of the DLS.

Experiments with the first-generation 4π hadronic detectors at the Bevalac—namely, the Plastic Ball and the Streamer Chamber—provided first insights into the dynamics of nuclear matter at high densities and temperatures through comparison of the experimental data with macroscopic and microscopic model calculations. However, still more precise and systematic data were necessary to determine the parameters of the nuclear equation of state. Such high-quality data were accumulated by the EOS TPC at the Bevalac. It is expected that the source temperature can be inferred from the energy distributions, the pressure reached in the reaction zone from the collective flow, the entropy from the ratio of protons to composite particles and from pion production, the source radii at freeze-out from the correlations of identical particles, and the amount of stopping from the rapidity distributions. Another important aspect is the study of multifragmentation. E895 will use the EOS TPC to extend all these measurements to the higher energies of the AGS.

Experiments

The Dilepton Spectrometer (DLS)

The DLS collaboration, from late 1986 until the closure of the Bevalac, carried out a systematic study of e+e- production as a function of beam energy and kinematics of the pair. The DLS results, about 30k pairs, represent the world's only e+e- data at Bevalac/SIS energies. Important results include: (1) existence of measurable dielectron yields, (2) observation of contributions from mesonic decays (π0, η, ρ/ω), bremsstrahlung, and Δ/N* decays, (3) strong energy dependence of the pd/pp yield ratios signifying the presence of the η-meson, (4) absolute value and shape of the mass spectrum at 5 GeV in p-p and p-d collisions, which shows a need to modify existing N-N model calculations (pp vs. pn contributions, inelasticity), and (5) observation of high mass pairs (>500 MeV) in Ca-Ca collisions, which may be evidence for pionic annihilation. Analysis continues on the high-statistics Ca-Ca studies and evolution of mass and pt distributions with projectile/target mass.

EOS TPC at the Bevalac

EOS was designed to study heavy-ion reactions over the whole energy range of the Bevalac. The TPC enables the measurement of the production cross-sections for protons, light composite particles, and pions over a large dynamic range. The EOS collaboration performed an extensive series of measurements prior to the shutdown of the Bevalac. Excitation functions of four systems (Ni + Cu, Ni + Au,
La + La, and Au + Au) were measured from 250 MeV per nucleon up to the highest energy. In addition, the systems Au + C, Kr + C, and La + C at 1 GeV per nucleon were measured.

The physics analysis of the data is being performed at LBL and other collaborating institutions. A complete excitation function for the directed flow in the Au + Au system has been measured. The new flow results show a striking scaling behavior that would be expected from nonviscous hydrodynamics. New correlation methods to study the nature of the directed flow have been developed. It can be shown that the flow is generated by particles being focused and having larger mean momenta in the flow direction. Systematic comparison of the data with model calculations are in progress. Preliminary results favor models with momentum-dependent interactions and a soft equation of state. In addition, multifragmentation of the Au + C system at 1 GeV per nucleon has been analyzed as a critical phenomenon. A method to extract critical indices from the data has been developed. Preliminary results show that the critical indices extracted are compatible with the critical indices of the liquid-gas phase transition.

**EOS TPC at the AGS (E895)**

E895 will carry out a systematic and exclusive measurement of the energy and mass dependence of particle production, correlations, and collective effects in Au + Au collisions at the AGS. In addition, E895 will study the dynamics of dilute nuclear matter and explore the emergence of critical phenomena (liquid-vapor phase transition) by varying the energy deposited into the Au projectile nucleus. E895 will measure the four-momentum of light mass particles, projectile fragments, and antiproton production. The experiment provides a large acceptance and thus many observables can be examined in fine detail at once.

**NA36 at the SPS**

NA36 was a TPC-based experiment designed to handle high charge multiplicity and high event rates. It measured strangeness production in relativistic heavy-ion collisions using $^{32}$S beams at 200 GeV/nucleon. About 6 million events were recorded, mainly with a Pb target. The experiment had very wide acceptance in rapidity and transverse momentum, so that it overlapped the phase space of all other experiments. Neutral strange particles ($\Lambda^0, \Lambda^\circ, K^0_s$), which decay to pairs of charged particles (protons, antiprotons, pions), were identified by the topology of their decays. Data-taking was completed in 1990. The $\Lambda^0$ production increases linearly with the event multiplicity and, for the same multiplicity, does not depend on the size of the target nucleus.

**NA35 at the SPS**

NA35 was a large acceptance experiment, having a large volume Streamer Chamber within a 1.5T magnetic field and a TPC downstream of the magnet. It measured many hadronic signals and has published results on particle spectra, two-particle correlations, strange particle yields, and other observables. LBL
produced 6,000 channels of readout electronics for the TPC, significantly expanding its capability. Data-taking was completed in 1992.

Analyses at LBL on the TPC data concentrated on charged kaon production, nuclear stopping, and pion interferometry. TPC results on $K^-$ production indicate a strangeness enhancement at midrapidity in agreement with previous results backward of midrapidity from the Streamer Chamber. This enhancement is a factor two for $S + S$ collisions with respect to an independent superposition of $p + p$ or $p + A$ interactions. Nuclear stopping, defined as the mean rapidity shift of projectile protons from beam rapidity, is estimated using TPC data in the forward direction by subtracting the number of negative hadrons from positive hadrons. For central $S + Au$ collisions the rapidity shift measured indicates a significant amount of stopping (as large as at AGS energies). With the high statistics of the NA35 TPC data, a decrease of observed source size with transverse momentum was found.

**NA49 at the SPS**

NA49 is a large acceptance experiment based on a set of Time Projection Chambers. Particle identification is performed primarily by the measurement of $dE/dx$ in the relativistic rise regime (leading to TPCs that are 3.6 m deep), supplemented by time-of-flight over a part of phase space. Event characterization for triggering is performed by forward calorimetry.

LBL's responsibility for NA49 hardware is the development and manufacture of electronics for the 182k TPC readout channels. This very large number of channels necessitated new developments in TPC front-end integrated circuitry for cost, engineering, and reliability reasons. LBL developed a 16-channel integrated preamplifier/shaper-amplifier and a 16-channel switched-capacitor-array/ADC. In addition, LBL produced the control-and-transfer boards and the readout boards. Lead beams were first delivered by the SPS in November 1994. Half of the TPCs and electronics were installed and the rest will be ready for the fall 1995 run.

**STAR at RHIC**

This experiment will consist of a Time Projection Chamber (TPC) and Silicon Vertex Tracker located inside a 5.2-m-diameter solenoidal magnet to provide tracking, momentum analysis, and particle identification of charged particles using the $dE/dx$ technique. The trigger detector systems include a central scintillator barrel around the TPC, vertex position detectors near the beamline just outside the magnet, and calorimeters located in the region of the beam insertion magnets to selectively veto events according to the number of spectators. Anticipated as upgrades are an electromagnetic calorimeter to trigger on transverse energy and measure jet cross-sections, a time-of-flight system surrounding the TPC for particle identification at higher momenta, and external time projection chambers outside the magnet to extend the pseudorapidity coverage.
LBL’s Relativistic Nuclear Collisions Program is providing a focus for these RHIC activities. With 40 physicists and engineers from LBL working on this experiment, the STAR collaboration now consists of 350 physicists and engineers from 34 institutions internationally. Within the STAR organization, RNC has primary responsibility for the TPC, TPC electronics, and overall detector integration. RNC also has significant responsibilities within the DAQ and software efforts in STAR. RNC physicists form the core of the software development that is focused on tracking and particle identification by $dE/dx$ in the TPC. STAR will be ready to begin taking data in 1999 when RHIC begins operations.

### Development

#### Microstrip Gas Chambers for TPC Readout

Traditionally, TPCs have been read out with multiwire proportional chambers located over a surface of pads that pick up the induced signal from avalanches on the wires. This technology sets a practical limit on the two-track resolution and the position resolution that can be obtained with a TPC. The new Microstrip Gas Chamber (MSGC) devices can overcome this limit and allow TPCs to be operated in much higher track density environments with improved position resolution. In the last year conductive coatings have been developed that stabilize the gas gain, reduce the leakage current, and make MSGC fabrication compatible with many substrates.

#### P-Type Silicon Drift Detectors

P-type silicon drift detectors have been designed and fabricated at LBL. Preliminary tests show that the detectors function well and that the signal transit time is linear with position for these devices. The energy and the two-track resolution are being measured. Work is also going on to integrate polycrystalline silicon voltage dividers directly on the detectors.

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The Nuclear Theory Program at LBL seeks to achieve a deeper understanding of the physical nature of quantal many-body systems at and below the hadronic level. Such studies involve developing and applying theories and methods for prediction, analysis, and interpretation of experiments. Research topics pursued include, in particular, intermediate- and high-energy nuclear collisions, properties and probes of hot and dense matter, structure of dense stellar objects, and macroscopic static and dynamical nuclear properties.

The reaction studies involve the development of transport models at the hadronic and partonic levels for addressing the physics of nuclear collisions at both intermediate and ultrarelativistic energies. The astrophysical efforts have been focused on the composition and structure of compact stellar objects and the effect of neutrino transport on supernova explosions. The macroscopic studies range from the equation of state of ultra dense matter and the associated phase transitions to the calculation of masses and fission barriers of ordinary or exotic nuclei. In addition, there is a continuing interdisciplinary effort in the area of chaos theory.

Ultrarelativistic Nuclear Collisions

The main motivation for the investigations of high-energy nuclear collisions is to study the quark-gluon substructure of nuclear matter and the possibility of a phase transition from hadronic matter to quark-gluon plasma at high-energy densities. The ultrarelativistic nuclear collision program in our group addresses both fundamental and phenomenological problems in this subfield. As a nuclear
theory group at a national laboratory, we have made a special effort to develop and implement models in particular to assist the analysis and understanding of both the existing and future experimental data, to find promising signatures for the phase transition, and to predict new results from fundamental theories.

The program includes topics from formal field theory to phenomenology of current and future high-energy hadron and nuclear collisions. Some aspects of the formal theoretical work are directly related to the problems that we encounter in developing phenomenological models. One major goal is to include all major features of the fundamental theories into a model that can describe ultrarelativistic heavy-ion reactions from low to high energies. Such a model can also guide experimentalists to design their detectors for the forthcoming RHIC collider (and the planned LHC) to best take into account the new physics in that energy regime. The existence of a major experimental effort within the Nuclear Science Division (NSD) using CERN and Brookhaven National Laboratory (BNL) facilities has naturally led to close interactions between theorists and experimentalists in this area. For example, since last year, joint Theory and RNC seminars have been held. Moreover, significant theoretical support has been provided for the planned STAR and PHENIX experiments at RHIC.

**Perturbative Approach to QGP Formation**

In the last few years, there has been increasing interest in a perturbative QCD-based description of high-energy heavy-ion collisions based on the parton model. It has been realized that hard or semihard processes will dominate the collision dynamics and constitute most of the initial energy deposition in the central region of ultrarelativistic nuclear collisions. Since the initially produced partons carry relatively large transverse momenta, it becomes possible to estimate the initial energy density and the equilibration time scales using pQCD. Similarly, probes of the formation of QGP using the hard processes can also be calculated perturbatively. Since 1993, we have begun a new program to investigate parton production and equilibration in ultrarelativistic nuclear collisions and the preequilibrium parton dynamics. Our program, including the summer workshop Preequilibrium Parton Dynamics at LBL in 1993, has played a pivotal role in stimulating discussions and international collaborations in this area of study. Several workshops (CERN, LBL, Trento) have been held in the U.S. and Europe since then.

**Hard Probes Collaboration**

As a result of the increased interest in the perturbative QCD approach to ultrarelativistic heavy-ion collisions, an international theory collaboration—Hard Probes of Dense Matter—has been formed, in which our group has played a leading role. The members of the collaboration are: J. Cleymans (Cape Town), K.J. Eskola (Helsinki), R.V. Gavai (Bombay), S. Gavin (BNL), S. Gupta (Bombay), D. Kharzeev (Moscow), E. Quack (GSI), P.V. Ruuskanen (Helsinki), K. Redlich (Wroclaw), H. Satz (CERN), G. Schuler (CERN), D.K. Srivastava (Calcutta), R.L. Thews (Tucson), R.L. Vogt (LBL), and X.-N. Wang (LBL).
The main purpose of this collaboration is to study hard processes in $pp$, $pA$, and $AA$ collisions systematically and explore their potential as probes of the dense matter formed in ultrarelativistic heavy-ion collisions. Two workshops have been held so far, one at CERN and the second at LBL (July 11–22, 1994). The collaboration has so far compiled systematic estimates of hard probe cross-sections in nucleon-nucleon collisions—including open charm, quarkonium, Drell-Yan pairs, direct photons, and high $p_T$ jets—on the nucleon-nucleon level, using the most detailed QCD calculations and the most recent parton distribution functions available. These calculations will serve as a baseline for measurements at RHIC and LHC. The compilation will be published as LBL/CERN reports and will be widely distributed. This report can serve as a handbook for both theorists and experimentalists of hard interaction rates. The next goal of this collaboration is to include nuclear effects on these hard processes.

Initial Conditions and Parton Distributions in Nuclei

The most important factor that controls the gluon equilibration time is the initial density. One of the uncertainties in estimating the initial parton production arises from the initial parton distribution in the colliding nuclei. Taking a perturbative approach to the problem of the nuclear modification of gluon structure function, we found that gluon shadowing can be generated perturbatively from gluon fusion in perturbative QCD.

The consequences of shadowing of the nuclear parton distributions on $J/\psi$ and $\Upsilon$ production have been explored in a specific model. It was found that momentum conservation and the $Q^2$ evolution of the parton distributions cause these heavy vector mesons to be affected differently with observable consequences. A more detailed calculation, including a discussion of the transverse momentum dependence, is forthcoming.

Approach to Parton Equilibration

Using the HIJING Monte Carlo model developed at LBL earlier, we have studied the space-time structure of initial parton production in ultrarelativistic heavy-ion collisions. It was found that the parton production time is on the order of 0.5 fm/$c$ and another 0.5 fm/$c$ later local isotropy is achieved by simple free streaming. An approach to the problem of QCD cascading was also made analytically. An example of radiative dilepton production was studied. This study has clarified certain problems related to Monte Carlo simulations of the problem. The subsequent evolution of the dense partonic gas to a thermally and chemically equilibrated quark-gluon plasmas is also investigated. Medium effects such as color screening, multiple scattering, and interference have also been investigated and incorporated. We find that gluons can achieve equilibrium when their initial density is high enough, but quarks cannot reach chemical equilibrium within the lifetime of the partonic system with serious consequences for detecting QGP. However, the preequilibrium parton interactions can be studied by measuring observables such as open charm production. We have calculated the open charm production from the
equilibrating parton gas and find the results are very sensitive to the initial parton density.

The long-range objective is to develop a space-time parton cascade program that uses HIJING as the initial condition prior to hadronization. This latter development is coupled to both the field theoretic and phenomenological studies described in subsequent sections. The space-time cascade can only be done after a proper understanding of how subtle interference phenomena—e.g., the Landau-Pomeranchuk-Migdal effect—can be included in a classical cascade simulation and how hard partons affect the underlying soft interactions.

**Parton Dynamics and Field Theory**

*LM Effect and Radiative Energy Loss*

Systematic studies of multiple scatterings and radiation within the framework of pQCD are in progress. Due to the unique features of QCD, the interference pattern of multiple radiation induced by multiple scatterings is very different from QED. We have confirmed the validity of the LPM effect in QCD. Our results show that the radiative energy loss could be much larger than the elastic contribution. Because of the LPM effect, the loss is highly sensitive to the infrared cutoff scale. We have investigated whether that extra sensitivity could be exploited as a tool to "measure" the cutoff scale in the vicinity of the QGP transition. For this purpose, jet quenching and monojet production were proposed. We found that a singular variation of the color screening mass near the QCD phase transition will lead to a unique energy dependence of the monojet rate. The same effect has also been included in the calculation of the gluon equilibration rate.

*Transport Properties in QCD*

Parton dynamics have also been studied in the context of high-temperature perturbative QCD calculations of transport properties. The transport properties of relativistic quark-gluon and electron-photon plasmas have been described in the weak coupling limit by including the Debye electric and dynamical magnetic screening of the interactions. Rates of momentum and thermal relaxation, electrical conductivity, viscosities, flavor and spin diffusion have been calculated for high-temperature cases. These transport coefficients have been applied to RHIC collisions, where temperatures are high. The color diffusion in a quark-gluon plasma is found to be much slower than the diffusion of spin and flavor because color is easily exchanged by the gluons in the very singular forward scattering processes. If the infrared divergence is cut off by a magnetic mass, the color diffusion rate is a factor $\alpha_s$ smaller than spin and flavor diffusion. A similar effect is expected in electroweak plasmas above $M_W$ due to $W$ exchanges.

*Dynamical Evolution in a Field Theory*

We are interested in applications of quantum field theory methods (e.g., $1/N_f$ expansion, loop expansions around background fields, closed time path
formalism) to study the formation and evolution of the quark-gluon plasma following a heavy-ion collision. These methods can also be applied to problems associated with the evolution of the hot dense matter after hadronization, such as the possible formation of disoriented chiral condensates.

We plan to apply the above-mentioned methods to QCD, first treating the chromoelectric field as an external classical field (lowest order in $1/N_f$), and then including dynamical gluons and photons in next order. As a first attempt in this direction, we are solving a simpler pure SU(2) Yang-Mills theory. A derivation of a phenomenological transport equation corresponding to the same problems (in the framework of our approximations) is also an important ingredient of the project. The kinetic approach is an intuitive and tractable one, but it is not known a priori, in such a complex system governed by strong interactions, if it is applicable at all. In order to verify which (if any) of the assumptions of the various kinetic models are valid, it will be useful to investigate whether the inclusion of these various effects in a kinetic model is appropriate for describing the physics.

Research into decoherence in the transition from quantum to classical behavior, chaotic behavior of nonlinear systems such as semiclassical QED and classical Weinberg-Salam theory, and the influence of classical dynamical chaos on multiple particle production at high energies has also been planned. Some of these projects require heavy computation and we have developed parallel algorithms for the connection machine. These algorithms are applicable to various dynamical problems in kinetic theory and field theory. They are especially useful for situations that are far from equilibrium.

Chiral Symmetry Restoration

With two physicists in the LBL Physics Division and the UC Berkeley Physics Department a collaboration was developed focusing on the possibility of producing large domains of chirally disoriented pion fields. The size of the domain in spatial rapidity was found to be around two units of rapidity, which could lead to some measurable clusters of chirally ordered pions in phase space. Simulations of the dynamical evolution of the chiral fields are performed that include both longitudinal and transverse expansions. It is found that large domains of disoriented chiral condensates can only be formed through a nonequilibrium rapid cooling, or quench. Studies of the low-momentum enhancement of the pion fields, two-particle correlations due to the squeezed state of the chiral fields, and the thermalization properties in the effective linear sigma model are still under way. We also studied the effects generated through the misalignment of the condensate with electroweak symmetry breaking. We pointed out the relevance of the decay of light vector mesons into dileptons as a signal for the formation of disoriented condensates. We predicted that the dilepton decay of the $\rho$ meson will be suppressed and/or the $\rho$ resonance peak widens, while the dilepton decay of the $\omega$ will not be affected by the condensate.

One of the major goals of the ultrarelativistic heavy-ion program is to detect the restoration of chiral symmetry at high temperature and/or density. To
successfully compare model prediction with experimental data, a transport model is needed that combines the physics of the hadronic phase with that of a chiral phase transition. The latter probably will mostly affect the long wavelength phenomena—such as, for example, in-medium masses—and thus can be included by means of collective (mean field) potentials. To this end, a chiral mean field model needs to be developed that besides chiral symmetry incorporates all other phenomena observed in lattice-gauge calculations around the phase transition—e.g., a sharp rise in the baryon number susceptibility. In a next step the urgent question of hadronization needs to be addressed to make contact with a parton cascade description. Again, useful guidance may be obtained from lattice-gauge determination of Bethe-Salpeter amplitudes around near-the-phase transition.

**Phenomenology**

*Phenomenology for Lattice-Gauge Calculations*

Lattice-gauge calculations provide useful and very interesting insight into the properties of hadrons close to and above the deconfinement phase transition. The behavior of the relevant correlation functions indicate that, even above critical temperature, there are strong color magnetic interactions between quarks, which lead to bound-state-like structures in space like Bethe-Salpeter amplitudes. To which extent these translate into "real" bound states—i.e., hadrons—needs to be investigated by carrying out an analytic continuation into real time. In principle, such an analytic continuation requires the knowledge of an infinite number of correlation functions and thus is difficult to carry out on the lattice. We have constructed, however, an analytic model that reproduces the lattice results for the Bethe-Salpeter amplitudes and hence (one hopes) contains the relevant physics. Our plan is, therefore, to use this model to carry out an analytic continuation. As a result, we will be able to address the question about the importance of the residual magnetic interactions for the transport properties of quarks and gluons in the deconfined phase. This, of course, is highly relevant for the parton cascade desorption of ultrarelativistic heavy-ion collisions.

*High $P_T$ Particles*

The phenomenological aspect of our relativistic nuclear physics program tries not only to provide constraints for the development of a realistic model at both low and high energies but also to explain the current experimental data and propose possible measurements in future experiments. We plan to continue investigating a variety of physics topics with HIJING, including $pA \rightarrow$ dihadron reactions and back-to-back two-particle correlations. Large $P_T$ particle production and suppression, especially baryons and kaons, can be used as a measurement of the jet propagation inside dense matter. Since a quark jet is more likely to produce a leading proton or $K^+$, whereas a gluon can produce both a leading proton ($K^+$) and antiproton ($K^-$), the relative suppression of protons ($K^+$) vs. antiprotons ($K^-$) can be used to measure the relative energy loss of gluons and quarks inside a QGP. Detailed analysis using HIJING is under way.
Heavy Quarks and Dilepton Background

Studies have also been made of heavy-quark and quarkonium production in hadron-proton, hadron-nucleus, and nucleus-nucleus collisions. Fruitful interactions with experimentalists have resulted, especially with the PHENIX collaboration at RHIC.

One line of research is concerned with $J/\psi$ suppression as a probe of dense matter. We found that interactions of the $J/\psi$ with primary nucleons alone cannot account for the observed $J/\psi$ suppression at the CERN SPS. However, if the density of comoving secondaries is five times that of nuclear matter in the ground state, the observed $J/\psi/\text{continuum}$ and $\psi'/J/\psi$ ratios can be accounted for. Predictions for Pb + Pb collisions at the CERN SPS have also been made.

It has long been expected that dilepton production may be used as a quark-gluon plasma probe. The rapidity distributions of thermal dileptons have been compared with dileptons from initial and thermal charm decays as well as Drell-Yan production at RHIC and LHC energies. The dominance of charm production at these energies demonstrates the importance of understanding charm production. As a further step, more refined calculations, including the invariant mass and transverse momentum distributions of the dilepton sources, are in progress, which will include specific detector geometries.

Collaborations with theorists in the particle physics community are also maintained. For example, the intrinsic charm model has been used to explain the asymmetry between leading and nonleading charm production (leading charmed particles contain projectile valence quarks, nonleading ones do not). This model has also been applied to the rare production of $J/\psi$ pairs in hadronic collisions and compared to other $\psi\psi$ pair production mechanisms. The intrinsic charm model highlights only one aspect of higher-twist QCD. The effect of higher-twist processes on the Drell-Yan angular distribution has also been studied. More work on this topic is planned.

QCD Phase Transition Effects on $f$ Production

Due to chiral symmetry restoration, the $f$ mass will decrease with temperature during the phase transition. If the transition is near first order, the system remains at a fixed temperature while converting from a plasma to a hadronic gas. The effect of the temperature dependence of the $f$ mass will then be reflected in a double peak structure in the dilepton spectrum. The peak at $m < m_f$ is due to $f$ decays in the mixed phase while the peak at $m_f$ arises from the decay after freezeout. The detection of the lower mass peak will be an indication of the presence of the mixed phase during the phase transition. The scaling behavior of thermal dileptons has also been studied.

Cross-Section Fluctuations in AA Collisions

A study of transverse energy fluctuation has been carried out in the BNL/AGS and CERN/SPS energy range. The interplay between cross-section fluctuations
from color transparency and nuclear correlations is able to account for the large fluctuations found in the tails of transverse energy spectra by NA34. The size of the cross-section fluctuations can be extracted from nucleon-nucleon diffraction experiments and inelastic shadowing in nucleon-deuterium scatterings at a wide range of collision energies. It is important to incorporate nuclear correlations that reduce the density fluctuations in the nuclei. As a consequence, the fluctuations in multiple nucleon-nucleon collisions, total multiplicity, and transverse energy in relativistic heavy-ion collisions are significantly reduced, particularly for heavy projectiles and targets. The numerical implementation of correlations and cross-section fluctuations in event generators for RHIC collisions are also discussed in these studies.

**Nuclear Dynamics**

The theory program has a continuing effort in the area of nuclear dynamics that addresses the transport properties of nuclear systems under the extreme conditions that can be generated in nuclear collisions at intermediate and relativistic energies. Because of the unique physical scenarios involved, this topic poses especially interesting challenges. An understanding of nuclear dynamics is also necessary for the interpretation of heavy-ion collision experiments and is thus of some urgency.

**Semiclassical Dynamics**

Many macroscopic nuclear properties, both static and dynamic, can be well described on the basis of semiclassical models, in which nucleons moving in a self-consistent, effective one-body field experience occasional two-body scatterings. In general, and especially when instabilities are encountered, it is necessary to incorporate the stochastic character of the elementary scattering processes, thus gaining an ability to treat catastrophic developments. This challenge has been the focal point for a continuing research effort, in which a Fokker-Planck treatment of the Boltzmann-Langevin theory has been developed and employed for understanding the equilibration dynamics and the triggering of catastrophies in nuclear matter. A study was recently completed in which the task of performing numerical simulations for unstable systems was addressed and a quantitative comparison was made between the lattice and test-particle methods. In another collaboration, an analysis was made of the Boltzmann-Langevin dynamics in nuclear matter and a comparison was made between the use of an orthogonal projection, as originally proposed, and the explicitly known dual basis.

A major remaining task is to apply this extended theory to nuclear multifragmentation dynamics. This undertaking requires the development of approximate methods, since the full theory is prohibitively computer intensive. For this purpose, simple analytical expressions for the transport coefficients have been derived. They are accurate for small temperatures and near equilibrium and are expected to be quantitatively useful for multifragmentation scenarios. The numerical effort associated with solving the Boltzmann-Langevin equation for the nucleon phase-space density $f$ can then be reduced by orders of
magnitude, by picking the stochastic changes in $f$ on the basis of the transport coefficients, rather than by simulating the basic two-particle two-hole processes as previously done. This novel method has been illustrated for a maximally simple Boltzmann-Langevin model applied to the equilibration in a Fermi-Dirac gas and is presently being implemented for realistic scenarios. Once completed and tested, this code will make it possible to address realistic collision scenarios and, in particular, to investigate the extent to which the much-discussed exotic multifragmentation processes do in fact occur and, if so, how the associated observables provide information about the inherent nuclear transport characteristics.

A number of alternative approaches to the approximate solution of the nuclear Boltzmann-Langevin problem are also being explored. A particularly promising approach consists in replacing the complicated Langevin term by a stochastic force that is tuned so that the same agitation rate is obtained for the most rapidly growing mode inside the unstable spinodal zone of nuclear matter. This novel type of dynamics, called Brownian One-Body Dynamics, has been implemented into an existing BUU code and exploratory studies are currently being made with a group of collaborators at GANIL.

The usual nuclear transport models assume that the dynamics are time-local. This idealization is hard to justify a priori and we have undertaken a study of the effect of a finite memory time on the agitation of unstable modes in nuclear matter. It was shown that the development of fragments can be significantly enhanced, typically by a factor of two, since the memory time tends to suppress the most rapid changes in force. Moreover, when included consistently, the finite memory time ensures that the collective modes are being populated in accordance with quantum statistics, rather than classical statistics, as is physically reasonable.

A-Body Treatments

A recent study has been made with the Antisymmetrized Molecular Dynamics model, for the purpose of assessing its statistical equilibrium properties, which are of decisive importance for the outcome of multifragmentation processes. Using those results as a reference, we have formulated a novel method for incorporating quantum fluctuations into molecular-dynamics simulations of many-body systems, such as those employed for energetic nuclear collision processes. Following Fermi's Golden Rule, we allow spontaneous transitions to occur between the wave packets that are not energy eigenstates. The ensuing diffusive evolution in the space of the wave packet parameters exhibits appealing physical properties, including relaxation toward quantum-statistical equilibrium. This method is presently being implemented into the standard AMD code and simulations are being carried out for the multifragmentation of gold; it is expected that the yield of intermediate-mass fragments will increase and thus be brought into better agreement with the observed data.
Spin-Isospin Modes

Nucleon resonances and mesons play a major role in nuclear collisions at bombarding energies from a few hundreds of MeV per nucleon up to AGS energies. It is therefore important to understand their properties in dense and excited matter. An effort has recently begun to develop a model basis for understanding and calculating such medium effects.

With a view toward implementation in microscopic transport simulations of heavy-ion collisions, the properties of spin-isospin modes were studied in nuclear matter consisting of nucleons and Δ isobars that interact by the exchange of π and ρ mesons. For a standard p-wave interaction and an effective g' short-range interaction, the dispersion relations for the spin-isospin modes, and the associated amplitudes, were calculated at various densities and temperatures within the random-phase approximation. Quantities of physical interest were then extracted, including the total and partial Δ decay widths and the Δ cross-sections in the nuclear medium. The self-consistent inclusion of the Δ width has a strong effect on the Δ cross-sections at twice normal density, as compared with the result of ignoring the width. Generally, the obtained quantities exhibit a strong density dependence, but are fairly insensitive to the temperature, at least up to $T = 25$ MeV. Finally, it was described how these in-medium effects may be consistently included into microscopic transport simulations of nuclear collisions, and the improvements over previous approaches were discussed.

These results are currently being applied to the production of dileptons in the medium. The implementation of the treatment into transport simulations is planned as the next natural step.

Nuclear Astrophysics

The Nuclear Theory Program encompasses a variety of efforts within the general area of astrophysics. While most studies are part of continuing interest in the composition and structure of compact stellar objects, recent activity has arisen concerning the roles of neutrino transport during supernova explosions.

Quark-Hadron Mixed Phase

It was demonstrated several years ago that, contrary to earlier work that incorporated unjustified idealizations, the mixed phase of the hadronic and quark matter phases would not be squeezed out of neutron stars but would occupy a rather wide radial region measured in kilometers. Further, it was shown that an inevitable consequence of the electric charge on quarks and baryons is that the mixed phase would take on such a geometrical structure of objects of one phase immersed in the other that the Coulomb and surface energies would be minimized. Presently, first results for the location, radial extent, and detailed structure, varying with location in the star, are being obtained. The variation with mass of the star is strong. Since a solid region within the star is most likely to effect pulsar glitches, we see in this a possible
reason for the strongly individualistic character of glitch behavior in different pulsars.

**New Class of White Dwarfs**

If the strange-matter hypothesis of Bodmer and Witten is true, then a new class of white dwarfs can exist whose nuclear material in their deep interiors can have a density as high as the neutron drip density, a few hundred times the density in maximum-mass white dwarfs and $4 \times 10^4$ the density in dwarfs of typical mass, $M \sim 0.6 M_\odot$. Their masses fall in the approximate range $10^{-4}$ to $1 M_\odot$. They are stable against acoustical modes of vibration. A strange quark core stabilizes these stars, which otherwise would have central densities that would place them in the unstable region of the sequence between white dwarfs and neutron stars.

**Subsidence of Protoneutron Star into a Black Hole**

A newly formed protoneutron star, prior to the loss of neutrinos, will consist of a charge-neutral mixture of neutrons, protons, electrons, muons, and trapped neutrinos in the lowest energy state available under these circumstances. However, in a few seconds, the neutrinos will escape, enabling the interior of the star to find a lower energy. We study two possibilities: (1) A significant number of baryons will, through the weak interaction, convert to hyperons; (2) hadronic matter may convert to quark matter in the interior where the pressure is high. In either case, the resulting softer equation of state will not support as large a range of stars either in mass or baryon number. Therefore, beyond the baryon number of either of the sequences equilibrated above there is a significant range of protoneutron stars that possess no hydrostatically stable configurations after neutrino loss. They will subside into a black hole on the time-scale of neutrino loss, about ten seconds, and after the processed material of the presupernova star has been ejected. The supernova and neutrino signal will therefore have the signature expected of neutron star formation. We discuss these mechanisms in connection with the apparent absence of a neutron star in SN1987A and the possible deficit of neutron-star supernova associations.

**Strange Stars to Strange Dwarfs**

All possible equilibrium sequences of compact strange-matter stars with nuclear crusts have been determined, ranging from massive strange stars to strange white-dwarf-like objects (strange dwarfs). The properties of such stars are compared with those of their nonstrange counterparts—neutron stars and ordinary white dwarfs. One of the striking features of strange dwarfs is that the entire sequence from the maximum-mass strange star to the maximum-mass strange dwarf is stable to radial oscillations. The minimum-mass star is only conditionally stable, and the sequences on both sides are stable. Such a stable continuous connection does not exist between ordinary white dwarfs and neutron stars, which are known to be separated by a broad range of unstable stars. As a result, we find an expansive range of very-low-mass (planetary-like) strange-matter stars (masses even below $10^{-4} M_\odot$ are possible) that arise as natural dark-matter candidates, which, if abundant enough in our galaxy, should
be seen in the gravitational microlensing searches that are presently being performed.

Strange and Charm Stars at Finite Temperature

In this project we study the properties of beta-equilibrated, electrical-charge-neutral quark-star matter at zero and finite temperatures, and determine its equation of state. The properties of sequences of quark stars, divided into strange- and charm-quark stars, depending on quark-flavor content, are investigated. The electrostatic potential of electrons inside and in the close vicinity outside of strange stars, which is of decisive importance for the possible existence of nuclear crusts on the surfaces of such stars, is computed for zero and finite temperatures. The structure and stability of quark stars against radial oscillations is discussed, and it is found that charm-quark stars are unstable against radial oscillations. Thus no charm-quark stars (and, as is demonstrated too, no quark-matter stars possessing still higher central mass densities) can exist in nature.

Nuclear Properties

The efforts of group members in extending our understanding of macroscopic nuclear properties have resulted in a number of important breakthroughs.

Nuclear Properties According to the Thomas-Fermi Model

We have developed a Thomas-Fermi model of average nuclear properties capable of reproducing the situation energy and density of nuclear matter, the surface and symmetry energies, the surface diffuseness, the optical potential (including its energy and isospin dependence), and other properties. Moreover, fast and accurate numerical techniques have been implemented for solving the Thomas-Fermi equations for deformed (fissioning) nuclear shapes. A long-standing problem concerning the curvature correction to the nuclear surface energy has been solved and the relationship between the compressibility of nuclear matter and that of finite nuclei has been elucidated. A table of some eight thousand predicted nuclear masses has been prepared. Fission barriers have been calculated and are in excellent agreement with measured values. Currently the important influence of angular momentum is being added to these calculations. Since the dripline behavior of these predictions is expected to be superior to that of liquid drop models, we can foresee a number of applications in astrophysics.

Relativistic Nuclear Matter

Knowledge of the equation of state of relativistic nuclear matter and asymmetric matter is of fundamental importance in astrophysics (e.g., supernovae and neutron stars) and in heavy-ion collisions. Models for the equation of state have been developed in the framework of the relativistic Bruckner-Hartree-Fock approximation. The relativistic field equations were solved self-consistently in the full (i.e., particle-antiparticle) Dirac space. The
results were compared with those of the standard method in which the scattering amplitude is determined for positive-energy spinors only. We find, for example, that the properties of relativistic asymmetric matter are similar to those obtained for the relativistic Hartree-Fock approximation. Relativistic effects were found to be important for obtaining saturation in nuclear matter at the empirical value.

### Transition from Order to Chaos

The development of a macroscopic theory of nuclear dynamics continues based on the parallel between a transition from ordered to chaotic nuclear motions and the transition from an elastic to a dissipative collective response of the nucleus. This research is being carried out in collaboration with a number of Polish physicists who have been funded by the U.S.-Polish Maria Sklodowska-Curie Joint Fund, and who are frequent visitors to the group. So far our major effort has been directed toward firmly establishing the connection between nuclear dynamics and the vast amount of current research on chaos, both classical and quantal. Current work is focusing more and more on questions concerning dissipation in the dynamics of simple model quantum systems.
Nuclear Data Evaluation Program: Isotopes Project

J.M. Dairiki

The Isotopes Project compiles, evaluates, and disseminates nuclear structure and radioactive decay data for basic and applied research. The group coordinates its activities with both the national and international data networks and, in particular, plays a major leadership role in the U.S. Nuclear Data Network (USNDN). The traditional strong data evaluation effort of the group continues; much of this effort is now directed toward the network's pioneering horizontal data evaluations. The Isotopes Project has become a lead data center for the development of new electronic dissemination and publication methods for nuclear data.

During the past year, the Isotopes Project hosted the 11th IAEA Advisory Group Meeting on the Coordination of the Nuclear Structure and Decay Data Evaluator's Network. This biennial meeting, held at LBL on May 16–20, 1994, was attended by 40 nuclear physicists from 14 countries. The meeting agenda focused on future planning and how to provide for the evolving data needs of researchers as research priorities change.

Data Evaluation

New research priorities present special opportunities and challenges for the nuclear data program. Two areas of opportunity are the needs of the high-spin research community—where new detector arrays such as Gammasphere and Eurogam are producing data at tremendous rates—and the needs of both the
basic and applied research communities for critically evaluated decay data standards. It was agreed at the 1994 international meeting that about 20% of the total international evaluation effort should be directed toward these new "horizontal" areas of evaluation. The Isotopes Project immediately implemented this decision and, as a result, over half of the evaluation effort is now devoted to horizontal evaluations, as discussed below.

**High-Spin Data Evaluation**

One of the recommendations of the May 1994 IAEA meeting was that ~2 FTEs from the present international nuclear structure evaluation effort should be devoted to evaluate, on a priority basis, the data from heavy-ion-induced gamma-ray spectroscopy experiments. An action item was placed on B. Singh (LBL and McMaster University) to organize this effort. He has identified ~2 FTEs from the data centers at LBL, Lund, McMaster, BNL, and ORNL, and preliminary mass-chain assignments (for high-spin data only) have been made. Two criteria were used to prioritize the mass chains for the initial assignments: (1) mass chains published before 1990, and (2) mass chains in the superdeformed regions (A = 130–137, 142–153, 189–198). There are about 40 mass chains in this category and none of them is presently being updated by the responsible center. High-spin data in seven mass chains have been updated so far. B. Singh also prepared a set of guidelines for both preparation and review of the high-spin evaluations and their inclusion in the Evaluated Nuclear Structure Data File (ENSDF).

In addition, a search is currently under way at LBL for a high-spin data coordinator to work with the data networks and the research community to provide the data needed by the community.

**Decay Data Evaluation**

In accordance with an action item from the May IAEA meeting (and in consultation with the research community), E. Browne (LBL), R. Helmer (INEL), and M. Schmorak (ORNL) have prepared a list of about 250 radionuclides of interest to both basic and applied researchers. This work is being done in collaboration with A.L. Nichols (AEA Technology, England) and K.D. Debertin (PTB, Germany) and is also coordinated with a broader international effort sponsored by the IAEA. After the initial list is approved, the collaborators will begin the comprehensive evaluation work.

**Astrophysics Data Evaluation**

At the May IAEA meeting, an action was placed on the network to keep abreast of and solicit activities in other areas where horizontal evaluations may be appropriate in the future. In collaboration with the LBL Institute for Nuclear and Particle Astrophysics (INPA) and the Particle Data Group, the Isotopes Project is exploring the data needs of the astrophysics community and how they might best be satisfied.
Mass Chain Evaluations

The group’s mass-chain evaluation responsibilities are unchanged, although in the short term we expect less action in this area. The Isotopes Project has permanent responsibility for evaluating mass chains with A = 81, 83, 89–93, 167–194, 206, 210–212, 215, 219, 223, 227, and for adapting evaluated data with A = 23–26, 33–44 into the ENSDF format. The group has accepted temporary responsibility for evaluating mass chains with A = 59, 76, 79, and 80, originally assigned to other centers. Two mass chains (A = 194 and 186) and one continuous evaluation are expected to be submitted for publication in calendar year 1995.

Publications

Table of Isotopes, 8th Edition

Between 1940 and 1978, the Isotopes Project produced seven editions of the Table of Isotopes. Each edition provided a comprehensive and critical evaluation of the known nuclear properties deduced from radioactive decay and reaction data. The 8th Edition is expected to be completed and sent to the publisher (John Wiley) later this year. Both printed and CD-ROM versions are being prepared and will be published simultaneously. The printed version will be two volumes (~3,000 pages) and is expected to cost under $150 including a free copy of the CD-ROM. The CD-ROM version contains the Table of Isotopes, Table of Superdeformed Nuclear Bands and Fission Isomers, radioactive decay radiation tables with energy-ordered gamma-ray and alpha-particle tables, Nuclear Science Reference Abstracts, and various nuclear charts and appendices. The CD-ROM will also provide copies of the Adobe Acrobat Reader viewer for both PC and Macintosh computers. Annual updates of the CD-ROM are planned.

Table of Superdeformed Nuclear Bands and Fission Isomers

The Table of Superdeformed Nuclear Bands and Fission Isomers has been updated and published as an LBL report (October 1994). This book contains adopted level data for each nucleus with superdeformed bands, the moment of inertia and induced moments for each band, and band level scheme drawings. Additional related data for actinide shape (fission) isomers have been included. Preprints were distributed at the meeting on Physics from Large Gamma-Ray Detector Arrays held in Berkeley, August 2–6, 1994. This publication, prepared in collaboration with McMaster University, will be updated annually. Data used for this publication are maintained in the Evaluated High-Spin Data File (EHSDF).

Electronic Data Dissemination

The Isotopes Project is developing electronic access to the Evaluated Nuclear Structure Data File (ENSDF), the Nuclear Science References (NSR) file, and related files. New electronic publications will provide an alternative to the
traditional hard-copy publications. Because the ENSDF format was developed 20 years ago, the file lacks the indexing, organization, and data structures necessary for fast and efficient data retrieval. Therefore, modernization of the database is currently under way. In its final form, ENSDF will be provided with an interactive file editor that will free evaluators from specific knowledge of data formats and also allow many more scientists to use the ENSDF tools and participate in evaluation.

**PAPYRUS-NSR**

A collaboration between the University of Lund and LBL has implemented and released the Nuclear Science References (NSR) file (produced by S. Ramavataram, Brookhaven National Laboratory) for PCs, as a complement to the existing on-line system. Retrieval of information can be done using the PAPYRUS bibliographic database management system, produced by Research Software Design. The entire database is up to date as of December 1993 and is being distributed on compact disks (CD-ROM). This system will be useful in particular for those who do not have on-line computer network access to NSR.

The release of Papyrus NSR was announced at the 1994 IAEA meeting in Berkeley and subsequently in the LBL weekly newsletter *Currents* and the APS Division of Nuclear Physics Newsletter. Approximately 850 complimentary copies have been distributed, many at the Fall Meeting of the American Physical Society Division of Nuclear Physics at Williamsburg. A demonstration of Papyrus NSR was enthusiastically received at the meeting on Physics from Large Gamma-Ray Detector Arrays held in Berkeley in August 1994. A survey has been enclosed with each CD-ROM to gain feedback for subsequent versions. An update is planned later this year.

**VuENSDF and World Wide Web**

VuENSDF is a computer code for viewing ENSDF-format data on personal computers. The present version supports the selection and display of data sets from the ENSDF file; both level scheme drawings and tabular listings are available. The drawings can be scaled interactively and rotational band drawings or radioactive decay schemes can be drawn. Coincidence gates can be set on decay schemes to highlight specific gamma rays and display the coincidence relationships within the decay scheme. An alpha test version of VuENSDF for the Macintosh has been widely distributed and is available in the Gammasphere user area at the 88-Inch Cyclotron. VuENSDF is currently being upgraded to C++ code to simplify porting the code to other computer platforms and to fully support the strengths inherent in object-oriented programming. Future enhancements of VuENSDF will include interrogatory database searching, format-free data entry, and full text and reference support.

A preliminary beta test version of VuENSDF is available on the World Wide Web. The Web is an ideal medium for making both data and interactive software programs available to all users. In coordination with the other data centers, we will continue to explore new ways to expand data services on the Web. In
particular, we plan to make the *Table of Isotopes* available on the Web (in addition to the regular CD-ROM updates).

**Nuclear Charts**

The Evaluated Nuclear Chart Data File (ENCDF), derived from ENSDF and other data files, contains ground-state and isomer information including half-lives, decay branching intensities, isotopic abundances, thermal neutron cross sections, and up-to-date information on atomic masses. Specialized charts have been prepared for researchers interested in radioactive beams and nuclear astrophysics; others can be provided upon request. ENCDF will be used to prepare Nuclear Charts for the *Table of Isotopes* and for development of the graphical interface to VuENSDF.

**Long-Term Challenge**

In the longer term, a major challenge is to incorporate the experimental and evaluated nuclear databases into a broader, computer-based nuclear science information system that could also include theoretical calculations, analysis tools, computer program libraries, and links to electronic scientific papers.
88-Inch Cyclotron Operations

C.M. Lyneis

The 88-Inch Cyclotron is a versatile and reliable accelerator of beams from hydrogen to uranium. It is operated by Lawrence Berkeley Laboratory (LBL) as a national facility in support of the U.S. Department of Energy programs in nuclear science. Forefront scientific research in nuclear structure, heavy elements, proton-rich nuclei, nuclear astrophysics, fundamental symmetries, and reaction mechanisms is carried out. During FY94, a total of 272 users took part in experiments utilizing 4,955 hours of beam on target. These scientists came from LBL (69), other national laboratories (30), universities (82), foreign institutions (50), and industrial companies (41). The Cyclotron plays an important role in educating and training young scientists at the undergraduate, graduate, and postdoctoral stages of their careers; for example, 40 postdocs, 66 graduate students, and 8 undergraduate students are presently involved in research at the facility. The Cyclotron also provides beams for the application of nuclear techniques to other areas of research, including biology and medicine and industrial applications. Industrial partners from aerospace and semiconductor corporations, as well as from NASA, DOE, and DOD laboratories, use beams from the Cyclotron to study the interaction of ions in microcircuits, simulating the cosmic-ray environment in space.

The 88-Inch Cyclotron is the site of Gammasphere, a high-resolution gamma-ray detector array that is a major initiative of the nuclear structure research community. Although still under construction, Gammasphere has been operating in an Early Implementation mode with 36 detectors since April 1993. It is scheduled to begin Phase I operation with 50–60 detectors in March 1995.
When completed in October 1995, it will consist of an array of 110 large Compton-suppressed germanium detectors that will be the most powerful such array in the world.

Accelerator Use

Operation of the 88-Inch Cyclotron was at seven days/week for the first nine months of FY94. In August, it was converted to six days/week until Gammasphere completed its transition to Phase I operation (late February 1995). In FY94, 4,955 hours were committed to research hours, up 15% from the previous year, reflecting the switch to the seven-day-per-week operation. The Accelerator Operation Summary (Table 1) shows that 84.5% of the scheduled time was used for research (beam on target) while the remaining time was divided between tuning (10.9%), machine studies (2.8%), and unscheduled maintenance (1.8%). Nuclear research accounted for 4,279 research hours, applied research for 542 hours, and biology for 134 hours. The applied research—in partnership with the aerospace industry, NASA, DOE, and DOD laboratories—consisted of two parts: (1) testing of microelectronics by using cyclotron beams to simulate space radiation, and (2) calibrating detectors for use in space flights. The biology research was done primarily in support of the NASA NSCORT program.

Ions, Energies, and Intensities

The 88-Inch Cyclotron, fed by the Electron Cyclotron Resonance (ECR) sources, provides a wide range of ions, energies, and intensities in support of the experimental program. Using the low- and high-temperature ovens in the ECR sources, most elements can be accelerated. The beams that have been accelerated are listed in Table 2. The isotopes, which are run from natural feeds, are listed in parentheses. In addition, many ions have been run using isotopically enriched source materials, including $^3\text{He}$, $^{13}\text{C}$, $^{15}\text{N}$, $^{18}\text{O}$, $^{21,22}\text{Ne}$, $^{33,34,36}\text{S}$, $^{44,48}\text{Ca}$, $^{64}\text{Ni}$, $^{70}\text{Ge}$, $^{78,86}\text{Kr}$, $^{136}\text{Xe}$. For the heavy-element program, 512 hours of $^{18}\text{O}$ and 228 hours of $^{22}\text{Ne}$ were scheduled during FY94. For Gammasphere, $^{36}\text{S}$ (356 scheduled hours), $^{48}\text{Ca}$ (336 scheduled hours), and $^{64}\text{Ni}$ (96 scheduled hours) beams were run. Our ability to economically produce these beams from isotopically enriched samples stems from the high efficiency of the ECR ion sources and excellent transmission through the cyclotron and beam transport lines.

The variety of beams, energies, and intensities described in Table 2 have been developed in support of the research programs. Heavy-element radiochemistry experiments require intense (several eµA) heavy-ion beams up to mass 48 at 6–8 MeV/nucleon. Groups studying heavy-ion reaction mechanism and complex fragmentation of highly excited nuclei use higher energy beams such as nitrogen and oxygen at 32 MeV/nucleon, neon at 25 MeV/nucleon, and krypton at 13 MeV/nucleon. In addition to the heavy-ion beams used with the cyclotron, the light ion beams continue to be frequently used. For example, the laser trapping of radioactive beams, which was first demonstrated in December 1993, uses 25
MeV proton beams to produce the $^{21}\text{Na}$. The study of $\beta$-delayed proton emission requires several $\mu$A beams of $^3\text{He}$ at 40 to 110 MeV. The nuclear astrophysics group typically uses beams of protons, deuterons, $^3\text{He}$ and $^4\text{He}$ at 8–25 MeV/nucleon.

**ECR Ion Source Development**

Besides providing high-charge-state ions for the Cyclotron, the Advanced ECR (AECR) source is used to continue source development. Performance of the AECR source, which is a single-stage source designed to operate only at 14 GHz (single-frequency heating), is improved by heating the plasma simultaneously with microwaves of 10 and 14 GHz (two-frequency heating). Plasma stability is improved and the ion charge-state distribution shifts to a higher charge state, which indicates an increase in the $n_e t_i$ product of the ECR plasma. With two-frequency heating, the greatest improvements on both charge state and current were with bismuth and uranium. During the tests, world record currents from an ECR source were produced for $\text{Ar}^{17+}$ (0.17 eJ.LA) and fully stripped $\text{Ar}$ (0.005 eJ.LA), $\text{Bi}^{21+}$ (12.1 eJ.LA), $\text{Bi}^{36+}$ (6.5 eJ.LA), $\text{U}^{33+}$ (12 eJ.LA), $\text{U}^{38+}$ (5.4 eJ.LA) and $\text{U}^{43+}$ (0.5 eJ.LA). Record high-charge-state ions of bismuth and uranium with lower intensity, such as $\text{Bi}^{51+}$, $\text{Bi}^{52+}$, $\text{U}^{52+}$, and $\text{U}^{53+}$, were also produced. With these high-charge-state ions, the 88-Inch Cyclotron accelerated bismuth and uranium to more than 5 MeV per nucleon for the first time.

**Facility for Exotic Atom Trapping (FEAT)**

Work began in FY94 to move the laser trapping research program into a dedicated beamline. A new vacuum tank was constructed for a magnet in the Cave 3 beamline to allow a third line to run from it. The shielding blocks between Caves 3 and 5 were moved to allow for an opening between the two caves. The oven to make the radioactive $^{21}\text{Na}$ or $^{209,211}\text{Fr}$ will be located in the Cave 3 beamline, and the radioactive atoms will be transported to Cave 5 for trapping. This project will be completed in FY95.

**Accelerator Improvement Projects (AIP) at the 88-Inch Cyclotron**

The FY93 AIP project, the Heavy Ion Performance Upgrade, has two parts. The first will improve heavy-ion transmission in the cyclotron by providing better vacuum, and the second will reduce the beam pulse width from the cyclotron to improve beam timing. The key component of the vacuum upgrade will be a new cryopanel that will be installed on the south side of the cyclotron. Cooling for the new cryopanel will be provided by a CT-1400 refrigerator. The engineering design for the panel has been completed; fabrication and installation are scheduled for this summer. The goal of the second project is to provide cyclotron beams with individual beam pulses reduced from the present 5–10 ns to 1 ns. This reduction in beam pulse size is requested by the Gammasphere users. The method is to use internal defining slits at radii of 5–10 inches to collimate the
beam, clipping off the edges of the pulses. In the first phase of this project calculational tools were developed to track the cyclotron orbits so that the optimum location and size of the defining slits could be determined. This was accomplished by adapting computer codes from NSCL at Michigan State University to the 88-Inch Cyclotron. The calculations are now complete and there is good agreement between centered orbits in the calculation and in actual cyclotron runs. The second phase was the development of instrumentation including a fast Faraday cup to measure beam timing. A multturn collimator was also installed and the phase width was brought down to approximately 1 ns. Improvements in the multturn collimator are under way and additional diagnostic equipment is being built so that the full system can be completed this year.

The FY94 AIP project will modernize the radiation safety interlock system of the 88-Inch Cyclotron. This upgrade involves designing, fabricating, and installing a second redundant interlock chain for each of the experimental caves and cyclotron areas. The new redundant chain will operate with Process Logic Controllers (PLCs), which will be the first time this method has been used at LBL. The electronic design is well along, the remote I/O units and the main PLC have been purchased, and conduit to the sensing devices is being installed.

**User Support**

The Research Coordination Group provides information, assistance, and coordination to users of the 88-Inch Cyclotron. It is the main contact between the Cyclotron operations staff and outside users. As such, the group is responsible for developing and maintaining experimental facilities at the Cyclotron, and for making these facilities attractive to a diverse group of users from around the country and, in some cases, from around the world.

Our users fall into two classes: (1) scientific users whose experimental proposals are reviewed by a Program Advisory Committee (PAC) and who are awarded time based on the scientific merits of their proposals (or who are awarded discretionary time by the Cyclotron Head), and (2) industrial users who purchase beam time for their own proprietary use.

The Research Coordination Group coordinates the PAC, which meets three times a year to review proposals for beam time. It supports the 88-Inch Users' Association and its Executive Committee through sponsoring telephone conferences or meetings of the Executive Committee on an as-needed basis to transmit user concerns to the Cyclotron management. It also sponsors an annual users' meeting at the fall meeting of the Division of Nuclear Physics of the American Physical Society. It supports the Gammasphere Users' Executive Committee through surface mailings and E-mail venues. It provides general information to users of the 88-Inch Cyclotron by publishing a newsletter six times per year. It supports the 88-Inch Users' World Wide Web service to provide news and information on the Cyclotron and its programs to users and the general public.
The Research Coordination Group has successfully dealt with the large increase in the number of outside users brought in by Gammasphere. During FY94, a total of 272 users took part in experiments amounting to 4,955 hours of beam on target, 2,700 for Gammasphere Early Implementation (EI). These scientists came from LBL (69 total, 14 EI), other national laboratories (30 total, 22 EI), universities (82 total, 72 EI), international (50 total, 39 EI), and industrial companies (41). There were 66 graduate students using the 88-Inch Cyclotron for some portion of their thesis research, and 8 undergraduates also working on experiments.

Nonnuclear Science Research

The 88-Inch Cyclotron is a major source of heavy-ion beams for Single-Event Effect (SEE) testing of solid-state components for the U.S. space program. Because of the ability to run “cocktails” of beams, enabling switches from one ion to another in a matter of minutes, it is possible to quickly establish the energy deposition level at which a SEE will occur. The availability of proton beams, used for studying radiation effects on charge-coupled devices, has further increased the demand for use of the Cyclotron.

The Aerospace Corporation, in cooperation with 88-Inch Operations, has installed a specially instrumented scattering chamber on a dedicated beamline in Cave 4b. When the full instrumentation of this chamber is complete in FY95, the 88-Inch will be able to support a state-of-the-art, user-friendly facility for industrial and government users on a cost-recovery basis. Work is in progress to develop and improve the beam diagnostics for a variety of energies and ions of interest to applied customers. This upgrade has benefited both smaller companies, which do not have the resources to provide their own diagnostics, and Cyclotron Operations with increased efficiency in tuning.

The Biomed Program, transferred to the Cyclotron from the Bevalac in FY93, ran very successfully in FY94. The effect of radiation on cells is studied through the use of high-energy protons, helium, and nitrogen to simulate the cosmic-ray environment of space.

Safety

We continue to devote significant effort to improving the safety and conduct of operations at the Cyclotron. EH&S Division staff are involved early in the scheduling cycle to flag and alleviate potential safety problems before they happen.

Publications

Table 1. FY94 88-Inch Cyclotron operating statistics.

<table>
<thead>
<tr>
<th>Accelerator Operation Summary</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Research</td>
<td>4,955 (hours)</td>
</tr>
<tr>
<td>Tuning</td>
<td>637</td>
</tr>
<tr>
<td>Machine Studies</td>
<td>163</td>
</tr>
<tr>
<td>Unscheduled Shutdowns</td>
<td>104</td>
</tr>
<tr>
<td>Scheduled Shutdowns</td>
<td>2,901</td>
</tr>
<tr>
<td>Electrical Energy Consumption (GWH)</td>
<td>7.9</td>
</tr>
<tr>
<td>Cost of Electrical Energy (thousands of dollars)</td>
<td>402</td>
</tr>
</tbody>
</table>

**Financial Support for Accelerator Facility Operation** (thousands of dollars)

- Heavy-Ion Physics (KB-02-02) | 3,420 |
- Low-Energy Physics (KB 04-02) | 0     |
- Biomedical and Environmental Research | 0     |
- Other Sources                 | 280   |
| Total                         | 3,700 |

**Experiment Summary**

<table>
<thead>
<tr>
<th>Beam Utilization for Research</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Research</td>
<td>4,279 (hours)</td>
</tr>
<tr>
<td>Atomic Physics</td>
<td>0</td>
</tr>
<tr>
<td>Biology and Medicine</td>
<td>134</td>
</tr>
<tr>
<td>Other Research</td>
<td>542</td>
</tr>
<tr>
<td>Total</td>
<td>4,955</td>
</tr>
</tbody>
</table>

**Nuclear Science Research**

- Number of Nuclear Science Experiments | 77 |
- Number of Scientists Participating   | 211 |
- Number of Students                  | 66  |
- Institutions Represented
  - Universities                       | 18  |
  - Other DOE National Laboratories    | 3   |
  - Other                             | 16  |

**Applied Research**

- Number of scientists and engineers | 61  |
- Institutions and Companies        | 13  |

**Percentage of Beam Time (all research)**

- In-House Staff                   | 39  |
- Universities                     | 19  |
- DOE National Laboratories         | 19  |
- Foreign Institutions              | 8   |
- Applied work                      | 15  |
| Total                             | 100 |
Table 2. 88-Inch Cyclotron beam list.

<table>
<thead>
<tr>
<th>Ion(^a)</th>
<th>High Energy(^b) (MeV/u)</th>
<th>Typical Current @ High Energy ((\mu)A)</th>
<th>Typical Current @ =5–6 MeV/u ((\mu)A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>55</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>p (pol.)</td>
<td>50</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>d</td>
<td>32</td>
<td>0.7</td>
<td>20</td>
</tr>
<tr>
<td>d (pol.)</td>
<td>32</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>(^3)He</td>
<td>45</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>(^4)He</td>
<td>32</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>(^7)Li</td>
<td>23</td>
<td>0.4</td>
<td>2</td>
</tr>
<tr>
<td>(^9)Be</td>
<td>25</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>(^{11})B</td>
<td>26</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>(^{12})C</td>
<td>32</td>
<td>0.01</td>
<td>12</td>
</tr>
<tr>
<td>(^{14})N</td>
<td>32</td>
<td>0.03</td>
<td>5</td>
</tr>
<tr>
<td>(^{16})O</td>
<td>32</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>(^{19})F</td>
<td>29</td>
<td>0.9</td>
<td>0.35</td>
</tr>
<tr>
<td>(^{20})Ne (22)</td>
<td>32</td>
<td>0.25</td>
<td>4</td>
</tr>
<tr>
<td>(^{23})Na</td>
<td>29</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>(^{24})Mg (25,26)</td>
<td>32</td>
<td>0.7</td>
<td>3</td>
</tr>
<tr>
<td>(^{27})Al</td>
<td>30</td>
<td>0.07</td>
<td>4.5</td>
</tr>
<tr>
<td>(^{28})Si (29,30)</td>
<td>32</td>
<td>2.2</td>
<td>2</td>
</tr>
<tr>
<td>(^{31})P</td>
<td>30</td>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>(^{32})S (34)</td>
<td>32</td>
<td>0.32</td>
<td>4</td>
</tr>
<tr>
<td>(^{35})Cl (37)</td>
<td>30</td>
<td>0.01</td>
<td>0.5</td>
</tr>
<tr>
<td>(^{40})Ar</td>
<td>23</td>
<td>0.04(^c)</td>
<td>1</td>
</tr>
<tr>
<td>(^{39})K</td>
<td>24</td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td>(^{40})Ca</td>
<td>23</td>
<td>0.13</td>
<td>2.5</td>
</tr>
<tr>
<td>(^{45})Sc</td>
<td>22</td>
<td>0.023</td>
<td>0.22</td>
</tr>
<tr>
<td>(^{48})Ti</td>
<td>21.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>(^{51})V</td>
<td>20</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>(^{52})Cr</td>
<td>20</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>(^{55})Mn</td>
<td>20</td>
<td>0.3</td>
<td>—</td>
</tr>
<tr>
<td>(^{56})Fe (54)</td>
<td>20</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>(^{59})Co</td>
<td>19</td>
<td>0.006</td>
<td>0.01</td>
</tr>
<tr>
<td>(^{58})Ni</td>
<td>19</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>(^{63})Cu (65)</td>
<td>18.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Table 2. Continued.

<table>
<thead>
<tr>
<th>Iona</th>
<th>High Energyb (MeV/u)</th>
<th>Typical Current @ High Energy (eμA)</th>
<th>Typical Current @=5–6 MeV/u (eμA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>84Kr (78,82,86)</td>
<td>14</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>107Ag</td>
<td>11</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>120Sn (118)</td>
<td>9</td>
<td>0.002</td>
<td>—</td>
</tr>
<tr>
<td>132Xe (129,131,136)</td>
<td>8</td>
<td>0.013c</td>
<td>0.013c</td>
</tr>
<tr>
<td>139La</td>
<td>8</td>
<td>0.002</td>
<td>0.03</td>
</tr>
<tr>
<td>159Tb</td>
<td>7</td>
<td>0.006</td>
<td>0.006</td>
</tr>
<tr>
<td>209Bi</td>
<td>5</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
<tr>
<td>238U</td>
<td>4</td>
<td>0.001</td>
<td>—</td>
</tr>
</tbody>
</table>

Notes for Table 2:

- Most abundant isotope is listed. Other isotopes run from natural feed are shown in parentheses. Their intensities are proportional to the isotopic abundance, and their high-energy values are proportional to $1/A^2$.
- For M>60, the high energy corresponds to 1 pnA of beam from the AECR.
- AECR measurement; other quoted currents are for ECR beams. AECR gives roughly 5x the ECR beam intensity for all but the heaviest (M>80) highest-energy ions.

The following ions have been run at the 88-Inch Cyclotron using isotopically enriched source material. The intensity is proportional to enrichment factor and currents for the same element in the table:

$^{13}$C, $^{15}$N, $^{18}$O, $^{21,22}$Ne, $^{33,34,36}$S, $^{36}$Ar, $^{44,48}$Ca, $^{70}$Ge, $^{78,86}$Kr, $^{136}$Xe
GROUP LISTS
Group Lists

Following are the names of people in the Nuclear Science Division groups. At the end of each list are the long-term visitors with their home institutions in parenthesis. [Group leaders are in bold face. * = Graduate student. ** = Undergraduate student.]

**Administrative Staff**

K. Balder-Froid
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R.E. Hodges
J.B. Lofdahl
M.K. Loo
M.E. Montgomery
B.E. Phillips
T.S. Pouncey
W.J. Smith-Burnett
M.B. Star
C.J. Sterling
J.C. Sterling
T.J.M. Symons, Director
P.M. Mendoza** (UC Berkeley)
W. Quan** (UC Berkeley)

**For Glenn T. Seaborg,**

**Associate Director at Large:**

N.B. Lockhart
J.K. Suzuki** (UC Berkeley)
S.L. Whyte
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W.H. Rathbun
E.B. Yee

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Y. Kluger
W.D. Myers
J. Randrup
W.J. Swiatecki
R. Vogt
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J.P. Helgesson (Lund University)

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D.M. Moltz
T.J. Ognibene*
M. Rowe*
B. Fischer* (UC Berkeley)

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R.M. Clark
M.A. Deleplanque-Stephens
R.M. Diamond
P. Fallon
I.Y. Lee
A.O. Macchiavelli
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J.E. Draper (UC Davis)
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Y.D. Chan
R.M. Larimer
K.T. Lesko
M.E. Moorhead
E.B. Norman
M.C. Perillo-Issac
R.G. Stokstad
I.D. Goldman (Universidade de São Paulo)
M.C. Moebus

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NUCLEAR STRUCTURE AND REACTIONS
Very recently, a $\Delta I = 2$ staggering was observed in the gamma-ray energies of the yrast superdeformed (SD) band\(^1\) in \(^{149}\text{Gd}\) and in the SD bands\(^2\) in \(^{194}\text{Hg}\). It has been suggested that such perturbations in the level energies could arise from \(Y_{44}\) deformations of the nuclear shape\(^3,4\).

In fact, Hamamoto and Mottelson have shown that staggering can occur as a result of tunneling between the four minima in angular momentum space generated by a potential related to the \(Y_{44}\) deformation. In this work we present a somewhat different approach to describe this phenomenon, namely one that involves the mixing of multiple \(K\)-bands. While implicit in the tunneling picture, our derivation explicitly shows the appearance of the \(K\)-bands, thus providing a familiar framework to introduce effective coupling terms in the Hamiltonian.

For a nucleus which has a \(Y_{44}\) deformation around the 3-axis (an axis of four-fold symmetry \(C_4\)) we have the rotational Hamiltonian:

\[
H = AI^2 + (A_3 - A)K^2,
\]

which describes a series of different rotational bands labeled by the quantum number \(K\). The \(C_4\) symmetry restricts\(^5\) the possible values of \(K\) to \(K = \Omega, \Omega \pm 4, \Omega \pm 8, \ldots\) etc. being \(\Omega\) the intrinsic component. Therefore, for a configuration relevant to the ground state of an even-even nucleus (\(\Omega = 0\)) \(K = 0, 4, 8, \ldots\) etc. Without mixing, the yrast states will be those of the \(K=0\) band, and as a consequence of eq. (1) there will be no staggering. Mixing between these bands has to involve to lowest order \(I_4^4\) and \(I_4^4\) to provide a \(\Delta K=4\) change. We thus introduce the simplest effective coupling of fourth order in the angular momentum operators that includes both a non-diagonal \((h_4)\) and a diagonal term \((h_0)\):

\[
H_c = h_4(I_4^4 + I_4^4) + h_0(I_4^2 I_2^2 + I_2^2 I_4^2 + 4(I^2 - K^2)^2),
\]

which can be written as in Ref. 3 as:

\[
B_1(I_1^2 - I_2^2)^2 + B_2(I_1^2 + I_2^2)^2,
\]

with \(B_1 = 4h_4\) and \(B_2 \approx 2(3h_0 - h_4)\).

Although it is still too early to attempt a "fit" of the parameters with experimental data, we have found that the coupling terms give rise to an important renormalization of the moment of inertia. In fact, without resorting to an extra term in the Hamiltonian that will cancel this effect, experimental values of \(\mathcal{B}(E2)\) and \(\mathcal{J}^{(1)}\) (characteristic of SD bands) imply \(\mathcal{J}_3 \approx \mathcal{J}_{\text{rigid}}\) and \(B_1/A \approx 0.01\). This seems to imply a rather large value of the \(Y_{44}\) deformation if this is a collective motion unless we can interpret \(A_3\) as an effective inertia generated by the alignment of single particle angular momentum\(^6\). It appears to be difficult to obtain values of \(B_1/A \approx 0.01\) from microscopic models; current calculations based on the Tilted Axis Cranking model\(^6\) give values about 10 times smaller.

References

\(^1\) Phys. Rev. C51 (1995)R1
\(^5\) I.M. Pavlichenkov and S.Flibotte, Proceedings of the "Conference on Physics from Large $\gamma$-ray Detector Arrays", Berkeley, California, USA, August 2-6 1994.
\(^6\) S.Frauendorf, in Ref. 4.
A Pair of Identical Superdeformed Bands in $^{136}$Nd

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Superdeformed (SD) states in $^{136}$Nd$^1$ were populated via the $^{100}$Mo($^{40}$Ar,4n) reaction at beam energies of 176 and 182 MeV. The beam, which was accelerated by the 88–Inch Cyclotron at the Lawrence Berkeley Laboratory, was incident on a stack of two self-supporting $\sim$500 $\mu$g cm$^{-2}$ $^{100}$Mo foils. Coincident $\gamma$-rays, emitted during the decay of high-spin states, were detected with the early implementation phase of the GAMMASPHERE array. For the experiments at 176 MeV and 182 MeV, the array consisted of 36 and 24 large-volume (relative efficiency $\sim$80%), Compton-suppressed, HPGe detectors, respectively. Approximately $1.8\times10^9$ and $1.0\times10^9$ events with a suppressed Ge-fold of $\geq3$ were recorded at the lower and higher beam energies, respectively.

The data for each beam energy were sorted into $\gamma-\gamma$ matrices and also into $\gamma-\gamma-\gamma$ cubes, to allow a search for new high-spin structures.

An excited SD band has been found and assigned to $^{136}$Nd. It displays the remarkable property of having transition energies identical to the half-points of the yrast SD sequence in $^{136}$Nd (to within $\pm1$ keV). Spectra for the new band and the known SD band in $^{136}$Nd are shown in the figure. The incremental alignment difference between the two structures is found to be close to unity. This represents the first convincing proof of the existence of identical SD bands in the A$\sim$130 region. The occurrence of the excited band can be explained in terms of either single-particle proton or neutron excitations. The difference in the alignments of orbitals involved in the excitation turn out to be roughly integer (a proton excitation to the $[532]5/2$ orbital best fulfills this requirement).

Footnotes and References


Excited Superdeformed Bands in $^{150}$Tb


An experiment to study SD states in $^{150}$Tb was performed at the Lawrence Berkeley Laboratory 88 cyclotron using the reaction $^{31}$P + $^{124}$Sn at a beam energy of 167 MeV using the early implementation of the GAMMASPHERE detector array. Approximately $1 \times 10^9$ fold suppressed Ge events were collected.

In total, three SD bands have been observed in this data set, one of which (band 1) has been reported previously and has been assigned a $\pi 6^3v^71^1$ high-N intruder configuration. Bands 2 and 3 are interpreted as excited SD bands and were observed for the first time in this data set.

The $\mathcal{S}(2)$ curve (fig. A) for $^{150}$Tb band 2 is reduced, by a constant amount, relative to that in $^{151}$Dy band 1. Since the 3rd $N=6$ intruder is calculated to contribute a constant amount to the total $\mathcal{S}(2)$ over the frequency range of interest, the properties of band 2 are consistent with a particle-hole excitation from the favoured signature of the [651]3/2 ($\alpha = +\frac{1}{2}$) proton intruder (3rd $N=6$) orbital into the unfavoured signature [651]3/2 ($\alpha = -\frac{1}{2}$) (4th $N=6$), i.e., band 2 is a proton intruder hole in the $^{151}$Dy band 1 SD configuration.

The $\mathcal{S}(2)$ (fig. B) of $^{150}$Tb band 3 exhibits a similar slope to that seen in $^{151}$Tb band 1, except at the lowest frequencies. In this case, the intruder configuration ($\pi 6^3v^72^2$) is the same as in $^{151}$Tb band 1 and the hole is in the [651]3/2 orbital. The rise in $\mathcal{S}(2)$ at low frequencies can be interpreted as a quasineutron ($N=7$) band-crossing. Similar observations, concerning both the rise and the relative comparisons in the $\mathcal{S}(2)$ moments of inertia, have also been reported for the pair of SD bands in $^{149}$Gd band 2 and $^{150}$Gd band 1.

Figure 1: Dynamic moments of inertia as a function of rotational frequency for (A) $^{150}$Tb band 2 and $^{151}$Dy band 1; (B) $^{150}$Tb band 3 and $^{151}$Tb band 1.
Properties of Superdeformed Bands in $^{153}$Dy*


Excited states in $^{153}$Dy were populated using the reaction $^{110}$Pd($^{48}$Ca,5n)$^{153}$Dy, for which a target stack of two isotopically enriched, self-supporting Pd foils (each $\approx 0.5 \text{ mg/cm}^2$) was bombarded at a projectile energy of 220 MeV. The $\gamma$ rays emitted in the compound-nucleus reactions were detected by the Gammasphere detector array, then consisting of 32 large ($\sim 75 - 80\%$ efficiency) escape-suppressed germanium detectors. Of the order of $10^9$ three- and higher-fold events were collected. Five SD bands have been observed in $^{153}$Dy. Two bands (bands 4 and 5) are observed for the first time whereas the three previously known bands $^1$ have been extended appreciably to both lower and higher spin states.

The assignment of band 1 to the $7_3$ intruder configuration seems unambiguous. For bands 2 and 3 the apparent lack of signature splitting suggests either the [402]5/2 or the [514]9/2 orbits which are well described by the strong coupling scheme. Note, that these bands display a high degree of "identicality" relative to the $^{152}$Dy SD core (the average transition energies of these two bands are nearly identical to the transition energies of the $^{152}$Dy yrast SD band). Bands 4 and 5 show rotational properties (in particular an apparent signature splitting) which closely resemble those calculated for the [521]3/2 Nilsson configuration, which is therefore a natural assignment. Moreover, the lack of other orbitals with such properties near the Fermi surface further strengthens this assignment.

The detailed properties of band 1 reveal some intriguing features. The dynamic moment of inertia, as a function of rotational frequency, is shown in the figure. Two principal features can be seen in the $\Sigma^{(2)}$-curve of band 1: (i) At the top of the band, the $\Sigma^{(2)}$-moment of inertia shows a sharp increase with rotational frequency. This may be interpreted as evidence for a band crossing involving the first $N=7$ proton intruder orbital, and could thus constitute the first observation of this orbital in atomic nuclei. (ii) The $\Sigma^{(2)}$ values show a small $\Delta I = 2$ stagger for rotational frequencies $\hbar \omega$ above 0.5 MeV. Thus, it appears that the energy levels in the band are experiencing small, alternating shifts. Such an effect has also been observed in SD bands in $^{149}$Gd $^2$ and $^{194}$Hg $^3$.

Footnotes and References

(1) Lawrence Berkeley Laboratory.
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Footnotes and References
Measurement of ultra–fast $\gamma$–ray transitions from heavy–ion compound–nucleus reactions*

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A method has been developed to improve the accuracy of the Doppler corrections for SD transitions. The majority of yrast lines decay from nuclei in vacuum but for ultra fast SD transitions a residual Doppler shift arises since they are emitted while the nucleus is travelling through the target material. The slowing-down of the recoiling nuclei was modeled using the Ziegler electronic and nuclear stopping powers. The velocity distribution of the recoiling nuclei was calculated as a function of decay time (including the feeding time) and then the decay of the recoiling nuclei is modeled, yielding velocity distributions as a function of SD transition energy, $v_{SD}(E_\gamma)$. The ratio $v_{SD}(E_\gamma)/\bar{v}_f$ (referenced to the average final velocity $\bar{v}_f$ in vacuum outside the target) was used to correct the "residual" Doppler shift of SD lines with energy $E_\gamma$. The figure shows gated spectra for two transitions in the strongest populated SD band in $^{153}$Dy (see accompanying contribution describing this experiment): a) prior to correction; b) and c) uncorrected but with detectors split into forward and backward angles; d) after correction. After the correction, peaks at the top of the bands have reverted to the expected resolution and less intense peaks become more visible in the spectra. For instance, for the 1409 keV peak in band 1 the FWHM was reduced from 11.1 keV to 6.2 keV. The method also allows one to estimate the transition quadrupole moment of a SD band from the relative centroid shifts in the peaks as seen in spectra b) and c). An answer of $Q_t=18\pm4$eb was derived for the yrast SD band in $^{152}$Dy in good agreement with previous results, while that (previously unmeasured) for the yrast band in $^{153}$Dy was found to be $Q_t=16\pm5$eb.

Footnotes and References

*NIM 354 (1995) 591

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Superdeformation in $^{154}$Er


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Since the discovery of a discrete superdeformed (SD) band in $^{152}$Dy it has been known that a stable second minimum in the potential energy surface of nuclei exists at large prolate deformation. As of this time SD bands have been discovered in more than 23 nuclei with proton numbers between 57 and 66. A number of theoretical calculations have predicted the existence of superdeformation in $^{154}$Er (Z=68), including Total Routhian Surface (TRS) and Hartree-Fock calculations. However earlier attempts to find an SD band in $^{154}$Er were unsuccessful. We report here the discovery of a superdeformed (SD) band consisting of 13 γ ray transitions in $^{154}$Er.

The experiment was performed using the $^{118}$Sn($^{40}$Ar,4n) reaction at $E(^{40}$Ar$)=185$ MeV and the early implementation of GAMMASPHERE. Approximately $6 \times 10^9$ unfolded triples events were obtained in 12 shifts. The SD band has been assigned to $^{154}$Er based on coincidences with known high spin states in $^{154}$Er. The γ ray transitions were confirmed to be stretched quadrupole through the use of an asymmetry ratio, $R_{asym} = [I_{\gamma}(\text{forward}+\text{backward})/I_{\gamma}(90^\circ)]$. The SD band in $^{154}$Er is unusual in several respects. The $\mathcal{J}(^{2})$ moment of inertia of the band is constant above $\hbar \omega = 0.45$ MeV and shows a sharp rise below this value, suggesting a paired band crossing. Figure 1 shows the experimental $\mathcal{J}(^{2})$ and the results of TRS and Cranked Shell Model calculations for the SD band in $^{154}$Er. This deviation between theory and experiment is the largest observed thus far in the A $\approx 150$ region.

Another unusual behavior of this band is that almost 80% of the intensity of the band enters the normal yrast cascade at the $J^\pi = 25^-$ state at 8015 keV. This implies a similarity between the SD state at the bottom of the band and the $J^\pi = 25^-$ state at 8015 keV, and indicates that it might be possible to find a discrete transition linking the SD band to the normal, yrast states.

Finally, the transition energies show a stagger in the $\Delta E_\gamma$ between $\Delta I = 2$ states for transitions above the crossing frequency. This type of stagger in the spectrum of a SD band has previously been associated with C4 symmetry in the Hamiltonian. However, the limited number of transitions in the band makes any assignment of C4 symmetry to this band extremely uncertain.

Footnotes and References


Figure 1: The $\mathcal{J}(^{2})$ moment of inertia for the $^{154}$Er SD band - Experiment and Theory
Excited Superdeformed Bands in $^{192}\text{Hg}$.

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The nucleus $^{192}\text{Hg}$ was studied at the Lawrence Berkeley Laboratory 88″ Cyclotron using the high resolution $\gamma$ ray spectrometer GAMMASPHERE. High angular momentum states were populated using the reaction $^{160}\text{Gd}^{(36}\text{S,4n)}^{192}\text{Hg}$ at a beam energy of 159 MeV. This work resulted in the first observation of excited superdeformed (SD) bands assigned to $^{192}\text{Hg}$.

One of the new SD bands (band 2) has properties that are very different from those of the $^{192}\text{Hg}$ yrast SD band (band 1). Band 2 (most likely to be a 2 quasiparticle band) has a pronounced increase or ‘hump’ in the dynamical moment of inertia, $\Sigma(2)$ (see figure). A likely cause for the increase in $\Sigma(2)$ would be a crossing between neutron quasiparticles based on an $N=7$ intruder and the $[512]5/2$ high-K state, analogous to the interpretation proposed for $^{193}\text{Hg}$ band 1.

The second excited SD band (band 3) has properties that are very similar to those of the $^{192}\text{Hg}$ yrast SD band (band 1). Indeed the transition energies for band 3 follow the $1/4$ points relative to band 1 and, in addition, the band 3 energies are within 1-2 keV of the transition energies reported for one of the excited SD bands in $^{191}\text{Hg}$² (band 2). However it is clear, from coincidence data, that band 3 belongs to $^{192}\text{Hg}$. It is therefore puzzling to observe an excited (2-qp band) in $^{192}\text{Hg}$ which has transition energies equal to those observed in a neighboring odd system, since this implies an alignment of $1/2h$.

There is no evidence for a signature partner to either of the excited SD bands in this data set. However band 2 appears at the $1/2$ way points relative to the much stronger yrast SD band (band 1) and any signature partner to band 2 may well be obscured by band 1. The intensities for these excited bands, relative to band 1, are $\sim 10\%$ and $\sim 5\%$ for bands 2 and 3 respectively.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure1.png}
\caption{Dynamic moments of inertia ($\Sigma(2) = \frac{4}{\Delta E_\gamma}$, where $\Delta E_\gamma$ is the difference in the in-band transition energies) as a function of rotational frequency for SD bands 1 and 2 assigned to $^{192}\text{Hg}$.}
\end{figure}

Footnotes and References

Superdeformation in $^{193}$Pb and the effects of the $N=7$ intruder orbital


We have observed six superdeformed (SD) bands in $^{193}$Pb, two of which have moments of inertia which are constant with respect to $\hbar \omega$ (flat bands). For nuclei with $A \approx 190$, the dynamic moments of inertia ($\langle J^2 \rangle$) of SD bands are characterized by a smooth increase with $\hbar \omega$, which has been attributed to the alignment of both high-$N$ quasiprotons and quasineutrons, and a corresponding reduction in pairing. The observation of flat bands in $^{193}$Pb and $^{195}$Pb suggests that quasi-proton alignment is not as important in Pb as in neighboring nuclei, and that the flat bands in the odd Pb nuclei may be a systematic effect, related to changes in the pairing correlations, deformation, or Fermi surface.

The $^{193}$Pb data set was obtained using the $^{174}$Yb($^{24}$Mg, 5n) reaction at a beam energy of 131 MeV. The target consisted of a stack of three self-supporting thin foils, each $\approx 500 \mu g/cm^2$. The beam was provided by the 88-Inch Cyclotron Facility, and $\gamma$-ray spectroscopy was done with GAMMASPHERE early implementation.

Assignment of the bands to quasiparticle configurations was based on relationships of gamma-ray energies in the different bands, comparisons of experimental rothians to cranked Shell Model predictions, and relationships between the experimental rothians. Bands 1 and 2 are assigned to the favored and unfavored signature components of the low-$K$ $N=7$ neutron orbital. Bands 3 and 4 are assigned to the $\nu(512)5/2$ orbital, and bands 5 and 6 to the $\nu(624)9/2$ orbital.

The $\langle J^2 \rangle$ versus the square of rotational frequency, $\hbar \omega$, for the six SD bands in $^{193}$Pb and that in $^{194}$Pb(1), and $^{191}$Hg are shown in Fig. 1(a) and (b). Bands $^{193}$Pb(3,4,5,6) [Fig. 1(a)] display the typical rise in $\langle J^2 \rangle$ with increasing $\hbar \omega$, and are very similar to that in $^{194}$Pb(1). Bands $^{193}$Pb(1,2) [Fig. 1(b)], however, have a much reduced $\langle J^2 \rangle$ slope with $\hbar \omega$. The absence of such rise in $\langle J^2 \rangle$ for $^{193}$Pb(1,2) implies that the quasineutron alignment is blocked, consistent with the interpretation that $^{193}$Pb(1,2) are based on the favored and unfavored signature components of the $N=7$ neutron orbital, respectively.

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Footnotes and References

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4L.P. Farris et al., to be published in Phys. Rev. C

Figure 1: $\langle J^2 \rangle$ versus $(\hbar \omega)^2$ for the six SD bands in $^{193}$Pb.
Superdeformation in $^{195}$Pb


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Four new superdeformed (SD) rotational bands have been observed in $^{195}$Pb, the first time superdeformation has been identified in an odd-$A$ Pb nucleus. and the first time that SD bands with constant dynamic moments of inertia ($\mathcal{J}^{(2)}$) have been observed in an odd-$A$ nucleus in the $A \approx 190$ region.¹

The $^{195}$Pb experimental studies were performed at the Lawrence Berkeley Laboratory 88-Inch Cyclotron, with the early implementation configuration of GAMMASPHERE. The $^{195}$Pb nuclei were produced with the reaction $^{174}$Yb($^{26}$Mg,5n) at a beam energy of 130 MeV.

Two of the SD bands have dynamic moments of inertia ($\mathcal{J}^{(2)}$) values that are approximately constant with rotational frequency, $\hbar \omega$, and we propose that they are built upon the favored and unfavored signatures of the $N=7$ neutron intruder orbital. The other two bands have $\mathcal{J}^{(2)}$ values that are similar to that of the yrast SD band in $^{194}$Pb, and are proposed to be signature partners built upon the deformation aligned $\nu[624]9/2$ orbital. These assignments are based upon comparison of the experimental Routhians and $\mathcal{J}^{(2)}$'s with the predictions of the cranked Woods-Saxon model².

The rise in $\mathcal{J}^{(2)}$ for SD bands in this mass region, such as for bands 3 and 4 in $^{195}$Pb (Fig. 1) results from the alignment of paired particles in high-$j$, low-$\Omega$ intruder orbitals, and from the gradual disappearance of pairing correlations with increasing frequency.³⁴ An odd particle in the low-$\Omega$ intruder orbital reduces the rise in $\mathcal{J}^{(2)}$ by blocking the alignment of pairs in that orbital. It was previously suggested that blocking of the alignment both neutron and proton intruder orbitals would be required to generate a constant $\mathcal{J}^{(2)}$ in the mass region.⁵ The discovery that this is not the case for $^{195}$Pb suggests that the proton alignment does not occur in $^{195}$Pb in the observed frequency range.

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Footnotes and References

¹L.P. Farris et al., to be published in Phys. Rev. C.

Figure 1: The $\mathcal{J}^{(2)}$ moments of inertia for the $^{195}$Pb SD bands. $^{195}$Pb: ○ — band 1, ■ — $^{195}$Pb band 2, ♦ — band 3, ▲ — band 4.
Superdeformation in $^{195-197}$Bi*†


Two reactions were used to populate high-spin states in $^{195-197}$Bi. The beams were provided by the 88-Inch Cyclotron facility at the Lawrence Berkeley Laboratory. Gamma-rays were detected with the Gammasphere array which, for these experiments, comprised 36 Compton-suppressed, large-volume (≈75–85% efficient) HPGe detectors. The first reaction was: $^{183}$W($^{19}$F,xn) at a beam energy of 108 MeV. It was aimed at populating states in $^{196,197}$Bi. The target consisted of 2×300 μg cm$^{-2}$ stacked $^{183}$W foils on thin carbon backings. A total of 8×10$^8$ three- and higher-fold events were collected. The second reaction was: $^{181}$Ta($^{20}$Ne,xn) at a beam energy of 123 MeV. It was aimed at populating states in $^{195,196}$Bi. The target comprised 2×350 μg cm$^{-2}$ self-supporting $^{181}$Ta foils. A total of 9×10$^8$ three- and higher-fold events were collected. The data were analyzed offline by sorting events in $E_{\gamma_1}$-$E_{\gamma_2}$-$E_{\gamma_3}$ cubes and gated $E_{\gamma_1}$-$E_{\gamma_2}$ matrices.

Three SD bands are seen in the data, and one has been assigned to each of $^{195,196,197}$Bi; note, the band assignments remain tentative. Spectra showing the three bands are presented in the figure. The properties of the bands in the odd-Bi nuclei are best reproduced if the odd proton, relative to the neighbouring even-Pb core, occupies the [651]1/2 ($\alpha$=−1/2) orbital. The band in $^{196}$Bi probably has this same proton configuration coupled to an additional j$_{15/2}$ neutron. The relative behaviour of the $\Omega^{(2)}$'s of these bands can then be understood in terms of Pauli-blocking effects. Our results represent the first observation of superdeformation in the Bi nuclei and confirm longstanding theoretical predictions.

Footnotes and References

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Performance of Gammasphere Split Detectors

An important property of large HPGe detector arrays is the energy resolution ($\delta E$) of the individual counters. The sensitivity or figure of merit of such an array for F-fold coincidence events depends on $1/\delta EF$. While intrinsic resolutions are usually 2 keV at 1 MeV, in a typical (Heavy-Ion, xn) reaction the effective resolutions are affected by Doppler broadening. These are most severe for those detectors positioned around 90° with respect to the beam direction.

Using a detector split in two halves, it is possible to reduce the degradation in the resolution by correcting the $\gamma$-ray energy in software using information on the energy deposited in each half of the detector. Shown in Fig. 1 are two possible solutions that have been considered for Gammasphere: 1) A physically split detector consisting of two D-shaped HPGe crystals housed in a single cryostat, usually referred to as "sliced" and 2) A single crystal with a segmented outer electrode referred to as "segmented". In the sliced configuration the two halves are treated as different detectors requiring two high-resolution electronic channels. In the segmented configuration there is only one high-resolution signal common to both sectors, obtained from the inner electrode; signals from the outer contact provide low resolution position information. Tests of each design with radioactive sources and in beam showed a considerable loss in efficiency (as compared with a normal detector with similar volume of Ge) for the split configuration. This and the extra cost in the electronics questioned the use of such a device for Gammasphere. However, the results for the segmented configuration were very good. As an example, we show in Fig. 2 a portion of a spectrum obtained in the reaction $^{56}Fe + ^{64}Ni$. Two peaks of around 660 keV are decomposed into the contributions from the two sides of the segmented detector using the simple algorithm of assigning the total energy to one side when its side-channel energy was larger than 50% of the total. By aligning the peaks in software before adding them we obtain an improvement of a factor of 1.3 in resolution. Both the energy difference and the width of the components in Fig. 2 are in agreement with simulations. The implementation of these detectors in Gammasphere will increase by a factor of about two the resolving power of the array. These detectors can also be used as polarimeters to obtain information on the electric or magnetic character of the $\gamma$-rays.

![Segmented and Sliced Detectors](image-url)

Fig. 1: Schematic drawing of the split detectors for Gammasphere.

![Spectrum](image-url)

Fig. 2: Portion of a spectrum showing the contributions from the two sides of the detector and their sum before applying the Doppler correction.
Transition State Rates and Complex Fragment Decay Widths*

L. G. Moretto, K.X. Jing, and G. J. Wozniak

In this work we show that the presence or absence of the transient time effects, which have been advocated as an explanation for large number of pre-scission particles (n, p, α and γ), should be directly observable in the excitation functions for the emission of fragments with different Z values. Our procedure uses predictions of the transition state method as a null hypothesis, and involves only replotting experimental data without invoking a specific model. Using the standard Fermi gas level density, we can rewrite the transition state fission rate in the following way:

\[
\ln R_r = \frac{a_Z}{2\sqrt{a_n}} (E - B_Z - E_r^s)
\]

where \(R_r\) is the reduced fission rate defined as

\[
R_r = \frac{\sigma_Z \Gamma_r}{\sigma_0} \frac{2\pi p(E - E_r^s)}{T_z}.
\]

The quantities \(a_Z\) and \(a_n\) are the level density parameters for the saddle point and the residual nucleus after n or p evaporation, respectively. \(E_r^s\) is the energy of the rotating ground state and \(E_r^s\) the saddle point rotational energy. \(B_Z\) is the conditional barrier for the emission of a fragment with atomic number Z. A plot of the left hand side of the above equation versus the square root of the intrinsic excitation energy over the saddle point should give a straight line, and the slope should give the square root of \(a_Z/a_n\). The suppression of the fission rate at higher excitation energies (shorter compound nucleus life times) from the predicted transient time effects should result in deviations from, or a sagging of, the straight line.

In Fig. 1 we have plotted the reduced fission rates, as suggested above, of all the excitation functions which have been measured for emission of complex fragments with Z-values 5-25 for four compound nuclei: \(^{75}\text{Br}\), \(^{90}\text{Mo}\), \(^{94}\text{Mo}\), \(^{110,112}\text{In}\). A plot of the left hand side of the above equation versus the square root of the intrinsic excitation energy over the saddle point should give a straight line, and the slope should give the square root of \(a_Z/a_n\). The suppression of the fission rate at higher excitation energies (shorter compound nucleus life times) from the predicted transient time effects should result in deviations from, or a sagging of, the straight line.

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1) Once one removes the phase space associated with the non-reactive degree of freedom at the conditional saddle point, the reduced fission rates are IDENTICAL for fragments of all Z-values.

2) For all fragments, there is no deviation from the expected linear dependence over the entire excitation energy from 60-140 MeV which corresponds to the compound nucleus life times ranging from \(3 \times 10^{-20}\) to \(1 \times 10^{-21}\) sec where the transient time effects were expected to appear. This seems to rule out, for all Z-values, transient time effects which should become noticeable with increasing excitation energy.

3) The slope, which correspond to \(\sqrt{a_Z/a_n}\), is essentially unity for all Z values of all systems studied.

4) The intercept of the straight line is essentially zero and shows no obvious dependence on the fragment Z-values (i.e., the collectivity).

We conclude that in this extended data set there is no evidence for transient effects either directly or through their expected dependence upon the mass of the emitted fragment.

Footnotes


Fig. 1. The logarithm of the reduced mass-asymmetric fission rate \(R_r\) divided by \(2\sqrt{a_n}\) vs the square root of the intrinsic excitation energy for four compound nuclei: \(^{75}\text{Br}\), \(^{90}\text{Mo}\), \(^{94}\text{Mo}\), \(^{110,112}\text{In}\). The solid line is the linear fit to the data. The error bars are smaller than the size of symbols.
Evidence for the Reducibility of Multifragment Emission to an Elementary Binary Emission In Xe–Induced Reactions

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The probabilities of emitting \( n \) IMFs (\( 3 \leq Z \leq 20 \)) for \(^{36}\text{Ar} + ^{197}\text{Au}\) reactions at intermediate energy were found to be binomially distributed\[1\]:

\[
P_n^m = \frac{m!}{n!(m-n)!} p^n (1-p)^{m-n}.
\] (1)

The parameter \( m \) represents the number of chances the system has to emit an inert fragment with fixed binary decay probability \( p \).

The above observation that multifragmentation is reducible to single–fragment emission is striking and leads us to search for evidence of this reducibility in the \(^{129}\text{Xe}\)-induced reactions.

For \(^{129}\text{Xe}\)-induced reactions on \(^{nat}\text{Cu}, ^{89}\text{Y}, ^{165}\text{Ho}\), and \(^{197}\text{Au}\) targets at bombarding energies of \( E/A = 40, 50 \) and \( 60 \) MeV, we determine experimentally the probability \( P_n \) of emitting \( n \) fragments as a function of the transversal energy \( E_t \). \( P_n \) is defined as \( P_n = N(n)/N(n) \), where \( N(n) \) is the number of events with \( n \) IMFs. The excitation functions \( P_n \) are plotted in the left panels of Fig. 1 for \( n=0 \) to \( n=10 \), together with the solid lines generated from the binomial distribution in Eq. 1 for the \(^{129}\text{Xe}\)-induced reactions on \(^{nat}\text{Cu}, ^{89}\text{Y}, \) and \(^{165}\text{Ho}\) targets at bombarding energy of \( E/A = 40 \) MeV. The input values \( p \) and \( m \) in Eq. 1 are extracted from the mean \( \langle n \rangle = mp \), and variance \( \sigma^2_n = \langle n \rangle (1-p) \). Excellent agreement between the experimental \( n \) IMFs emission probabilities (symbols) and the binomial calculations (curves) for the entire \( E_t \) range is observed for all values of \( n \) independent of the specific target. This remarkable agreement means that the probability \( P_n \) is indeed binomial and can be reduced to an elementary binary probability \( p \).

To investigate the temperature dependence of the elementary probability, \( 1/p \) is plotted as a function of \( E_t^{-1/2} \) (Arrhenius plot) in the right panel of Fig. 1 for the above reactions. A most remarkable result is that these Arrhenius plots for different targets collapse onto a nearly universal line, which is a linear fit to the data. The linearity of these Arrhenius plots clearly illustrates \( p \)’s “thermal” dependence of the type \( p = e^{-B/T} \), assuming \( E_t \) to be proportional to the excitation energy. The parameter \( B \) is the barrier associated with a given decay channel under consideration, and \( T \) is the temperature of the emitting system. \(^{129}\text{Xe}\)-induced reactions at the two higher bombarding energies also show a similar reducibility and target independence.

Figure 1: For the \(^{129}\text{Xe}\)-induced reactions (\( E/A = 40 \) MeV) on \(^{nat}\text{Cu}, ^{89}\text{Y}, \) and \(^{165}\text{Ho}\) targets: the experimental (symbols), and the calculated probability (lines) to emit \( n \) IMFs as a function of \( E_t \) (left panel), and the Arrhenius plots (right panel).

Reference
Binomial Reaction Mechanisms
R. Ghetti, L.G. Moretto, L. Phair, J. Randrup, K. Tso, K.X. Jing, and G.J. Wozniak

Multifragmentation in intermediate energy heavy ion reactions, has been under intense experimental and theoretical study for several years, but many issues are still unresolved. In an effort to understand the underlying production mechanism, excitation functions of n-fold complex fragment events have been measured and it was recently observed that they are rigorously binomially distributed\(^1\). This experimental finding imposes a constraint on theoretical models. In order to investigate whether existing models are compatible with the constraint of binomial product distributions, we have studied the predictions of several theoretical models such as simultaneous statistical multifragmentation models (FREESCO\(^2\) code, BERLIN\(^3\) code) and sequential compound nucleus decay (GEMINI\(^4\) code).

Calculations were performed with the chemical equilibrium statistical code FREESCO. This code treats intermediate energy nuclear collisions by assuming thermal and chemical equilibrium within a certain interaction volume. The participating portion of the system is assumed to decay accordingly to the available classical phase space. This prescription generates approximately binomial distributions, as can be seen in Fig. 1 (left panel) where the excitation functions are shown from the disassembly of a \(^{197}\text{Au}\) nucleus together with their binomial fits. This result can be interpreted by considering that binomial probabilities represent a generalization of independent fragment production that would generate Poissonian distributions as in a grand canonical ensemble. In the FREESCO approach, a mathematical method is developed in order to approximate the exact microcanonical treatment by solving the grand canonical equation and to derive the statistical properties of the fragments from a factorized partition function. In this way, the finite size of the system is taken into account, and deviations from Poissonian are introduced, leading to the nearly binomial distributions shown in Fig. 1. Since the calculations were performed at high excitation energies (E>7.5 MeV/A), they show declining intermediate mass fragment (IMF) multiplicities and a fall of multifragmentation. The elementary binary emission probability, deduced from the multifragment emission probabilities through the binomial equation\(^1\), is decreasing with increasing excitation energy in this particular regime (Fig. 1 right panel).

Fig. 1 Left panel: excitation functions from the disassembly of a \(^{197}\text{Au}\) nucleus with excitation energies in the range 1500 to 3000 MeV. Symbols: FREESCO calculated probabilities for 1-10 fold IMF events. Solid lines: binomial fits with parameters extracted from the average multiplicity and the variance at each excitation energy\(^1\). Right panel: elementary probability 1/p plotted (in log scale) as a function of E\(^{-1/2}\).

The BERLIN microcanonical multifragmentation code also generates binomial distributions\(^5\). GEMINI calculations were performed for an excited \(^{197}\text{Au}\) nucleus with excitation energies of 0 to 1000 MeV. In the very low energy region the calculated excitation functions are approximately binomial but gradually evolve to become negative binomials at high energies where the fragment production process is cascade like, i.e. excited primary fragments have a significant probability to decay into additional fragments.

Footnotes and References
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Reducibility and Thermal Scaling of Charge Distributions in Multifragmentation

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Intermediate-mass-fragment multiplicity distributions at intermediate energies have been shown [1] to be binomial and thus reducible at all measured transverse energies $E_t$. From these distributions a thermal binary event probability $p$ can be extracted.

Reducibility demands that the probability $p(Z)$, from which an event of $n$ fragments is generated by $m$ trials, is the same at every step of extraction. Consequently, the charge distribution for the one-fold events is the same as that for the $n$-fold events and equal to the singles distributions, i.e.:

$$P(1)(Z) = P(n)(Z) = P_{\text{singles}}(Z) = p(Z).$$ (1)

If the one-fold = $n$-fold = singles distribution is thermal, then $P(Z) \propto e^{-B(Z)}$ or $T \ln P(Z) \propto -B(Z)$. This suggests that, under the usual assumption $E_t \propto E^*$, the function

$$\sqrt{E_t} \ln P(Z) = D(Z)$$ (2)

should be independent of $E_t$.

In the $^{36}\text{Ar}+^{197}\text{Au}$ reaction considered here, the charge distributions are empirically found to be exponential functions of $Z$ ($P_n(Z) \propto e^{-\alpha_n Z}$). In light of the above considerations, we would expect for $\alpha_n$ the following simple dependence

$$\alpha_n \propto \frac{1}{T} \propto \frac{1}{\sqrt{E_t}}$$ (3)

for all folds $n$. Thus a plot of $\alpha_n$ vs $1/\sqrt{E_t}$ should give nearly straight lines. This is shown in Fig. 1.

The expectation of thermal scaling appears to be met. For each value of $n$ the exponent $\alpha_n$ shows the linear dependence on $1/\sqrt{E_t}$ anticipated in Eq.(3). However, the extreme reducibility condition demanded by Eq. (1), namely that $\alpha_1 = \alpha_2 = \ldots = \alpha_n = \alpha$, is not met. Rather than collapsing on a single straight line, the values of $\alpha_n$ for the different fragment multiplicities are offset one with respect to another by nearly a constant quantity.

One can fit all of the data remarkably well, assuming for $\alpha_n$ the form:

$$\alpha_n = \frac{K'}{\sqrt{E_t}} + nc$$ (4)

which means more generally for the $Z$ distribution

$$P_n(Z) \propto e^{-\frac{B(Z)}{T} - ncZ}.$$ (5)

Thus, we expect a more general reducibility expression for the charge distribution of any form to be:

$$[\ln P_n(Z) + ncZ] \sqrt{E_t} = F(Z)$$ (6)

for all values of $n$ and $E_t$. Hence, it is possible to reduce the charge distributions associated with any intermediate mass fragment multiplicity to the charge distribution of the singles.

![Fig. 1.](image.png)

In our specific case the offset $c$ in Fig. 1 may be related to an asymptotic combinatorial structure of the multifragmentation process in the high temperature limit. Consider the Euler problem of an integer $Z_0$ to be written as the sum of smaller integers $Z$. It can be shown [2] that the resulting integer distribution has the form

$$n_Z = \frac{n^2}{Z_0^2} e^{-\frac{n^2}{Z_0}}.$$ (7)

This expression has the correct asymptotic structure for $T \to \infty$ required by Eq.(5) with $c = 1/Z_0$. The value from Fig. 1 is $c \approx 0.016$ which corresponds to a value of $Z_0 \approx 60$ which is quite reasonable for the source size.

References
Phase Coexistence in Multifragmentation?

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We report possible evidence for a transition from a two-phase to a one-phase regime obtained by analyzing charge distributions and their dependence on IMF multiplicity \( n \).

It has been found \([1]\) that the charge distributions for any value of \( n \) can be expressed empirically in terms of the equation

\[
P_n(Z) \propto e^{-n \frac{Z}{T}}.
\]

(1)

Assuming \( E_t \propto E^* \), this equation can be written in terms of the temperature \( T \):

\[
P_n(Z) \propto e^{-\frac{E_t(Z)}{T} - n \frac{Z}{T}} = e^{-\left(\frac{AE_t(Z)}{T} + \Delta S(n, Z)\right)}.
\]

(2)

The first term in the exponent can be interpreted as an energy or enthalpy term, associated with the energy (enthalpy) needed to form a fragment. The second term might point to an asymptotic entropy associated with the combinatorial structure of multifragmentation. It was observed that a term of this form arises naturally in the charge distribution obtained by the least biased breaking of an integer \( Z_0 \) into \( n \) fragments \([1]\). Such a \( Z \) distribution is given by:

\[
P_n(Z) \propto \frac{n^2}{Z_0} e^{-\frac{Z}{Z_0}} = cn^2 e^{-cnZ}.
\]

(3)

While this form obviously implies charge conservation, it is not necessary that charge conservation be implemented as suggested by Eq. (3). In sequential thermal emission, for example, any given fragment does not know how many other fragments are going to follow its emission. The resulting charge distributions cannot reflect charge conservation under the constraint of \( n \) fragments.

On the other hand, in a simultaneous emission controlled by a \( n \) fragment transition state, fragments would be strongly aware of each other and would reflect such an awareness through the charge distribution.

The question then arises whether \( c = 0 \) or \( c > 0 \), or even better, whether one can identify a transition from a regime for which \( c = 0 \) to a new regime for which \( c > 0 \). In order to answer this question, we have studied the charge distributions as a function of \( n \) and \( E_t \) for \( ^{36}\text{Ar} + ^{197}\text{Au} \) at \( E/A = 110 \text{ MeV} \). The extracted values of \( c \) are shown in Fig. 1 as a function of \( E_t \). It is interesting to note that \( c \) starts at or near zero for small \( E_t \) and seems to saturate at a constant value for large \( E_t \).

This behavior can be compared to what happens as a fluid moves from the region of liquid vapor coexistence to the region of overheated and unsaturated vapor. In the coexistence region, the properties of the saturated vapor cannot depend on the total mass of fluid. The presence of the liquid phase guarantees mass conservation at all average densities for any given temperature. A change in mean density (volume) merely changes the relative amount of the liquid and vapor, without altering the saturated vapor properties. Hence, the vapor properties (and in particular the cluster size distributions) cannot reflect the total mass or even the mean density of the system. In our notation \( c = 0 \).

On the other hand, in the region of unsaturated vapor, there is no liquid to insure mass conservation. Thus the vapor itself must take care of this conservation, at least grand canonically. In our notation, \( c > 0 \).

Percolation calculations show a similar transition as a function of bond breaking probability \( p \). (See Fig. 2)

\[
\text{FIG. 1. The value of } c \text{ as a function of } E_t \text{ for the reaction } ^{36}\text{Ar} + ^{197}\text{Au} \text{ at } E/A = 110 \text{ MeV}.
\]

This behavior can be compared to what happens as a fluid moves from the region of liquid vapor coexistence to the region of overheated and unsaturated vapor. In the coexistence region, the properties of the saturated vapor cannot depend on the total mass of fluid. The presence of the liquid phase guarantees mass conservation at all average densities for any given temperature. A change in mean density (volume) merely changes the relative amount of the liquid and vapor, without altering the saturated vapor properties. Hence, the vapor properties (and in particular the cluster size distributions) cannot reflect the total mass or even the mean density of the system. In our notation \( c = 0 \).

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Percolation calculations show a similar transition as a function of bond breaking probability \( p \). (See Fig. 2)

\[
\text{FIG. 2. For percolation, the value of } c \text{ as a function of } p \text{ for } Z_0 = 97 \text{ (circles) and } Z_0 = 160 \text{ (squares).}
\]

References

The isotopic production cross sections and momenta of all residues with nuclear charge greater than 39 from the reaction of 26, 40, and 50 MeV/nucleon $^{129}$Xe + Be, C, and Al were measured using a magnetic spectrometer. The isotopic cross sections, the momentum distribution for each isotope, and the cross section as a function of nuclear charge and momentum are presented.

The experimental Z value versus velocity distributions are consistent with those determined from complex fragment coincidence data. This study provides a determination of the relative amounts of incomplete and complete fusion that is complementary to that extracted in studies of complex fragments. Events with very low excitation energies are easily detected in the present work. These data provide strong evidence for an incomplete fusion reaction mechanism.

One intriguing feature observed is a strong independence of the average mass for each element from the entrance channel of the reaction. In Fig. 1, the average mass of each element is shown for the 50 MeV/nucleon $^{129}$Xe-induced reactions on three different targets Be (solid curve), C (dashed line), and Al (dotted line). The stable isotopes are represented by solid squares and the proton drip line by a stair stepping solid line. For all three targets, the average mass for each element lies slightly on the proton rich side, but shows essential no dependence on the mass of the target. In the lower portion of the figure, the widths of the mass distributions show a similar independence.

Such an independence is qualitatively consistent with a incomplete fusion mechanism where the masses and excitation energies of the excited compound nuclei depend only on the amount of mass picked up from the target and not the specific target nucleus. These excited compound nuclei than decay by emitting neutrons and light charged particles causing the evaporation residues to end up on the proton rich side of the chart of the nuclides. In fact, this target independence can be reproduced by calculations using an incomplete fusion model coupled to a statistical decay model.

![Figure 1: The average A and the FWHM of the mass distribution for each element from the 50 MeV/nucleon $^{129}$Xe + Be (solid), C (dashed), and Al (dotted) reactions. The stair-stepping line shows the proton-rich limit of the known isotopes. Filled square represent the positions of the stable isotopes.](condensed from LBL-36731)
High Purity Carbon Foils

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The level of purity of a target foil is very important in low cross section nuclear reactions. Carbon foils prepared by two different techniques were analyzed for their surface and bulk content of light impurities such as nitrogen, oxygen, and sodium.

The first foil (A) was produced by vacuum evaporation. In this procedure, a source of spectrographically pure carbon, in the form of graphite, is evaporated in vacuum, onto a glass plate coated with a parting agent. The parting agent is used to facilitate the removal of the foil, typically accomplished by floating the foil onto a water surface. Even though the parting agent is washed from the surface of the foil, some of the parting agent (typically a soap) may remain adsorbed onto the foil surface.

A promising alternative technique is chemical vapor deposition. In this technique, a hydrocarbon gas is "cracked" at a high temperature in an inert gas environment, and carbon is deposited onto a bed of molten metal. When the molten metal cools, the carbon foils curl off the metal surface. A second foil was prepared by this technique.

Measurements of the surface and bulk impurities were made using two different analytical techniques. Rutherford Backscattering Spectrometry (RBS) was used to gauge the surface purity of the two foils. This technique measures the energy of a light projectile when it is backscattered by nuclei on the surface of a sample.

A comparison of the spectra of the two foils is shown in Fig. 1. Notice the very large carbon edge at approximately 500 keV and the marked nitrogen and oxygen edges on the magnified scale. From this figure, it is clear that Foil B is substantially purer than Foil A.

Since the graphite used to manufacture the foils is very pure, it is instructive to determine if the majority of the contamination is on the surface or in the bulk of the foil. Secondary Ionization Mass Spectrometry (SIMS) is an analytical technique that can be used to measure impurities in the bulk by etching away a portion of the foil surface. The SIMS data indicate that the contamination for both foils is primarily on the surface.

In summary, we have determined that carbon foils prepared by chemical vapor deposition are purer than those prepared by vacuum evaporation onto a coated glass slide. A significant impurity in foils prepared by the latter technique is sodium. Since spectrographically pure carbon is used in both procedures, a small amount of sodium is likely introduced by the parting agent used to coat the glass slide.

Figure 1: RBS spectra of Foil A (upper) and Foil B (lower). Foil A shows impurity peaks for nitrogen, oxygen, and sodium, whereas Foil B shows no impurity above the limits of detection. Note scale change; position of edge due to backscattering indicated.

*Condensed from LBL-36953
Search for Beta-Delayed Proton Emission from $^{77}$Zr

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Observation of beta-delayed proton emitters has proven to be an effective tool in extending knowledge of the nuclear mass surface towards the limits of proton stability. In recent years, our group has measured the decays of $^{61}$Ge, $^{65}$Se and $^{73}$Sr$^1$, the heaviest members of the A=4n+1, $T_z=3/2$ mass series observed to date. Each of these nuclides was produced via (HI, 3n) fusion-evaporation reactions on stable Z=N targets. The reaction products were then transported by He-jet to particle identification telescopes where their decays were observed. Because of the lack of stable Z=N targets or beams above Ca, $^{77}$Zr represents the heaviest member of this mass series which may be studied using this technique.

$^{77}$Zr provides an extreme test of nuclear models. It has three fewer neutrons than the next lightest isotope observed to date and thirteen fewer neutrons than the lightest stable isotope. Nuclides in this region of the Chart of Nuclides are known to be strongly deformed$^2$. In order for nuclear models to accurately predict the mass of $^{77}$Zr, they must presumably account for this deformation. Of the 1986-1987 Atomic Mass Predictions$^3$ for the three heaviest members of the A=4n+1, $T_z=3/2$ mass series, the predictions of Comay-Kelson-Zidon and Masson-Janecke have been most successful. This is somewhat surprising since these models only account for nuclear shape indirectly. The predictions agree within approximately 250 keV for $^{61}$Ge, but gradually diverge for higher mass members of the series; the predictions for $^{77}$Zr cover a 1500 keV range. This may be due to subtle differences in the methods of prediction becoming more pronounced as they are applied to systems farther from stability.

To produce $^{77}$Zr, we bombarded a separated-isotope $^{40}$Ca target with a 160 MeV $^{40}$Ca beam (mid-target lab energy) generated at the 88-Inch Cyclotron. Reaction products were thermalized and attached to KCl aerosols in a He-jet and transported to a moving tape in the center of an array of four gas $\Delta E$ - gas $AE$ - silicon E particle identification telescopes subtending a solid angle of $\sim$16% of 4$\pi$. During this experiment we clearly saw evidence of the beta-delayed proton decays of $^{65}$Se and $^{73}$Sr. We also observed several protons at a lab energy around 4.2 MeV. This is of interest since three of the 1986-1987 Mass Predictions calculate a proton lab energy from the decay of $^{77}$Zr through its Isobaric Analog State (IAS) in $^{77}$Y that is within 130 keV of this energy.

Since the yields of $^{65}$Se and $^{73}$Sr formed via $^{40}$Ca($^{40}$Ca,3n)$^{65}$Se and $^{40}$Ca($^{40}$Ca,α3n)$^{73}$Sr reactions were much larger than expected, we repeated the experiment at a lower beam energy. We used a $^{40}$Ca beam with a mid-target lab energy of 147 MeV in an attempt to enhance the 3n out over the α3n out channels. As expected, the $^{65}$Se and $^{73}$Sr yields dropped considerably, and a few proton counts around 4.2 MeV were again observed.

To ensure that the observed proton counts are from the decay of $^{77}$Zr and not from some other source, we bombarded a separated-isotope $^{40}$Ca target with a 140 MeV $^{36}$Ar beam. Unfortunately, these results also showed evidence for a weak proton group at approximately 4.2 MeV, indicating that the source is fully or partially from a Z≤38 beta-delayed proton emitter.

Noting the above, a shorter half-life or a smaller production cross section than expected could explain the lack of an unambiguous observation of $^{77}$Zr. Extrapolating half-life results from the gross theory of beta decay$^4$, $^{77}$Zr has a half-life of 5-20 ms. If the predicted half-life is much shorter than the transit time of our He-jet system (~25 ms), then there will be significant losses due to decay in transit. The ALICE$^5$ predicted cross section for the $^{40}$Ca($^{40}$Ca,3n)$^{77}$Zr reaction at beam energies of 140-160 MeV is ~100 nb, roughly a factor of three smaller than the $^{40}$Ca($^{36}$Ar,3n)$^{73}$Sr reaction used to produce $^{73}$Sr in ref. [1]. For the production of $^{73}$Sr and $^{65}$Se, it was found experimentally that ALICE overpredicted the cross section by a factor of 10-20; if this trend holds for $^{77}$Zr, a cross section of 5-10 nb would be expected. Any of these effects combined with the possibility of a lighter emitter masking the $^{77}$Zr group would be sufficient to prevent our observation of beta-delayed protons from $^{77}$Zr.

Low Energy Beta-Delayed Alpha Decay of $^{20}$Na

T. J. Ognibene, D. M. Moltz, M. W. Rowe, R. J. Tighe and Joseph Cerny

The decay of $^{20}$Na has been studied extensively because it represents an example of beta-delayed alpha emission in light nuclei. The $\beta-\alpha$ decay branch to the ground state of $^{16}$O proceeds mainly through two states to give well known alpha groups at 2.150 MeV and 4.432 MeV. This fact has been utilized in ascertaining the alpha particle clustering nature in both $^{16}$O and $^{20}$Ne. The $\beta-\alpha$ decay of $^{20}$Na is also of astrophysical importance. The $^{16}$O($\alpha,\gamma$)$^{20}$Ne reverse reaction provides a weak breakout pathway from the hot CNO cycle to the rp-process of heavier element production in supernovae.

We initially observed an unexpected low energy alpha group while searching for low energy protons from the isobaric analog state of $^{23}$Al[1]. It appeared to scale with the production of $^{20}$Na and had a half-life consistent with that known for $^{20}$Na. Based on proton calibrations, this group has an energy of $\sim$600-750 keV. Unfortunately, in these experiments, there were copious alpha particles from the decay of $^{8}$B, formed from reactions with carbon contaminants. These alphas form a pseudo-continuum that partially masks $^{20}$Na alphas.

To determine unambiguously the source of the low energy alpha group, we decided to employ the He-jet fed on-line mass separator, RAMA [2]. We have recently completed a series of upgrades [3] to RAMA to place the ion source in the bombardment area and have measured an $\sim$1% efficiency for sodium ions and a full width at one tenth max. resolution of 300. Additionally, we measured a 40 ms total transit time for the multiple target/multiple capillary target configuration.

We used the 88-Inch Cyclotron to bombard 5 targets of $\sim$2 mg/cm$^2$ natMg and $^{24}$Mg with 40 MeV protons to produce $^{20}$Na via the $^{24}$Mg(p,$\alpha$) reaction. Energetic recoils were thermalized and attached to KCl aerosols in a He support gas and transported 0.4 m to the entrance of RAMA. Nuclei were then ionized, accelerated, mass separated and brought to a focus on a thin (20 $\mu$g/cm$^2$) carbon foil in the center of our low energy proton detector ball, which was located at a shielded detector station. The detector ball consists of 6 gas $\Delta E$-gas $\Delta E$-Si E telescopes subtending $\sim$24% of $4\pi$. Through hardware and software gating techniques we are able to identify protons and alphas free from beta contamination on an event by event basis.

The figure below shows a preliminary spectrum of identified alpha particles from one of these telescopes. To obtain an accurate energy calibration, we are modeling the response of the detector to low energy alphas. This includes taking into account the energy loss of the alpha as it passes through the window, the gas and the Si dead layer as well as applying corrections for electronic nonlinearities.

There are two excited states in $^{20}$Ne from which this new low energy alpha group could originate; a 1$^-$ state at 5.785 MeV and a 3$^-$ state at 5.622 MeV. Both are fed by first forbidden beta decay and would emit alphas with lab energies of 844 keV and 714 keV, respectively. Preliminary data analysis suggests the alpha energy is closer to 714 keV than 844 keV. The intensity of this group is $\sim$4% of the main (2.15 MeV) group.


![Mass 20 spectrum](image-url)
Lipophilic Hydroxypyridinones as Liquid/Liquid Extracting Agents for the Actinides*

Alan C. Veeck, Donald W. Whisenhunt Jr.*a, Xu Jideb, Kenneth N. Raymondb, Darleane C. Hoffman

The Hanford Tank Farm, located in Hanford, WA, is a Department of Energy (DOE) waste storage site that maintains 61 million gallons of mixed waste contained in 177 underground storage tanks. The waste was generated by a variety of chemical processes used from 1944 through 1990 to separate plutonium (from uranium and fission products) for use in the nation's nuclear arsenal. Because the tanks are not designed for permanent storage, and because of a number of hazards associated with the tanks, the DOE will be considering a number of strategies to remediate the waste in the very near future. The most cost-effective means of remediation involves separating the low-level waste (LLW, mostly non-toxic chemical waste), which represents the bulk of the waste, from the smaller amount of high-level waste (HLW, mostly transuranic elements and fission products).

A ligand which can strongly and selectively bind actinide metal ions while in the presence of many other metal ions and competing ligands would be very useful in the waste remediation scheme mentioned above. The actinides, especially Pu(IV) and Th(IV), are "hard" Lewis acids (due to their large charge-to-ionic radius ratios); they share this property with Fe(III), and much of the same metal-ligand chemistry that is known about Fe(III) can be applied to the actinides. The strongest chelating ligand for Fe(III) is enterobactin, a naturally occurring molecule that contains three bidentate catechol binding groups. It has been found that the actinides bind more strongly to chelating groups that are a little less basic than the catechol moiety. Slightly more acidic functional groups, like hydroxypyridinones (HOPOs), have proven to be among the best. For this reason, a series of liquid/liquid extractants based upon HOPOs has been synthesized (Figure 1). Two HOPO chelators have been synthetically altered for the organic phase by the addition of different lipophilic "tails".

Liquid/liquid extraction is a technically simple and economic means to effect the separation of the actinides; extraction tests are currently underway to find the best extractors, and testing of the best extractors with real waste will begin in the near future.

Figure 1. Lipophilic liquid/liquid extracting agents: five lipophilic groups (R), shown on the right, have been attached to the bidentate chelating moieties 3-hydroxy-4-pyridinone (3,4-HOPO) and 3-hydroxy-2-pyridinone (3,2-HOPO).

Footnotes

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Actinide Cation-Cation Complexes

N. J. Stoyer, D. C. Hoffman, and R. J. Silva

The +5 oxidation state of U, Np, Pu, and Am is a linear dioxo cation (AnO$_2^+$) with a formal charge of +1. These cations form complexes with a variety of other cations, including actinide cations. Other oxidation states of actinides do not form these cation-cation complexes with any cation other than AnO$_2^+$; therefore, cation-cation complexes indicate something unique about the chemistry of AnO$_2^+$ cations compared to the chemistry of actinide cations in general. The first cation-cation complex, NpO$_2^+$-UO$_2^{2+}$, was reported by Sullivan, Hindman, and Zielen in 1961. Of the four actinides that form AnO$_2^+$ species, the cation-cation complexes of NpO$_2^+$ have been studied most extensively while the other actinides have not. The only PuO$_2^+$ cation-cation complexes that have been studied are with Fe$^{3+}$ and Cr$^{3+}$ and neither one has had its equilibrium constant measured. Actinides have small molar absorptivities and cation-cation complexes have small equilibrium constants; therefore, to overcome these obstacles a sensitive technique is required. Spectroscopic techniques are used most often to study cation-cation complexes. A relatively new absorption spectroscopy technique called Laser-Induced Photacoustic Spectroscopy which is two to three orders of magnitude more sensitive than conventional absorption spectroscopy was used in this research. The equilibrium constants for the complexes NpO$_2^+$-UO$_2^{2+}$, NpO$_2^+$-Th$^{4+}$, PuO$_2^+$-UO$_2^{2+}$, and PuO$_2^+$-Th$^{4+}$, determined at an ionic strength of 6 M using LIPAS are: 2.4 ± 0.2, 1.8 ± 0.9, 2.2 ± 1.5, and ≈ 0.8 M$^{-1}$, respectively. See Figure 1 for the spectra used to calculate the equilibrium constant of the PuO$_2^+$-UO$_2^{2+}$ complex.

Figure 1: Spectra for the PuO$_2^+$-UO$_2^{2+}$ complex experiment at $\mu = 6$ M. The spectra shown are for a calculated PuO$_2^+$ concentration of 0.0924 mM (solid line), 0.0553 mM PuO$_2^+$ with 0.144 M UO$_2^{2+}$ (dashed line), 0.0924 mM PuO$_2^+$ with 0.0964 M UO$_2^{2+}$ (dotted line), and 0.0924 mM PuO$_2^+$ with 0.0482 M UO$_2^{2+}$ (dot-dashed line). Spectra are normalized at 567.5 nm, the isobestic point. The error bar at 564.0 nm on the solid line is typical of the errors for these spectra. $S$ is the LIPAS signal, a dimensionless number proportional to absorbance.

Footnotes and References

*This work constitutes the major part of Nancy J. Stoyer's Ph.D. Thesis completed December 1994 at University of California at Berkeley.

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On-Line Isothermal Gas Chemistry Experiments with Bromides of Hf and Ta


The Heavy Element Volatility Instrument (HEVI) was used to investigate the volatilities of hafnium (HfBr₄) tetrabromide and tantalum pentabromide (TaBr₅). HEVI is an on-line isothermal gas chromatography system which separates short-lived volatile halides according to their volatility. Short-lived isotopes of Hf and Ta are produced at the 88-Inch Cyclotron using a ²²Ne⁶⁺ beam on a mixed ¹⁴⁷Sm/¹⁷⁷Eu target.

Reaction products, transported by a He/MoO₃ gas jet, were continuously collected on a quartz wool plug, kept at 900°C, inside a quartz chromatography column. The bromides were formed by adding 150 ml/min HBr gas. Volatile species were carried to the cooler, isothermal section of the column by the He flow, where chromatography was performed. The separated species were attached on KCl aerosols in N₂, and transported through a capillary to a glass frit where they were collected and counted using an intrinsic Ge detector.

Fig. 1 shows the relative chemical yields of HfBr₄ and TaBr₅ as a function of the isothermal temperature in the chromatography column. The Ta bromides are shown to be much less volatile than the Hf bromides. The drop in yield for the Hf bromides at higher temperatures is not yet explained.

Using a Monte Carlo simulation program, it is also possible to determine the adsorption enthalpy of the species from these data. The adsorption enthalpy was found to be -151 kJ/mol for ¹⁶₆TaBr₅ and -87 kJ/mol for ¹⁶²HfBr₄. Approximate error for these measurements is ±5kJ/mol.

Figure 2 shows the group 4 volatility trends. Our most recent experiment does not agree with previous results on the volatility of HfBr₄. Similar plots for the group 4 and 5 chlorides, as well as our results for the group 5 bromides (not shown) show a similar decrease in volatility (more negative adsorption enthalpy value) for the Hf and Ta species, with the transactinides resembling the lighter homologs Zr and Nb in adsorption enthalpy values and volatilities.

Footnotes and References

2 A. Türler et al., LBL-31855, Annual Report (1991)
3 B. Kadkhodayan, Ph.D thesis (1993)
On-Line Liquid-Scintillation Counting in Heavy Element Research


The investigation of the chemical and nuclear properties of heavy elements requires special techniques. Due to low production rates and very short half-lives, a highly efficient detection system and an on-line separation method are necessary. Actinide and transactinide elements decay primarily by α-particle emission or spontaneous fission (SF) and thus, a detection method that is capable of measurement of α-energies and SF ratios is required.

The SISAK 3 system is the fastest of several on-line systems developed for solution chemistry. It uses liquid-liquid extraction with very fast rotating centrifuges to investigate the extraction behavior of short-lived heavy elements.

Previously, liquid-scintillation counting was used mainly to detect low energy β-emitters. Detection of α-emitters was restricted because of interferences from β-radiation. Therefore, a method to discriminate against β-radiation in liquid-scintillation measurement of heavy elements is necessary.

To combine the SISAK 3-system with a liquid-scintillation system, a scintillation cocktail is needed that contains a selective extraction agent which can also function as a sensitive scintillator.

We have developed a Liquid-Scintillation-System (LISSY) that permits continuous measurement of α-particles and SFs.

We are able to measure half-lives, α-energies, and SFs. Using α-α correlations positive identification of specific nuclides can be made.

Pulse-shape discrimination allows suppression of > 98% of β-radiation from the decay of other heavy ion reaction products. Energy resolutions as good as ~ 220 keV for 6-7 MeV α-energies can be obtained. It is also possible to measure SF to alpha ratios of heavy elements.

Using the appropriate software, it is possible to detect spontaneous fission ratios of heavy elements.

LISSY in combination with SISAK 3 will be used to detect 1.8 s-261Ha produced in the 243Am(22Ne, 4n) reaction, and 2.1 s-262Rf and 1.5 s-259Fm produced in 248Cm+18O reactions at the 88-Inch-Cyclotron at LBL.

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Fig. 1. The liquid-scintillation-system (LISSY) for on-line counting. The window of the photomultiplier as well as the counting cell are made of quartz glass to reduce the background.
Solvent Extraction Studies of Rutherfordium (Element 104)
C.D. Kacher, A. Bilewicz*, and D.C. Hoffman

The chemical behavior of rutherfordium and its lighter group 4 homologs Zr and Hf was studied by performing solvent extraction experiments with the appropriate tracers from HBr solutions into 0.35 M tributylphosphate (TBP) in benzene. Group 4 Ti was studied by atomic absorption spectroscopy (A. Bilewicz*). The Ti solutions were prepared by dissolution of TiO2 in HBr solutions.

261Rf was produced in the heavy ion fusion reaction 248Cm(18O,5n) at Lawrence Berkeley Laboratory's 88-Inch Cyclotron. Production rates typically were on the order of a few atoms per minute or less. 261Rf was then transported to a collection plate inside a chemistry hood via a He/KCl aerosol jet.

In the solvent extraction experiments, the organic phase was preequilibrated once with an appropriate aqueous phase. Each phase was 300 μl. Tracer was added and the phases were mixed for one minute, centrifuged for 30 sec, separated, and counted in a gamma (Canberra System 100) or alpha (Ortec ADCAM) spectrometer system. The procedure for 261Rf (t1/2 = 78 sec) was similar except that only the organic phase was counted and each experiment took about 60 sec to complete. The Ti results were determined with a Pye Unicam SP-9 atomic absorption spectrometer.

Zr, Hf, and Rf were studied over a range of concentrations from 7.75 M to 9.0 M HBr and Ti was investigated from 9.0 M to 12.0 M. Unfortunately, 12 M HBr was not available except for the Ti studies. The results in Fig 1 show that the extraction decreases in the order Zr>Hf>Rf>Ti. Thus, Zr and Hf have a higher complexing strength with bromide than do Rf or Ti. Since only neutrally charged complexes extract, the extracted complex is most likely MBr_xH_yTBP, where x is 4, 5, or 6 and y is the TBP solvation number. Further studies will be required to learn whether Rf or Ti comes next in the order of extraction. Assuming the extraction trend in the chloride system (Fig 2) is similar to the trend in the bromide system, Rf could be expected to start extracting between 9 and 10 M HBr.

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Fig. 1. % extraction of the group 4 elements and pentavalent Nb from various [HBr] into 0.35 M TBP in benzene. Ti data from A.Bilewicz, private communication.

Fig. 2. % extraction of the group 4 elements from various [HCl] into 0.35 M TBP in benzene. Zr, Hf, Rf data from K.R. Czerwinska, C.D. Kacher, et al., Radiochimica Acta, 64, 29 (1994). Ti data from A. Bilewicz, private comm.
The tentative results from a previous experiment\textsuperscript{1} using the Automated Rapid Chemistry Apparatus (ARCA) prompted a confirmation experiment to verify the production of $^{263}$Rf. The same $^{249}$Bk($^{18}$O,4$n$) reaction was used to produce $^{263}$Ha, and then look for its electron-capture decay daughter, $^{263}$Rf. The separation once again involved eluting Ha from cation exchange columns in 0.075M α-hydroxyisobutyrate (α-HIB) and Rf fractions in 0.5 M α-HIB. However, the separation was performed manually and a larger column with a synthetic cation exchange resin composed of sulfonated polystyrene chains was used.

The activity was transported via the KCl/gas-jet and collected on a teflon disc for a total of 12 minutes to take advantage of the observed 600 second $^{263}$Rf half-life from the previous experiment. Halfway through the experiment, the activity collection time was increased to 20 minutes because the SF's in the Rf fraction seemed long compared to the sample counting interval.

A total of 11 fissions were observed over the course of 238 experiments. Because of suspected background contamination from previous experiments, five PIPS detectors were counted for a period of 10 days after the experiment was completed to check for any background contamination. The background was found to be 0.5 fissions/detector/day. Hence, the 11 fissions observed were consistent with the detector background and could not be attributed to SF from $^{263}$Rf.

Based on a 10 nb cross section for $^{263}$Ha and a 5% EC branch from the previous experiment, 98 $^{263}$Rf fission events were expected, assuming a 100% SF branch for $^{263}$Rf. Since only 11 fissions were observed, all attributed to $^{256}$Fm, and assuming that an equal number of fissions from $^{263}$Rf had to be observed in order to make a positive identification, we could have detected a 0.5% EC branch from $^{263}$Ha. This result is inconsistent with our previous experiment that indicated a 5% EC branch from $^{263}$Ha.

Several explanations could account for not observing the EC branch in the current experiment. Perhaps $^{263}$Rf has a smaller SF branch and a larger alpha branch than expected. However, no alphas as long as 12000 seconds were observed that could be attributed to the decay of $^{263}$Rf. It is possible that the alphas could have been masked by $^{214}$Po\textsuperscript{1} (E\textsubscript{α} = 7.687 MeV). But only two alpha events from the $^{263}$Rf alpha daughter $^{259}$No (E\textsubscript{α} $^{259}$No = 7.5 MeV) were observed. It is therefore unlikely that a significant alpha branch in $^{263}$Rf exists. The two events would correspond to an alpha decay branch of close to 2% based on the 98 $^{263}$Rf fission events expected during this experiment.

Another possibility is that the masked $^{263}$Rf alphas decayed to $^{259}$No which then EC decayed to $^{259}$Md ($t_{1/2}$=103m). However, the primary decay mode in $^{259}$Md is SF so this decay chain is, therefore, unlikely. It is also possible that $^{263}$Rf EC decayed to the unknown isotope $^{263}$Lr, in which case, the decay of $^{263}$Lr might have gone unnoticed.

Since it was found in later experiments that Hf sticks to teflon, another explanation is that $^{263}$Rf stuck to the teflon discs that were used to collect the activity from the gas-jet during this experiment.

In the ARCA experiment, the apparatus which was used also was made of teflon. However, the activity which came into contact with teflon was mostly $^{263}$Ha. It was then sorbed on a column where it EC decayed to $^{263}$Rf which could then be eluted.

References
\begin{enumerate}
\end{enumerate}
Electron-Capture Delayed Fission Properties of $^{242}$Es


Electron-Capture Delayed Fission (ECDF) is a decay process whereby a parent nucleus undergoes electron-capture (EC) decay, populating excited states in the daughter nucleus which fission before deexcitation to the ground-state. This decay mode permits the study of fission properties (mass distributions, total kinetic energy (TKE) distributions and fission barrier shapes) in the EC daughter, which may have a ground-state spontaneous fission branch too small to study. In order for delayed fission to compete with other decay modes in the daughter, the electron-capture Q-value ($Q_{EC}$) must populate high-lying states in the daughter which are comparable in energy to the height of the fission barrier. Our group has found ECDF branches for a number of neutron-deficient actinides where $Q_{EC}$ exceeds 4.0 MeV.

Previous studies indicate that the log of the probability of delayed fission (PDF) increases linearly with increasing $Q_{EC}$. We chose to study $^{242}$Es, which has a $Q_{EC}$ of 5.6 MeV. This is about 1.0 MeV greater than in other actinides for which ECDF has been measured, and would result in a PDF of approximately $10^{-2}$. Also, the fission properties of $^{242}$Cf (the EC daughter) could be determined, which would be nearly impossible otherwise.

The $^{242}$Es was produced by bombardment of a $^{233}$U target with a $^{14}$N$^{4+}$ beam at the 88-Inch Cyclotron. The reaction products were swept in a KCl/He aerosol from the target chamber through a capillary to our rotating wheel detection system. The products were collected on thin polypropylene foils located on the periphery of the rotating wheel. It was moved at preset intervals between two pairs of silicon detectors, which were used to detect fission events and α-particles. X-ray and γ-ray detectors were placed in close proximity to the silicon detector pairs so that K X-rays from the electron-capture could be detected in coincidence with fissions. We observed α-particles with an energy of 7.9 MeV which come from the decay of $^{242}$Es, as well as 16 fission events. Based on the lifetimes of the fissions and α-decays, we estimated a half-life of 10 seconds for the $^{242}$Es. The fission events showed an asymmetric mass distribution with an average TKE of about 180 MeV. By assuming that the alpha and electron-capture branches are equal ($\lambda \alpha / \lambda_{EC} = 1$), a delayed fission branch of $6.0 \times 10^{-3}$ was calculated.

Interfering activities produced from an impurity in the target prevented us from determining the $^{242}$Es EC branch and hence the PDF. In the future we plan to repeat the experiment with a cleaner target to get a more precise value of the PDF.

Footnotes and References


![Graph](image)

Fig. 1. Probability of delayed fission (PDF) as a function of electron-capture Q-value ($Q_{EC}$).
Gamma-Ray Studies of the Spontaneous Fission of $^{242}$Pu and $^{252}$Cf Using Gammasphere


Spontaneous fission (SF) gamma-rays of $^{242}$Pu and $^{252}$Cf have been studied at Gammasphere. Preliminary analysis of the $^{242}$Pu data has concentrated on extracting relative intensities of ground rotational transitions as a function of number of neutrons emitted. “Cold fission”, or zero-neutron fission,¹ is observed in a number of fissioning systems, including initial studies of the $^{142}$Xe → $^{100}$Zr, $^{140}$Xe → $^{102}$Zr, $^{139}$Xe → $^{103}$Zr, $^{138}$Xe → $^{104}$Zr, $^{140}$Te → $^{102}$Mo, $^{138}$Te → $^{104}$Mo, $^{136}$Te → $^{106}$Mo, and possibly $^{132}$Sn → $^{110}$Ru pairs. Yields of product isotopes have been measured for the even-even Xe-Zr systems (see Figure 1), with the odd-A systems currently under investigation. The fitted Gaussians indicate a difference between the SF of $^{242}$Pu and thermal-neutron-induced fission of $^{241}$Pu. Although the yields of the Xe-Zr isotopes are nearly the same at the maximum of the distribution, and the centroids are nearly identical, the thermal-neutron-induced fission distribution is wider, because of the additional energy available in the fissioning system from the neutron binding energy.

Preliminary analysis of the $^{252}$Cf SF gamma-rays has yielded a wealth of information on nuclear structure of neutron-rich isotopes² and odd-Ru isotopes.³ Intense study of the Ba-Mo fission pair has revealed fission with zero-neutrons up to ten-neutrons emitted and a second fission mode ~ 7% the intensity of normal assymetric fission indicating one fission partner is highly deformed at scission.

Footnotes and References

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Fig. 1. Yields as a function of Xe mass number for the Xe-Zr fission products following the spontaneous fission (SF) of $^{242}$Pu (open triangles) and thermal-neutron-induced fission of $^{241}$Pu (solid squares). The curves are Gaussians fitted to the SF data (solid) and thermal-neutron-induced data (dashed).

Footnotes and References

Evidence of unique parity band structure in neutron-rich odd-A Ru isotopes


With prompt gamma-ray and x-ray spectroscopy on fission fragments from $^{252}$Cf and $^{242}$Pu spontaneous fission, several new transitions in $^{109,111}$Ru have been identified. These and previously known transitions form sequences that are suggestive of a $\Delta J = 2$ band structure. Triaxial rotor-plus-particle calculations and an examination of systematics of $J^\pi = \frac{11}{2}^-$ states in odd-A nuclei with $A \approx 110$ support our hypothesis that the observed band is built on the unique parity $h_{\frac{3}{2}}$ orbital.

Footnotes and References

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Identification of the New Isotope $^{114}$Ba and Search for its Alpha and Cluster Radioactivity


The first searches for $^{114}$Ba $\rightarrow$ $^{12}$C + $^{102}$Sn were performed by Oganessian and co-workers in 1992-93. They bombarded a nickel target with the internal $^{58}$Ni beam of the U-400 cyclotron and, by using a theoretical estimate of 1 $\mu$b for the cross section for the reaction $^{58}$Ni($^{58}$Ni,2n)$^{114}$Ba, they deduced a total collection of 3 $\times$ 10$^6$ $^{114}$Ba atoms in a very high neutron background. In a polycarbonate film surrounding the target they detected $\sim$10$^3$ tracks. All of them were attributed to recoils of fast-neutron-induced reactions with nuclei in the film except for $\sim$10 tracks that were found to have a range long enough to be compatible with $^{12}$C spontaneously emitted by $^{114}$Ba. From this result they determined an upper limit of 10$^{-4}$ for the branching ratio for carbon emission. Later they reduced the neutron background by transporting the reaction products far from the target with a gas jet. Nevertheless, the neutron background was still too high to permit them to improve their limit on the branching ratio.

In our experiment we searched for carbon emission from $^{114}$Ba under cleaner experimental conditions and without making any assumption about the $^{114}$Ba half-life or the $^{58}$Ni($^{58}$Ni,2n)$^{114}$Ba reaction cross section. Using the on-line mass separator at the GSI Unilac we produced $^{114}$Ba and measured its production cross section to be 0.20$^{+0.13}_{-0.09}$ $\mu$b. The new isotope $^{114}$Ba represents the heaviest N = Z + 2 nucleus known to date. With $\Delta$E-E telescopes we measured the total ($\beta$-decay) half-life to be $T_{\beta}$ = 0.43$^{+0.30}_{-0.15}$ s and the partial $\alpha$-decay half-life to be $T_{\alpha} \geq 1.2 \times 10^2$ s (1 MeV $\leq E_{\alpha} \leq 4$ MeV) for $^{114}$Ba. With barium-phosphate track detectors we found a half-life for spontaneous $^{12}$C emission $T_C \geq 1.1 \times 10^3$ s based on three carbon events. This result is the first limit, and encouraging preliminary evidence, for cluster radioactivity from mass-separated $^{114}$Ba. If it is confirmed in future, it would mean that theoretical predictions underestimate the decay rate by factors ranging from 10$^5$ to 10$^{12}$; it would also be the only case where cluster radioactivity dominates over alpha-decay. The future experiment will use glass detectors that will be heated just before the run to remove all background tracks.

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Enhancing the sensitivity of CR-39 detectors to relativistic ions by etching in potassium and sodium hydroxides

Y. D. He and M. Solarz

To record particles of increasingly lower ionization (i.e., lower \( Z/\beta \)), various attempts have been made to improve the sensitivity of CR-39 detectors. These efforts include the addition of small amounts of chemical additives to CR-39 during the manufacturing process, the treatment of CR-39 by a laser beam before exposure to nuclear particles, the pre-soaking of CR-39 after exposure in some special liquids, and the use of chemical reagents other than NaOH such as potassium hydroxide (KOH) for etching. Among these various approaches towards improving the sensitivity of CR-39 detectors, the last one is relatively prudent because the procedure takes place after irradiation.

We tested the feasibility of improving the sensitivity of CR-39 plastic detectors to relativistic ions by etching them in a mixture of 6.5N KOH and 6.25N NaOH. We examined the variation in sensitivity with fractional content of KOH in the mixed KOH + NaOH etchant at 60 °C, by using a beam of 200 A GeV \(^ {32} \)S at CERN SPS. We find that the detector response reaches a maximum when 6.5N KOH:6.25N NaOH \( \sim 1:3 \) at 60 °C. At the peak ratio, the detection threshold of CR-39 is one charge unit lower than those obtained from other etchants (see Table 1). Measurements made with an automated scanning system of etch pits developed in different etchants lead roughly to the same charge resolution \( \sigma_Z = 0.10 \pm 0.02 \) charge unit for one pair of etch pit measurements in the range \( 6 \leq Z \leq 16 \) at a sampling distance \( L_s \sim 47 - 57 \mu m \).

It is worthwhile to emphasize that the above results are obtained for CR-39 (DOP) etched in mixtures of 6.5N KOH and 6.25N NaOH at 60 °C. The variation in sensitivity with the mixture ratio might depend on the normality of solution and etch temperature. It is suggested, based on the work presented in this paper, that the mixed KOH + NaOH could be used as an etchant for CR-39 detectors in future heavy ion experiments to yield a better sensitivity.

Dependence of CR-39 etch rates on concentration of etched products in sodium hydroxide etchant*

M. Solarz and Y. D. He

We have measured the etch rates and the response to 200 A GeV $^{32}$S ions of CR-39 plastic detectors etched in 6.25N NaOH at 50 °C for various time intervals. We find that both the general etch rate and track etch rate change with the accumulated quantity of plastic etch products deposited into the etchant, as shown in Figure 1. This characteristic of the etching environment has probably not received adequate attention among CR-39 users.

It is generally known that the performance of nuclear track detectors is influenced by the etching condition including etchant, temperature, and normality. Therefore, careful control of etching conditions is needed in order to optimize the detector performance and to be able to reproduce experimental results. The data presented in this paper show that the etch rates depend, evidently, also on the concentration of etched product. Being aware of these dependences, it would seem to be possible for users of CR-39 to choose reagent etchants with specified etch histories so as to obtain different desired response of their plastic detectors.


Figure 1: The general etch rate $v_G$, track etch rate $v_T$, and the response $s$ to 200 A GeV $^{32}$S ions as a function of the concentration of CR-39 etched product in 50 °C 6.25N NaOH. The solid symbols are data in Table I, while the open symbols are data obtained from a 16 hour etch in fresh NaOH, after having etched for 355 hours.
IsoSpin Laboratory Target Studies

M.A. Stoyer, J.M. Nitschke,* and R.J. Donahue

Progress was made in several areas of target development for the proposed radioactive nuclear beam facility generically known as the IsoSpin Laboratory (ISL). On the nationwide front, a radioactive nuclear beam facility based on the Isotope Separator On-Line (ISOL) method as envisioned in the 1991 ISL Whitepaper1 was given high priority in the NSAC Nuclear Physics Long Range Plan for the next five years. Many physicists and chemists are interested in the timely construction and operation of such a facility. Our group made contributions to the updated ISL Whitepaper.2

At LBL we have been investigating several aspects of the target. A high-voltage target test stand has been successfully used to test a water-cooled target design and four He gas-cooled designs. Gas cooling of the target results in a significantly smaller target (less to dispose of when the irradiation is complete) and allows full range of cooling/heating of the target; because during low-power runs the target might have to be heated to achieve the optimum operating temperature. Finite Element Heat Transport (FEHT) calculations have been performed to not only compare with the target designs being tested, but to model and predict the modifications needed to improve the target design. FEHT calculations are currently two-dimensional, but extension to three-dimensional modelling is in progress. Quite uniform longitudinal temperature profiles have been achieved with the latest He gas-cooled target design and a uniform input heat distribution. The primary proton beam energy deposition in the target will of course not be uniform, however, modification of the cooling channel widths and spacings should compensate for the beam deposition profile.

Another important aspect of the target is the prediction of the beam intensities available for experiments including all practical factors possible in order to have as realistic predictions as possible. The code system3 was completed except for the program to properly include neutrons below 20 MeV for the LAHET4 calculations. Radioactive growth and decay, and a global (same for all elements) time for diffusion, desorption, ionization, extraction and acceleration of a species are included in the calculations. It is recognized that the diffusion/desorption process is highly element dependent, and depends also on target matrix, temperature, material and geometry. Proper treatment of the diffusion/desorption is yet to be included. TSAO5 calculations have been performed for CaO, La, Nb, Ta, Pb and UC targets, and LAHET and FLUKA6 calculations have been performed for UC targets. Comparisons between the codes and with experimental data are under investigation.

Footnotes and References

1 The IsoSpin Laboratory: Research Opportunities with radioactive Nuclear Beams, LALP-91-51 (1991).
6 A. Fasso, et al., presented at the Workshop on Simulating Accelerator Radiation Environments, January 11-15 (1993), Sante Fe, NM.
User-Friendly Data Acquisition and Control for Cyclotron Irradiations*

M.A. McMahan and Arie Katzi

The 88" Cyclotron is used for basic research in nuclear science as well as by industrial users and some biologists. The requirements for data acquisition are widely varying, with the key features being flexibility, reliability, and user-friendliness.

For the special needs of small user groups and for beam developments, a MACINTOSH was chosen for its user-friendliness. CAMAC was used as the interface between the detector and computer in order to take advantage of the hardware available in the NSD Equipment Pool. National Instruments' Labview software was chosen because there was some experience with it at the facility.

Signals from a generic detector are massaged by standard NIM modules. The signals are read into the CAMAC modules (Analog-to-digital converters (ADCs), Time-to-digital converters (TDCs), or scalers). CAMAC input/output modules are used to monitor and control the cyclotron beam. A GPIB (General Purpose Interface Bus) crate controller is interfaced to a GPIB I/O board in a MAC Quadra 650.

A suite of Labview programs has been written to meet the various needs of small users and for beam line diagnostics. These include i) a program to measure the fluence and uniformity of the beam for irradiations using high energy light ions, ii) a program to measure the fluence of the beam for irradiations using heavy ions, and iii) a program used to verify the correct ion species and energy of the beam using a silicon detector or detector telescope. For each of these applications, a VI (Labview subroutine) was written which is callable from the initial menu of the testing program suite. For example, in the energy measurement program, this VI looks for a LAM from an ORTEC AD811 peak-sensing ADC with one or more silicon detector signals. On detecting a LAM, the program reads the ADC and uses the non-zero channels to increment a spectrum. Because of the triggering requirements of this VI, it runs much slower than the dosimetry programs. In order to speed it up, acquisition proceeds for a given number of triggers before the spectra is displayed. One can use cursors to mark the channels or a Gaussian fitting routine to get the fit the peaks.

The combination of Labview reading over the GPIB to the CAMAC Controller is a slow system. This is not a problem for fluence measurements for irradiations since the beam intensities used are typically very low (100s of counts/second), and the dose accuracy needed not too high. Speed becomes more of a factor in the energy measurement program. The program typically acquires only about two events/second. However the energy is only measured occasionally and thus the lack of throughput is more frustrating than a real hindrance.

Another disadvantage of Labview for this application is that is requires lots of memory (≈20 MBytes) so is not able to run on a MAC that is not configured for it.

On the other hand, once Labview is learned it is easy to program. Thus this system is very versatile and can easily be tailored for a specific experiment. This factor outweighs all the disadvantages in our experience. It has been very well received by experimenters and operations staff alike.

Footnotes and References

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"Not all computer work is done on-line, of course. CD-ROMs have become the latest rage for users at home or on the job," are LBL Director Charles V. Shank's introductory remarks about \textit{Papyrus}™ NSR in his 1994 Report to the Regents of the University of California.

In May 1994, the Isotopes Project in collaboration with Lund University, Sweden, released \textit{Papyrus NSR}, the first nuclear structure bibliographic database on CD-ROM. The database contains over 130,000 references from \textit{Nuclear Structure References (NSR)}, the on-line database for low- to medium-energy physics maintained by Brookhaven National Laboratory. A special version of the program \textit{Papyrus}, developed by Research Software Design, Inc., in Portland, Oregon, manages the 150-Megabyte database. Users can search \textit{Papyrus NSR} by author, title, journal, publication year, words in the title, \textit{keywords}, or combinations of these. \textit{NSR keywords} are a unique feature of this database. They provide fast access to information that are indexed by properties such as chemical element name, mass and atomic numbers, half-life, nuclear moment, superdeformation, nuclear reaction, and others. Moreover, the following \textit{special} keywords: \textit{ATOMIC MASSES}, \textit{ATOMIC PHYSICS}, \textit{COMPILATION}, \textit{NUCLEAR MOMENTS}, \textit{RADIOACTIVITY}, \textit{NUCLEAR REACTIONS} and \textit{NUCLEAR STRUCTURE} (theory), allow searching by these general topics.

The Isotopes Project has publicized the CD-ROM in newsletters from the American Physical Society Division of Nuclear Physics, International Atomic Energy Agency (IAEA) Nuclear Data Section, and more recently, in the European journal \textit{Nuclear Physics News}. About one thousand free CD-ROMs have been distributed at scientific meetings, and throughout the scientific community upon request. Current plans are to update and release \textit{Papyrus NSR} yearly.

\textit{Papyrus NSR} runs on IBM/PC-compatible computers. A 386-based system with DOS version 6.2 and WINDOWS version 3.1 or later is sufficient for an efficient operation.

\textbf{Footnotes and References}

\textsuperscript{™} \textit{Papyrus} is a trademark of Research Software Design
GAMQUEST, A Computer Program to Identify Gamma Rays

E. Browne

The characteristic energies and intensities of gamma rays emitted by radioactive isotopes are commonly used as fingerprints for isotope identification. This specificity is the foundation of neutron-activation analysis and the basis for the analysis of radioactivity in environmental samples. Because of the large number (over 60,000) of known gamma rays from radioactive decay, analysis can be a formidable task, especially when applied to complex spectra with numerous gamma rays. GAMQUEST\(^1\) can help overcome this difficulty by comparing spectral lines with gamma-ray data contained in a large database from the Table of Radioactive Isotopes\(^2\). For each retrieved gamma ray, GAMQUEST displays the energy, intensity, the name and half-life of the emitting isotope, and the energies and intensities of the two most intense gamma rays emitted by the isotope. Additional searching conditions applied to gamma-ray intensities, and to the isotope's half-life, mass number A, and atomic number Z may be included to reduce the number of superfluous matches. A second program option produces, for individual isotopes, a list of emitted x rays and gamma rays. The program stores the retrievals into files that may be printed, or transferred by electronic mail to other computers, as well as edited and displayed on the screen at the end of each session.

GAMQUEST runs on the CSA1 and CSA2 computers of the Lawrence Berkeley Laboratory (LBL) VAX/6610 cluster of Digital Equipment Corporation (DEC) computers. The program, written in DEC Command Language (DCL) for the Virtual Memory System (VMS) operating system, executes several procedures that operate a large relational database from the Table of Radioactive Isotopes. Datatrieve\(^3\) (a DEC database management system) manages this database, which is on disk in the Common Data Dictionary (CDD). Users can run GAMQUEST from individual accounts, or from a Guest Account, through Hepnet (using DECNET), Internet (using TELNET), or World Wide Web (using NETSCAPE, MOSAIC, or LYNX). The account may be accessed through World Wide Web at the following locations:


Footnotes and References


3 **Datatrieve**, a database management system from Digital Equipment Corporation, Maynard, Massachusetts.
Cyclotrons for Radioactive Beams

D. J. Clark* and F. Marti**

This paper discusses the magnet design of a cyclotron to be used as the primary accelerator for the ISL project [1]. Previous designs were discussed in Refs. [2], [3]. This design has a proton energy of 600 MeV with 100 µA current. It has a single stage, a normal conducting magnet coil and a 9.8 m outside yoke diameter. The rf system is similar to that of Ref. [3], with 2 dees in opposite valleys supported on axial dee stems that run at the 4th harmonic. Auxiliary dees or cavities near the edge increase the turn separation there to give single turn extraction.

This 8 sector design completes the previous work with a final magnet iron design which gives orbit stability. The required increasing field with radius is obtained by increasing the fractional hill width with radius. The magnetic field was calculated with the 3D code TOSCA. The 3D grid used by TOSCA is shown in Fig. 1. The magnetic field from TOSCA was used in the equilibrium orbit code (E.O.C.) GENSPEO to find the axial and radial frequencies. The field was also Fourier analyzed to find average field and its gradient, the flutter and the spiral angle of the lowest harmonic of the field. The approximation for Nuz and Nur using these values agrees well with the E.O.C., and both show orbit stability. Even without further shimming phase slip would allow acceleration to about 580 MeV for 2 MeV/turn energy gain. However this 8 sector magnet has low flutter focusing in the center region and poor transit time in the first turns for a dee-in-valley design like this one. The design chosen previously [3] makes a transition to a 4 sector structure at the center to solve these problems. While this appears to work, a simpler solution is to use 4 sectors for the whole magnet, unless resonances are a problem.

A 4 sector magnet having the same spiral and fractional hill width as the 8 sector design was calculated with TOSCA. Equilibrium orbits were found with the E.O.C. up to 600 MeV. The Nur of the E.O.C. reaches almost 1.8 at 3 m, but does not cross the resonance at 4/2 = 2.0. A phase plot where Nur = 1.8 shows good stability. Phase plots where Nur = 4/3 show slow instability for a few MeV, but this should be crossed safely with 2 MeV/turn energy gain. The resonance at Nur = 3/2 was not investigated, but may be crossed with some correction coils in that region. More careful study is necessary to study the effects of these resonances.

The secondary accelerator in the BenchMark design [1] is assumed to be a linac. Cyclotrons can go to higher energy more economically and can also have excellent beam quality with single turn extraction. The challenge is to get both good transmission and high beam quality with cyclotrons. The most economical design is to start with a high charge state, U^{34+}, from an ECR source, which has been demonstrated by existing ECR sources, followed by a K-1200 cyclotron. Development is necessary to produce high charge states in an ECR at high efficiency in the environment of possible high gas flow from the target.

![Figure 1. TOSCA grid for 8 sector magnet.](image)

Footnotes and References


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Two-Frequency Plasma Heating in a High Charge State ECR Ion Source*  
Z.Q. Xie and C.M. Lyneis

The performance of the LBL Advanced Electron Cyclotron Resonance (AECR) ion source, which is a single stage source designed to operate at 14 GHz alone (single-frequency heating), is enhanced by heating the plasma simultaneously with microwaves of 10 and 14 GHz (two-frequency heating). The source was recently modified so that both 10 and 14 GHz microwaves could simultaneously be injected into the main chamber. The magnetic field shape of the AECR source can be adjusted by lowering the magnetic field at the center so that the closed ECR resonance surfaces at both 10 and 14 GHz coexist and are well separated. With the two ECR heating surfaces, electrons can gain energy at either one of the two ECR surfaces. The less localized plasma heating improves the plasma stability and more wave power can be injected into the plasma to generate a higher density of energetic electrons. A higher population of the energetic electrons in an ECR ion source can result in an enhanced production of high charge state ions. With this technique, 6.5 eμA of Bi\(^{36+}\), 1.1 eμA of Bi\(^{41+}\) and 0.24 eμA of Bi\(^{44+}\), 10 eμA of \(^{238}\)U\(^{35+}\), 1.5 eμA of \(^{238}\)U\(^{41+}\) and 0.5 eμA of \(^{238}\)U\(^{43+}\) have been produced which are 2 to 5 times better than single-frequency heating. The charge state distribution shifts to higher charge state, as shown in Figure 1, indicating an increase in the electron energy \(E_e\) or density \(n_e\) of the ECR plasma. With two-frequency heating, the source can produce more than \(1\times10^9\) pps of fully stripped argon. Very high charge state and low intensity ion beams of bismuth and uranium produced by the source were injected into the 88-Inch Cyclotron. After acceleration to energies greater than 6 MeV/nucleon, the extracted beam intensities were \(1\times10^6\) pps or higher for Bi\(^{50+},^{51+}\) and \(^{238}\)U\(^{52+},^{53+}\).


Figure 1. Charge state distributions for \(^{238}\)U produced by the AECR source are shown for two cases. Curve 1 indicates the best distribution obtained with single-frequency (14 GHz) heating. Curve 2 shows the distribution obtained with two-frequency (14 + 10 GHz) heating. The peak charge state shifts from 33+ in curve 1 to 36+ in curve 2.
NUCLEAR ASTROPHYSICS AND WEAK INTERACTIONS
Sudbury Neutrino Observatory,  
Photomultiplier Tube Support Structure  
Kevin T. Lesko, Yuen-Dat Chan, Maria Isaac, Martin Moorhead, Eric Norman, Robert Stokstad and the Sudbury Neutrino Observatory Collaboration

The Sudbury Neutrino Observatory (SNO) detector is a large heavy water Čerenkov detector designed to detect neutrinos in a 1000 ton D$_2$O target. The detector has sensitivity to the total neutrino flux, $\nu_x$, independent of family ($x= e, \mu, \tau$) and to the $\nu_e$ flux, separately, by measuring the elastic scattering, charged and neutral current signals. The detector is located in a mine two kilometers below ground near Sudbury, Ontario Canada. The mine is an active nickel mine operated by INCO, Ltd. The D$_2$O is contained in a thin-wall acrylic sphere, six meters radius, which is itself suspended in a 11 meter radius cavity filled with $\sim$7800 tons of ultrapure water.

Installation of the detector began this year. The upper 60% of the steel geodesic structure was installed and suspended in the detector cavity during the Winter of 1994-5 under the direct supervision of the LBL team. The PMT panel assemblies mounted on the geodesic sphere began installation in the Spring of 1995. The installation of the acrylic sphere will then follow this activity. The PMT support structure will then be completed in 1996. The water fill and beginning of data collection will then ensue.

Lawrence Berkeley Laboratory designed and supplied the Photomultiplier Tube Support Structure, which will position and secure the 9500 PMTs used to detect the Čerenkov light generated by neutrino interactions in the D$_2$O. The experimental constraints on the design require an extremely low radioactivity contamination of detector components, submersion in ultrapure water for a period of at least ten years, restricted maintenance opportunities, and installation in an active nickel mine while simultaneously maintaining clean-room conditions.

The PMT Support Structure load bearing structure is based on a three-frequency icosahedron geodesic structure, 9 m in radius. All elements of the geodesic structure have been tested for low level radioactivity and are below 15 ppb level established for the detector; typically the levels were less than 5 ppb. All low level radioactivity measurements were performed at LBL's Low Level Counting facilities, either at the LBL site or at the Oroville Dam facility.

The panel assemblies that house the light concentrators and the PMTs were assembled at LBL's clean room assembly facility and shipped to Sudbury, where the PMTs and concentrators have been installed. The components shipped to Canada were packaged to preserve their cleanliness. All fasteners and the plastic elements that make up the panels were tested for cleanliness and low level radioactivity. Again, all components were lower than the 15 ppb level for [U, Th] contamination. These measurements encompassed both the raw materials and the completed components.

LBL continues to supply guidance to and perform R&D for the SNO collaboration on control of contamination. LBL works with the installation contractors and the other detector component suppliers to assure that the low levels of contamination control will be met during the installation of the detector during the next two years.

Footnotes and References
Sudbury Neutrino Observatory, Monte-Carlo Simulations and Data Analysis

Martin Moorhead, Yuen-Dat Chan, Maria Isaac, Kevin T. Lesko, Eric Norman, Robert Stokstad and the Sudbury Neutrino Observatory Collaboration

SNOMAN, the Monte-Carlo simulation and data analysis program for the Sudbury Neutrino Observatory (SNO), is in a period of rapid development as the construction phase of the Observatory nears completion. The LBL group has played a major role in the development of this code and this effort has increased as LBL's hardware responsibilities have been met.

One major area of LBL contribution to SNOMAN has been the graphical display package. Over the past year this task has been extended to include a user interface for SNOMAN using the Windows Motif package. The value of such a user interface, given the complexity of a large program like SNOMAN, is becoming increasingly apparent as members of the SNO collaboration switch over from hardware responsibilities to simulation issues. The user interface will also help in the comparisons between different SNOMAN runs at different institutions, since it records all the run dependent input parameters in a standard format.

More recent LBL contributions to SNOMAN have been made in photon transport, geometry and input parameters for radioactive decay schemes and reaction cross-sections. The goals of these contributions have been to provide accurate and detailed treatments of i) backgrounds from radioactivity in the photomultiplier support structure and other components, and ii) calibration sources, in particular the $^{16}$N and $^{17}$N sources which are being developed at LBL.

On the data analysis side several event fitters are being developed using neural network, maximum likelihood and other techniques. The aim of these fitters is to reconstruct event position and direction as well as to provide some particle identification capabilities. The latter task is particularly important in the case of separating single electron events (the charge current reaction) from neutron capture events on $^{35}$Cl (the neutral current reaction). Recent results indicate that it will be difficult to achieve event-by-event separation, but that the two classes of events can be separated on a statistical basis which will enable the determination of the overall number of events in each class from a mixed data set.

An Analysis of MSW (matter-enhanced neutrino oscillation) distortions of the charge current spectrum has begun. From this analysis it has become clear that the theoretically favored 'small-angle MSW' solution to the solar neutrino problem produces a measurable distortion of the charge current spectrum. However, this distortion occurs mostly at low energy (5-7 MeV, near threshold) where it is obscured by neutron capture events on deuterium. To remedy this problem it is proposed to introduce 30 Kg of $^6$Li (in the chemical form of $^3$Li) into the D2O in order to capture >99% of the free neutrons on $^6$Li and reduce the rate of capture on deuterium by a factor >25.

A two meter diameter test detector is being built in Seattle with 100 photo multipliers (c.f. the 18m diameter and 10,000 PMT SNO detector). The primary aim of this test detector is to test the electronics and DAQ system and also to exercise the MC simulation and analysis chain with real events from calibration sources which will be used in SNO. The LBL group has taken a leading role in this test facility by designing the lay-out of the 100 PMTs and performing a dry assembly of the 2 m spherical support structure, as well as incorporating this geometry into the SNOMAN code and developing a fitter which can be used on either the 2m test detector or the 18m SNO detector. The ultimate objective of the 2m test detector is to provide real data which will thoroughly test the basis of the Monte-Carlo so that we are only doing 'fine tuning' when the real SNO detector is turned on in '96.

Footnotes and References
Sudbury Neutrino Observatory, Cleanliness Program Implemented

Robert Stokstad, Kevin T. Lesko, Yuen-Dat Chan, Maria Isaac, Martin Moorhead, Eric Norman, and the Sudbury Neutrino Observatory Collaboration

The need for control of surface contamination in the construction of the SNO detector in an active nickel mine was described in previous Annual Reports.\textsuperscript{1,2} Since then, the Laboratory has reached the stage where the cleanliness procedures could be implemented. We describe here our experience so far.

The period before August of 1994 involved a large amount of heavy construction as the site evolved from a cavity blasted in the rock to an environment for installation of the detector. The ceilings, walls, and floors were prepared and finished. The installation of the infrastructure—electrical, mechanical, plumbing, HVAC, including equipment to be used in the installation of the detector—was followed by a rough clean up involving the removal of large amounts of detritus. During this period the Laboratory was supplied with air from the mine's ventilation system. This air is laden with dust.

A key point on the way to creating a clean laboratory was the commissioning of the SNO ventilation system in August. Air from the mine supply was now filtered, at first with fairly rough filters (30\% and 95\% dust removal) and then with HEPA filters that remove 99.95\% of the particulate. This clean air was then supplied to five other ventilation units located throughout the Laboratory, which recirculate, cool, and further filter the air. With clean air and clean water available, establishing clean conditions in the Laboratory could begin in earnest. This required the removal of the large amounts of dust that had settled out on all surfaces and was accomplished with the use of power spray washers and a number of other devices for mechanical cleaning. Elbow grease was applied liberally.

Controls on personnel and material entering the Laboratory were instituted in a gradual manner corresponding to the gradual increase in cleanliness within. Equipment brought into the Laboratory was cleaned in the "Car Wash," a transition area between the mine drift outside and the clean laboratory inside. Workers entering the Laboratory began to use the Personnel Entry in which they removed the contaminated clothing worn in the mine, showered, and changed into clean garments.

Achieving a clean laboratory is an iterative process, since it is impossible to clean the entire Laboratory all at once, and there were occasional setbacks. For example, improper operation of the HVAC system during commissioning required that the ducts be cleaned sooner than anticipated. The waterproofing on the duct insulation had to be improved in order to wash it; the filter system for the water would malfunction, turning the water, intended for cleaning, red with rust. Nevertheless, during the period from September '94 through about February '95, the level of cleanliness improved steadily even as the completion and commissioning of installation equipment proceeded apace.

The level of cleanliness was monitored in several ways. The quality of the air was indicated by sampling the number of particles per unit volume. The CLASS of the air (particles/ft\(^3\) \(> 0.5\mu\)) improved from the order of \(10^5\) to \(10^4\) and eventually to order \(10^3\) in some areas. The rate at which dust settled on surfaces was monitored with witness plates—flat test surfaces in representative locations from which collected dust could be removed and measured. The x-ray fluorescence system designed for this purpose was commissioned and has performed as expected. Dust deposition rates came down to about 1-3 \(\mu\)g/cm\(^2\)/month. This was still higher than desired, but installation of clean components could begin in February, '95. A program of maintenance cleaning has been instituted. Constant surveillance will be required if the cleanliness goals are to be achieved. Future challenges will be the installation of the acrylic vessel and, at the close of construction, removal of heavy equipment and staging that was initially installed under dirty conditions.

\textsuperscript{1} NSD Annual Report, 1991, p. 81.
\textsuperscript{2} NSD Annual Report, 1992, p. 87
A system to produce and deliver short-lived radioisotopes for calibrating the SNO detector has been developed at Chalk River Laboratories. Using 14-MeV neutrons from a small D-T generator and a gas transport scheme, calibration sources such as $^{16}\text{N}$ ($E_\gamma = 6.13$ MeV) and $^8\text{Li}$ ($Q_B = 13$ MeV) can be produced via $(n,p)$ and $(n,\alpha)$ reactions, respectively, and delivered into the SNO detector. Knowing the neutron detection efficiency of SNO is crucial to the success of the neutral-current aspect of the experiment. Thus, it seemed worthwhile to investigate the possibility of using this same, gas-transport system to measure this important quantity.

The short-lived isotope $^{17}\text{N}$ ($t_{1/2} = 4.17$ s) is a well-known $\beta$-delayed neutron emitter. More than 95% of the beta decays of $^{17}\text{N}$ populate levels in $^{17}\text{O}$ that are unbound with respect to neutron decay. This leads to the emission of monoenergetic neutrons with energies (and intensities) of 0.383 MeV (34.8%), 0.884 MeV (0.6%), 1.171 MeV (52.7%), and 1.170 MeV (7.0%). A single $^{17}\text{N}$ decay inside the D$_2$O volume of SNO could thus produce two signals: a prompt signal associated with the beta emission, followed some milliseconds later by the capture of the moderated neutron. One can imagine either letting the beta go into the D$_2$O to produce Cerenkov light, or stopping the beta in the walls of a decay chamber made out of scintillator. In either case, one would have a "tagged" source of neutrons for determining the neutron detection efficiency of SNO.

In order to determine if sufficient quantities of $^{17}\text{N}$ could be produced via the $^{17}\text{O}(n,p)$ reaction using 14-MeV neutrons, a test was carried out at the D-T generator in the Health Physics Department at AECL Research, Chalk River. 14-MeV neutrons from this generator were used to irradiate known mixtures of $^{16}\text{O}$ and $^{17}\text{O}$ gases. A closed gas loop continuously flowed the gas from a target cell to a decay chamber. A 1" thick plastic scintillator paddle and a 40% efficient Ge detector were placed up against the decay chamber to measure the betas and gammas emitted in the decays of $^{16}\text{N}$ and $^{17}\text{N}$. With the gas loop filled with natural isotopic composition oxygen, the only gamma-rays observed above room background were those from the decay of $^{16}\text{N}$. However, when we used a mixture of 39.5% $^{16}\text{O}$ + 55.9% $^{17}\text{O}$ + 4.6% $^{18}\text{O}$, we also observed the 871-keV gamma ray characteristic of $^{17}\text{N}$ decay. By measuring the relative yields of the 871- and 6129-keV gamma-rays we determined the $^{17}\text{O}(n,p)$ cross section to be 28±5 mb (Ref. 3).

During our run, the Chalk River D-T generator emitted approximately $2.6\times10^9$ neutrons per second into $4\pi$. This produced an observed $^{17}\text{N}$ decay rate in our decay chamber of approximately 300/second. Taking $10^8$ neutrons/second into $4\pi$ as being within the reach of the planned SNO D-T generator, allowing (pessimistically) for a 50% loss of the $^{17}\text{N}$ due to decay in the transport capillary at SNO, and assuming that we would use 100% enriched $^{17}\text{O}$ gas, then we could confidently produce up to 10 $^{17}\text{N}$ decays/second inside the SNO D$_2$O volume. Thus, $^{17}\text{N}$ offers a relatively simple and clean way to measure the neutron detection efficiency of SNO.

Footnotes and References
*Chalk River Laboratories, Chalk River, Canada
The Neutral Current (NC) detection is extremely important aspect of the SNO detector which will permit us to explore neutrino oscillations as an explanation of the Solar Neutrino Problem. The Sudbury Neutrino Observatory is developing two schemes for neutron detection. One is based on the addition of a salt, MgCl to the D_2O. The ^35Cl captures the neutrons liberated through NC reactions and produces ~8 MeV of gamma radiation. These gamma rays are converted to Čerenkov light as they Compton scatter in the water. This light is viewed by the array of PMTs. The other scheme will deploy an array of ^3He counters in the D_2O. The array of discrete counters (NCDs) has the advantages of permitting a real-time and simultaneous determination of the NC and the CC signals, and improved sensitivity to supernova signals and time-varying NC signals.

The Lawrence Berkeley Laboratory group has joined the NCD project previously made up of the groups at Los Alamos National Laboratory, University of Washington, and Guelph University. We will be bringing our Low Background Counting expertise to the NCD project and direct-count many of the components that go into the NCDs. The NCDs are deployed in the D_2O and extremely low levels of contamination are permitted. Our experience in measuring and controlling contamination on the PMT Support Structure will be used in producing, transporting and installing the NCDs. We will apply the quality control and quality assurance procedures we developed for the PMT Support Structure to the NCD project. We are enhancing our simulation effort at LBL and applying this effort to determining the photodisintegration backgrounds for the NCDs, in particular by looking at beta-gamma coincidences and direct localized signals.

The NCD Project was recently reviewed by the Department of Energy and has been approved for funding in FY95.
Further Studies on the Evidence for a 17-keV Neutrino in a 14C-Doped Germanium Detector*

F.E. Wietfeldt, E.B. Norman, Y.D. Chan, M.T.F. da Cruz(a), A. García(b), E.E. Haller (c,d), W.L. Hansen (c), M.M. Hindi (e), R.-M. Larimer, K.T. Lesko, P.N. Luke (c), R.G. Stokstad, B. Sur, and I. Zlimen

In 1991 our group reported a preliminary result from the measurement of an 14C-doped segmented germanium detector. (1) A spectral distortion was seen near the endpoint that was consistent with the emission of a neutrino mass $17 \pm 2$ keV and $\sin^2 \theta = 1.4 \pm 0.5\%$. The evidence for emission of a 17 keV neutrino in the fits to the 14C data, apparently confirming Simpson's and Hime's results, was very exciting. It helped fuel the debate over its existence. However there were some serious anomalies in the data that needed to be understood before a conclusion about the massive neutrino could be made. One concern was the observed coincidence rate; approximately 9% of the center region signals were vetoed by signals in the guard ring.

In order to further study the coincidence signals, a CAMAC-based multi-parameter data acquisition system was set up in the Low Background Counting Facility. This allowed the detector's center and guard ring signals to be recorded separately for each event. Six days of 14C data were collected. To our surprise, not only was the coincidence rate very high, a large fraction of the events fell into radial bands with the guard ring energy proportional to the center energy.

In an additional test, the detector was scanned with a highly collimated 500 μCi point source of 141Ce. Starting at the center of the detector face, the source was moved radially outward in 0.5-1.0-mm increments to the outer edge of the guard ring and a spectrum was collected at each increment. This data indicated that ionization charge was divided between the center and the guard ring when a gamma-ray interacted under the groove.

The probability of charge division for events under the groove was quantified by comparing the photopeak and tail areas in center and guard ring spectra as the source was scanned across the detector. Charge division was observed to occur for about 70% of all interactions under the groove. This explains the high coincidence rate observed in the 14C experiment. The volume under the groove is 13.8% of the volume in the center region. If the 14C is distributed uniformly throughout the crystal, the coincidence rate should be about $(0.7)(0.138)=9.7\%$ due to charge division. The demonstrated presence of charge division under the groove and carbon clusters invalidates the original analysis that showed evidence of a 17 keV neutrino admixture in the spectrum and we retract that result. There is strong circumstantial evidence that the distortion originally observed was due to contamination of the beta spectrum by decays under the groove where the charge was split. This contamination spectrum has an endpoint very close to the kink position and about the correct magnitude. In any case, the most recent data no longer support the presence of a 17 keV neutrino emission in the 14C beta spectrum.

* Condensed from LBL-36136

Footnotes and References

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The feasibility of the observation of a signal from the allowed 2ν double beta decay of $^{150}$Nd to the excited states of $^{150}$Sm has been extensively studied.

The half life for the allowed double beta decay transition of $^{150}$Nd to the ground state of $^{150}$Sm was recently measured to be $(1.70 \pm 0.35) \times 10^{19}$ years [1]. On the basis of the expected phase space dependence of the transition probability, one can predict a lifetime of the order of $10^{20}$ years for the (2ν) double beta decay of $^{150}$Nd to the first $0^+$ excited state of $^{150}$Sm. The de-excitation from this level gives rise to two coincident gamma-ray lines, 334 and 406 keV.

The double beta decay transition of $^{100}$Mo to the first $0^+$ excited state of $^{100}$Ru has recently been measured and the resulting lifetime of the decay, based on the cascade gamma-rays is $(6.1 \pm 1.8 - 1.1) \times 10^{20}$ years [2], at the 68% confidence level limit, in agreement with the predicted value of $(6.4 \pm 1.9 - 0.6) \times 10^{20}$ years.

Such experiment requires a very low background level, both from the sample itself and the experimental setup. With this constraint in mind we have prepared two different samples of neodymium oxide and have measured their gamma-ray backgrounds at the Oroville low background facility. The contamination level in one of these samples was measured to be 1.2 ppb on Th and 0.6 ppb U.

We plan to use two low background 160 cc HPGe detectors inside a $4\pi$ NaI veto shield. We will collect multiparametric of the two HPGe and the NaI shield, recording energy and time information.

We have performed extensive Monte Carlo calculations and background studies, taking into account the actual contamination of the sample and the background levels at Oroville. According to these calculations we are able to obtain a sensitivity level of $10^{20}$ years, the expected lifetime of the $^{150}$Nd double beta decay to the first $0^+$ excited state of $^{150}$Sm.

Footnotes and References

Laser Trapping of Radioactive Atoms

S. J. Freedman, B. K. Fujikawa, M. A. Rowe, S. Q. Shang and E. Wasserman

Following our success in trapping of the 22.5-sec half-life $^{21}$Na atoms at the LBL 88" Cyclotron, we have spent the year improving several aspects of the trapping apparatus in preparation for experimental applications. The apparatus is relocated to a new area in Cave 5. The atomic beam oven is located in Cave 3, a radioactive atomic beam passed through the slow-down magnet inside the wall between Cave 3 & 5, the beam is stopped and loaded into a MOT in Cave 5. Two laser tables are set up placed in Cave 5. This will allows us to eliminated optical fibers and to use the full laser power. According to off-line measurements, the trapping efficiency will be improved because of the increased power by at least a factor of 5.

We have designed a new high temperature oven which releases reaction product more quickly. By using a MgO powder target, a 25 MeV proton beam was used to produce $^{21}$Na by $(p,\alpha)$ reaction. With 150 nA beam on the target, we can produce a $^{21}$Na beam $2 \times 10^9$/sec at 1200°C, which is 10 times better than the previous oven. Another benefit is that the $^{21}$Na beam free of the target material. This will increase the trap lifetime, allowing us to accumulate $^{21}$Na longer. In the next stage, we will add a multi-channel collimator to the oven and improve the scheme for transverse cooling. With these improvements, the number of trapped $^{21}$Na atoms will be more than adequate for a precise beta asymmetry measurement.

For off-line development, we are working on rf spectroscopy to expedite a precise measurement of the hyperfine structure with trapped sodium atoms. We plan to capitalize this technique to $^{21}$Na. This will give first physics measurement with laser trapped radioactive atoms. We are investigating schemes which provide polarized atoms trapped atoms. The rf spectroscopic technique we are working on should allow to precisely characterize nuclear polarization.

Our methods are very general and should be easily adapted to other rare isotopes. As an example, we have used our oven to produce neutral atomic francium beam by an Au($^{18}$O, xn)Fr reaction. A francium beam of $2 \times 10^9$/sec has been made. This flux is adequate for us to trap francium. We are continuing to develop the techniques for exploiting traps for precision measurements of weak-interaction parameters. The first such experiment is a measurement of the beta-asymmetry parameter in the mirror beta-decay of $^{21}$Na. The critical electron detectors for this experiment were assembled this year. This measurement can provide an interesting test of the handedness of the weak interaction.

![Figure 1. Plane view of the new Cave 5.](image)
A New Magneto Optical Trap by Non-Cycling Transition

S. J. Freedman, Z. T. Lu, M. A. Rowe, S. Q. Shang and P. van der Stratent

It is normally assumed that in order for a magneto optical trap (MOT) to operate a cycling transition is required. In the normal MOT a laser detuned from resonance transition provides the trapping force. Occasionally, an atom de-excites to another hyperfine component of the ground state because of an inevitable though small probability for non-resonant excitations. The cure is a "repumping" laser beam at a different frequency to insure that atoms do not remain in a "dark" state for long. The function of the each lasers is well defined: one provides the trapping force and the other insures that the atoms remain susceptible to the force. We have discovered a more general situation in which a MOT is be formed by simultaneous excitation by two or more non-cycling transitions. The trapping dynamics in very different from a standard MOT. Here the roles of the trapping and pumping lasers are no longer uniquely defined. In some cases, atoms can be "shelved" among states providing a method of preparing both pure and mixed states of the trapped atoms. The new scheme may also be useful for trapping complicated atoms that do not exhibit cycling transitions at all. Forming the new MOT required a carefully designed system because the trapping force is smaller.

We demonstrated the new MOT with the F=1 to F'=2 and F=2 to F'=2 transitions in sodium. Our success was possible because of an efficient loading scheme we recently developed [1]. As shown in Fig. 1 MOTs are formed in three places when the trapping laser is scanned over the atomic resonances. Two of these correspond to the known 1 to 1 and 2 to 3 transitions, for which a single transition is responsible for the trapping force. However, the signal in the middle of the scan is from a combination of F=1 to F'=2 and F=2 to F'=2 transitions working together to make a trap. Distinct from other traps this MOT can trap atoms with a linear combination of the F=1 or F=2 ground state. We have developed a three dimensional simulation based on a theoretical model developed at the Utrecht University. The simulation displays the qualitative features demonstrated by the experiment. In particular, the calculation shows that the new trap is due to the combination of the F=1 to F'=1 and F=2 to F'=2 transitions. There are several interesting features of the new trap and some possible applications for studies with radioactive atoms.

![Fluorescence signal from trapped atoms as a function of laser frequency. Dots are the experimental results. Solid lines are simulations.](image)

Footnotes and References

† Debye Institute, Utrecht University, The Netherlands

Determination of $G_V$ from the Superallowed Fermi Decay of $^{10}\text{C}$

B.K. Fujikawa, S.J. Freedman, and E.G. Wasserman

The weak vector coupling constant, $G_V$, is a fundamental parameter of the Standard Model of Electro-Weak Interactions. The most precise determination of $G_V$ comes from measurements of superallowed Fermi $\beta$-decays. Such determinations involve precise measurements of the partial $0^+ \rightarrow 0^+$ half life and the $\beta$ endpoint energy, along with careful, state of the art, theoretical nuclear physics calculations of the radiative and isospin symmetry breaking corrections. Measurements and calculations of these parameters have been made for the superallowed Fermi decays of $^{10}\text{C}$, $^{14}\text{O}$, $^{26}\text{Al}$, $^{34}\text{Cl}$, $^{38}\text{K}$, $^{42}\text{Sc}$, $^{46}\text{V}$, $^{50}\text{Mn}$, and $^{54}\text{Co}$. Although the weak vector coupling constant obtained from each of these decays are in good agreement with one another, the value of $G_V$ obtained implies a non-unitary Cabibbo-Kobayashi-Maskawa matrix which would be inconsistent with the Standard Model. In addition, the weak vector coupling constant obtained from the superallowed decays is inconsistent with the value of $G_V$ obtained from neutron $\beta$-decay. Although, there exists exotic extensions to the Standard Model which could explain these discrepancies, the reliability of the calculation of the isospin breaking correction is in question.

We are currently working on a precision measurement of the branching ratio: $^{10}\text{C}(0^+, \text{gs}) \rightarrow ^{10}\text{B}(0^+, 1.74\text{MeV}) + e^- + \nu$. This branching ratio is essential for the experimental determination of the partial $0^+ \rightarrow 0^+$ half life for the Fermi decay of $^{10}\text{C}$. At present, the uncertainty of $G_V$ from $^{10}\text{C}$ Fermi decay is dominated by the experimental uncertainty of this branching ratio. The value of $G_V$ determined from $^{10}\text{C}$ is very important, since the magnitude of the isospin breaking corrections decreases with the nuclear charge $Z$ and $^{10}\text{C}$ is the nucleus of lowest $Z$ Fermi decays.

Figure 1 shows the levels of $^{10}\text{B}$ and $^{10}\text{C}$ that are relevant to this experiment. All $^{10}\text{C}$ decays produce a 718 keV $\gamma$-ray. Decays to the $^{10}\text{B}(0^+, \text{1.74MeV})$ state produce an additional 1022 keV $\gamma$-ray. Therefore the branching ratio is simply equal to the relative intensity ratio $I(1022 \text{ keV})/I(718 \text{ keV})$.

**Footnotes and References**


Figure 1. The $\beta$-decay of $^{10}\text{C}$.

The experiment is being done at the GAMMASPHERE facility at the LBL 88-Inch Cyclotron. The Cyclotron provides an 8MeV proton beam to make $^{10}\text{C}$ through the $^{10}\text{C}(p,n)^{10}\text{B}$ reaction. The $\gamma$-rays from $^{10}\text{C}$ decay are detected with the germanium detectors in the GAMMASPHERE array. The relative efficiencies of these detectors are calibrated with the $\gamma$ cascade that results from the $^{10}\text{B}(p,p')^{10}\text{B}$ reaction. The detection of a 414keV $\gamma$-ray is used to tag excitations to the $^{10}\text{B}(0^+, 1.74\text{MeV})$ state which decays to the ground state by emitting exactly one 1022 keV $\gamma$-ray and one 718 keV $\gamma$-ray. Details of this experiment is described elsewhere. This experiment is scheduled to begin taking data on May 17, 1995.
Resolution of the long-standing question of the origins of CP-violation has been hindered by our failure to observe CP-violation outside of the neutral kaon system. Unlike its component symmetries, invariance under CPT (simultaneous inversion under parity, charge conjugation, and time reversal) is required on very general grounds. If CPT is conserved, then CP-violation implies simultaneous time reversal invariance violation (TRIV). Thus studies of TRIV provide another avenue for investigating CP-violation.

TRIV could appear in the beta decay of free polarized neutrons as a non-zero triple correlation, $D(\sigma \cdot p_p \times p_e)$, among the neutron polarization, and the proton and electron momenta. In the Standard Model TRIV effects in the neutron are vanishingly small. Due to the fortuitous smallness of T-conserving final state effects in neutron decay, the observation of $D > 10^{-5}$ would be a clear indication of physics beyond the Standard Model. Many extensions to the Standard Model contain additional T-violating parameters that contribute to $D$ in lowest order. Improving the current limit would constrain these extensions.

We formed the EMIT collaboration in order to undertake a new search for TRIV in neutron decay. We are employing a new detector geometry that greatly enhances the sensitivity to $D$. The full detector, consisting of an octagonal arrangement of four beta and four proton detector panels about a longitudinally polarized cold ($<0.025\text{eV}$) neutron beam is shown in Fig. 1.

Following the success of a proof-of-principle test run at the NIST Cold Neutron Research Facility (CNRF) using prototype detectors of each type, we began construction of the full detector, polarizer, and associated beamline.

The LBL group is responsible for the construction, and characterization of the detector, electronics, and data acquisition systems. Plastic scintillator paddles are used to detect the betas. The low kinetic energy of the recoiling protons ($<750\text{eV}$) makes detecting them more difficult. They are electrostatically focussed and accelerated to $35\text{keV}$ onto thin-windowed PIN diode detectors.

After assembly, the detector system will be moved to the CNRF where the first-data will be taken in late 1995. We expect to achieve a sensitivity to $D$ of $3 \times 10^{-4}$, about an order of magnitude better than the previous neutron experiments. In the future, we plan to run on a more intense neutron beam. For example, at the ILL in Grenoble, France, the higher cold neutron flux would allow further improvement to a statistical uncertainty of $2 \times 10^{-5}$.

Footnotes
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Limits on Dark Matter Using Ancient Mica*

D.P. Snowden-Ifft, E.S. Freeman and P.B. Price

The combination of the track-etching method and atomic force microscopy allows us to search for Weakly Interacting Massive Particles (WIMPs) in our Galaxy. In an initial search in $8 \times 10^4 \mu m^2$ of 0.5 Gyr-old muscovite mica, using an Atomic Force Microscope provided by the Nuclear Science Division, we found no evidence of WIMP-recoil tracks. This enables us to set limits on the mass and cross section of WIMPs which are comparable to the best spin-dependent limits from Ge detectors. Unlike the Ge detectors, however, the mica method is far from being background-limited. The three sources of background are recoiling daughter nuclei due to alpha decay of traces of uranium and thorium and recoiling atoms of the mica (K, Si, Al, or O) struck by fast neutrons or penetrating muons. (The muons themselves have too low a $dE/dx$ to produce a signal.) We argue that background recoils may not appear until we have pushed our current limits down by several orders of magnitude.

The LBL Low Background Facilities (LBF) consist of a Berkeley site and an Oroville site. The Berkeley site was established in 1963 and consists of a 3m by 7m x 3m room surrounded by 1.6m of specially-selected low-background concrete shielding. The aggregate in this concrete consists of serpentinite gravel which is low in Uranium, Thorium, and Potassium. This barrier was made to shield against accelerator-produced neutrons and natural gamma radiation as well as some cosmic rays. Also, the low-activity concrete emits little radon, and a HEPA filtered air system constantly purges the room.

Detectors at this site include a 20 cm diameter by 10 cm thick NaI detector and two 30% P-type Ge spectrometers. These detectors are shielded by 10 cm of Pb and one of them has an external active cosmic ray suppressor.

The resulting shields reduce the background to the point where internal activity in the detectors and cosmic rays are the dominant source of background. Besides the three detectors operated by the facility, "guest" detectors involved in experiments requiring low-background environments often reside at the facility.

The LBF Oroville site is located in the powerhouse of the Oroville Dam, under 180 m of rock cover. This site now has a 115% N-type Ge spectrometer and is used for our most sensitive counting. Sensitivities of 50 parts-per-trillion (ppt) for Uranium and daughters, 200 ppt for Th and daughters, and 100 parts-per-billion for K are realized at the Oroville site. In neutron activation of semiconductor-grade Si, parts-per-trillion sensitivity for 29 elements is realized in wafer-sized samples.

The main projects during the past year involved continued screening of detector-construction materials for SNO and the UCB Dark Matter Search, counting parts returned from the Hubble Space Telescope, Instrumental Neutron Activation Analysis of Silicon Semiconductor Materials (under a technology transfer grant), site boundary air sample monitoring, and characterization of Bevalac concrete blocks for re-use or disposal.

During the coming year, additional work is expected in materials screening for SNO and Dark Matter detectors, continued work on Neutron Activation Analysis of Si under a CRADA (Cooperative Research & Development Agreement) with Charles Evans & Associates, radiological site characterization in the vicinity of the new waste handling facility, characterization techniques for activity in concrete, and additional environmental air pollution research efforts. The facilities will also be involved in a double beta decay experiment with the Norman Group.

The Figure below shows a typical air sample taken at LBL. The dominant isotopes observed are \(^{7}\text{Be}\), formed by cosmic-ray interactions in the air, and \(^{210}\text{Pb}\), from Radon decay.

* Summer Student 1994, 1995
Cosmic-ray Activation of Parts on the Hubble Space Telescope
A.R. Smith, R.J. McDonald, D.L. Hurley, and E.B. Norman

The Hubble Space Telescope (HST) was deployed into a low equatorial orbit on April 25, 1990 and parts were returned to earth at the end of the First Servicing Mission on December 12, 1993. For these 3 years and 232 days, the HST and its components were exposed to solar and galactic cosmic-rays. Four stainless steel (SS) screws from the Wide Field Planetary Camera, an invar mirror mount, and an aluminum handle were obtained from the Goddard Space Flight Center and analyzed for induced radioactivity at the LBL Low-background Facility's Oroville counting site. The screw heads were exposed directly to the space environment, while the shanks and threads were somewhat shielded by the screw itself and the material into which it was seated. The mirror mount was internal to the spacecraft as was the DF224 handle.

Eleven months into this mission, a near-instantaneous injection of solar protons formed an intense radiation band in between the two previously known Van Allen belts at an altitude of 4000 to 10000 miles above the earth. While the HST is not this high, over the course of three years, this radiation belt dissipated via a scattering of particles to lower levels. Thus, the HST was exposed to higher levels of proton irradiation that would have been predicted from the LDEF experience. This resulted in about a factor of 3 higher activation than expected from LDEF.

The parts were analyzed at the Oroville site of the LBL Low-background Facilities on a 115% N-type-Ge spectrometer 180 meters underground sensitive at the level of 0.02 gamma/minute level. The data were corrected for self-absorption and decay since December 12, 1993, the time at which the parts were returned to earth.

The following Table lists the values of the activities produced in units of PCi/kg.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Screws</th>
<th>Mirror Mount</th>
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</thead>
<tbody>
<tr>
<td>$^{46}$Sc</td>
<td>42.5±4.0</td>
<td>10.8±1.7</td>
</tr>
<tr>
<td>$^{54}$Mn</td>
<td>380±14.</td>
<td>200±10.</td>
</tr>
<tr>
<td>$^{56}$Co</td>
<td>220 ± 22.</td>
<td>96 ± 10.</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>294±36.</td>
<td>172±24.</td>
</tr>
<tr>
<td>$^{58}$Co</td>
<td>114±48.</td>
<td>138±8.</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>2.9±0.3</td>
<td>3.3±0.3</td>
</tr>
<tr>
<td>$^{88}$Y</td>
<td>9.6±1.7</td>
<td>-</td>
</tr>
</tbody>
</table>

All the observed radionuclides, except $^{88}$Y, are expected and can be produced by reactions of energetic particles (mostly solar protons in the tens to hundreds of MeVs energy range) on iron. $^{88}$Y possibly comes from interactions on heavier trace elements, perhaps Mo. Activation by the higher-energy galactic component of the cosmic rays is a minor contributor to the activation of these surface-mounted parts, playing a more dominant role where the part is shielded.

The only cosmic-ray-induced activity in the Al handle was $^{22}$Na, at the 250 pCi/kg level.
Instrumental Neutron Activation Analysis of Silicon Semiconductor Material


Instrumental Neutron Activation Analysis (INAA) can provide improved sensitivity to selected contaminants in silicon compared to other presently available methods. Since the sensitivity to trace elements in a host material is dependent on the extent of neutron activation of the host, the ultra-pure silicon used in semiconductor fabrication is an ideal matrix for trace element analysis via INAA. Even within a nuclear reactor, minimal observable gamma-ray-emitting activities are produced in the silicon.

Samples of float-zone Si, some with oxide coating, some with implanted Zn, and some with memory fabrications, were prepared from pieces of Si wafers or from whole 100 mm diameter Si wafers, about 0.5 mm thick. These pieces were scored and broken under cleanroom conditions to fit into 1.7 cm diameter by 10 cm long quartz tubes. The tubes were evacuated, sealed, and sent to the University of Missouri Research Reactor for irradiation. All irradiations were done utilizing a flux of 8E13 neutrons/sec/cm². Activation times of 20 minutes to 10 hours were used.

The pure Si samples were etched in nitric and hydrofluoric acids until about 10% of the material was removed. As shown in the spectrum at the bottom, after the decay of the short-lived As and Au, only small amounts of Cr (1.0 PPT) and Sb (0.4 PPT) remain in the bulk Si.

Detection limits were calculated considering a 2σ minimum on the measured background and wafer-sized samples (10 g) and 10 hour irradiations at 8E13 neutrons/sec/cm². The table below shows limits for 43 elements in parts-per-trillion (PPT).

<table>
<thead>
<tr>
<th>Element</th>
<th>Limit (PPT)</th>
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<tbody>
<tr>
<td>Na</td>
<td>&lt;300</td>
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<tr>
<td>K</td>
<td>7.2</td>
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<tr>
<td>Ca</td>
<td>260</td>
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<td>Sc</td>
<td>0.0011</td>
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<td>Cr</td>
<td>0.43</td>
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<td>Fe</td>
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<td>Co</td>
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<td>Zn</td>
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<td>Cd</td>
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<tr>
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</tr>
<tr>
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<tr>
<td>Sb</td>
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</tr>
<tr>
<td>Cs</td>
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</tr>
</tbody>
</table>

Si Wafers: 6.9 g, 600 min irradiation, 160 hr Count at Oroville (2nd count)
RELATIVISTIC NUCLEAR COLLISIONS
Inclusive proton cross sections from 800 MeV/n $^{139}$La + $^{nat}$La

D. Cebra, and the EOS collaboration

The inclusive proton production cross sections from the reaction 800 MeV/n $^{139}$La + $^{nat}$La have become a 'benchmark' measurement in relativistic heavy-ion reactions; however there still exist discrepancies between published experimental results 1 2 and between various model predictions 3. The EOS collaboration has remeasured these cross sections, improving on the previous results and extending the measurements in two important ways. We extend the coverage in polar angle down to 0°, and we extend the lower momentum cut off down to 50 MeV/c. These new data provide stricter constraints on the models because the regions where the target and projectile remnants contribute to the cross sections are now measured.

In Fig. 1, the $p_{like}$ Lorentz invariant cross sections,

$$\sigma_I = \frac{E \, d^2 \sigma}{p^2 \, dp \, d\Omega} \quad (1)$$

for are plotted against the laboratory momentum. The data only for the 20° cross sections are plotted, as these results have presented the major discrepancies between the published data and the models. In the top panel of the figure, the data measured by the EOS TPC are compared to the measurements by Hayashi et al. 1 and to the recent measurements by Dardenne et al. 2. The shape of these spectra, above 500 MeV/c, is characteristic of thermal emission from a moving source. Below 500 MeV/c there is evidence of emission from the target remnant. This region is characterized by a significantly steeper slope parameter and an almost isotropic emission pattern. The contribution of the projectile spectator source is evident as a flattening of the cross sections around 1.5 GeV/c. The new EOS data agree well with the data of Hayashi et al. for momenta below 1 GeV/c. We observe significant disagreement for higher momenta. A comparison of the models to the measured p-like cross sections is shown in lower portion of the figure. The EOS data are compared to QMD results from Aichelin et al. 3 and to BUU results using the model of Li and Bauer. 4. The models show extremely good agreement with the data. The BUU model reproduces both the low momenta and the projectile velocity regions of the spectrum.

**Footnotes and References**

Light Fragment Production and Power Law Behavior in Au + Au Collisions*

S. Wang, D. Keane, and the EOS Collaboration

Measurements of single-particle-inclusive spectra indicate that the observed invariant momentum-space density $\rho_A$ for fragments with mass number $A$ and momentum $Ap$ closely follows the $A$th power of the observed proton density $p_1^A$ at momentum $p$. We test this power law behavior in 1150A GeV Au+Au reactions by studying $\rho_A$ as a function of fragment transverse momentum per nucleon, $p^\perp/A$, azimuth relative to the reaction plane $\Phi$, rapidity $y'$, and multiplicity. The upper panels of the figure show the dependence on $p^\perp/A$ of the density in five intervals of $y'$. In this figure, the solid, dashed, and dotted curves denote the density of protons, the squared density of protons, and the three-halves power of the deuteron density respectively. The solid circles and open circles denote density of fragments with $A=2$ and 3 respectively. Using a linear scale on the ordinate, the insets in the upper right corners show the same data with better resolution at lower $p^\perp/A$. In general, we find that the power law behavior does not hold as accurately at lower $p^\perp/A$. For results that follow, a cut requiring $p^\perp/A \geq 0.2 \text{ GeV/c}$ is imposed. The center panels of the figure show the dependence of momentum-space density on $\Phi$. The lower panels of the figure show the densities of in-plane transverse momentum per nucleon, $p^x/A$. We also test the power law behavior through azimuthal asymmetry comparisons for Au+Au samples at beam energies of 0.25, 0.6, 0.8, and 1.0A GeV. Overall, we conclude that the simple momentum-space power law consistently describes light participant fragment production at $p^\perp/A \geq 0.2 \text{ GeV/c}$ over a remarkably wide range of $p^\perp/A$, $\Phi$, $y'$, multiplicity and beam energy in intermediate-energy heavy-ion collisions, and in particular, the increase in sideward flow with fragment mass is well described by a momentum-space power law under these conditions.

Flow in Ni + Au at Bevalac energies

J. Chance, and the EOS collaboration

Collective behaviour in nucleus-nucleus collisions at Bevalac energies continues to be a topic of interest to the nuclear physics community. The determination of the Equation of State of nuclear matter remains elusive due to additional factors such as momentum dependent interactions and in-medium nucleon cross sections. With 4π experiments such as the EOSTPC at the Bevalac one hopes to further constrain the various theoretical models.

In previous Bevalac experiments flow has emerged as a good measure of collective behaviour. In EOSTPC we have studied flow in the large Au + Au systems. Here we present results in the Ni + Au systems where we can study flow up to 2A Gev beam energy. We analyze flow using the familiar S - curve plots of $\langle P_x/A \rangle$ in the reaction plane versus rapidity plots.

Figure 1 shows such a plot for protons, tritons an alphas in Ni400 + Au. Here we include only events with impact parameter $b<4$fm. The lab rapidity has been scaled by the beam rapidity. We extract slope values where the curve crosses the x - axis. The TPC acceptance is better than 90% for the region where we fit for the slope.

In Figure 2 we plot the proton flow for all the Ni + Au systems as well as the predictions from a BUU calculation with a soft and hard equation of state. Momentum dependent interactions were not included in this BUU version. At lower energies the EOSTPC data shows better agreement with the hard EOS while at the high 2A Gev energy the data falls somewhere in between hard and soft. Further analysis of the experimental and theoretical data should constrain the EOS more and provide a glimpse of what to expect for the EOSTPC experiment at the AGS.

Footnotes and References

1 M.Parlman,LBL-Report 36280
Pions as Probes of Collective Effects as Studied by the EOS TPC

J. C. Kintner and the EOS collaboration

Pion production from heavy-ion collisions has been suggested as a sensitive probe of the hottest, densest stage of the reaction. Pions are interesting because they are produced particles, not present in the original nuclei. Here we show in-plane transverse flow and squeeze-out of pions from the system 1960 MeV/nucleon Ni + Cu.

Figure 1 shows azimuthal distributions with respect to the reaction plane for $\pi^{-}$'s at mid-rapidity. The top panel shows no squeeze-out for $\pi^{-}$'s with low transverse momentum. At higher transverse momenta, as seen in the bottom panel, we see a clear squeeze-out signal. The reaction plane was determined with the Danielewicz and Odyniec Method\textsuperscript{1} using only forward going baryons. Since pions are not used, auto-correlations are absent. The fits shown are to:

$$N = P_1(1 + P_2\cos\phi + P_3\cos2\phi)$$

The $P_2$ term is sensitive to emission within the reaction plane, and the $P_3$ term is a measure of the out-of-plane emission, or “squeeze-out,” which has been seen for $\pi^0$'s in Au + Au.\textsuperscript{2}

Figure 2 is a plot of the average $\langle p_x/m \rangle$ for protons and $\pi^{-}$'s. The top panel shows protons and $\pi^{-}$'s from peripheral collisions. For protons, we note the characteristic s-curve as reported by Martin Partlan.\textsuperscript{3} The flow for $\pi^{-}$ is anti-correlated to that of the protons. The lower panel shows that central $\pi^{-}$’s have an opposite slope from that of the peripheral $\pi^{-}$’s. The $\pi^{-}$’s from central events are correlated to the baryon flow, while those from peripheral events seem to be anti-correlated. Bass has predicted this for Au + Au.\textsuperscript{4}

Footnotes and References

\textsuperscript{1}P. Danielewicz, G. Odyniec, Phys. Lett. B 157 146
\textsuperscript{3}M.D. Partlan, et al submitted to Phys. Rev. Letters
\textsuperscript{4}S.A. Bass, C. Hartnack, H. Stöcker, and W. Greiner, Preprint

Figure 1: Azimuthal Angle Distributions ($\phi$) with respect to the reaction plane for pions at mid-rapidity ($-0.25 < y_{cm} < 0.25$) from central collisions ($M > 25$).

Figure 2: In-plane transverse flow ($\langle p_x/m \rangle$) of protons and negative pions in 1960 MeV/nucleon Ni+Cu.
A high statistics sample of Λ's produced in 2 GeV/nucleon \(^{58}\)Ni + natCu collisions has been obtained with the EOS Time Projection Chamber. Λ's are reconstructed in the TPC through the charged particle decay: \(\Lambda \rightarrow p + \pi^-\), which has a branching ratio of \(\sim 64\%\). After all TPC tracks in an event are found and the overall event vertex has been determined, each pair of \(p\pi^-\) tracks is looped over and their point of closest approach is calculated. Pairs whose trajectories intersect at a point other than the main vertex are fit with a V0 hypothesis from which an invariant mass and momentum are extracted. Cuts are made on quantities such as distance of decay from the main vertex, impact parameter, \(\chi^2/\nu\) etc. in order to eliminate the combinatoric background. The invariant mass distribution resulting from one particular set of cuts is shown in Fig. 1. The combined acceptance plus efficiency is \(\sim 20\%\).

The coverage of the EOS TPC is essentially 100% for \(y > y_{cm}\) and extends down to \(p_T = 0\) where interesting effects such as collective radial expansion may be important. In addition, the detection of a majority of the charged particles in the TPC, along with the presence of directed flow for protons and heavier fragments at this beam energy, allows for the correlation of Λ production with respect to the event reaction plane. Figure 2 shows the average in-plane transverse momentum, \(\langle p_T' \rangle\), versus rapidity for protons and Λ's as determined by our preliminary analysis. The statistical errors are large but the overall trend is clear — the Λ's "flow" in the same direction as the protons. Detailed simulation studies are underway to determine the effects of acceptance and background on the Λ directed flow. Preliminary comparisons to the cascade code ARC have been made.

Footnotes and References

1M. Justice et al., LBL-37020
Heavy Ion Fragmentation Cross Sections from LBL Experiment E938H.
Mats Cronqvist and the E938H collaboration

Studies of the origin, propagation and effects of galactic and solar system cosmic rays depend critically on the quality of the nuclear reaction cross section predictions for cosmic rays in matter. The Transport Collaboration was formed to investigate, theoretically and experimentally, these cross sections. The major goals of the collaboration are:

• Measuring certain important cross sections
• Improving the understanding of these reactions by studying the systematics of the cross sections
• Applying the experimental and theoretical knowledge to the interpretation of cosmic ray data.

The UCB/LBL Transport collaborators have been focusing their efforts on the staging and analysis of experiment E938H, performed at the LBL’s HISS facility using heavy ion beams from the Bevatron. E938H was specifically designed to be a high precision experiment (uncertainties of less than 10%). Twenty different beams, from $^4$He to $^{58}$Ni ranging from 393 to 910 MeV/A in energy, were studied using a liquid hydrogen target. This is an energy-mass range where high-quality cross section data is vital for the study of interstellar cosmic ray propagation.

The experiment consisted of an upstream and a downstream (of the target) part. The upstream detectors measured flux and vectored the incoming beam. The downstream part measured the charge and mass of the produced fragments. The charge was measured by a detector system immediately downstream of the target. The fragments then passed through the HISS magnet, where the mass was determined by analyzing information about the deflection angle, measured by a large area drift chamber, and the time of flight, measured by a scintillator hodoscope.

The charge resolution was typically 0.25 charge units and the mass resolution 0.3 mass units.

Figure 1. E938 experimental setup.

Figure 2. Mass histogram for Al isotopes.

The analysis of the charge-changing cross sections have been finished for all the beams, and is published. The elemental cross section analysis is virtually finished, and is now being written up. We have calculated preliminary isotopic cross sections for a few systems, and the analysis of the remaining beams is underway. Comparisons between our preliminary cross sections and various parameterizations and models shows general qualitative agreement, but quantitative differences of as much as factors of 2. This illustrates the need for further development of the predictive power of these models.
Dielectron Production in Ca+Ca Collisions, \( E_k = 1.05 \text{ GeV/nucleon} \)

R. J. Porter for the DLS Collaboration

Measurements of dielectron pairs produced in heavy-ion collisions can provide information about specific processes involved in the collision. The dielectron signal has an unique advantage over hadron spectra for investigating features of heavy-ion collisions due to the weak coupling of the pair members to the hadronic medium of the collision. It is expected that dielectron pairs retain information about their production mechanisms, probing even the early hot-dense phases of the collision.

Estimates of the mechanisms responsible for dielectron production in the 1-2 GeV/nucleon collision energy range suggest that Dalitz decays (\( \Delta \) and \( \eta \)) and \( \pi^+ \pi^- \) annihilation may dominate the pair yield[1]. The original pair samples from A+A collisions obtained by the Dilepton Spectrometer (DLS) collaboration lacked the statistical precision needed to distinguish between different model interpretations of the signal. The present true-pair sample from Ca+Ca collisions, 3804±151, is about 15 times larger than that obtained in the original DLS measurements. The mass spectrum of true-pairs shown in figure 1 illustrates the statistical significance in this data set.

The charged-particle multiplicity associated with the dielectron signal also contains information about the production mechanisms[2]. The DLS multiplicity measurement is dominated by participant protons rather than produced pions. Figure 2 shows the relative probability that a given multiplicity is observed in association with an electron pair to that observed with a 'minimum bias' trigger. The data are consistent with a linear dependence. The like-sign pairs, however, show the quadratic dependence expected from the coincident detection of particles produced in independent processes during the collision.

![True Pair Yield](image)

**Figure 1:** Dielectron yield mass spectrum from Ca+Ca collisions at 1.05 GeV/nucleon

![Like Sign Pair Yield](image)

**Figure 2:** True pair and like-sign pair yields' dependence on the event multiplicity.

References

Study of Particle Production in RHI Collisions at the AGS

J. Engel for the E878H collaboration

We began our relativistic heavy ion (RHI) program at Brookhaven National Laboratory's AGS with experiment E802 lured by the possibility that the transition to the elusive quark gluon plasma (QGP) might be witnessed at the high densities and temperatures available in collisions at the AGS. In line with predictions that the QGP would be heralded by an increase in the strangeness, E802 was the first to observe such an increase in the K+/π+ ratio in central Si-Au collisions over that observed for p-p (20%:5%). Unfortunately there is no silver bullet; the increase in strangeness was also consistent with other thermal and rescattering theories which do not require a QGP transition. The task then became one of characterizing the high density high temperature matter to further test and ultimately refine the theoretical models. So we continued to study the systematics of the forward and transverse neutral energy produced in these heavy ion collisions, continued to measure the semi inclusive spectra and yields of K's, π's, p's, d's, and pbars, and eventually compared p-A and A-A collisions with the same apparatus. Ultimately we found that although the global variables, such as transverse neutral energy produced in these collisions, were consistent with the incoherent superposition of contributions from individual p-A reactions, the relative yields of produced particles were dramatically different. Specifically the K+/π+ multiplicity ratio was found to range from 9% in peripheral collisions to 19% for central Si-Au collisions. Further the largest K+/π+ ratios were observed in events that left the least energy in the zero degree calorimeter, suggesting that multiple interactions are an important mechanism in RHI particle production.

While the importance of multiple interactions lead to E859 and the development of a sophisticated second level trigger capable of on-line momentum and mass reconstruction which would allow interferometry of π's and K's, it was the combination of this mechanism and increase in pbars with target mass and centrality observed in E802 that lead to the UC group branching out from the small but significant beam definition role performed in E802/859/866 to propose and stage E858. Although different in approach both E858 and E859 shared the common goal of trying to calculate the actual source size in these reactions and determine hadronization lengths; E858 by coalescence of anti-nucleons and E859 via Bose-Einstein interferometry. While E859 was the first to report results of K+ two particle correlations and that the source size was comparable to that of π+ pairs of similar rapidity: E858 reported the first observation of dbars produced in RHI reactions and at a level significantly lower that predicted by the well established coalescence model.

The success of E858 naturally lead to E878, where a state of the art centrality detector was added to enable characterization of the geometrical aspects of the collision process and determine the level of pbar annihilation present. The operation and performance of this detector in a high rate Au beam environment, and interpret the multiplicity data in terms of the impact parameters of the nucleus-nucleus collisions is in a recent article submitted to Nuclear Instruments and Methods. Finally although an further increase in strange quark production has been observed by E866 in the K+/π+ ratio, E878 finds no evidence for the formation of new particles having lifetimes > 10ns, after viewing 2x10**12 Au+Au interactions at 10.6 A*GeV/c at 0 degrees. An article describing this extension of the rare particle sensitivity limits set in E858 has been submitted to PRL.
Optimization of the Spectrometer Setup for the BNL Experiment E896.

I.M. Sakrejda and the E896 Collaboration

The BNL experiment E896 was designed to search for a six quark, short lived strange particle, \( H^0 \), produced in relativistic Au+Au collisions at a beam energy \( 11.6 \text{GeV/nucleon} \). The spectrometer (Fig. 1) consists of a sweeping magnet that removes charged particles produced in the interaction from the detection area, a set of 96 planes of drift chambers positioned in a 1.8T magnetic field, a centrality detector upstream from the target and neutron detectors downstream from the drift chambers.

The \( H^0 \) particle will be identified by its decay pattern \( (H^0 \rightarrow \Sigma^- p, \Sigma^- \rightarrow n\pi^-) \) in the drift chambers\(^1\). The geometry of the spectrometer was optimized via Monte Carlo simulations, to provide a low background for this identification. The superconducting 5.0T magnet will remove most of the charged particles from the forward cone (It has been proved in the process of the experiment approval that a conventional magnet could not provide enough sweeping power.). This magnet has a wide horizontal opening that minimizes interactions of the charged particles with its edges. It was filled with a vertical, wedge shaped collimator that protects the top and the bottom of the drift chambers from neutral particle interactions. The sensitive area (shadowed in Fig. 1) occupies only a part of the chamber volume. The clearance on both sides minimizes the amount of background that comes from the interactions of neutral and remaining charged particles with the vertical walls of the chambers. The beam is allowed to traverse the chamber which is filled with a mixture of Helium and Ethane to reduce production of \( \delta \) rays. Lack of a wall between the deflected beam and the sensitive area allows for a good coverage for particles produced with low \( p_t \) (Fig. 2). Fig. 2 shows a typical central

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\(^{1}\)BNL AGS P896 Proposal

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Footnotes and References

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1. BNL AGS P896 Proposal
Neutron Induced Background Reactions in the BNL E896 Drift Chamber.

Eleanor Judd and the E896 collaboration

Experiment 896 (E896) at the Brookhaven National Laboratory (BNL) is designed to perform a definitive search for the $H^0$ particle. This is the proposed 6-quark strangelet (udsuds) that is most likely to be bound.

The 896 Experiment has been optimized to search for $H^0$'s decaying via the channel $H^0 \rightarrow p\Sigma^-, \Sigma^- \rightarrow n\pi^-$. The sensitivity of the experiment is limited by the rate at which fake $H^0$ signals are produced in the drift chambers. One source of background is due to interactions between other neutral particles (e.g., neutrons) and the chamber material. These interactions can produce a pair of oppositely charged tracks, one of which could subsequently decay to produce just one more charged track. The result would be a fake $H^0$ signal in the chamber.

This rate was evaluated by generating ARC Au-Au interactions and tracking the particles through the E896 apparatus. The neutrons that entered the DDC were then fed back into ARC to generate nX interactions for each of the 6 elements (H, He, C, Fe, W and Au) that make up the DDC. Finally the nX interactions were filtered to look for those that simulated a fake $H^0$.

A number of reactions were found to contribute, of which $n + n \rightarrow n + p + K^- + K^0$ had the highest cross-section. The rate of these interactions increased as the target nucleus increased in size from H to Au. However, at the same time the rate of secondary interactions, producing more charged particles, also increased. If another charged particle is produced then the reaction no longer looks like an $H^0$ decay, so it can no longer contribute to the fake $H^0$ rate. As a result it was only the most peripheral nX interactions that contributed to the background rate, and carbon that had the highest branching ratio.

The invariant mass of the fake $H^0$'s was calculated by assuming that the positive particle was a proton and the negative particle was a $\Sigma^-$. The majority of fake $H^0$ candidates had invariant masses much greater than 2.5 GeV/c². This means that they cannot really contribute to the fake $H^0$ background.

In order to estimate the background rate, the branching ratios for nX$\rightarrow$fake $H^0$ were combined with the neutron rate, and the proportion of each element in the DDC to yield a rate of $< 1.2 \times 10^{-05}$ fake $H^0$ in the DDC per central Au-Au interaction. Fig. 1 shows the distance of these fake $H^0$ candidates from the target. In order to contribute to the background rate the fake $H^0$ must seem to originate at the target.

This is unlikely for many of these reactions because they involve the production of undetected neutral particles that also carry momentum. If the requirement is made that the fake $H^0$ should point back to within 1 cm of the target position then all the branching ratios, are reduced by a further factor of at least 0.0025 to yield a rate of $< 3.0 \times 10^{-08}$.

Figure 1. Distance of Fake $H^0$ from Target
New Crystal Barrel Results in the Scalar Meson Sector


The main physics motivation of our experimental program is the search for new forms of hadronic matter like glueballs, hybrids and multiquark states. The identification of such states would have a major impact on the understanding of quantum chromodynamics in the confinement region. The Crystal Barrel detector\(^1\) at LEAR (CERN) provides a powerful instrument for these studies in antiproton-proton annihilations, in which quarks and gluons are copiously produced.

The sector of scalar \(J^{PC} = 0^{++}\) mesons is particularly attractive, since the classification of the scalar ground states is still in doubt. More candidates exist than are required by the \(0^{++}\) nonet, and most models predict exotic mesons in the 1-2 GeV mass range. An analysis of final states of three pseudoscalars decaying to six photons is very sensitive to scalar mesons decaying into two pseudoscalars. By applying highly constrained kinematic fits to a large sample of 0-prong triggered data (16.8 \(\times 10^6\) events), the following channels were assigned.

<table>
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<td>712</td>
<td>6.3 (\pm 1.0)</td>
</tr>
<tr>
<td>(\pi^0 \pi^0 \eta)</td>
<td>280</td>
<td>6.7 (\pm 1.2)</td>
</tr>
<tr>
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<td>180</td>
<td>2.0 (\pm 0.4)</td>
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<tr>
<td>(\pi^0 \pi^0 \eta')</td>
<td>7</td>
<td>Preliminary</td>
</tr>
<tr>
<td>(\pi^0 \eta \eta')</td>
<td>1</td>
<td>0.25 (\pm 0.05)</td>
</tr>
</tbody>
</table>

The quality and very high statistics of this data is shown in the Dalitz plot for the reaction \(\bar{p}p \rightarrow 3\pi^0\) (Fig. 1). The partial wave analysis of these reactions (as well as \(\bar{p}p \rightarrow 3\pi^0 \pi^+ \pi^-\)) has revealed the following new resonances\(^2\):

The \(a_0(1450) (m = 1450 \pm 40 \text{ MeV}, \Gamma = 270 \pm 40 \text{ MeV})\) in the \(\pi^0 \eta\) decay channel. Its mass and width make it a natural candidate for the ground state of the isovector mesons.

The \(f_0(1500) (m = 1500 \pm 15 \text{ MeV}, \Gamma = 120 \pm 25 \text{ MeV})\) in its decays to \(\pi^0 \pi^0, \eta \eta,\) and \(\eta \eta'.\) It is considered a good candidate for the lowest lying glueball. In order to further clarify its internal structure, information on its decay branching ratio into \(\bar{K}K\) is required. For this purpose the Crystal Barrel is presently being upgraded with a new \(K_S\) trigger.

![Figure 1: 3\(\pi^0\) Dalitz plot.](image)

Footnotes and References


First Observations of Pontecorvo Reactions With a Recouling Neutron*
and the Crystal Barrel Collaboration

The Crystal Barrel collaboration has been making systematic studies of anti-proton annihilation at rest on both protons and deuterons using the LEAR facility at CERN. In simple nucleon-anti-nucleon annihilation, two or more mesons are usually emitted. However, in anti-nucleon annihilation on deuterium occasionally only one meson is emitted, recoiling against the remaining proton or neutron. These "extraordinary annihilations" are called Pontecorvo reactions\(^1\). These reactions are usually explained either as annihilation on a single nucleon followed by absorption of a meson by the spectator nucleon, or as a more direct production of the two body final state\(^2\).

Measurement of these reactions can test these models. The only Pontecorvo reaction previously measured is \(\bar{p}d \rightarrow \pi^- p\). We have made the first measurements of three other Pontecorvo reactions of the type \(\bar{p}d \rightarrow Xn\) and set a limit on a fourth. From a sample of \(4 \times 10^6\) "all-neutral" triggers we search for events of the type \(\bar{p}d \rightarrow Xn\) where \(X \rightarrow 2\gamma, 3\gamma\). These events show up along a curved band in the scatter plots of \(m_{N\gamma}\) vs \(P_{\text{tot}}\), representing the missing neutron (see figure 1). The \(\pi^0, \eta\) and \(\omega\) peaks are clearly visible, while the \(\eta'\) peak is not statistically significant.

\[
\begin{align*}
\text{BR}(\bar{p}d \rightarrow \pi^0 n) &= (7.03\pm0.72)x10^{-6} \\
\text{BR}(\bar{p}d \rightarrow \eta n) &= (3.19\pm0.48)x10^{-6} \\
\text{BR}(\bar{p}d \rightarrow \omega n) &= (22.8\pm4.1)x10^{-6} \\
\text{BR}(\bar{p}d \rightarrow \eta' n) &\leq 14x10^{-6}
\end{align*}
\]

These results are in fair agreement with the statistical and dynamical models assuming a two step process.

Footnotes and References
\(^*\)C. Amsler et al., submitted to Zeit. Phys. A
\(^1\)B. M. Pontecorvo, Sov. Phys. JETP 3, 966 (1956).

Figure 1: Scatterplots of \(P_{\text{tot}}\) vs \(m_{N\gamma}\). (a) 2 photons, with \(\pi^0, \eta\) and \(\eta'\) masses shown, (b) 3 photons with \(\omega\) mass shown.
An enhancement of $\Lambda$ production that could indicate a QGP phase transition in the relativistic heavy ion collisions drew a lot of research interest in the last few years. Both CERN experiments, NA35 and NA36, reported more $\Lambda$'s produced per event than expected from a simple convolution of the pA interactions, but they disagree as to the extent of this enhancement. This together with a recent detailed study of the NA36 electronics response** prompted an effort to re-analyze the data and investigate the impact of the ~15% change in the chamber efficiency on the strangeness analysis. Additionally, in order to verify the results another set of data taken with a different magnet polarity, that could be looked at as a different experiment, was analyzed.

Results of this analysis are shown in fig. 1. Both magnet polarities give the same result which confirms internal consistency of the analysis. They also indicate that the $\Lambda$ production increases linearly with the event multiplicity and for the same multiplicity does not depend on the size of the target nucleus. Another important observation comes from a comparison of the $\Lambda$ rapidity distributions from the S+Pb (Fig. 2) and S+S reactions with the model predictions.

This result shows more strangeness production than one could expect from the convolution of the pA collisions (Fritiof 7.0) but less than models that allow the secondaries to reinteract between themselves (VENUS, RQMD) would make. It indicates that the reinteractions of the secondaries are needed to correctly describe the interaction, but the amount of rescattering in these models is far too big. In the S+S analysis the models show the same relationship to the data, however, the discrepancy is not as large. This fact should help to determine the source of the differences. Both sets of data show also a strong disagreement (Fig 2) with the NA35 data. This discrepancy should be cleared up as soon as possible.

Footnotes and References

*Space Sciences Lab, UC Berkeley.
**D.E. Greiner, Calibrations of the CERN Experiment NA36.
1. E.G. Judd, LBL report LBL-36945.
In general large solid angle tracking experiments need to have an accurate Monte Carlo simulation in order to make the corrections necessary to produce device independent physics measurements. The high multiplicity environment of relativistic heavy ion collisions makes the Monte Carlo more important while at the same time making the task more difficult. Tracks will merge and cross, the efficiency to find them becomes not only a function of the resolution of the hardware but also a function of the tracking software used to search for them.

NA36 uses a standard method to calculate the efficiency of finding the \( V^* \) topology. This is to generate a \( V^* \) that can be found in the TPC and embed it in actual data. When this is done one needs to know in detail how the detector responds to tracks which may be close to each other. In the NA36 TPC the spacing of the short anode wires determines the track pair resolution in the bend plane, this is straightforward to simulate. However, in the drift direction the track merging is a function of the response of the electronics to a pair of pulses arriving at the anodes close or overlapping in time. In mid 1994 we decided to make some measurements to verify our assumptions about the response of our discriminators.

Using the NA36 TPC in the same configuration as was used for taking ion data we measured the response of the electronics to pulses produced by electrons from a Sr\(^{90}\) source. \(^1\) Fig. 1 shows the response that we found for a case where there were several pulses present in a short time period. The discriminator response to the trailing edge of the pulse was different than the nominal threshold value, the threshold had risen while the pulse was present. This response was fit to a model and the threshold curve shown in Fig. 1 is the model description of the discriminator behavior. The model was fit to a large set of single and multiple pulse data and found to have an accuracy of 8 ns. This was sufficient for our simulation needs as the digitization bin size of the TDC's was 25 ns. The efficiency to find \( V^* \)'s was recalculated and applied to the data for finding the lambda particle. We found that the efficiencies were about 6 to 30% lower than we had calculated assuming a perfect discriminator depending on the exact rapidity of the particle and the multiplicity of the event.

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Fig. 1. Response of the NA36 discriminator to a set of pulses close in time.

![Fig. 1. Response of the NA36 discriminator to a set of pulses close in time.](image)

The best measure of the change to our results can be seen in fig. 2 where we compare the polarity averaged data with the new efficiencies with that presented at Quark Matter 93. \(^3\) The overall change is a 16% increase in the average cross section.

### Footnotes and References

1. Invited Talk Strangeness'95 (to be published by AIP) see LBL-36882
2. Invited Talk Quark Matter 95, Nucl. Phys. A (to be published) see LBL-36945

*Space Science Lab of UC Berkeley.

1. Invited Talk Strangeness'95 (to be published by AIP) see LBL-36882
2. Invited Talk Quark Matter 95, Nucl. Phys. A (to be published) see LBL-36945
Transverse energy production in Pb+Pb collisions at 158 GeV/Nucleon

S. Margetis, I. Huang and the NA49 Collaboration

Transverse energy ($E_T$) production near mid-rapidity ($2.1 < \eta < 3.4$) for Pb+Pb collisions at 158 GeV/nucleon was measured with the NA49 calorimeters [1],[2]. The data analysis procedures are described in [3]. Figure 1 shows the resulting $E_T$ distributions for minimum bias Pb+Pb interactions together with FRITIOF and VENUS model predictions. Also shown are S+Au data properly scaled in the same acceptance. The data favor the VENUS model concerning $E_T$ production. Bjorken’s formula can be used in order to estimate the energy density $\varepsilon$ during the collision. The resulting density for the Pb+Pb system is $\varepsilon = 3.0$ GeV/fm$^3$, which is about 18 times higher than the ground state energy of nuclear matter (0.16 GeV/fm$^3$) and is in the range where deconfinement is predicted. Table 1 summarizes some of the collision parameters for Pb+Pb and S+Au. $n_{total}^{part.}$ is the total number of participants and $\nu/\nu_{part.}$ is the total mean number of binary collisions per participant nucleon assuming a mean free path ($\lambda_{inel}$) for nucleons in nuclei of 2 fm (i.e. $\sigma_{inelastic}^{pp}(200GeV) = 33$ mb). We observe that similar energy density was achieved in central S+Au collisions at the slightly higher energy of 200 GeV/nucleon. However, there is a much larger volume for the Pb+Pb system. We also observe that the produced $E_T$ per participant is the same for both systems although the number of collisions ($\nu$) each participant nucleon suffers is higher by 45% for Pb+Pb. Thus the data suggest that rescattering among participant nucleons does not significantly contribute to the $E_T$ production. This is in agreement with previous NA35 results where a similar observation was made concerning the number of produced pions per participant nucleon.

The ratio of electromagnetic and hadronic $E_T$ components [2] of the data does not suggest any large non–statistical fluctuations in the relative abundance of neutral and charged pions.

Figure 1: Differential cross section distributions of the transverse energy produced in the collisions, as measured by the Ring calorimeter in the pseudorapidity region $2.1 < \eta < 3.4$. FRITIOF and the VENUS calculations are also shown.

<table>
<thead>
<tr>
<th>System</th>
<th>$n_{total}^{part.}$</th>
<th>$\nu/\nu_{part.}$</th>
<th>$E_T^{b=0}$</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>GeV</td>
<td>GeV/fm$^3$</td>
</tr>
<tr>
<td>S+Au</td>
<td>113</td>
<td>3.6</td>
<td>1.31</td>
<td>2.8</td>
</tr>
<tr>
<td>Pb+Pb</td>
<td>390</td>
<td>5.2</td>
<td>1.33</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 1: Kinematical parameters and energy density in central S+Au (200 GeV/nucleon) and Pb+Pb (158 GeV/nucleon).

References


Preliminary Inclusive Spectra from Central Pb+Pb Collisions at 158 GeV/nucleon

M.A. Bloomer and the NA49 Collaboration

The $p_T$ and rapidity distributions of produced particles in heavy ion collisions are thought to measure the effects of reinteractions and collective flow during the expansion phase of the collision. Particularly interesting is an enhancement of pion production at low $p_T$ ($< 300$ MeV/c) as reported by some experiments.\(^1\)

Preliminary spectra of negative hadrons were measured in central Pb+Pb collisions at 158 GeV/nucleon during the first run of CERN SPS experiment NA49. The momentum $p_T$ of charged particles produced in these collisions was obtained by reconstructing the trajectories of tracks swept by two consecutive dipole magnets into the Main TPC. All negatively-charged tracks from the analysis of 1000 events were assigned a pion mass in order to calculate their rapidity $y$.

Fig. 1 is the measured inclusive distribution (defined as $\frac{1}{p_T} \frac{dN(y)}{dy}$) for primary negative hadrons (mostly $\pi^-$) within a rapidity window of $3.5 < y < 4.0$. This incorporates corrections for detector acceptance, tracking efficiency and subtraction of background tracks (non-hadrons and secondary pions) which were compatible with the track selection criteria. Also shown (normalized to the Pb+Pb spectrum) is the inclusive spectrum of $\pi^-$ from pp collisions at a comparable energy.\(^2\) Pion spectra from central Pb+Pb collisions have a considerably larger exponential slope at large $p_T$ than those of pp collisions. However, they appear to be very similar in shape to the spectra from $^{32}$S projectiles on both light and heavy targets (not shown here).

By integrating these spectra one obtains the rapidity distribution shown in Fig. 2. Note that the data points below $y = 2.9$ have been obtained by reflecting actual measurements for $y > 2.9$. The shape of $dN/dy$ is very close to Gaussian with a width of 1.4 rapidity units and a peak value of 210 particles per unit rapidity. This large width excludes the possibility of an isotropic emitting system, e.g. a fireball.

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Footnotes and References

Detection of charged kaons in Pb + Pb at 160 GeV/nucleon via decay topology

G. Cooper, P. Jacobs, and the NA49 Collaboration

Charged kaons can be identified in Pb + Pb collisions through identification of the characteristic one prong decay in the NA49 experiment's Time Projection Chambers. Kinematic limits on the decay angle as a function of momentum permit discrimination of one-prong kaon decays from those of lighter particles, such as pions. This technique supplements particle identification by energy loss and time-of-flight measurements. It was used in S + Nucleus collisions at 200 GeV/nucleon in the NA35 experiment. Figure 1 shows the NA49 TPC's expected acceptance of kaons having identifiable decays.

An analysis code was developed to reconstruct decay vertices from found tracks in the detectors. This code may be used to identify both one-prong, charged particle decays and two-prong, neutral particle (V) decays. The code is integrated in the NA49 analysis environment.

One-prong and V decays have been successfully identified in simulated data and data obtained in the November 1994 run at CERN. Figure 2 shows one-prong decays found in 90 central Pb + Pb collisions from the CERN run. Points between the two curves are primarily kaon decays. Pion decays are nominally limited to small angles (below the lower curve). Likewise, kaon decays fall below the upper curve. The yield is roughly consistent with model calculations.

Calculation of the reconstruction efficiency and estimation of the background are now underway. Production data analysis awaits final tuning of the cluster finding and track reconstruction algorithms.

Footnotes and References

During the past year we have completed a unified, detailed simulation package for the entire NA49 experiment, based upon the GEANT v3.21 simulation program from the CERN Library. Uses of the simulation package include estimation of acceptances, efficiencies and backgrounds for physics analysis, debugging of tracking software, investigation of new physics, and detector design. The package accepts input in the form of particle kinematics from a variety of sources (standard physics event generators such as Fritiof or Venus, or special events generated by hand), passes the particles through the NA49 setup using greater or lesser detail of the interaction of particles with the setup, and assembles the results into standard NA49 data structures for further analysis. The chain consists of several links: (i) standard input of simulated physics events, (ii) definition of the NA49 geometrical setup including materials, (iii) the core GEANT code, and (iv) a postprocessor to assemble the results of the GEANT run into standard structures.

(i) Event Input: A standalone package has been written to standardize the event format of a variety of event generators (Fritiof, Venus), permitting a uniform input to GEANT as well as standalone analysis of the generator output.

(ii) Geometrical description (GNA49_GEO): Detailed descriptions of the NA49 magnets, Time Projection Chambers, Time-of-Flight Walls, etc. were developed within the framework of a standard geometry description shell*. All materials of any significance for generating multiple scattering, interactions, gamma conversions, etc. were included. All essential parameters are drawn from the standard NA49 Database, guaranteeing that geometrical parameters are (i) common between simulation and tracking, and (ii) the same as those used in the actual data taking.

(iii) Core GEANT Code (GNA49): Central events of ultrarelativistic heavy ion collisions can be extremely large. The core GEANT code breaks single events into manageable subevents in order to process them efficiently. Special routines handle low energy delta electrons and other tracks which pass at oblique angles over the TPC pad rows, as well as tracks due to showering in dense materials which nevertheless generate ionization in the sensitive detectors.

(iv) Postprocessor (G2DS): The subevents produced by GNA49 are reassembled and analysis structures filled from the raw GEANT output. Extensive crossreferences (pointers) between structures are resolved. Dynamic memory management is used to allow running as a UNIX filter, virtually without time overhead on the core GEANT.

Performance: GNA49 utilizing GEANT v3.21 runs substantially faster than previous versions of GEANT. CPU times on an HP735 for a central lead-lead event at 160 GeV/nucleon vary between 80 seconds for the simplest simulation (decays and multiple scattering only) to about 10 minutes for the most detailed, which is comparable to the time needed for tracking and reconstruction and is therefore tolerable. Comparison with recorded data shows that GNA49 is a reasonably good model of the NA49 environment. Some refinement of detector materials is still needed, however.

Footnotes and References

*P. Jacobs, STAR Note #85.
MTSIM: The NA49 Main TPC Simulator
Milton Toy and the NA49 Collaboration

In the NA49 experiment, realistic simulated raw data are essential for providing a controlled environment in which the performance of the TPCs and analysis software can be evaluated. The applications include (i) the determination of the tracking efficiency, which involves the search for several simulated tracks that have been embedded into the background of a raw data event, (ii) development of background-sensitive reconstruction software for rare decay searches, particle identification through dE/dx, and two-track resolution studies, and (iii) investigations of experimental effects from the readout electronics performance and the TPC gas parameters on cluster-finding and tracking.

The creation of simulated events begins with GNA49, which is based upon the GEANT detector simulation program from CERNLIB. The output of GNA49 consists of the intersection points of charged particle tracks with rectangular pad-timeslice gas volumes along with the associated momentum vectors and energy depositions. However, in order to accurately describe the detector response, effects from the gas (such as drift velocity and diffusion), electronics (such as gain, noise, non-linearities, and pad-sense wire coupling), and the binning of the signal with a finite pad and timeslice size must be taken into consideration.

The Main TPC simulator, MTSIM, takes GEANT data and generates a data event in the same format as the raw data by transforming the GEANT points into digitized charge clusters. For each pad row, formulations developed by PEP4 and ALEPH\(^1\) are used to parameterize the spatial resolutions and physical sizes of the measured charge clusters in pad-timeslice space by taking into account gas and geometry effects.

Footnotes and References
\(^1\)R. Sauerwein, TPC-LBL-83-18
ALEPH Handbook, ALEPH 89-77

The data are then binned into pad-timeslice pixels and electronic effects are added to give simulated ADC counts.

Comparisons with recorded data show that MTSIM accurately models the NA49 MTPC response with a small number of tunable parameters.

Fig. 1 shows the occupied pixels in pad-time space for sector 1, pad row 1, in the right MTPC for a central Pb+Pb collision at 158 A GeV/c. Fig. 2 shows the occupied pixels in pad-row space for a narrow slice in time for sector 1.

Figure 1: Occupied pixels, time vs. pad

Figure 2: Occupied pixels, row vs. pad
Readout electronics for the TPC detectors in NA49


The central detectors of experiment NA49 are four time projection chambers to allow tracking of the produced charged particles of the Pb on Pb collision over a wide range of phase space. The readout electronics for these detectors was designed at LBL based on the experience from EOS and NA35.

The four TPCs of experiment NA49 will have 182,000 electronics channels. For the run in 1994 with a reduced detector configuration, 90,000 channels were installed. The CT boards and receiver boards were fabricated in spring of 1994 and then tested at LBL. The integrated circuits on the front end boards were designed at LBL, produced locally and shipped to MPI Munich for testing and mounting on the front end boards.

The installation of the electronics system on the detector took place in the weeks preceding the NA49 run with lead beam at the CERN SPS accelerator. First analysis of the data showed that almost all of the over 90,000 channels worked and performed as specified. Fig. 2 shows data as received from one TPC pad in a Pb-Pb collision event. More sophisticated analyses, like cluster finding and tracking of charged particles was possible a few hours after the detector was turned on.

The electronics channels for the remaining two TPC detectors (VTPC1 and MTPC1), that are being built at CERN, will be installed in the fall of 1995.

Figure 1: Schematic of the NA49 electronics.

Figure 2: Amplitude distribution over drift time as measured in one TPC pad.

The charge signal coming from the pad in the read out plane of the detector is first amplified and shaped on the front end board. The analog shape of the signal is then stored in a 512 cell long switched capacitor array (SCA) and subsequently digitized by an 9 bit ADC (Fig. 1). The CT board collects the data of 24 front end boards (768 pads) and sends it via an optical link (62.5 MHz) to the receiver board. The receiver board contains a DSP processor (Motorola 96002) and has enough memory to store information from 32 events. Pedestal subtraction and data compression are performed on this board. Its output memory can be accessed by the NA49 data acquisition system via VME bus.
Cluster Finding and Space Point Extraction for the STAR TPC  
*M.A. Lisa and the STAR Collaboration*

The first step in the analysis chain for STAR TPC data is the extraction of spatial information from the digitized pixel data coming from the STAR front-end electronics (or from the TPC slow simulator, TSS). The TCL package in the TPC Analysis Shell (TAS) performs this function, producing space point information for tracking algorithms further in the chain.

![Figure 1: Low-noise, isolated clusters in an inner sector pad plane produced by tracks with crossing angles $\alpha = 22^\circ, \lambda = -10^\circ$ (lower cluster) and $\alpha = 5^\circ, \lambda = 3^\circ$ (upper cluster).](image1)

The cluster finder identifies isolated groups of pixels with ADC values above threshold, in the pad-time bucket plane for each padrow in the TPC. The hitfinder extracts space point information for isolated clusters, deconvoluting clusters originating from more than one track. (Deconvolution is not yet implemented in the released code.) A Gaussian fit is performed in the pad direction. In the time direction, a realistic fit to the pulse shape on a pad is used, incorporating known signal diffusion and electronics characteristics. The “orientation” of the cluster with respect to the padplane, which is related to the track crossing angles $\alpha$ and $\lambda$, is also calculated.

Figure 1 shows two isolated clusters found on the inner sector. The reconstructed track crossing point and orientation is indicated for each cluster.

Figure 2 shows a projection of generated and reconstructed hits onto one endcap of the TPC for a study event. Noise gives rise to “ghost” hits upon reconstruction, and degrades the spatial resolution of the hit reconstruction. TCL evaluation codes indicate that the spatial resolution for such a simple event is several hundred microns in each direction, for realistic noise settings in TSS.

![Figure 2: Projection of a simple event onto one endcap. GEANT hits are shown as points. Reconstructed hits are shown as circles (those that are associated with a GEANT track), or as stars (“ghost” hits).](image2)
A Time Projection Chamber currently under construction at LBL\(^1\), is the heart of the STAR spectrometer. It will facilitate event by event analysis of 100 GeV/nucleon collisions of Au+Au beams at the RHIC Collider. This event-by-event analysis is a unique feature of STAR. Good performance of a tracking algorithm that will reconstruct tracks of charged particles traversing the TPC is essential for its success. A detailed description of this algorithm was given in the 1993 Annual Report\(^2\). Since then the main effort was invested in extending the acceptance for both primary and secondary tracks and improving the track quality. A second pass through the data in the track finding was implemented. Once higher momentum tracks are found, hits that belong to them are removed from the pool and the track-finding process is repeated on the remaining hits with modified parameters and tolerances. It significantly improved the track finding efficiency defined as (# of reconstructed tracks)/(# of generated tracks) in a given \(p_t\) bin, especially for the low transverse momentum tracks (Fig. 1). In order to aid in perfecting the track quality, a tool that allows us to compare the Monte Carlo tracks that form the input to the simulations and the reconstructed tracks was developed. As an example of this evaluation Fig. 2 shows the comparison of the number of hits that were on the original track and the number of points that were assigned to it in the process of track-finding.

All the changes described above opened up the acceptance window for STAR to \(|\eta|<1.8\) and lowered the \(p_t\) threshold to 100 MeV/c. This enhances STAR capability to obtain interesting physics results.

**Footnotes and References**

\(^1\)STAR Conceptual Design Report, PUB-5347


Figure 1: Track finding efficiency\(^3\) for one (shaded) and two (not shaded) passes through data.

Figure 2: Correlation between the generated (ngen) and found (nrec) hits in a central Au+Au event (~2000 tracks in the TPC).
Charged Particle Identification in the STAR TPC
I.M. Sakrejda, J. T. Mitchell and the STAR Collaboration

Charged particle identification in the STAR TPC will be accomplished by examining the energy deposited by the track as it traverses the gas volume of the TPC. A feasibility study\(^1\) shows that there is a clean separation of protons from kaons and pions up to a momentum of 1.1 GeV. Kaons can be easily separated from pions if their momentum is below 600 MeV (Fig. 1).

This feasibility study was based on the assumption that we can precisely measure the primary ionisation these particles generate in the TPC. But there are numerous effects that modify the signal and prevent the recorded information from becoming direct measure of the original charge. Among the effects that modify this original ionisation are an attenuation of the signal during the drift, gas gain, electronics amplification, signal digitisation and 10–8 bit translation\(^2\).

In order to unfold the impact of these processes, a sequence of calibration procedures was designed. High momentum, high \(\eta\) tracks that traverse full length of the TPC and come from the minimum bias events so they can be unambiguously and easily identified, will be used to measure (among other things) the signal attenuation due to electron absorption in the gas. This is especially important if the He-Ethane mixture is used (it can cause up to \( \sim 20\% \) signal loss over the 2 m drift distance). Additional calibration will be done with the minimum ionizing muons during the cosmic ray test. Both cosmic rays and the stiff tracks from the minimum bias events will be used to calibrate the gas gain. Changes in the gas gain that depend on temperature and pressure will be monitored in a test chamber installed in the gas system, as well as with minimum bias events taken periodically during data taking.

In order to calibrate the electronics response, an option to pulse the wire ground plane with an arbitrary waveform was implemented. The pulser test will be run periodically to monitor any changes of electronics with time, and also after every major shutdown to make sure that any electronics that was replaced is correctly calibrated. The ADC pedestals will be calculated by the i660 processors in the DAQ system. Data used for the pedestal calibration will be taken between events. 30 empty events will be used to average the pedestals. Pedestals will be calculated, and later on subtracted, from every time pixel in each electronics channel. All the procedures described above should facilitate exact reconstruction of the primary ionisation along the particle trajectory and protect the detector from degradation of the particle identification capability.

Figure 1: Ionisation density versus momentum for particles from one central Au+Au event (* - protons, o - kaons, + - pions). The lines show the Bethe-Bloch curves.

\footnotesize
Footnotes and References
\(^1\) J.T. Mitchell and the STAR Collaboration, LBL Annual Report 1993
\(^2\) Roy Bosingham \textit{Do Eight Bit Suffice?}, STAR Note # 116
Particle Identification in the STAR TPC using Multiple Coulomb Scattering

M.A. Bloomer, J.K. Ellis, D.L. Olson and the STAR Collaboration

STAR intends to identify hadrons in the TPC using multiple ionization sampling within the TPC gas. However, electrons and pions within the momentum range $100 < p < 200$ MeV/c have similar values of $dE/dx$ and hence cannot be distinguished. A similar problem occurs between electrons and kaons and protons but at higher momenta (where the expected electron contamination is much less).

An alternative method of particle identification was investigated in which one measures small angle scattering (mostly due to multiple Coulomb collisions). Emulsion experiments have used this technique successfully in order to measure $p\beta$ of particles.\(^1\) This technique involves following a charged track and measuring transverse displacements from some initial vector at fixed intervals along its trajectory. At each interval the slope of the trajectory at the end point is determined, as well as the difference in slopes between adjacent intervals (by convention always taken to be positive). The distribution of such differences measures the width of the small angle scattering distribution; therefore, the average angle, $\bar{\alpha}$, between sections of length $t$ is inversely proportional to $p\beta$:

$$\bar{\alpha} = \frac{K(t, \beta)}{p\beta} \sqrt{\frac{t}{100}} \tag{1}$$

where $t$ is in microns, $p$ is the total momentum, and $K(t, \beta)$ is a slowly varying function of $t$ and $\beta$. Unlike $dE/dx$, there are no regions of overlap between particle species. However, it remains to be demonstrated that the track-by-track fluctuations in $\bar{\alpha}$ are small enough to provide the necessary discrimination.

A simulation was carried out with GEANT using a large field-free volume of P10 gas, 20 cm by 20 cm wide and 4 m long. All normal physics processes were turned off except multiple Coulomb scattering (MCS), continuous energy loss, and $\delta$-ray production. Protons, pions, kaons and electrons of momenta varying from 50 MeV/c to 1 GeV/c were shot lengthwise into this volume along the $z$ axis. $\bar{\alpha}$ was calculated for each track from the transverse displacements (i.e. in $x$ and $y$) measured at 20 fixed intervals of 20 cm length each along the initial direction vector.

Fig. 1 shows the distribution of $\bar{\alpha}_y$ (for displacements in the $yz$ plane) for this particle mix at a fixed input momentum of 100 MeV/c. One can see that the distributions for electrons and pions are resolvable but have considerable overlap. Protons at this momentum stop within the gas and hence were excluded from the plot.

One would expect more pessimistic results for the actual STAR TPC, since (i) $\bar{\alpha}$ has to be re-defined for the highly curved low momentum tracks, and (ii) track lengths within the TPC are less than 4 m. However, this preliminary investigation demonstrates some particle discrimination power using MCS measurements, which could be used in conjunction with $dE/dx$ to improve particle identification.

Footnotes and References

Event Visualization of STAR TPC Data

M.A. Bloomer, L. Pereira, and the STAR Collaboration

The high multiplicity of central Au+Au events at RHIC presents a serious challenge to the task of visualizing the data of large acceptance tracking detectors such as the STAR TPC. Traditional 2D projections and 3D perspective views as have been used in other experiments are inadequate. Two recent technologies might enable the user to visually analyze very complicated events more easily:

- **stereo vision**: viewing images with depth perception and color; and
- **animation**: rendering images quickly enough to give the impression of movement.

We have begun investigating these techniques with prototype TPC data visualizer programs developed on Silicon Graphics™ workstations. The add-on hardware necessary for stereo vision was obtained commercially. All visualizers run under IRIX™ 5.2 and make extensive use of the GL™ and OpenGL graphics libraries. They can display individual TPC pixels, space points from reconstructed clusters, GEANT hits and reconstructed tracks from the full event or any subset using a variety of graphical or ntuple-like selection mechanisms.

Both stereo and animation have proven to be very effective in making the physical appearance of the TPC data more comprehensible. One visualizer was used successfully to improve the TPC track reconstruction algorithm. However, users tended to reduce the data displayed to the minimum necessary anyhow. On an Indigo²™ with X/Z graphics hardware, we were still at least an order of magnitude slower than necessary for effective animation of all TPC points and tracks from a full central RHIC Au+Au event. The figure below demonstrates the user interface for the pixel data visualizer (non-stereo version) for one RHIC pp event. Some interesting capabilities of the pixel display are: (i) a mouse-controlled 3D cursor which can be used to select objects in the 3D space of the detector; and (ii) “crystal ball” mode whereby the user can grab the detector and rotate/translate it using the mouse.

Formal requirements and preliminary design documents have been written which describe the functionality and user interface of future STAR data visualization applications which incorporate both stereo and animation. The prototype visualizers are being integrated into this framework, and extended to support pure Xwindows (e.g. on non-SGI platforms).
Event by Event Analysis with the STAR TPC

J. T. Mitchell, S. Paganis, L. Ray, I.M. Sakrejda and the STAR Collaboration

Capability of doing event by event analysis is a unique feature of the STAR detector. Among many event-by-event measurements of global observables that are possible using STAR are:

- Temperature of $\pi^\pm$, $<p_t>$ of $\pi^\pm$ and $K^\pm$
- Flavor content (K/$\pi$ ratio)
- Charged-particle multiplicity
- Entropy density
- Pion source size
- Degree of fluctuations in $d^3n/dp_t d\eta d\phi$, energy, entropy and isospin

Simulations that evaluate performance of the baseline detector show that some of these measurements could be done with the TPC only. As an input for this simulations 100 central Au+Au FRITIOF events were used. These events were processed by the detector simulation package and the analysis software. In order to evaluate the event temperature a function:

$$f(m_\perp) = a \times m_\perp^2 \exp(-m_\perp/T)$$

where:
- $m_\perp$ - transverse mass
- T - event temperature
- a - normalisation constant

was fitted to a spectrum of all identified pions in the 200 MeV < $m_\perp$ < 1.0 GeV range. Comparison between the reconstructed and the generated temperature is shown in Fig. 1. The 4MeV width of the distribution is driven by the fit error. The same sample of events was used to look at the K/$\pi$ ratio. Fig 2 shows that the ratio is well reproduced for 200MeV < $p_\perp$ < 600 MeV.

Footnotes and References
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Department of Physics, University of Texas, Austin, TX 78712

1J.W. Harris The Physics and Experimental Program of the Relativistic Heavy Ion Collider (RHIC), LBL Report, LBL 36250.

Figure 1: Pion temperature distribution.

Figure 2: K/$\pi$ ratio for 200 < $p_\perp$ < 600 MeV.
The STAR TPC Slow Simulator  
W.G. Gong and the STAR Collaboration

The response of a time-projection-chamber (TPC) can be simulated with respect to an ionization cluster. A TPC simulator is useful for (1) evaluating the TPC performance such as spatial resolution and two-track separation; (2) optimizing the cluster-finding algorithm; (3) testing data compression in the data acquisition system design. For STAR physics simulations, a fast simulator [1] has been used so far, but it lacks many physical considerations. We have improved and implemented a slow simulator based upon an early work [2].

In this slow simulator [3], electron clusters along charged particle tracks are generated by the Geant in the TPC volume. Each cluster is transported in a uniform electrical drift field from a space point to the sense wire plane. Gas gain fluctuation is incorporated according to the Polya distribution. Both longitudinal and transverse diffusions are considered, they are folded with the measured pad-response-function and shaper-response-function to determine the charge signal distribution among pads and time-buckets. The shaper-filtered white noise is added to the signal at each pixel. The signal is then digitized to produce the pixel data.

To evaluate the two-track separation capability of the STAR-TPC, we used three close pion tracks of $P_t = 1.0\text{GeV}/c$, $\eta = 0.1 (\text{or} \theta = 84.3^\circ)$ within each sector. Figure 1 displays the simulated pixel data with four different track separations. We find that two tracks with separation of $\Delta \theta = \Delta \phi \approx 1.0^\circ$ can be resolved by a hit-finder with simple deconvolution algorithm. We also processed one HIJING event of Au+Au collision at $E/A = 100 \text{GeV}/\text{nucleon}$. A total of 9 million pixel data were produced by the slow simulator for an input of 705000 ionization clusters. Figure 2 displays a plot of pulse height spectrum vs. pad number and time bucket for an outer-sector row. The averaged pixel occupancy is about 13%.

Reference

Figure 1: Capability of two-track separations: $\Delta \theta = \Delta \phi = 0.5^\circ$ (top-left), $1.0^\circ$ (top-right), $1.5^\circ$ (bottom-left), and $2.0^\circ$ (bottom-right).

Figure 2: Simulated pixel data from an Au+Au collision.
Progress Report on the STAR TPC Construction


and the STAR Collaboration

Much of the detailed design work has been completed for the STAR TPC which is scheduled to take beam at RHIC in 1999. Two major components of the TPC are under production; the field cage structure and the end cap pad plane sectors.

The field cage will be a free standing cylindrical structure, 4 meters long by 4 meters in diameter, built from copper kapton skins on a Nomex honey comb core. A 5.7 cm gas envelope will provide electrical insulation for the field cage which is designed to operate at 85 kV. A variety of tests have been carried out to verify the design of the field cage and gas insulator. These tests are presented in another section of this report. Construction of the field cage is proceeding. A mandrel and tape winding machine (see figure 1) for forming the field cage and its surrounding gas envelope has been built. Production procedures have been developed and tested and the final construction is ready to start.

The pad plane read out of the STAR TPC is separated into 12 sectors each of which is divided into two parts, an inner radius sector module and an outer radius sector module. The outer sector modules are under production. Several of the outer sectors have been completed and have passed final production testing. These tests include a gas gain uniformity check at three points on each anode wire, over voltage tests with a hot beta source and measurements of wire tension. The gas gains have been found to be uniform to 3% rms and the sectors can be operated at well above normal voltage. The inner sectors are designed and ready for production to begin as soon as the outer sectors are completed. A series of tests (reported elsewhere in this report) of the inner sector design have been completed.

The design of the laser system and gas system are well under way. The velocity feedback control of the field cage voltage supply has been designed and hardware has been purchased. The controlling software is currently under development. Progress has also been made on the MWPC anode voltage control system and prototype gating drives have been built and tested.

Footnotes and References

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Fig. 1. Mandrel and tape winding machine used in the production of the TPC gas vessel and outer field cage. In this figure aluminum strips are being wound on with epoxy to form the skin of the gas vessel.
STAR TPC Gas Studies
Eric Hjort, Howard Wieman, Adam Sobel

The STAR TPC is designed to use a mixture of 90% Ar + 10% Methane (P10) as its counting gas. An alternative gas consisting of 50% He and 50% Ethane is also under consideration because its longitudinal diffusion is about 50% that of P10 and it results in less multiple scattering. When He/Ethane is used with a drift field of 400 V/cm the drift velocity is equal to that of P10 (at 130 V/cm) thereby eliminating the need for different electronics for the two gas mixtures. Other operating parameters do differ between the two mixtures, however, such as the gain as a function of voltage and the effects of impurities on electron capture during the drift time. We report here on studies regarding these two points.

Figure 1 shows a plot of the gas gain versus anode wire voltage for both P10 and the He/Ethane mixture. It is necessary to increase the voltage about 200 Volts in order to attain the same gas gain in He/Ethane as in P10. This could result in high voltage stability problems, however, spark tests have shown that the stability is a function of the gas gain, not voltage, so for a given gas gain we expect similar high voltage stability in either gas.

The STAR TPC has a maximum drift distance of 2 meters and the He/Ethane mixture is not commonly used for such a long drift distance. It is therefore necessary to determine what conditions are required in order to minimize signal attenuation due to electron capture. Figure 2 shows first results of using He/Ethane with a long (1 meter) drift distance. The fractional signal is the ratio of the drifted signal amplitude from an $^{55}$Fe source to an undrifted signal. Test 1 and 2 were done at 5 and 6 ppm O$_2$ and 12 and 140 ppm H$_2$O, respectively. The drift velocity as a function of the drift field is also shown for comparison. Later tests not shown on the graph have achieved a best fractional signal of 88% for a 1 meter drift at 400V/cm. Future tests will attempt to measure the electron attenuation as a function of O$_2$ content as well as the effectiveness of gas filters. The results shown here were achieved with commercial, unfiltered He/Ethane.

![Figure 1. Gas gain as a function of anode voltage for P10 and He/Ethane.](image1)

![Figure 2. Fractional signal and drift velocity as a function of drift field for a 1 meter drift in He/Ethane.](image2)
STAR Field Cage Quarter Scale Prototype Testing
M. Smith, D. Shuman, R. Wells, H. Wieman, A. Lebedev*, and the STAR Collaboration

In order to test the voltage holding ability of the STAR Field Cage and the surrounding gas insulator between Field Cage and gas cylinder, a quarter scale prototype of the Field Cage with surrounding gas cylinder was constructed and put through three stages of tests. This prototype had a gas insulating gap of 5.7 cm, slightly under the planned gap of 5.7 cm. The three stages of testing consisted of: short term testing (i.e. ramping up the voltage until a spark occurred), long term testing (ramping to a particular voltage and waiting for a spark to occur), and then short term testing again while the Field Cage was subjected to an intense beam of protons.

The initial purpose of short term testing was to condition the Field Cage for higher voltages. Argon and Nitrogen gases were used, and it was found that the breakdown voltage was correlated with the voltage ramp-up time and the rest time between breakdowns. The maximum breakdown voltage for Nitrogen was found to be 119 kV, below the expected value.

In long term testing with Nitrogen, the goal of 25% over planned operating voltage for one week was not achieved, thus other gases were considered. The gas Hexafluoroethane (C2F6) was chosen as: 1) the relative electric strength is 1.8 times greater than that for Nitrogen and 2) its previous use in ion chambers, leading us to believe that small amounts diffusing into the TPC would not cause an electron attenuation problem. This second point was confirmed in tests with <1% C2F6 in P10 (90% Argon-10% Methane) showing that there was no attenuation of electrons, but the gain was decreased, e.g. by one-half at 0.1% C2F6 in P10. In Figure 1 is a graph of measurements from spark gap tests showing the relative affect of C2F6 on Nitrogen breakdown voltage. Long term test results with C2F6 exceeded our goal, holding at 28% over voltage for more than a week before being terminated because of time constraints.

Due to the experience of others1 it was felt that a flux of low energy ionizing particles might cause a spark in the insulating gas. To test if this would be a problem, the prototype was exposed to a flux of low energy protons at LBL’s 88-inch Cyclotron using Nitrogen and then C2F6 as an insulating gas. In both cases we found that for the expected particle flux this mechanism for breakdown should not cause a problem. Results were: 1) in Nitrogen at operating voltage there was no breakdown until we exceeded 2000 times expected flux and 2) in C2F6 there was never a breakdown, even at 40% over operating voltage at 106 times expected flux.

Footnotes and References
* Moscow Engineering Physics Institute
1. R. Baur et al CERN-PPE/93-169, 6 Sept. ’93
In an effort to optimize the design of the STAR TPC inner sectors, we have built several small multiwire proportional chambers with pad readout. The chambers differ from one another primarily in the wire plane positions. Properties to be studied include gas gain, electrical instability and pad response function.

The chambers are very similar to the actual STAR TPC sectors. They consist of one plane of shield (ground) wires (0.075" diameter, 1mm pitch), one plane of anode (sense) wires (0.020", 4mm pitch), and the pad plane (PC board). The pad plane has rows of pads 2.85mm by 11.5mm separated by 0.5mm with the capability to read out each individual pad. The total active area is about 3"x3". A gas mixture of 90% argon and 10% methane (P-10) was used for these tests.

The chambers differ in the gaps between the layers. One chamber has 1.5mm between the pad plane and the anode wires and 1.5mm between the anode wires and the shield wires (1.5-1.5 for short). The others are 2-2, 2-3 and 4-4. In addition, one other chamber has been built with the 2-2 wire spacing, but with field wires (grounded) between each anode wire (2-2 fw).

Gain versus voltage measurements have been made for each chamber (see Fig. 1) and are comparable to calculations done using GARFIELD\textsuperscript{1}. All measurements were done using a 200ns shaping time to simulate the current specifications of the STAR TPC readout electronics. For this reason, gains quoted in this summary are lower than the actual gas gains by about 40%. Count rate measurements (using Fe-55) indicate that the counting plateaus of each of the chambers end between measured gains of 17000 and 30000 with no obvious correlation to wire geometry. Furthermore, these chambers show no signs of any type of discharge until far above the operating voltage we intend to use for the STAR TPC, even when exposed to an 85 µCi Sr-90 β-source.

Pad response measurements focus on two properties: the pad response width and the pad to anode signal ratio. For pad response width, we have used a Gaussian as a sufficient approximation to the actual response. At a measured gain of 1600, using a localized signal comparable to an Fe-55 signal, the 2-2 chamber has a pad response width of as low as 2.0mm while the 2-3 chamber is slightly wider at 2.1mm. In one measurement, increasing the initial signal size by a factor of twenty increased the 2-2 width to 2.6mm. Also at a gain of 1600, the signals on the 2-2 and 2-3 pads centered below a localized source were, respectively, 26% and 36% of the anode signal. In addition, increasing the gain to 3200 decreased the 2-2 ratio to 22%. These preliminary results suggest that a larger anode signal causes a wider pad response function and a lower pad to anode signal ratio. Further tests are in progress to quantify this effect and to further determine the characteristics of all of the chambers.

Footnotes and References

\textsuperscript{†} Univ. of Texas, Austin
1. R. Veenhof, CERN Program Library entry W5050.

![Fig. 1. Gain curves for the various chambers, showing data points and exponential curve fits. Also included are data (not fitted) from the EOS TPC prototype.](image-url)
Because of the extremely high multiplicity, the 138,000 STAR TPC pads each require an independent waveform digitizer. Each channel is connected to a low noise preamplifier/shaper (SAS) which shapes the TPC signal to 200 nsec FWHM, a 512 deep switched capacitor array (SCA), which samples and stores the signal and a 12 bit digitizer. All of the analog functions are implemented in small (2.9" by 7") 32 channel FEE cards. Most of the functionality is implemented in two fully custom chips, a 16 channel wide preamplifier shaper (SAS), and a 16 channel wide SCA/ADC. Both chips are implemented in 1.2 μCMOS technology.

The SAS chip includes a low noise integrating preamplifier, followed by a two pole shaper and an output buffer capable of driving a 50 pF load. The shaper includes a 1/t tail correction. For 12 pF pad capacitance the chip noise level is ~720 electrons. For minimum ionizing particles, this gives a 20:1 signal to noise ratio. Saturation sets in at 40 times minimum ionizing, or 640,000 electrons.

The SCA is a 512 channel switched capacitor array. It will sample at 12.3 MHz if P-10 gas is used in the TPC, or at 6.15 MHz for helium-ethane. The storage is linear over a 2 volt range, with a 1 mV noise floor, giving 12 bits of dynamic range. The SCA includes a 12 bit Wilkinson rundown ADC. Only 10 bits of conversion are used in STAR. All channels are converted in parallel. Counting a 75 MHz clock on both clock edges, a 10 bit conversion takes 6.28 μsec, allowing all 512 samples to be converted in 3.5 msec. Double buffering allows conversion to continue while the preceding conversion is read out. The boards can accommodate additional SCAs to record 1024 samples.

The system specifications are given in Table 1. The system noise comes from 3 places: the SAS chip, the SCA chip, and the TPC pad plane. For the typical pad plane capacitance of 12 pF, the SAS contribution is about 720 electrons and the SCA contributes about 390 electrons. The pad plane introduces noise through the dielectric loss angle of the capacitance (essentially the AC resistance). For the measured tan(δ) ~ 0.014, the pad plane contributes about 300 electrons. The quadrature sum of these is 870 electrons, slightly over the 800 electron design goal. This can be compensated for by slightly increasing the wire gain in the TPC.

Reference

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<thead>
<tr>
<th>Channels</th>
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<tr>
<td>System Noise</td>
<td>870 electrons (avg.)</td>
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<tr>
<td>Input Capacitance</td>
<td>30 pF max; 12 pF average</td>
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<tr>
<td>Min. Ionizing Signal</td>
<td>16,000 electrons</td>
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<tr>
<td>Maximum Signal</td>
<td>640,000 electrons</td>
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<tr>
<td>Shaping Time (FWHM)</td>
<td>200 nsec</td>
</tr>
<tr>
<td>SCA Sample Rate</td>
<td>12.3/6.15 MHz (P-10/He-Eth)</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>100 mW/channel</td>
</tr>
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Table 1. FEE System parameters.
STAR Front End Electronics Readout

The STAR FEE readout board is the connecting link between the STAR FEE cards and the STAR data acquisition (DAQ) system. Each readout board provides timing information to and receives data from up to 36 FEE boards (1176 channels). It multiplexes the data and sends it over a 1.2 Gbit/sec fiber link to DAQ. Trigger and clock information is received over a clock/trigger bus, while a slow control interface serves to control the board and read out temperatures, voltages, and related parameters.

The Finisair fiber optic link is driven by an HP Gigalink (HDMP-1012) serializer chip, which receives 20 bits of data at a 62.5 MHz clock rate, two 10 bit data words in parallel. Data is transmitted to this serializer chip from the FEE cards over a 40 bit wide bus running at 31.25 MHz; data is read from the FEE cards in the order required by the DAQ system. The data is ordered so that, when it reaches the DAQ receiver cards it is time ordered, with adjacent pads adjacent in memory. In addition to the FEE cards, the bus also connects to a memory which is large enough to store one complete event. This memory can record events for later playback via the fiber link over slow controls.

Clock and trigger information is transmitted to the readout board over the clock and trigger bus. This bus comprises 8 signals: the RHIC strobe, a data strobe at 5 times the RHIC clock frequency, a 4 bit data bus, and one spare clock. Running the 4 bit data bus at 5 times the RHIC clock frequency allows us to transmit 20 bits every crossing: a 4 bit trigger word, a 4 bit DAQ word, and, for triggers or aborts, a 12 bit trigger token. The trigger token describes the trigger type (nothing, data trigger, various calibration triggers, abort, or clear). The DAQ word and trigger token are stored and transmitted to DAQ over the fiber link in the event of a valid trigger or abort.

The slow controls link is based on native HDLC. It runs at 1 Mbit/sec. The link will be used to control the state of the readout and FEE boards, turn groups of FEE boards on and off, and allow slow controls to ask the board to report on various voltage and temperature readings. It also has read and write access to the memory described above, to allow for a full check of the DAQ multiplexing. On command, it can report the geographical addresses of the FEE cards (obtained from the TPC pad plane PC board) and readout board. The readout end of the link is implemented in a 68302 microprocessor serial port; the other end connects to a VME board.

The readout board receives power over 75 foot long cables from supplies located on the detector platforms. Because of the long cable run, the boards will incorporate on-board regulators. The power supplies will be ferro-resonant supplies, chosen for the simplicity, reliability and inherent overvoltage and overcurrent protection. The power supplies will be controlled by the slow control system, using commercially available hardware.

The readout board design is well specified, and final detailed design is beginning.

<table>
<thead>
<tr>
<th>Channels / Readout Board</th>
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</tr>
</thead>
<tbody>
<tr>
<td>FEE Boards / Readout Bd.</td>
<td>36</td>
</tr>
<tr>
<td>Fiber Link speed</td>
<td>1.2 Gbit/sec</td>
</tr>
<tr>
<td>Slow Controls Link Speed</td>
<td>1 Mbit/sec</td>
</tr>
<tr>
<td>Power Supply</td>
<td>+8 V 20 A</td>
</tr>
<tr>
<td></td>
<td>-8 V 20 A</td>
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</tbody>
</table>

Table 1. FEE Readout parameters.
SCI is an approved IEEE standard defining a high speed (1 GByte/sec) split transaction network. It merges the shared memory concept with a bus-like architecture. SCI supports transparent read and write transactions to or from any node in a network of up to 65,000 nodes based on a 64-bit address. Many different nodes may share cached copies while the network ensures cache coherence throughout the network. Due to its unique features and performance, SCI is the ideal network for both the STAR data acquisition and the trigger backbone.

As a first test setup three SPARC stations were connected in a three node SCI network using the Dolphin SBUS-SCI bridge. The available driver software allows for two communication scenarios: I/O channels and shared memories. I/O channels are virtual point to point links that allow one node to send sequential data to another node. The SCI based shared memory allows transparent load/store transactions anywhere in the shared memory region by all nodes in the SCI network. Both communication scenarios were tested and functioned satisfactorily. In channel mode 10MB/s could be transferred. This data rate utilizes about 10% of the available network bandwidth. Therefore in a larger system many nodes could perform such a transaction without interfering with each other. In the shared memory scenario read latencies of about 5.5μs and write latencies of about 4.5μs were observed. It is therefore possible to send a message of 1 to 64 bytes to another system within less than 7μs. Once the network paths for a shared memory region are setup all following transactions proceed without further intervention by the driver because the region is directly memory mapped into the applications address space. Routing and flow control are entirely handled by the SCI hardware. SCI allows therefore very fast and efficient message passing. The SBUS-SCI board has a DMA engine built in to move data from a local memory segment to the remote shared memory. The node-to-node data rates observed there were about 12MB/sec.

The observed data rates and latencies are determined by the SBUS interface and the SCI node interface chip. Figure 1 shows a typical trace of the receiving SCI node chip while two remote nodes are simultaneously moving data (dmove64) into the local shared memory using DMA. The node chip clock is running here at 62.5 MHz

Figure 1: Logic analyzer trace of SCI SBUS board receiving shared memory moves simultaneously from two other SCI nodes

Incoming packets are identified by long IFLAG pulses. The SCI node chip responds by requesting the local bus (CBUS) of the bridge (SREQ) and transferring the packet into the local FiFo buffer (SBSY, SDVAL). The SBUS interface logic responds by requesting SBUS mastership (BR, BG) and further transferring the packet to the final memory location (AS, RD). The observed latencies are:

- Latency through bypass FIFO: 224 ns
- Latency IFLAG to SREQ: 800 ns
- CBUS dmove64 transaction time: 768 ns

These numbers indicate a theoretical dmove receiving bandwidth of about 40MB/sec assuming zero latency write acknowledgments.

However in order to complete the transaction the SBUS board has to become SBUS master and write the 64-byte packet to the requested address. It takes the SBUS board about 2.2μs (with respect to the leading edge of SBSY) to complete the request.

Figure 1 shows another interesting feature - the behavior of the SCI node chip if two packets arrive close to each other. The third dmove64 packet (IFLAG) arrives while the second packet is still being transferred at the CBUS side. However it is obviously buffered resulting in the third CBUS transaction. This allows measuring the fastest rate at which the SBUS board would be able to receive data. Packets arriving at a higher speed would be busy-retried by the node chip. The second and third SBSY cycles are 3.2 μs apart. This corresponds to a maximum receiving data rate of 20MB/sec.
SCI is a split transaction high-speed network (up to 1Giga byte/sec) that allows shared memory like intercommunication between the various nodes of the system. These features make it the ideal solution for the STAR data acquisition and third level trigger backbone.

Most of the latest high-speed processor architectures like the PowerPC and DEC alpha support PCI as local I/O bus. The latest VME boards implementing these processors use also PCI as local I/O bus. Therefore an SCI-PCI bridge is useful in two scenarios: to connect a stand-alone computer with local PCI bus to the SCI network or to connect a VME-PCI computer to the SCI network allowing direct VME-SCI transactions.

A prototype of a symmetric PCI-SCI bridge was designed for real-time data acquisition purposes. This project is being carried out in collaboration with the CERN RD24 project. Its most important features are:

- support transparent PCI→SCI and SCI→PCI read/write transactions
- PCI→SCI address translation
- SCI→PCI access control
- initialization from both PCI and SCI
- high-speed chain mode DMA controller initiated from both PCI and SCI
- PCI interrupt generation, PCI→SCI interrupt forwarding
- SCI initiated generation of special SCI transactions like locks.
- locked PCI transactions
- PCI multi processor capable
- compliant with the PCI CMC form factor allowing it to be implemented on a single height VME board

Figure 1 shows a sketch of the functional blocks of the SCI-PCI bridge. Its major components are two FPGAs, the 32KB high-speed dual ported memory, the SCI node interface and the PCI bus interface. One FPGA controls the SCI part of the DPM and the second the PCI side. This architecture allows one to implement the dual ported memory as a cut through elasticity buffer between SCI and PCI. It serves also as address translation and access control lookup table, mailbox region and DMA chain mode descriptor table.

In order to achieve optimal performance the SCI-PCI bridge implements a read ahead cache and write posting buffers for transparent read/write transactions across the network. These features can be, however, avoided for I/O control transactions.

Special SCI transactions can be executed by mocking up the appropriate packet in a reserved region of the DPM. Upon a certain command the bridge will send out the packet and preserve the response.

The chain mode DMA controller allows to fetch scattered data blocks and merge them in the destination memory anywhere in the SCI network. The data granularity is 64 bytes.

The design of the bridge is currently being done in VHDL using Exemplar for synthesis and Neocad for place and route. The first version of the bridge will implement a packet mode, which allows one to test all hardware feature of the device with the aid of driver software. This packet mode will then receive more and more upgrades until the full design is finished.

The current status of the project is that the PC layout is out for commercial bid. The PCI slave and DPM interface and the SCI packet mode implementation are written and simulated.
The STAR Trigger Token Concept


The STAR detector setup implements several hundred readout modules, producing independent data sets that have to be merged into one event. It is essential to have a mechanism that guarantees that an event is compiled of the correct subevents. One way to solve that generic problem is to implement counters on each readout module that are reset at begin run time and incremented upon each bunch crossing. If, however, a counter runs out of phase it will be unclear if this was due to a missing RHIC strobe or due to a lost trigger command.

Another approach is to distribute a unique identifier that is generated together with the trigger. This identifier could be, for example, the 64 bit bunch crossing number, which is unique throughout the lifetime of the experiment. The distribution of a trigger and all associated parameters should not introduce extra dead time. All bits associated with a given trigger have to be transmitted during the period of one RHIC strobe (110ns). Bandwidth limitations and cost considerations drive this bit count to be significantly less than 64.

This leads to the STAR trigger token concept. Taking into account that an event will be moved only as one contiguous entity, after it was built within DAQ, the event identifier has to be unique only during the time between the actual trigger and when the event is built. The maximum trigger rates and the maximum latencies define the maximum number of these identifiers required at any point in time. For STAR these are less than 4000. These identifiers are meaningless numbers, therefore, they are called trigger tokens. Part of the trigger data stream is the 64-bit bunch crossing number which makes any event, once it is built, unique throughout the lifetime of the detector.

Figure 1 shows the format of the 20-bit data that is associated with each trigger in STAR and transmitted during the appropriate bunch crossing. The first nibble, the trigger command, defines the nature of the actual trigger like physics trigger, calibration trigger, L1/L2 accept, abort, reset, clear etc. The second nibble defines a DAQ readout qualifier that is broadcast to the DAQ front-end of all involved detectors. The trailing three nibbles define the actual trigger token.

For every trigger a trigger token is used. Trigger tokens are returned to the trigger system upon aborts or after the event is completely built by DAQ. In order to guarantee the uniqueness of the token the STAR trigger system will stop issuing triggers if it runs out of tokens.

This requirement turns out to be a great simplification of the whole detector architecture, because the number of outstanding events is limited. Due to the fairly small maximum number of outstanding events, it is possible to design a subdetector system if it produces small subevents to supply enough buffer space for the up to 4095 outstanding events. In this scenario the event is copied upon a L0 trigger into a buffer slot identified uniquely by the trigger token. After any associated special handling and processing it is transmitted to DAQ upon a L2 accept, which is accompanied by the appropriate trigger token and transmitted to all coincident front-end systems like a trigger.

A trigger token is returned by DAQ after the event is completely built. Any latencies in any subdetector system will cause a given token to be alive for a longer period of time but does not cause any buffer allocation problems or data overrun hazards.

A subdetector system designed in this manner does not have to produce a subdetector dead time signal at all. It is virtually dead time free. The whole functionality of the conventional dead time logic is absorbed into the trigger token concept. The only case where dead time would arise is when the trigger system runs out of trigger tokens. This is a pathological case, because in this case one of the involved STAR subsystems violated either the maximum trigger rate or readout latency. However, in no case would events already accepted be destroyed. The STAR Time-of-Flight subdetector has already adopted this concept.
The Trigger L1 and L2 system are two layers of veto processor farms that reduce the maximum primary trigger rate. Their principal difference is the time budget for the trigger decision and the available input data. Figure 1 sketches an overview of the STAR trigger system including L0 and the Trigger/DAQ interface (TDI). The digitized raw data of the trigger detectors is stored every bunch crossing in buffers holding 65000 bunch crossings. This input data stream is also fed into a tree structure of field programmable gate arrays (FPGA) allowing a very flexible analysis of the trigger detector data. The end of this L0 analysis chain is the Trigger Control Unit that fires triggers depending on the result of the FPGA tree. The TCU is the only instance in STAR that will fire triggers. All higher levels in the trigger system can only abort an already issued trigger. If a subdetector wants to fire a trigger it can request a trigger by asserting the appropriate input bits to the TCU within the specified time lines. The output of the TCU is a request queue that drives the L1 veto processor farm.

The input data available to the L1 veto processors is shown in the following list:

- coarse pixel array (64 bytes)
- MWC/CTB multiplicity, dipole analysis, special topology, higher moments (4x2 bytes)
- VPD (2 bytes)
- VTC (2 bytes)
- EMC (36 bytes)
- trigger word, trigger action word (2x2 bytes)

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- VPD (2 bytes)
- VTC (2 bytes)
- EMC (36 bytes)
- trigger word, trigger action word (2x2 bytes)

The L1/L2 trigger analysis code will be implemented within this very flexible framework. Many different analysis code scenarios have already been studied. Each STAR collaborator is invited to use this framework to try to implement his or her favorite trigger algorithm.
The most demanding part of the STAR architecture is the third level trigger architecture of the TPC and SVT subdetectors. These detectors produce the largest amount of data as shown in Table 1.

Table 1: STAR third level trigger data volumes

<table>
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<th>TPC sector segment</th>
<th>SVT sector segment</th>
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<tr>
<td>raw data</td>
<td>5.8 MB</td>
<td>3.3 MB</td>
</tr>
<tr>
<td>average occupancy</td>
<td>10%</td>
<td>3.9%</td>
</tr>
<tr>
<td>zero-suppressed data (including 20% overhead)</td>
<td>700kB</td>
<td>160 kB</td>
</tr>
<tr>
<td>space point data</td>
<td>54 kB</td>
<td>27 kB</td>
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<tr>
<td>tracks (6 real numbers per space point for outer 16 pad rows)</td>
<td>80 kB</td>
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<tr>
<td>tracks (10 real numbers per track)</td>
<td>80 kB</td>
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The third level trigger processor farm has to veto 99% of the events that are accepted by trigger levels one and two. Therefore the required bandwidth to communicate between the TPC and SVT receiver boards and the third level trigger processors is about two orders of magnitude higher than the tapping requirements. The appropriate data rate requirements result from the design requirement that the L3 input event rate is 100/sec.

Figure 1: STAR third level trigger data flow

There is a large variety of structural scenarios of how to implement the third level trigger processor farm. One possible architecture takes into account that the bulk of the TPC and SVT trigger analysis (hit and track segment level) are completely independent. In this scenario the first level of analysis can be done independently on a sector by sector basis. Therefore there is only very little communication between the TPC sector and SVT segment crates required. Figure 1 shows an appropriate third level trigger data flow diagram. The TPC readout and L3 electronics will be split into 24 independent sector crates and correspondingly the SVT setup into 8 independent segments. Each TPC L3 sector crate would consist of 6 receiver boards serving one TPC sector. Each SVT segment would consist of three receiver boards. The number of L3 local processors is not finalized yet. The TPC and SVT tracks are sent from each L3 local network to the L3 global processor farm.

Figure 2 sketches the appropriate implementation of the TPC and SVT third level trigger farm. SCI is the ideal backbone network which allows the communication between the various subsystems. All local L3 TPC sector or SVT segment crates are connected through bus bridges to a global network, which serves several functions:

- data transport mechanism for the L3 summary data to the L3 global processor farm
- event build and readout path
- on-line monitoring access
- transport mechanism for communication between TPC sectors or SVT segments
Design of STAR On-line Software

D. L. Olson, C. P. McParland and the STAR Collaboration

For a modern large scale experiment like STAR, the software to control and operate the experiment is of considerable size and complexity. It must be robust since the detector will be operating for several thousand hours per year, for many years. It is developed by many people, at numerous locations. It must support many independent activities for both the detector assembly and integration phase and the detector maintenance phase. These requirements and boundary conditions lead to the necessity of building software system that it is reliable, partitionable and maintainable, i.e., it must have some planning and forethought. For all of these reasons, an effort is underway in STAR to design this software.

A methodology for constructing the initial model of the entire STAR on-line software and electronics system was used for developing requirements and an essential model of the system. One of the main goals of following this methodology is to identify clear interfaces so that different work groups may proceed effectively.

A sample from the essential model is shown in figure 1, which shows the top level view of the system. The circle represents everything inside the system, the rectangles represent entities which are external but affect the system, and the arrows represent the events (stimuli) that are exchanged. The set of diagrams comprising the essential model form a hierarchy in which each circle on one diagram (the parent) expands to another full page diagram (the child). All of the events entering or leaving the circle on the parent diagram are represented as entering or leaving around the edge of the child diagram. An example of descending two levels from the diagram in figure 1 is shown as figure 2, the major subsystems.

In addition to the essential model diagrams are a set of requirements documents. These requirements documents are organized along the major divisions of effort; data acquisition, trigger, slow controls, on-line software, TPC, SVT, EMC, TOF, XTPC, and interfaces. When finished one will be able to identify the effect of each requirement in the essential model.

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Fig. 1. External view of the STAR On-line System.

Fig. 2. View of major subsystems. Detectors includes all detectors, i.e., TPC, SVT, ... DAQ-Trigger includes the combined data acquisition and trigger. The subsystem monitors includes all the on-line monitoring and calibration processes.
The STAR experiment will generate raw data at 20MB/sec and is expected to have an aggregate data access bandwidth requirement at the central processing facility of more than 100MB/sec. This should operate continuously, year-round. With this level of data bandwidth requirements, it is essential that STAR have an efficient software package for moving data into and out of programs, and around the computing facility. This needs to be efficient in both size of the data representation and in the number of cpu cycles required to transport the data. It is also essential that the data representation be independent of the native format of any particular cpu architecture since the life of the data is much longer than the time scale for new cost-effective cpu architectures. Existing data I/O software packages did not fulfill these requirements so the STAR project undertook the development of the necessary software as a key component of the software infrastructure, we call this the dataset library.

Figure 1 shows how this library fits into the architecture for XDR† and the higher layers of STAR software. This library uses a data encoding standard which is compatible with the XDR standard. The purpose of this standard is to address deficiencies in XDR for encoding scientific data. Data structures described in this standard can be encapsulated in basic XDR data types. These data structures are called tables.

The canonical encoding for tables has left-to-right or big endian byte ordering and use the IEEE Standard encoding for floating-point numbers. Tables contain one and two byte data types not defined in the XDR standard and these types may be aligned on boundaries that are not a multiple of four bytes. Table data is encapsulated in the XDR opaque type. Definitions of table types and datasets are encoded as standard XDR types. This encoding matches the data structures generated by compilers on many popular workstations and computers. For these machines encoding and decoding is not required and I/O for table data becomes binary reads and writes.

A dataset is a collection of tables. Datasets have a hierarchical structure. An example of the language is used to specify the tables that make up a dataset and the hierarchical tree structure of the dataset is shown in figure 2, along with a graphical representation.

Footnotes and References
*Presented at Computing in High Energy Physics '94, LBL-35822
† LBL Information and Computing Science Division

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Fig. 1. Overview of dataset architecture in relation to XDR.

Fig. 2. Graphical view of a dataset hierarchy and its associated string descriptor.
The Offline Production System for STAR
M.A. Bloomer, R.C. Jared, D.L. Olson and the STAR Collaboration

A timely analysis of STAR data requires an offline data reduction system which can keep pace with the raw data rate anticipated for STAR (one 20 MB event/sec). We have begun to document the functional requirements of this system and the design of its individual software components.

Fig. 1 is an essential model diagram of the offline system which shows the interfaces among the major subsystems and data stores. Processes are shown as circles, the data stores as parallel lines, and the arrows show the direction of the information flow. The subsystems are: (i) offline system control, (ii) event reconstruction (reduction of raw data into physical quantities like tracks, energies, momenta, etc.), (iii) detector calibration, (iv) event simulation (simulated raw data), (v) data visualization, (vi) μDST production (smaller subsets of DST-level data which pertain to a particular physics analysis), and (vii) a data file manager and event catalogue.

Preliminary design documents already exist for event reconstruction and data visualization. A complete task list of software modules for event visualization, event simulation, TPC and event reconstruction was put together, including timelines and personnel requirements.

The prototype event reconstruction system was recently completed and consists of global tracking (matching reconstructed tracks between the TPCs and SVT) and particle identification (using dE/dx from the TPC and SVT, and time-of-flight from the TOF barrel). The design document was essential for the integration of different reconstruction modules into a functioning data processing chain.

In order to test the offline system, a prototype offline production directory structure on the RHIC computers was started. It supports (i) standard directories for data files, batch scripts and log files; (ii) documented (via the data file manager) simulated data sets; and (iii) working executables with accompanying KUMAC scripts for correct execution. A major concern now is that the estimated computing power needed for STAR data processing (based on current prototypes) is 240 Gflops, considerably larger than what RHIC will be able to provide. We will aim at improving the performance of the offline software so as to reduce the computing power needed to process the data.

Figure 1: STAR Offline System Essential Model.
Electromagnetic production of hyperfragments in ultrarelativistic heavy-ion collisions*

Y. D. He and P. B. Price

We explore the possibility of hyperfragment production due to the extremely intense flux of photons generated by an ultrarelativistic heavy nucleus in distant collision. We suggest that hyperons electromagnetically produced in collisions beyond the range of nuclear interaction bind to nuclear fragments and form hyperfragments. The cross section is estimated to be accessible to future experiments at the Relativistic Heavy Ion Collider and Large Hadron Collider. We also discuss its signature and detection.

In $A_P + A_T$ collision the virtual photon energy spectrum created by one of the nuclei ($A_T$) and seen by the other ($A_P$) can be derived with Williams-Weizsäcker method. $dN_\gamma/dE_\gamma$ is a function of $x \equiv E_\gamma b_{\text{min}}/(\gamma \beta hc)$. The cutoff in the spectrum is given by $E_{\gamma}^\text{max} = \gamma hc/b_{\text{min}}$ with $b_{\text{min}} \sim r_0(A_P^{1/3} + A_T^{1/3})$ and $r_0 \sim 1.35$ fm. The cross section for the electromagnetic production of hyperons (e.g., $\Lambda$) can be calculated as:

$$\sigma_{A_P A_T \rightarrow \Lambda X} = f \times \sigma_{A_P A_T \rightarrow \Lambda X},$$

in which $f$ is estimated to be $\sim 0.05-0.1$, depending on $A_F$. We estimated $\sigma_{A_P A_T \rightarrow \Lambda A_F X}$ for various colliding systems. At RHIC energies, the cross section will be $\sim 10\text{mb}$ for $Au + Au$ collisions and should be measurable. The cross section for multi-$\Lambda$ hyperfragment production is estimated to be negligibly small.

Behaviors of hyperfragments are expected to be different from those of nuclear fragments in angular distribution, kinetic energy, charge spectrum, decay mode, and interaction cross section. In particular, the appearance of hyperfragments would be signaled as anomalon-like behavior, namely that the instantaneously measured mean-free-path varies with the distance from its origin. The electromagnetic production of hyperfragments would probe a different aspect of properties of hypernuclei from those produced via other mechanisms.

Although the primary goal of heavy ion colliders is to study central nucleus-nucleus collisions, these colliders also produce interesting physics when the nuclei miss each other, but the electromagnetic fields of the nuclei collide. While this ‘two photon’ physics has traditionally been studied at high energy \(e^+e^-\) colliders, heavy ion colliders can reach unmatched particle production rates because the \(\gamma\gamma\) luminosity is proportional to \(Z^4\).\(^1\)

In addition to the high luminosity, heavy ion collisions provide some unique opportunities. Because \(Z\alpha \approx 0.6\) for gold, heavy ion collisions can probe strong field QED.\(^2\) In addition, the presence of nuclei allows for the production of particles in a bound state of the nucleus. Although these calculations are very difficult, it may be possible to study \(\tau\) atoms, or possibly charmed nuclei.

We have been studying \(\gamma\gamma\) physics in two contexts: what interesting physics can RHIC do, and what physics is accessible to the STAR detector, possibly with minor enhancements. Most of the STAR accessible physics is similar to that studied at \(e^+e^-\) colliders, but benefits from the greatly increased luminosity.

For this physics, the heavy ion environment presents three disadvantages. First, the coherent photon flux is cut off at an energy of \(\gamma\) times the nuclear size; this is about 3 GeV for gold at RHIC.

Second, nuclear collisions can create a large background. One obvious and fairly well understood effect of this is to reduce the usable \(\gamma\gamma\) luminosity by an amount corresponding to impact parameters smaller than the nuclear size, where the nuclear interaction clearly overwhelms the electromagnetic interaction.

Third, grazing nuclear collisions might mimic electromagnetic interactions. We have identified at least three techniques to reduce the background. First, most interesting two photon final states have low charged and neutral multiplicities. The average multiplicity for hadronic collisions, even those involving single nucleons, is much higher. For example, the rate of hadronic collisions producing four charged and no neutral particles (relevant for an \(\eta_c\) search) is of order 4,000/year, far lower than the production rate for most final states of interest. Second, in \(\gamma\gamma\) collisions the final state perpendicular momentum scale is set by the nuclear size (about 30 MeV/c for gold), well below that expected for hadronic events. Finally, in a two photon interaction, the nuclei are expected to remain intact, while in a hadronic interaction they are likely to fragment; a downstream veto calorimeter can separate the two classes of events.

Both the multiplicity and the perpendicular momentum cuts are less effective in a non-hermetic detector. However, because missed particles tend to increase the total perpendicular momentum, these problems are manageable. For STAR, for example, a simple requirement, that there be less than 6 charged tracks in the trigger detectors should suffice for level 0 triggering. Simple topology requirements could be applied later, in trigger level 3, to further reduce the triggered event rate. Finally, the veto calorimeter could be included in the trigger, to veto events with nuclear fragments.

References


P-Type Silicon Drift Detectors

Silicon drift detectors (SiDDs) are of interest for charged particle tracking because of their excellent energy resolution and two-dimensional position resolution.\textsuperscript{1,2} We have taken a new approach by using p-type silicon rather than neutron transmutation doped, n-type silicon as the substrate material.\textsuperscript{3} Potential advantages of p-type substrates include lower cost and higher device yield and radiation hardness.

We have successfully designed and fabricated 16 cm\textsuperscript{2} p-type SiDDs (pSiDDs), and are presently in the process of characterizing their performance. Fig. 1 shows signals measured with a Nd:YAG laser focused at five different locations on the pSiDD. The time at which the signal arrives increases as the laser is moved farther from the readout electrode, since charge generated farther from the readout plane takes longer to drift to the electrodes. The increase in the signal width at larger drift distances is due to the longer collection time during which the charge packet diffuses. Fig. 2 shows the relation between the position of an incident laser beam and the measured drift time; such linearity is essential for position determination. The hole drift velocity and mobility derived from the data agree with the expected values to within 1%.

Fig. 3 shows the spectrum of 241 Am measured with a pSiDD. The energy resolution is 3 keV FWHM for the 59 keV line, with the electronics contributing the dominant component of the noise. At present, we are improving the readout electronics to achieve better energy resolution and developing a technique for measuring two track resolution.

* Engineering Division, LBL.
We have recently been developing a process for integrating polycrystalline silicon (poly-Si) voltage dividers on p-type silicon drift detectors (pSiDDs). In a silicon drift detector, a constant electric field is created to sweep out signal charge by applying linearly varying voltages to a series of parallel electrodes. The position resolution of the detector is directly related to the uniformity of the electric field, so that precise bias of the field-shaping electrodes is important. We chose to investigate poly-Si bias resistors because they are voltage-independent and promise greater uniformity than other biasing techniques that have been used with SiDDs.

A schematic of the poly-Si resistor network, as it will be incorporated on the pSiDD, is shown in Figure 1. To test the process before implementing it on the pSiDD, we designed photolithography masks which allowed us to compare resistors of varying linewidths and lengths. A resistor fabrication process was developed which uses phosphorus implantation to dope the poly-Si. To determine the optimal phosphorus implant dose, we fabricated resistors using four different implant doses. The sheet resistance for different implant doses is shown in Figure 2. The data indicate that the sheet resistance varies less rapidly at higher doses, so to achieve the most reproducible and uniform resistors, we expect that an implant dose of \( \approx 5 \times 10^{14} \text{ cm}^{-2} \) will be optimal.

In testing the fabrication process, we cleaved samples in half after the phosphorus implantation and deposited a SiO\(_2\) cap layer over half of the pieces before annealing the poly-Si. A cap layer is often grown over ion-implanted poly-Si in order to prevent out-diffusion of the dopant atoms during annealing. However, our measurements show that the resistors fabricated with and without the SiO\(_2\) cap layer are nearly identical, and thus we have concluded that the SiO\(_2\) cap layer can be safely omitted from the process. As seen in Fig. 2, the uniformity of the poly-Si is good: e.g., the \( 10^{15} \text{ cm}^{-2} \) doses resulted in resistance variations of 2% over 8 cm\(^2\). It was also seen that resistances scaled linearly with resistor length and width, giving us flexibility in designing resistor dimensions to yield the target value of 200-300 k\(\Omega\).

Fig. 1 Schematic of poly-Si resistors integrated on the p-SiDD.

Fig. 2 The resistance of 16 \( \mu \text{m} \) wide, 3264 \( \mu \text{m} \) long, implanted poly-Si lines at different locations on the sample. Open and filled symbols respectively denote samples annealed with and without a SiO\(_2\) cap layer.

* Engineering Division, LBL.
The Microstrip Gas Chamber (MSGC) has become an attractive choice for tracking applications that require low mass, high spatial resolution and high rate capability. However, one problem with the MSGC is the gain instability caused by positive ion accumulation on the insulator surfaces. Two possible solutions exist: (1) ion implantation, and (2) using the electronically-conducting glass substrate. However, a more attractive solution may lie in conductive coating[1]. We have recently developed two methods to coat a conductive layer with either S8900 glass film[2] or doped amorphous Si film (a-Si:C:B). We find that both coating techniques can stabilize the gas gain, reduce the leakage current, and make the MSGC fabrication compatible with many substrates.

Figure 1 shows the structure of a MSGC built with the conductive coating. Two types of MSGCs were studied. The first type (I) used either quartz or alumina substrate after sputtering a layer of 0.5 to 1.0 μm S8900 glass film. The Al electrode-pattern of 10 μm-wide anodes and 90 μm-wide cathodes at one pitch of 200 μm was fabricated. In the second type, the Corning-7059 glass was used as the substrate after coating a layer of 0.1 μm thick amorphous Si film doped with C and B (a-Si:C:B) in a PECVD chamber. It used two pitches of Cr electrode-patterns. One had 5 μm-wide anodes and 95 μm-wide cathodes at a 200 μm pitch (II-a). The other had 5 μm-wide anodes and 195 μm-wide cathodes at a 300 μm pitch (II-b).

All of our MSGCs were tested using 55Fe x-ray sources. The energy resolutions at 6 keV were 15% to 20%. The gas gains were mostly stable within a few percent indicating the effectiveness of our conductive coatings. Figure 2 shows the measured gas gains as a function of anode bias voltages. Using the Ethane \((C_2H_6)\) mixture, the MSGCs of type (I) and (II-a) with 200 μm pitches have a maximum gain about 2500, but the MSGC of type (II-b) with a 300 μm pitch can reach a gain over 5000. Further studies on rate capability and aging behavior are in progress using a newly-installed x-ray machine.

**Reference**


VTX: A compact TPC with Microstrip readout for STAR

S. Margetis, H. Wieman, W. Gong and the STAR Collaboration

A preliminary feasibility study for a very low mass microTPC vertex detector (VTX) in STAR has shown that the VTX is a very promising technology for physics measurements in high multiplicity environments[1],[2]. The basic idea of a microTPC design is to combine in a compact detector three basic elements: 1) A low diffusion gas (e.g. DME[3]), 2) compact monolithic FEE IC and 3) micro-strip readout chambers. The unique potential features of such a detector include: a) Very low mass (< 1% X0), with, virtually, no mass in the tracking volume, as compared to conventional designs based on Silicon technology, b) Excellent position resolution (< 50μm), c) Low channel count (20K channels for 4 padrows), and d) Simpler geometry, better uniformity, and easier alignment and control relative to its Silicon based counterparts. These features will result in better tracking efficiency, impact parameter resolution, momentum resolution and coverage at low momenta, as well as less background from γ conversions.

The parameters of the VTX design are summarized in table 1. The detector consists of a cylindrical drift volume of 2x14 cm and two readout end–cups, one on each side. The readout modules are arranged in four concentric padrows with 2 cm distance between them. A cross section of the configuration of the readout modules is shown in Fig. 1. The optimization of two track resolution of the detector and the requirements on the FEE specifications calls for operation at low gas gain, short readout anode length (3 mm) and low drift velocity. An R&D effort is currently underway[4].

References


S.E. Baru et al.: NIM A323(1992)151


Table 1: Gas parameters and matched VTX parameters for L_{drift} = 14 cm.

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<tr>
<td>σ_T</td>
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<tr>
<td>v</td>
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<td>Track area, 3σ_Lx3σ_T</td>
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Figure 1: Readout module configuration in the VTX.
Nuclear Theory
Expansion, thermalization and entropy production following high-energy nuclear collisions

H. Heiselberg and X. N. Wang

The thermalization process is studied in an expanding parton gas using the Boltzmann equation with two types of collision terms. In the relaxation time approximation we determine the criteria under which a time-dependent relaxation time leads to thermalization of the partons. We calculate the entropy production due to collisions for the general time-dependent relaxation time. In a perturbative QCD approach on the other hand, we can estimate the parton collision time and its dependence on expansion time. The effective ‘out of equilibrium’ collision time differs from the standard transport relaxation time, \( \tau_r \approx (\alpha_s^2 \ln(1/\alpha_s)T)^{-1} \), by a weak time dependence. But it is still Debye screening and Landau damping that regulate the singular forward scattering processes. We find that the parton gas does thermalize eventually but only after having undergone a phase of free streaming and gradual equilibration where considerable entropy is produced (“after-burning”). The final entropy and thus particle density depends on the collision time as well as the initial conditions (a “memory effect”). Results for entropy production are presented based upon various model estimates of early parton production.

We studied a one-dimensionally expanding parton gas created in the wake of nuclear collisions. Within the Boltzmann equation in the relaxation time approximation we find that the rapid expansion is closer to free streaming than hydrodynamic expansion for times shorter than typical collision times of partons, \( \tau_0 \approx \tau \leq \theta \). Only at times much larger than the characteristic collision times, \( \tau \gg \theta \) may the parton gas thermalize and expand hydrodynamically. However, if the collision time increases with time the gas may never thermalize. Parametrizing the collision time as \( \theta = \theta_0 (\tau/\tau_0)^p \) the condition for equilibration and hydrodynamical expansion is \( p < 1 \). We calculate how much entropy is produced in the collisions.

We find that the parton gas does equilibrate eventually with these collision times but only after having undergone a phase of free streaming and gradual thermalization where considerable entropy is produced (“after-burning”). The final entropy and thus particle density depends on the collision time as well as the initial conditions (a “memory effect”). For various models predicting the preequlibrium scenarios the entropy production is significant. The total entropy and particle production is estimated to be doubled or tripled with respect to the initial value.

These estimates do not include particle production which by itself adds to the entropy production. On the other hand particle production will also increase the density and thus shorten the effective collision time which leads to a decrease in entropy production.

Most analyses assume a constant density in space but large density fluctuations may well be present in the initial parton plasma. This will increase the average entropy production for both elastic and inelastic scatterings since these are proportional to the initial densities squared as well as the final densities through the stimulated emission factors (for bosons) or Pauli blocking factors (for fermions). High density regions (“hot spots”) will equilibrate thermally and chemically faster than low density regions. At the same time, however, the free streaming will tend to reduce density fluctuations.

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Approach to parton equilibration *

X. N. Wang

Hard or semihard interactions happen in a very short time scale and they generally break color coherence inside an individual nucleon. After the fast beam partons pass through each other and leave the central region, a dense partonic system will be left behind which is not immediately in thermal and chemical equilibrium. Partons inside such a system will then further interact with each other and equilibration will eventually be established if interactions are frequent enough among the sufficiently large number of initially produced partons. Due to the asymptotic behavior of QCD, production rates of hard and semihard partons are calculable via pQCD during the initial stage of heavy ion collisions. The color screening mechanism in the initially produced dense partonic system may make it also possible to use pQCD to investigate the thermal and chemical equilibration of the system.

In this talk I reviewed the pQCD-based models of ultrarelativistic heavy ion collisions. In this framework the reaction dynamics can be described by perturbative parton scatterings and radiations. Using a model estimate of initial parton production, it is found that there are enormous number of partons produced during the overlap period of two colliding nuclei. Thereafter, local isotropy in the momentum distribution might be reached. Parton proliferation through induced radiation and parton fusion further drive the parton system toward a fully equilibrated parton plasma. The quarks always lag behind gluons in reaching their equilibrium. Due to the energy consumption by parton production, the parton gas cools down faster leading to a reduced plasma lifetime of 4 - 6 fm/c.

Throughout the production and evolution of the partonic system, interference effects play an important role in multiple collisions, the correct implementation of which will be a great challenge to any classical cascade models. Especially, the destructive interference among different amplitudes of gluon radiation induced by multiple scatterings suppresses soft gluons whose formation time is larger than the mean-free-path of parton scatterings inside a QCD medium. A detailed analysis of the radiation amplitudes reveals the underlying physics which contradicts the intuitive picture of a classical cascade model. One way to incorporate the LPM effect in the parton interaction simulations is to consider both the initial and final state radiation together for each scattering and impose the formation time requirement, $\tau_{QCD} < \lambda_f$, for the integration over the phase-space of the radiated gluons. This will lead to a reduced parton equilibration rate.

I also discussed the uncertainties in the initial conditions and the experimental probes of the early parton evolution. All in all, these uncertainties arise from our ignorance of the nonperturbative physics and our inability to calculate the soft processes in the framework of QCD. In the pQCD-based models I have reviewed here, the uncertainties really lie in the cut-off, $p_0$, which supposes to separate nonperturbative soft interactions from perturbative hard processes. Since soft and hard physics do not have a definite boundary, the resultant parton production from hard or semihard is very sensitive to the cut-off. The accompanying soft parton production is not known in this model and may only be estimated by simple models like the color flux-tube model.

*LBL-36885, invited talk at Quark Matter'95, to appear in the proceedings.
PQCD-based partonic picture of high-energy nuclear collisions

X. N. Wang

In this review, I presented a PQCD-based picture of ultrarelativistic heavy-ion collisions. In this framework, a nucleus in the infinite momentum frame consists of many partons (quarks and gluons). The interactions among these partons can be divided into perturbative, which can be described by PQCD calculation, and nonperturbative, which can only be modeled phenomenologically. I have demonstrated that PQCD processes dominate the underlying dynamics of heavy-ion collisions at extremely high energies. I argued that the soft component of a Pomeron exchange would be suppressed in the presence of a dense and hot partonic plasma, though it is still important in the initial parton scatterings in the early stage of the heavy ion collisions and is responsible for the initial soft parton production. It is then reasonable to assume that the evolution of the initially produced partons can be described by PQCD processes. Using the initial conditions estimated by the HIJING Monte Carlo model, the following picture emerges:

1. During the early stage in ultrarelativistic heavy-ion collisions, hard or semihard parton scatterings, which happen in a time scale of about 0.2 fm/c, produce a hot and undersaturated parton gas. This parton gas is dominated by gluons and is far from chemical equilibrium. Multiple hard scatterings suffered by a single parton during this short period of time when the beam partons pass through each other are suppressed due to the interference embedded in the Glauber formula for multiple scatterings. This leads to the predicted disappearance of the Cronin effect. Interference and parton fusion also lead to the depletion of small $x$ partons in the effective parton distributions inside a nucleus. This nuclear shadowing of parton distributions reduces the initial parton production.

2. After two beams of partons pass through each other, the produced parton gas in the central rapidity region starts its evolution toward (kinetic) thermalization and (chemical) equilibration through elastic scatterings and induced radiations. The kinematic separation of partons in the central slab of about 1 fm through free-streaming gives an estimate of the time scale $\tau_{\text{iso}} \sim 0.5 - 0.7$ fm/c, when local isotropy in momentum distributions is reached. Further evolution of the parton gas toward a fully equilibrated parton plasma is dictated by the parton proliferation through induced radiation and gluon fusion. Though the gluon equilibration rate is reduced by the inclusion of the Landau-Pomeranchuk-Migdal effect, gluon fugacity still increases rapidly toward its equilibrium value. Due to the consumption of energy by the additional parton production, the effective temperature of the parton plasma cools down considerably faster than the ideal Bjorken's scaling solution. Therefore, the life time of the plasma is reduced to 4 - 6 fm/c before the temperature drops below the QCD phase transition temperature.

3. The evolution of the quark distribution always lags behind that of gluons due to a smaller equilibration rate and the initial density. For heavy quarks, the equilibration rate is even smaller. Take charm quarks for example. The thermal production during the equilibration period is much smaller than the initial direct production, due to the small initial gluon fugacity and the short life time during which the temperature remains high enough to produce charm quarks. Therefore, observation of large charm enhancement would imply high initial gluon density and thus a longer life time of the parton plasma.

Open charm production in an equilibrating parton plasma

P. Lévat, B. Müller, and X. N. Wang

In this paper, we have calculated open charm production in an equilibrating parton plasma, taking into account the evolution of the effective temperature and parton fugacities according to the solution of a set of rate equations. In the evaluation of the interaction rate \( R_3 \) for induced gluon radiation, a color dependent effective formation time was used which reduces the gluon equilibration rate through LPM suppression of soft gluons. In the calculation of the pre-thermal contribution to open charm production, correlation between momentum and space-time was also included. This correlation reduces the pre-thermal charm production as compared to the uncorrelated one used in a previous estimate.

We found that both the thermal contribution during the parton equilibration and pre-thermal contribution with the current estimate of the initial parton density from HIJING Monte Carlo simulation are much smaller than the initial direct charm production (see Fig.1). However, the final total charm production is very sensitive to the initial condition of the parton evolution. If uncertainties in the initial parton production can increase the initial parton density, e.g., by a factor of 4, the total secondary charm production will become comparable or larger than the initial production, due to both the increased production rate and longer life time of the parton plasma (see Fig.2). We also found that open charm production is more sensitive to the initial temperature of the parton system than the initial parton fugacities. Therefore, open charm production is a good probe of the initial parton distribution in phase-space and the thermalization and equilibration time of the parton plasma.

Fig. 5
Initial (solid), pre-thermal (dot-dashed), and thermal (dashed) charm production for central \( Au+Au \) collisions at RHIC energy. The dotted line is the thermal production assuming an initial fully equilibrated QGP at the same temperature.

Fig. 7
Initial (solid), pre-thermal (dot-dashed) and thermal (dashed) charm production for initial parton densities 4 times higher than HIJING estimate, but with the same (ordinary lines), or reduced initial temperature, \( T_0 = 0.4 \) GeV (lines with stars).


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The Landau-Pomeranchuk-Migdal effect in QCD and radiative energy loss in a quark-gluon plasma

M. Gyulassy, M. Plümer, and X. N. Wang

We extended our previous derivation by considering the role of gauge invariance and target radiation in the case of spin 1/2 quarks to improve our estimate of radiative energy loss of a fast parton inside a quark gluon plasma. Our main result [Eq. 1] interpolates between the factorization and Bethe-Heitler limits, and has unique nonabelian properties. The factorization limit is of course consistent with the general bound imposed by the uncertainty principle, but reveals peculiar energy and temperature dependence of the mean square radiation transverse momentum controlling that energy loss. The resulting radiative energy loss reduces to the simple form,

$$\frac{dE_{\text{rad}}}{dz} \approx \frac{C_2\alpha_s}{\pi} \langle q^2 \rangle \left[ \ln \left( \frac{\xi}{1 + \xi^2} \right) + \xi \ln \left( \frac{1}{\xi} + \frac{1}{1 + \xi^2} \right) \right],$$

(1)

which depends on a dimensionless variable,

$$\xi = \frac{\tau_2 E}{\mu^2 \lambda}.$$  

(2)

The total energy loss is very sensitive to the color screening scale in the plasma. The double logarithmic energy dependence of $dE_{\text{rad}}/dz$ is the result of non-abelian aspects of the LPM effect in QCD. The same effect should be responsible for the limited gluon equilibration rate as discussed before.3

Our derivation improves the previous ones35 in a number of ways. First, an effective formation time $\tau_{\text{QCD}}$ in QCD radiation was used to account for the color interference due to multiple scatterings. The dependence of this effective formation time on the color representation of the jet parton gave rise to the different color factors, proportional to $C_2$, for the radiative energy loss of a quark and gluon. In contrast both are proportional to $C_A$ in the case of a single scattering. Secondly, the gluon spectrum including radiation from both the jet line and the internal gluon line and regulated consistently with the requirement of gauge invariance was used. However, it is still an idealization to the physically realizable situation in nuclear collisions because a number of strong assumptions were made in its derivation. The strongest is the extrapolation of pQCD in a regime $q \sim 1$ and the assumption that the interaction range is small compared to the color relaxation mean free path. We have therefore left with an explicit dependence on $\mu$ in $dE/dz$ since strong nonperturbative variations of $\mu(T)$ occur in the vicinity of $T_c$. The basic result that $dE/dz$ is proportional to $\mu^2$ is however very general and consistent with the uncertainty bounds.

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How disoriented chiral condensates form: quenching vs. annealing

M. Asakawa, Z. Huang and X.-N. Wang

One of the proposed explanations for the Centauro events in high energy cosmic ray experiments is the coherent emission of pions from a large domain of disoriented chiral condensate (DCC). Rajagopal and Wilczek proposed that a nonequilibrium phase transition through quenching can generate large DCC domains. To model a quench, one can evolve the classical fields according to the zero temperature equations of motion from a chirally symmetric initial condition with short correlation lengths. In this Letter, we argue that fluctuations introduced in the initial configuration actually render the effective potential to a non-zero temperature one. The interaction between the mean fields and the fluctuations as well as their evolution can be automatically included in the numerical simulations of the equations of motion. Using an ensemble averaging technique, we demonstrate the relaxation of the fluctuations and the occurrence of the chiral phase transition due to the longitudinal and transverse expansions which are consistently included in our study. By choosing different initial configurations, we study the evolution of the system in both quenching and annealing scenarios.

In the standard linear $\sigma$-model, the equations of motion are given by,

$$\Box \phi = \lambda (v^2 - \phi^2) \phi + H n_\sigma,$$

(1)

where $\phi \equiv (\sigma, \pi)$ is a vector in internal space, $n_\sigma = (1, 0)$, and $H n_\sigma$ is an explicit chiral symmetry breaking term due to finite quark masses. In the following, we shall use $\lambda = 19.97$, $v = 87.4$ MeV, and $H = (119 \text{ MeV})^3$, with which $m_\sigma = 135$ MeV and $m_\pi = 600$ MeV at $T = 0$.

Neglecting the corrections due to quantum fluctuations, the time evolution of $\langle \phi \rangle$ and $\delta \phi$ can be consistently solved through numerical simulations of the classical equations of motion. Since the fluctuations can evolve with time according to a given relaxation mechanism, the time evolution of the field configuration obtained already includes the effect of the time dependence of the effective potential. The use of equations of motion does not ensure that the effective potential takes its zero temperature form or that chiral symmetry is spontaneously broken. What matters most is the initial fluctuation of the system.

We carry out numerical simulations of the equation of motion, including both the longitudinal and transverse expansions. We have shown that the usual prescription for a quench actually already includes the effect of fluctuations. The relaxation of the fluctuations and their effect on the effective potential are automatically included in the evolution of the system which undergoes both longitudinal and transverse expansions. Mass splitting of the pion and sigma fields at the classical level during the chiral phase transition has been clearly demonstrated. We have also shown in our numerical calculations that DCC domains of a typical size up to 4-5 fm can form for realistic parameters in the linear $\sigma$-model if the quenching initial condition is realized. Furthermore, we have demonstrated that such a quenching condition cannot be achieved by relaxing a system from a chirally symmetric phase through expansions. We will discuss elsewhere whether and how a quenching initial state can be realized in hadronic or nuclear collisions.

Signals of disoriented chiral condensates

Z. Huang, M. Suzuki and X.-N. Wang

The most direct test for an ideal DCC would be the observation of an anomalous isospin charge distribution

\[ P(r) = \frac{1}{2\sqrt{r}} \]  

(1)

where \( r = n_{\pi^0}/(n_{\pi^0} + n_{\pi^+}) \). This prediction results from a long-range correlation in the isospin direction for a given event.

In this paper we study a possible signature of the formation of DCC, assuming that its space-time spread grows much larger than \( 1/m_\pi \). We focus on the misalignment of the DCC with the direction of the electroweak symmetry breaking. When the hadronic resonances decay inside the DCC, their electromagnetic decay modes show a clear signal of the disorientation of the background. In contrast, purely hadronic decay modes are not affected by the disorientation in the limit of a small explicit chiral symmetry breaking and a slow space-time variation of the DCC. We study the dilepton decays of \( \rho \) and \( \omega \), since the DCC affects the \( \rho \) and \( \omega \) mesons quite differently because of their different chiral properties.

We show that the misalignment of the DCC with the electroweak direction results in the suppression of the decay \( \rho^0 \rightarrow \ell^+\ell^- \) by a factor of two on average, while no suppression is expected for \( \omega \rightarrow \ell^+\ell^- \). The marked difference between \( \rho \) and \( \omega \) arises from their different chiral properties. This is in sharp contrast to the QGP, which affects equally the \( \rho^0 = \frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d) \) and the \( \omega = \frac{i}{\sqrt{2}}(\bar{u}u + \bar{d}d) \) except for the large difference in their lifetimes which favors \( \rho^0 \rightarrow \ell^+\ell^- \) over \( \omega \rightarrow e^+e^- \) during the hadronic expansion. Some may question whether the \( \rho \) and the \( \omega \) can be produced at all in the QGP. It appears that the DCC is a less hostile environment for these resonance to be formed. In any case, we have to learn about it from experiment. It is clearly necessary to carry out more detailed theoretical analysis of the outgoing dilepton spectrum for the space-time dependent DCC of which we have little understanding at present.

In order to carry out our test in experiment, we need to know the relative production rate of \( \rho \) and \( \omega \) in hadron collisions. At very low energies, it is known that the production rates for the \( \rho^0 \) and the \( \omega \) are equal in pp collision: \( \sigma(\rho^0)/\sigma(\omega) = 1.0\pm0.2 \) at \( \sqrt{s} = 5 \) GeV; \( \sigma(\rho^0)/\sigma(\omega) = 1.07\pm0.2 \) at \( \sqrt{s} = 6.8 \) GeV. Recently, the cross sections were measured at higher energy by NA27 experiment through the hadronic decay modes. The result is \( \sigma(\rho^0) = (12.6\pm0.6) \) mb vs. \( \sigma(\omega) = (12.8\pm0.8) \) mb in pp collision at \( \sqrt{s} = 27.5 \) GeV. The quark model predicts that these cross sections ought to be equal. Though an independent check for their separate cross sections would be desirable, the equality of the production rates appears to be a very safe assumption.

A search for the Centauro events has been made by UA5 and UA1 at \( \sqrt{s} = 546 \) GeV and by UA5 at \( \sqrt{s} = 900 \) GeV. An upper limit was set on the Centauro production by UA5 at the level of a few times \( 10^{-3} \) per inelastic events at \( \sqrt{s} = 900 \) GeV. Since an ideal DCC with large correlated domains will generate the Centauro and anti-Centauro events, there has been so far no evidence for clear DCC events. We hope that our suggestion made in this paper will be considered in future experiments searching for DCC, in both hadronic and heavy nucleus collisions.

High $p_T$ jet production in $pp$ collisions *

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Production rates of large $p_T$ jets in $pp$ collisions at RHIC and LHC energies are studied in this paper using the next-to-leading order calculation of S. D. Ellis, Z. Kunszt and D. Soper. The computed inclusive one-jet cross sections are compared against the CERN and Fermilab jet data from $p\bar{p}$ and $pp$ collisions. The dependence of the results on the choice of parton distributions and renormalization/factorization scales is investigated.

An overall conclusion from the comparison to the data is that the next-leading-order (NLO) QCD prediction is successful in reproducing the observed energy dependence, shape, and absolute magnitude of the data. Certainly, within the (systematic) errors given by the experiments, the agreement between the data and the NLO results is good. What is remarkably different from the Born cross sections, is that no K-factors are used, and the results from experiments using different jet sizes are directly compared with the corresponding NLO predictions.

However, especially in comparison to the UA1 data at $\sqrt{s} = 500$ GeV and 546 GeV, there are slight deviations: the NLO prediction seems to fall below the measured points. This could be due to the following uncertainties. The jet definition and jet finding algorithms in different experiments differ slightly from each other, and from what is used by Ellis et al. Moreover, since the experiments are observing final state hadrons, not partons, there exists also a nonperturbative uncertainty related to the hadronization of the partons. In their study, Ellis et al estimated an uncertainty $\sim 6$ GeV/$p_T$ resulting from a nonperturbative uncertainty of 1 GeV in the jet transverse energy. This becomes relatively larger at small $p_T$, and is therefore typically more in the ranges of $p_T$ measured by UA1.

Also, the size of the jet is larger in the UA1 than in the CDF experiment. With a larger jet size, the nonperturbative uncertainty is also expected to be larger.

On the perturbative side, we expect a residual perturbative uncertainty to be related to the scale dependence of the results. We find that inclusion of the NLO terms decreases this uncertainty from the LO case. For the NLO calculation at $\sqrt{s} = 200$ GeV with $\mu = p_T$ and with $p_T$ fixed, the uncertainty is $\lesssim 60\%$. At $\sqrt{s} = 5.5$ GeV, the uncertainty is $\lesssim 20\%$. The LO results clearly have a stronger scale dependence.

An interesting result is that the Born cross section multiplied by a constant factor, $K = 2$ for $\sqrt{s} = 200, 500$ GeV and $K = 1.5$ for $\sqrt{s} = 5.5$ and 14 TeV, seems to account for the full result amazingly well over the whole range of $p_T$ considered. Note that these numbers hold exactly only for the scale choice $\mu = p_T$. In general, however, the $K$-factor depends on the scale choice and especially on the jet size, so a general $K$-factor cannot be given.

From the NLO QCD calculations the theoretical inclusive cross sections for large $p_T$ jet production are well under control. The theoretical perturbative uncertainties have greatly been reduced by the inclusion of the NLO terms. We hope that together with the recent data from HERA, the jet measurements could be used to determine the gluon distributions in protons and, ultimately, in nuclei.

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The production of charmonium pairs in the same reaction is expected to be exceedingly rare in QCD. However, the NA3 collaboration has measured $\psi\psi$ pair production in multi-muon events near threshold. Asymmetry extended to the momentum and induction by these leading-twist mechanisms, updating the results and find that these models are unable to produce $\psi\psi$ pairs with large $x_{\psi\psi}$.

We then turn to a higher-twist mechanism that easily produces fast $Q\bar{Q}$ pairs: intrinsic heavy quark components in the projectile wavefunction. We previously evaluated the probability for two $J/\psi$'s to originate from an intrinsic $|\bar{u}d c\bar{c}c\bar{c}\rangle$ Fock state and reproduced the general features of the data. We also consider other sources of double $J/\psi$ production by intrinsic heavy quark states. An intrinsic $b\bar{b}$ pair, $|\bar{u}d b\bar{b}\rangle$, could decay into $\psi\psi$ pairs, as in leading-twist $b\bar{b}$ production. Additionally, an intrinsic $|\bar{u}d c\bar{c}b\bar{b}\rangle$ state could produce $\psi\psi$ pairs from a $B$ decay with the coalescence of the $c\bar{c}$ pair into a $J/\psi$. We also calculate $\psi\psi$ pair production through leading-twist $c\bar{c}$ production with the projectile in an intrinsic $c\bar{c}$ state.

From the magnitude of the cross sections, it appears that approximately 50% of the measured $\psi\psi$ cross section can be attributed to leading-twist mechanisms. However, only the higher-twist mechanisms produce fast $\psi\psi$ pairs. Particularly, the $|n_{\psi}c\bar{c}c\bar{c}\rangle$ configuration can also account for the size of the $\psi\psi$ cross section.

The correlations in $B\bar{B}$ production also suggest an intriguing test of the intrinsic heavy quark mechanism. The same correlations should be observable in measurements of the $D^-/D^+$ asymmetry extended to the momentum and invariant mass distributions of $D\bar{D}$ pairs.

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Intrinsic Charm Contribution to Double Quarkonium Hadroproduction

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It is quite rare for two charmonium states to be produced in the same hadron collision. However, the NA3 collaboration has measured a double $J/\psi$ production rate significantly above background in multi-muon events with $\pi^-$ beams at laboratory momentum 150 and 280 GeV\textsuperscript{1} and a 400 GeV/c proton beam\textsuperscript{2}. The integrated $\pi^-N \rightarrow \psi\psi X$ production cross section, $\sigma_{\psi\psi}$, is $18 \pm 8$ pb at 150 GeV/c and $30 \pm 10$ pb at 280 GeV/c, and the $pN \rightarrow \psi\psi X$ cross section is $27 \pm 10$ pb. The relative double to single rate, $\sigma_{\psi\psi}/\sigma_{\psi}$, is $(3 \pm 1) \times 10^{-4}$ for pion-induced production where $\sigma_{\psi}$ is the integrated single $\psi$ production cross section.

The laboratory fraction of the projectile momentum carried by the $\psi\psi$ pair is always very large, $x_{\psi\psi} \geq 0.6$ at 150 GeV/c and $x_{\psi\psi} \geq 0.4$ at 280 GeV/c. In some events, nearly all of the projectile momentum is carried by the $\psi\psi$ system. In contrast, perturbative $gg$ and $q\bar{q}$ fusion processes produce central $\psi\psi$ pairs, with $\langle x_{\psi\psi} \rangle \approx 0.4-0.5$ in the laboratory. The average invariant mass of the pair, $\langle M_{\psi\psi} \rangle = 7.4$ GeV, is well above the $2m_\psi$ threshold with all events at $M_{\psi\psi} > 6.7$ GeV. The proton events have a somewhat lower invariant mass, $\langle M_{\psi\psi} \rangle \approx 6.8$ GeV.

We explore a higher-twist production mechanism in QCD where forward single and double $\psi$'s are created through the materialization of intrinsic $c\bar{c}$ Fock components of the pion or proton projectile. The heavy constituents carry the majority of the projectile momentum to minimize the off-shell energy of the wavefunction, corresponding to configurations with equal rapidity constituents. If the intrinsic $Q\bar{Q}$ coalesces into a quarkonium state, the momentum of the two heavy quarks is combined. In fact, two intrinsic $c\bar{c}$ pairs may appear in the fluctuations of the projectile wavefunction and coalesce to form a pair of $\psi$'s.

The intrinsic $c\bar{c}$ production cross section from an $|uvcc\rangle$ configuration, $\sigma_{ic}(hN) = P_{ic}\sigma_{ic}(p\bar{p})/(4m_c^2)$ was estimated\textsuperscript{3} to be $\sigma_{ic}(\pi N) \approx 0.5 \mu$b and $\sigma_{ic}(pN) \approx 0.7 \mu$b for a beam momentum of 200 GeV. If one assumes that all of the NA3 double $J/\psi$ events arise from intrinsic $|uvcc\rangle$ Fock states, then the required normalization for this state can be determined from $\sigma_{ic}^\psi(hN) = f_{\psi/k}^2(P_{ic}/P_{ic})\sigma_{ic}(hN)$ where $f_{\psi/k}$ is the fraction of $\psi$'s produced from an intrinsic $c\bar{c}$ state and $P_{ic}$ is the probability to produce a pair of intrinsic $c\bar{c}$ states in the projectile, $P_{ic} \approx 4.4\% P_{ic}$.

We find $\langle M_{\psi\psi} \rangle_\pi \approx 7.7$ GeV and $\langle M_{\psi\psi} \rangle_p \approx 7.4$ GeV. We also find $\langle x_\psi \rangle_\pi = 0.36$ and $\langle x_\psi \rangle_p = 0.33$. The single $J/\psi$ distributions from the $|uvcc\rangle$ state have a lower average $x_\psi$ than those from $|uvcc\rangle$ Fock states, where $\langle x_\psi \rangle_\pi = 0.62$ and $\langle x_\psi \rangle_p = 0.51$. The intrinsic charm model predicts $\langle x_{\psi\psi} \rangle_\pi = 0.72$ and $\langle x_{\psi\psi} \rangle_p = 0.64$.

The intrinsic charm model provides a natural explanation of double $J/\psi$ hadroproduction. The model can also be used to predict the features of heavier quarkonium hadroproduction, such as $\Upsilon\Upsilon$, $\Upsilon\psi$, and $(bc)(\bar{c}\bar{b})$ pairs. More generally, the intrinsic heavy quark model leads to enhanced open and hidden heavy quark production and leading particle correlations at high $x_F$ in hadron collisions.

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Consequences of Nuclear Shadowing for Heavy Quarkonium Production in Hadron-Nucleus Interactions*

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The production of charmonium and bottomonium states in hadron-nucleus interactions does not increase linearly with the nuclear target mass $A$. Additionally, the ratio of hadron-nucleus to hadron-nucleon production, $S_A = \sigma_{hA}/\sigma_{hp}$, is not constant but decreases with increasing $x_f$, the fraction of the center of mass momentum carried by the produced resonance. We examine the role of nuclear shadowing, the modification of parton distributions in the nucleus, in quarkonium production.

Deep inelastic scattering (DIS) data on $R_A = F_A^A/F_2^A$ show that: i) nuclear shadowing begins to set in at $x_{Bj} \leq 0.06$ for all nuclei ($R_A < 1$); ii) $R_A$ has a very weak $Q^2$ dependence; and iii) an enhancement, or antishadowing, exists for $0.06 < x_{Bj} \leq 0.25$ ($R_A > 1$). In addition, data on $J/\psi$ production with Sn and C targets show an enhancement of $(13 \pm 8)\%$ for $0.05 < x_{Bj} < 0.3$, interpreted as gluon antishadowing.

We adopt a shadowing model consistent with the DIS data to study the effect of nuclear shadowing on $S_A$. In the laboratory frame, shadowing is the result of the interaction of hadronic fluctuations of the virtual photon, e.g. $q\bar{q}$ pairs, with the nucleus. If the transverse momentum of the pair is small, the jets are aligned along the direction of the virtual photon. However, if the transverse momentum of the fluctuation is large, nonaligned hadronic configurations, which interact differently, are simultaneously present.

Gluon shadowing should be larger than sea quark shadowing since the interaction of a $q\bar{q}g$ configuration in the $\gamma^*$ wavefunction with the target should be stronger than a $q\bar{q}$ configuration. The overall enhancement is consistent with the data used to constrain the shape of the gluon distribution in the antishadowing region. A weak $Q^2$ dependence for $R_A$ is obtained while a stronger $Q^2$ dependence is found for the gluon ratio, $R_A^G = G_A/G_N$.

Antishadowing is a general consequence of baryon number and momentum conservation in a nucleus. To satisfy the sum rules and simultaneously allow for shadowing at $x < 0.04$, the nuclear parton distributions must be enhanced at higher values of $x$. We assume that the enhancement is shared by the valence quarks and gluons since the sea quark enhancement is consistent with zero.

Accounting for the primordial transverse momentum of the partons, $q_T$, may reduce the magnitude of $S_A$ since the transverse momentum spectrum may be broadened in a nucleus because of Fermi motion. This effect appears because the data is in a finite $p_T$ interval. The convolution produces an $x_f$-dependent effect on $S_A$, reducing the effect of antishadowing and marginally affecting the shadowing.

We point out two major consequences of shadowing and antishadowing for $J/\psi$ and $\Upsilon$ hadroproduction based on these very general arguments. Since $m_T$ is three times larger than $m_\psi$, the $\Upsilon$ is primarily produced within the antishadowing region of the target at present energies. However, $Q^2$ evolution reduces the effect of both shadowing and antishadowing in $\Upsilon$ production with respect to $J/\psi$. Shadowing will dominate the nuclear effects at RHIC and LHC.

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The production of quarkonium states below the open charm/bottom thresholds presents a particular challenge to QCD. Because of the relatively large quark masses, $c\bar{c}$ and $b\bar{b}$ production should be perturbatively calculable. However, the subsequent transition from the predominantly colour octet $Q\bar{Q}$ pairs to physical quarkonium states can introduce nonperturbative aspects, leading to some model-dependence.

We use a generalisation of the colour evaporation model to calculate the production of quarkonium states below the open charm/bottom thresholds. We calculate the total "hidden" charm cross section, $\sigma_{cc}$, by integrating the $c\bar{c}$ production cross section over the $c\bar{c}$ pair mass from $2m_c$ to $2m_D$. Subsequently, the $c\bar{c}$ pair becomes a singlet through "colour evaporation". The $c$ and the $\bar{c}$ either combine with light quarks to produce charmed mesons, or bind with each other to form a charmonium state. More than half of $\sigma_{cc}$ produces open charm if $m_c \approx 1.5$ GeV. Indeed, the fraction of $\sigma_{cc}$ producing charmonium rather than open charm is thus about 10%. We also estimate that about 7% of the subthreshold $b\bar{b}$ cross section leads to $J/\psi$ production.

The generalised colour evaporation model predicts that the energy dependence of charmonium production is the same as $\sigma_{cc}(s)$. Consequently, the $\chi/\psi$ and $\psi'/\psi$ production ratios are energy-independent, as observed up to Tevatron energies. The available bottomonium data also agrees with constant production ratios in the same energy range. The ratios are also independent of the projectile (pion or proton) and target (from protons to nuclei).

The energy dependence of $J/\psi$ production in $pN$ collisions, $\sigma_{pN-J/\psi} = 0.025 \sigma_{cc}(s)$, is obtained from the hidden charm cross section $\sigma_{cc}$ calculated in next-to-leading order with the normalisation fixed empirically. We have used the MRS D\textsuperscript{12} and GRV HO\textsuperscript{3} parton distribution functions. For the GRV set, we have used $m_c = 1.3$ GeV, with both renormalisation and factorisation scales fixed to $m_c$. In the MRS calculation, $m_c = 1.2$ GeV was used, with the scales set at $2m_c$. These parameters provide an adequate description of open charm production, although the results tend to lie somewhat below the measured total $c\bar{c}$ cross sections.

We also compared the longitudinal momentum dependence of charmonium production with recent experimental results and found that the $x_F$ distributions are also consistent with the colour evaporation model.

We thus extrapolate the color evaporation model to ultrarelativistic heavy-ion collider energies. Our $J/\psi$ cross sections calculated with the recent parton distribution functions are typically a factor of 20 higher than those given by an earlier empirical parametrisation, $\sim \exp(-15M/\sqrt{s})$, at LHC energies. This increase, confirmed by new high energy $\Upsilon$ data, is due to the increasing gluon distribution at small $x$. At LHC energies, both the $J/\psi$ and $\Upsilon$ rapidity distributions remain rather constant out to $y \approx 4$, providing a large window for forward detection. At RHIC energies, the $J/\psi$ distributions are not as broad, with a forward plateau of 2-3 units. The $\Upsilon$ rapidity distributions at RHIC energies are quite similar for both sets.

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Heavy Quark Production in $pp$ Collisions*

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Charm and bottom quark production from the initial nucleon-nucleon collisions will be copious at the RHIC and LHC colliders. Heavy quark decay into leptons will represent a significant background to dilepton production in heavy ion collisions. A quantitative knowledge of the production cross section in $pp$ collisions is a prerequisite for the detection of collective effects, such as heavy quark production by rescattering and by the quark-gluon plasma, which would appear as a deviation from the simple superposition of hadronic collisions.

The Born level production proceeds by gluon fusion and quark-antiquark annihilation while at next-to-leading order (NLO), quark-gluon scattering, is also included. The parton distributions are evaluated at the factorization scale $\mu_F$. The short-distance cross section, a perturbation series in $\alpha_s(\mu_R)$, is evaluated at the renormalization scale $\mu_R$. Both scales are of the order of the heavy quark mass and $\mu_F = \mu_R = \mu$ is used. The cross section should be independent of the scale. If the $\mu$ dependence is strong, the perturbative expansion is untrustworthy. The rather large ratio, $K$-factor, between the NLO and Born cross sections suggests that further corrections are needed since charm and bottom quarks are "light" when $\sqrt{s}$ is large. Our calculations are done with a program developed by Nason and collaborators	extsuperscript{1}. Similar work was done by Smith, van Neerven, and collaborators	extsuperscript{2}. We estimate heavy quark production in proton-proton collisions at RHIC ($\sqrt{s} = 200$ and 500 GeV) and LHC ($\sqrt{s} = 5.5$ TeV and 14 TeV), according to our present theoretical knowledge.

We have used two sets of recent parton distribution functions MRS D–'	extsuperscript{3} and GRV HO	extsuperscript{4}. We find reasonable agreement with the $c\bar{c}$ total cross section measurements for $m_c = 1.2$ GeV and $\mu = 2m_c$ with MRS D–' and for $m_c = 1.3$ GeV and $\mu = m_c$ with GRV HO, providing an extrapolation point to higher energies. We use $m_b = 4.75$ GeV and $\mu = m_b$ for both sets of parton distributions in calculations of $b$ production. Although the MRS D–' and GRV HO distributions give an equally valid description of the data at ISR energies and below, the results diverge at higher energies due to the different values of $m_c$ and $\mu$ used. The $b\bar{b}$ results are similar since the same $m_b$ and $\mu$ are used. For $b\bar{b}$ production at 14 TeV, the results differ by 30% while the $c\bar{c}$ cross section is 3-5 times larger for MRS D–' than the GRV HO at this energy.

The scale runs with $p_T$ in the single inclusive and double differential distributions. The $p_T$ distributions were calculated with $y < |1|$ at the LHC and $y < |0.35|$ at RHIC. In general, the LO mass and rapidity distributions are nearly equivalent to the NLO results scaled by a theoretical $K$ factor independent of $M$ and $y$. When the scale runs with $p_T$, the single inclusive $p_T$ distributions also exhibit a nearly constant theoretical $K$ factor. We have also calculated $c\bar{c}$ and $b\bar{b}$ decays into dileptons at RHIC and LHC. We account for correlated and uncorrelated lepton pair production from charm decays.

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Incorporation of Quantum Statistical Features in Molecular Dynamics

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Molecular dynamics simulations are useful for understanding both statistical and dynamical properties of many-body systems in a variety of physical contexts. But the foundation and interpretation of such approaches are problematic when quantum systems are addressed.

The many-body system is usually represented as a (possibly antisymmetrized) product of parametrized single-particle wave packets, \( < \mathbf{r}_1, \ldots, \mathbf{r}_A | \mathbf{Z} > \), and equations of motion for the parameters are then derived from a suitable variational principle. This corresponds to a mean-field treatment of the quanta and the ensuing parameter dynamics is then effectively classical,

\[
i \hbar \mathbf{C} \cdot \dot{\mathbf{Z}} = \partial \mathcal{H} / \partial \mathbf{Z},
\]

where \( \mathcal{H} = < \mathbf{Z} | \hat{H} | \mathbf{Z} > \) is the expectation value of the \( A \)-body Hamiltonian operator \( \hat{H} \) with respect to the particular state \( \mathbf{Z} \). Consequently, the statistical properties of the system will be classical rather than quantal, thus casting doubt on the quantitative utility of results obtained in complicated scenarios where quantal statistics plays a major role.

This generic shortcoming of molecular dynamics originates in the neglect of the spectral distribution of energy eigenvalues associated with the wave packets which are not energy eigenstates. The probability for the wave packet \( \mathbf{Z} \) to contain eigenstates of energy \( E \) is given by the spectral strength function,

\[
\rho_E (\mathbf{Z}) \equiv < \mathbf{Z} | \delta (\hat{H} - E) | \mathbf{Z} > ,
\]

which is spread around the expectation value \( \mathcal{H} \) with a variance \( \sigma^2_Z > 0 \).

The equation of motion (1) determines the evolution of the wave packet parameter vector, \( \mathbf{Z}(t) \), in an entirely deterministic manner and without any physical effect of the spectral structure of the wave packet. In order to provide the system with an opportunity for exploring and exploiting the various eigencomponents contributing to its wave packet, we augment the equation of motion by a stochastic term that may cause occasional transitions between different wave packets. Guided by Fermi's Golden Rule, we then adopt the following form for the differential rate of transitions from a given wave packet \( \mathbf{Z} \) to others near \( \mathbf{Z}' \),

\[
w(\mathbf{Z} \rightarrow \mathbf{Z}') = \frac{2\pi}{\hbar} | < \mathbf{Z}' | \hat{V} | \mathbf{Z} > |^2 \rho_E (\mathbf{Z}') .
\]

The resulting model is akin to the transport treatment of Brownian motion, but it employs a Langevin force that originates in the quantal fluctuations and, significantly, the ensuing stochastic molecular dynamics populates the parameter space in a microcanonical manner.

The observed production of several massive fragments in heavy-ion collisions has proven difficult to reproduce by ordinary molecular dynamics, because any massive fragments formed are too excited and quickly break up. However, if the presently proposed stochastic transitions are incorporated, an excited massive prefragment will explore its spectrum of eigenstates and may thereby become trapped into more bound configurations, leading to an enhanced survival probability. We are presently exploring this central issue by means of dynamical simulations and it appears very likely that the proposed model may account better for the fragment yields.

\[2\] Y. Nara, A. Ohnishi, and J. Randrup, in preparation


\[\]
Brownian One-Body Dynamics in Nuclei\*  
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We have developed a novel simulation model for nuclear dynamics in the intermediate-energy regime where the semiclassical one-body description is expected to be applicable. The augments the standard BUU equation by a stochastic addition to the one-body potential, \( \delta U(r, t) \).

The object of study is the reduced one-body phase-space density \( f(s, t) \) where \( s \equiv (r, p) \) denotes a point in phase space. The presently most advanced dynamical one-body description, the Boltzmann-Langevin model, considers three distinct sources for the evolution of \( f(s) \):  

\[ \frac{\partial f}{\partial t} = \{ h[f], f \} + \tilde{I}[f] + \delta I[f] \ . \tag{1} \]

The first is the collisionless propagation of \( f \) in the self-consistent one-body field described by the effective Hamiltonian \( h(s) = p^2/2m + U(r) \); this part is often referred to as the Vlasov propagation and is the semi-classical analogue of the Time-Dependent Hartree Fock approximation. The second source of evolution, \( \tilde{I}[f] \), represents the average effect of the residual Pauli-suppressed two-body collisions; this is the term included in the standard BUU description. The third term, \( \delta I[f] \), is the Langevin term, ordinarily assumed to be Markovian and to represent the fluctuating part of the two-body collisions.

The basic idea of the method is to replace the actual stochastic collision term \( \delta I \) by a suitable stochastic one-body potential \( \delta U(r, t) \). The corresponding equation of motion is then obtained by making the following replacement in (1),

\[ \delta I[f] \rightarrow \tilde{I}[f] = -\delta F[f] \cdot \frac{\partial f}{\partial p} \ , \tag{2} \]

where \( \delta F(r, t) = \partial U/\partial r \) is the associated Brownian force (having \( \langle \delta F \rangle = 0 \)). Since we wish the resulting Brownian one-body dynamics to mimic the BL evolution, the stochastic force is assumed to be local in space and time. Moreover, since we wish to match its effects in nuclear matter, which is isotropic, the force may also be taken to have rotational invariance. Its correlation function can then be written

\[ \langle \delta F(r_1, t_1) \delta F(r_2, t_2) \rangle = 2\tilde{D}_0 I \delta(r_{12}) \delta(t_{12}) \ , \tag{3} \]

where \( I \) is the unit tensor. The resulting dynamics is then qualitatively similar to that resulting from the BL equation (1) but the associated diffusion coefficient is modified to

\[ 2\tilde{D}(s_1; s_2) = 2\tilde{D}_0 \frac{\partial f(s_1)}{\partial p_1} \cdot \frac{\partial f(s_2)}{\partial p_2} \delta(r_{12}) \ , \tag{4} \]

which can be expressed analytically, once the local density \( \rho(r) \) and temperature \( T(r) \) have been extracted.

In developing this method we have been motivated by the urgent need for dynamical simulations of reactions under current investigation with advanced detector arrays around the world. While the BL model is probably the presently best-founded model for this task, it is rather computer-demanding in realistic scenarios. The present method offers a relatively easy tool for obtaining approximate results while more elaborate implementations are in progress, since it can readily be implemented into existing codes based on the test-particle method. Applications are presently in progress for three-dimensional multifragmentation processes.\(^1\)

It should finally be noted that the presented approach provides a general framework for studying the kinetics of gases subject to Brownian motion and it may therefore be of interest beyond the confines of nuclear physics.

\(^{1}\)Work in progress by the authors.
Simulation of Transport Equations for Unstable Systems: Comparison between lattice and test-particle methods

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Over the past decade, there has been considerable interest in time-dependent nuclear mean-field theory, due in large part to its success in describing many aspects of intermediate-energy nuclear collisions. In particular, the semiclassical version of the time-dependent Hartree-Fock model has been extended by incorporating a Pauli-suppressed collision term, leading to the Boltzmann-Uhling-Uhlenbeck transport model. These theories produce a single trajectory for the system in the one-body phase space, $f(r,p,t)$. Consequently, they cannot describe fluctuations and so are inadequate for addressing such phenomena as correlations in light-particle emission, fluctuations of one-body observables, and multifragmentation. A suitable extension of the transport theory is therefore required. However, existing prescriptions apply only to small-amplitude fluctuations near equilibrium.

A possible extension to non-equilibrium scenarios with large-amplitude fluctuations consists in adding a stochastic term in the equation of motion for the one-body density, leading to the Boltzmann-Langevin theory.\textsuperscript{1} The new stochastic term, $\delta I[f]$, is ordinarily assumed to represent the fluctuating effect of the two-body collisions.

A Fokker-Planck transport formalism was developed for treating the BL problem.\textsuperscript{2} It offers a convenient formal framework for discussing stochastic one-body dynamics. Several applications have been made to fluctuations of one-body observables in nuclear dynamics and it has been demonstrated that the lattice phase-space method (i) produces results that are in very good agreement with expectations based on statistical mechanics, and (ii) is able to break symmetries that have been artificially imposed on the initial density, thus making the approach suitable for addressing multifragmentation processes.\textsuperscript{3}

The present study compares this numerical method with the more familiar test-particle method, especially in the presence of instabilities when numerical errors are critical.

The equivalence between the two methods was demonstrated for the average one-body dynamics, and the numerical errors were discussed. The lattice treatment was then extended to incorporate the Langevin fluctuation term and we showed that the resulting approach is reliable for describing processes in which fluctuations play a decisive role, such as in multifragmentation events. The BL model allows one to include both the stochastic collisions, which create the seeds for the density fluctuations, and the effective field, which propagates and amplifies them, thus leading the system towards fragmentation. We have shown how the early evolution can be quantitatively understood within linear response theory, with a dispersion relation that predicts the growth of instabilities to good accuracy. The dependence of the source terms on density and temperature was also briefly illustrated.

This exposition complements earlier presentations and is intended to provide a better understanding of the lattice method and test-particle methods, as well as their mutual relationship.


Analysis of Boltzmann-Langevin Dynamics in Nuclear Matter*

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The Langevin extension of the nuclear Boltzmann model is a significant advance, since it makes it possible to address processes in which fluctuations play a major role, such as nuclear multifragmentation caused by the irreversible development of unstable bulk modes. To gain insight into this key process, a recent study addressed the early evolution of nuclear matter in the spinodal zone of the phase diagram. The system is then mechanically unstable and the density fluctuations generated by the Langevin term may be amplified by the self-consistent effective field, leading towards catastrophic transformations of the system into an assembly of nuclear clusters.

That work developed a convenient formal framework which provides instructive insight into the unstable dynamics and makes it possible to obtain quantitative results. Within the regime of linear response, the Vlasov eigenmodes, \( f_k(p) \), develops harmonically in time with eigenfrequencies \( \omega_k \) determined by the associated dispersion relation. The history of a given system is then characterized by the corresponding amplitudes \( A_k(t) \). When an average is taken over the entire ensemble of possible histories, these vanish on the average \( \langle A_k \rangle = 0 \), since the same is true for the Langevin term \( \delta I \). However, their correlation coefficients \( \sigma_{\nu\nu'} = \langle A_k^{\nu} A_k^{\nu'} \rangle \) are governed by simple feed-back equations of motion, in which the fluctuations generated by the Langevin term are either magnified or suppressed by the adjusting effective field,

\[
\frac{d}{dt} \sigma_k^{\nu\nu'}(t) = 2D_k^{\nu\nu'} - i(\omega_\nu - \omega_\nu')\sigma_k^{\nu\nu'}(t) .
\] (1)

The agitation rate is given in terms of source terms \( D \) for which approximate expressions were derived, and they have been used to obtain quantitative results. It is especially important to know accurately the agitation rates for the most unstable modes, since these will tend to become dominant, and in fact the final outcome may depend sensitively on their value.

Therefore we have revisited this problem. Utilizing both elementary methods and the frequency-dependent response function, we have found the explicit form of the dual basis states,

\[
\phi_k(p) \equiv \sum_{\nu'} \sigma_k^{\nu\nu'} f_k^{\nu'}(p) \sim \frac{1}{k \cdot v - \omega_\nu} ,
\] (2)

So it is possible to obtain the source terms directly from the basic diffusion coefficient \( D \),

\[
D_k^{\nu\nu'} = \langle \phi_k^{\nu'} | D | \phi_k^{\nu} \rangle .
\] (3)

The source terms for the correlated agitation of any two modes can then be extracted directly, without consideration of the other modes. This facilitates the analysis of collective modes in unstable matter and makes it possible to assess the accuracy of an approximate projection technique employed previously.

The projection method using the exact dual basis states is reliable for times exceeding the respective amplification time, \( t > t_k \). But further improvement is needed near the spinodal boundary (where \( t \to \infty \)). This is of practical importance, since the systems prepared in heavy-ion collisions are initially situated outside the spinodal region and so must cross the boundary to become unstable.

Effect of Memory Time
on the Agitation of Unstable Modes in Nuclear Matter*

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The present investigation has focused on the effect of a finite memory time in the stochastic term of the nuclear Boltzmann-Langevin equation on the agitation of collective modes in unstable nuclear matter. In the standard BL model, the stochastic term is local in time, as would be appropriate if the two-body collisions can be considered as instantaneous. Under such idealized circumstances, density undulations are generated only indirectly as the local rearrangements in momentum space are propagated by the mean field. By contrast, the extended BL model maintains the random force for a finite length of time and thereby provides a direct coupling between the two-body collision processes and the collective modes.

The memory time presents the shortest time scale in the problem, in so far as it is expected to be given approximately by the duration of an individual two-body collision, \( t_c \approx a/v_F \approx 6 \text{ fm/c} \) (twice the range divided by the relative speed, which is about the Fermi speed since the collisions only involve states in the Fermi surface). This is considerably shorter than the growth time for even the fastest unstable mode, which is about \( t_k \approx 20 \text{ fm/c} \). It is also fairly short compared to the free propagation time of a nucleons between collisions, \( t_{\text{free}} \approx \lambda/v_F \approx 20 \text{ fm/c} \). One might then expect that the transport process would retain a Markovian character.

However, the finite memory time in the microscopic collision kernel gives rise to a non-trivial modulation of the effective source terms that agitate the unstable modes in the spinodal phase domain, \( D_k^{\nu\nu'}(t) = 2 \delta_k^{\nu\nu'} \chi_k^{\nu\nu'}(t) \). As a consequence, the evolution of the covariance coefficients \( \sigma_k^{\nu\nu'}(t) \) then deviates from what would be obtained without a memory time, as expressed by the time-dependent correction factors \( \tilde{\chi}_k^{\nu\nu'}(t) \). These factors can deviate significantly from unity, particularly in the domain where the fastest growth occurs. It therefore appears important to incorporate such memory effects in BL simulations, especially in the presence of instabilities.

The correction factors ultimately attain constant values, and the evolution is then similar to what the standard treatment would give, except for the time-independent renormalization of the source terms. But this limiting simplicity emerges only relatively slowly, particularly for the mixed factor \( \tilde{\chi}_k^{++}(t) \). The table below shows the asymptotic values of the correction factors for a range of physically relevant scenarios:

<table>
<thead>
<tr>
<th>( T ) (MeV)</th>
<th>( \rho = 0.3 \rho_0 )</th>
<th>( \rho = 0.5 \rho_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.11 / 0.92</td>
<td>1.10 / 0.95</td>
</tr>
<tr>
<td>5</td>
<td>1.29 / 0.79</td>
<td>1.23 / 0.91</td>
</tr>
<tr>
<td>4</td>
<td>1.67 / 0.55</td>
<td>1.46 / 0.85</td>
</tr>
<tr>
<td>3</td>
<td>2.66 / 0.00</td>
<td>2.03 / 0.71</td>
</tr>
</tbody>
</table>

The present analysis has been confined to the idealized scenario of initially uniform nuclear matter, which can be subjected to near-analytic treatment by previously developed methods. Nevertheless, our conclusions are expected to hold for more complicated dynamical scenarios, such as may be encountered in nuclear collisions. Thus, if quantitatively reliable results are to be obtained from numerical simulations based on the BL model, it appears necessary to refine the treatment to take account of the memory time in an appropriate manner.

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We have investigated the properties of spin-isospin modes in an infinite system of interacting nucleons, Δ isobars, and π and ρ mesons at various densities and temperatures. The aim has been to derive and discuss quantities that can be incorporated in a transport description of a heavy-ion collision, by use of a local density and temperature approximation.

Within the random-phase approximation we have derived dispersion relations for the spin-isospin modes and the amplitudes of the their components. While the dispersion relations yield the energy-momentum relation of each mode, the character of the modes is determined by the amplitudes of the different components. In both the spin-longitudinal and spin-transverse channels, we find two collective modes, while the remaining modes are non-collective in their nature. The non-collective modes correspond in a transport description to propagation of uncoupled nucleons and Δ isobars, while the collective modes correspond to propagation of quasimesons. These quasimesons can be incorporated in a transport description in a manner analogous to how real pions have been incorporated in standard treatments based on vacuum properties. One notable feature of the lower pionic mode in the spin-longitudinal channel is that it gradually loses its collective character when it enters the region of non-collective modes.

The decay of a Δ isobar into a nucleon and a spin-isospin mode is governed by the partial Δ decay widths. Therefore, we have calculated total and partial Δ decay widths within the model. At twice normal density the total Δ width is significantly enhanced at low Δ energies. However, this enhancement is mainly associated with the decay to non-collective nucleon-hole modes, while instead the partial width for the decay to the lower pionic mode is reduced. At finite temperatures up to $T = 25$ MeV the total Δ width is almost unaffected, while the partial widths change somewhat with $T$.

The partial Δ widths representing decay to non-collective modes correspond in transport models to processes like $Δ + N \rightarrow N + N$. Since these processes are already explicitly included in the transport description, these partial widths should be ignored, while the corresponding cross sections should contain the in-medium modifications. Examples of such in-medium cross sections have been calculated. When the Δ width is included self-consistently in the formalism the cross section $\sigma(N + N \rightarrow Δ + N)$ is significantly enhanced at low center-of-mass energies, $(\sqrt{s} \sim 2.0 - 2.2$ GeV), while at $\sqrt{s} \approx 2.3$ GeV, only a small enhancement with nuclear density is found. We have found that all the calculated cross sections are almost independent of temperature up to $T = 25$ MeV.

This work constitutes a more consistent way of obtaining and incorporating in-medium effects in transport descriptions of heavy-ion collisions than previous works\(^1\). We expect that our model will be applicable in transport models up to moderately large bombarding energies of about 1 GeV per nucleon. Furthermore, we have so far not included any density dependence of the coupling constants, $g'$ correlation parameters, form factors, and meson masses, such as may result from a possible partial chiral restoration, since we feel that such effects at the present stage not are very well known.

Footnotes and References

\(^1\)Supported by the Swedish Natural Science Research Council (NFR).
Dilepton production is a promising tool for studying the hot and dense nuclear medium, since final-state interactions are very weak, as first pointed out by Gale and Kapusta. In a schematic model of nuclear matter, they considered dileptons arising from different processes, using relativistic kinetic theory. The production of dileptons from $\pi^+\pi^-$ annihilation was found to depend sensitively on the dispersion relation of the pionic mode. The treatment was later improved by deriving the dispersion relations of the pionic modes in a simple two-level $\Delta$-hole model consisting of a pion and a $\Delta$-hole state. Additional improvements were subsequently made.

Part of these results have been used in both fireball and transport models to describe dilepton production in heavy-ion collisions. However, a simple two-level $\Delta$-hole model has been used throughout. In this work we reconsider dilepton production from $\pi^+\pi^-$ annihilation in nuclear matter, employing a more realistic model that includes both nucleon-hole and $\Delta$-hole excitations as well as pions. We calculate the dispersion relations in a non-relativistic RPA formalism, treating interactions between pions, nucleon-hole, and $\Delta$-hole states. This yields the energies of all the eigenmodes and their expansion amplitudes on the various elementary excitations. There are two collective modes, corresponding to those of the simple two-level model. In addition we obtain a number of nucleon-hole or $\Delta$-hole like modes. These modes are mainly non-collective, each being dominated by a single nucleon-hole or $\Delta$-hole component.

The appearance of non-collective modes in the formalism requires special attention. Although non-collective in character, these modes will acquire a small pion component in the wave function (usually $<1\%$), and will thus contribute to the dilepton yield. The collective modes are well described by Bose-Einstein statistics, since their strength is spread over a large number of elementary excitations. By contrast, the non-collective modes are dominated by a single baryon-hole excitation which is thereby exhausted. Therefore, the mean number of non-collective modes follow Fermi-Dirac statistics. This is an important feature, because those non-collective nucleon-hole modes that have very small energy for finite momenta would be drastically overpopulated if Bose-Einstein statistics were used.

Comparing the results of a simple two-level $\Delta$-hole model with the results from using a more realistic dispersion relation including $\pi$, nucleon-hole, and $\Delta$-hole excitations, we have found a substantial enhancement of the dilepton yield for invariant masses in the region $M<250\text{ MeV}/c^2$, arising from the annihilation of non-collective low-energy high-momentum nucleon-hole modes having a (very) small pion component. We have ignored the vertex corrections which may reduce the dilepton yield somewhat. The evaluation of the dispersion relation at a temperature of $T=100\text{ MeV}$, rather than at zero temperature, does not affect the total dilepton yield much, but causes a significant degree of redistribution of the contributions from the different types of annihilation process.

Footnotes and References

1Supported by the Swedish Natural Science Research Council (NFR).
The surface response for charge exchange \((p,n)\) and \((^3\text{He},T)\) reactions is studied in the \(\Delta\) region using the semi-infinite slab model\(^1\). The contribution to the total response from different decay channels \((NN, N\pi, \pi)\) is calculated. These decay channels correspond to the exclusive channels \((pp,p\pi^+,\pi^+)\) measured in recent \((p,n)\) and \((^3\text{He},T)\) experiments\(^2\).

In the semi-infinite slab model we find a reasonably good qualitative agreement with the experimental inclusive and exclusive responses. We have found that the response of the exclusive decay channels is more sensitive to \(g'\)-parameters, the absorption function at the external vertex and the \(\Delta\) width, than the total response. Our calculations indicate that a \(g'\) parameter set with low values of \(g'_{N\Delta}\) and \(g'_{\Delta\Delta}\) (\(\sim 0.3\)) is favoured. The 2p-peak seen in the exclusive experimental spectra, can in the semi-infinite slab model be enhanced by allowing the reaction to probe larger nuclear densities at the surface.

In the spin-longitudinal channel the response is determined by the pionic branch of the spin-isospin mode and the energy dependence of the \(\Delta\) width. In nuclear matter the position (in \(\omega\) and \(q\)) of the pionic branch depends strongly on the nuclear density. This points to the importance of using an absorption function at the external vertex that probes the correct region of density in the surface. The spin-longitudinal response also depends strongly on the in-medium properties of the spin-isospin mode. Especially the decay modes of the \(\Delta\) in the medium modify the response. Hence it is important to incorporate the in-medium properties of the \(\Delta\) in a consistent way. We have taken into account the in-medium properties by using a \(\Delta\) width from microscopic calculations in nuclear matter. This \(\Delta\) width has been used as a non-local, or a local, imaginary \(\Delta\) potential in the semi-infinite slab model.

The results obtained with the \(\Delta\) width represented as a non-local or a local \(\Delta\) potential are similar. Only minor differences are seen in the exclusive channels, while the total responses are practically equal. This result is not obvious since the density in the surface region varies substantially within the range of the non-locality in the non-local representation.

In the transverse channel the response is much less sensitive to parameters and absorption functions. This is because the response is determined by a \(\Delta\)-hole branch which comes at higher energies and is smeared out by a large \(\Delta\) width at these energies.

We conclude that the basic processes in the decay of a spin-isospin mode, created for example in a \((p,n)\) reaction, is well understood within the semi-infinite slab model. However the responses in the exclusive channels depend on the angle between the propagating spin-isospin mode and the surface, and to make a quantitative comparison with experimental exclusive channels, it is necessary to use a model with a more realistic geometry.

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Footnotes and References


\(^1\)Supported by the Swedish Natural Science Research Council (NFR).

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\textit{Ann. Phys.} \textbf{157}, 29, (1984);
H. Esbensen, H. Toki and G.F. Bertsch,

The Nuclear Thomas-Fermi Model*

W.D. Myers and W.J. Światecki

In trying to understand astrophysical systems such as a collapsing and rebounding supernova or the resulting neutron star, one needs information concerning the properties of nuclear matter in the bulk, for example its compressibility for various values of the neutron-to-proton ratio. It would be nice to study directly these and other properties, such as the surface energy (including the curvature correction), the dependence of the surface energy on the N/Z ratio, and the binding energy curve of unbound neutron matter, for example. However, one has to proceed indirectly, by developing a theoretical model that is fitted to finite nuclei and then extrapolating to infinite or semi-infinite nuclear matter. By asking appropriate questions of the model one can then estimate, more or less reliably, various properties of the macroscopic nuclear fluid.

For this purpose we have applied the statistical Thomas-Fermi model to a comprehensive survey of macroscopic nuclear properties. The model uses a Seyler-Blanchard effective nucleon-nucleon interaction, generalized by the addition of one momentum-dependent and one density-dependent term. The adjustable parameters of the interaction were fitted to shell-corrected masses of 1654 nuclei, to the diffuseness of the nuclear surface and to the measured depths of the optical model potential. With these parameters nuclear sizes are well reproduced, and only relatively minor deviations between measured and calculated fission barriers of 36 nuclei are found. Other extreme situations to which the model is applied are a study of Sn isotopes from $^{82}$Sn to $^{170}$Sn, and the rupture into a bubble configuration of a nucleus (constrained to spherical symmetry) which takes place when $Z^2/A$ exceeds about 100.

On a finer scale there are some systematic discrepancies in the trends of fission barriers, density distribution profiles and the optical model potential. But overall we now have available a robust statistical model that shows a good correspondence with a large and varied amount of data on finite nuclei.

Footnotes and References
* LBL-36004 and Proceedings of the XXIX Zakopane School of Physics, Poland, September 5-14,1994.
The effective compressibility coefficient $K(A,Z)$ of a finite nucleus can be considerably lower than the compressibility $K_0$ of standard, uncharged nuclear matter. We have derived a formula for $K(A,Z)/K_0$ which is both simple and free of adjustable parameters. The physical input in the derivation is the observation that, apart from the Coulomb energy, the ratio $K/K_0$ should be approximately proportional to $E/E_0$. For uncharged finite nuclei, we might expect

$$K(A,Z) = \frac{E_n(A,Z)}{-a_1} K_0,$$  \hspace{1cm} (1)

where we have written $E_n(A,Z)$ for the nuclear binding energy per particle in the absence of the Coulomb energy, and $a_1$ for the magnitude of the binding energy per particle in standard nuclear matter: $a_1 = 16$ MeV.

This expectation is confirmed by the results of Ref. 1 where, for a series of model nuclei, calculated according to the Thomas-Fermi method, the binding energy per particle and the effective stiffness $K_{\text{eff}}$ were determined (in the case of $N = Z$ and no Coulomb energy). The results (where $x = A^{-1/3}$) could be accurately represented by

$$E = 16.527(1 - 1.2264x - 0.5016x^2 + 0.9651x^3)$$ \hspace{1cm} (2)

$$K_{\text{eff}} = 301.27(1 - 1.3495x - 0.7104x^2 + 1.5704x^3).$$ \hspace{1cm} (3)

In the presence of electrostatic forces the argument for the proportionality between $K(A,Z)$ and $E(A,Z)$ is no longer valid because the Coulomb energy, being produced by long-range forces, does not vanish at some finite characteristic scaling $l_C$. Even so, the modification of eq. (1) caused by the Coulomb energy is readily derived.

After some analysis we find that the binding energy per particle of finite nuclei is given, to an approximation sufficient for our purposes, by

$$E(A,Z) = -16.04 + 18.5 A^{-1/3} + 9.1 A^{-2/3} - 11.6 A^{-1} + \frac{32 I^2}{1 + 1.87 A^{-1/3}} + \frac{3}{5} \frac{e^2}{1.14 A^{4/3}} \frac{Z^2}{A^{4/3}} \text{ MeV}.$$ 

This leads to

$$K(A,Z) = \left(1 - 1.153x - 0.567x^2 + 0.723x^3 - \frac{1.995 I^2}{1 + 1.87x}\right) 234 - 3.75 \frac{Z^2}{A^{4/3}} \text{ MeV}. $$

Using the assumption of a universal scaling dependence of the nuclear part of the binding energy of nuclei we derived a simple formula for the stiffness against scaling of finite nuclei.

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Footnotes and References

* LBL-36204, To be published in Nuclear Physics.

Nuclear Properties According to the Thomas-Fermi Model*

W.D. Myers and W.J. Świątecki

In order to formulate a statistical model of nuclear properties we combine the Thomas-Fermi assumption of two fermions per $\hbar^3$ of phase space with an effective interaction between nucleons that contains seven adjustable parameters.\(^1\)\(^2\) After allowing for shell effects, an even-odd correction and a congruence energy ("Wigner Term"), six of the seven parameters were fitted to 1654 ground state masses of nuclei with $N,Z \geq 8$, together with a constraint that ensures agreement with measured values of the nuclear surface diffuseness. The RMS deviation in the fit to masses was 0.655 MeV, and the calculated values exhibit no drastic discrepancies even for $A = 3$.

Calculated sizes of nuclear charge distributions are also found to agree closely with measurements. Calculated fission barriers were compared with 40 measured values down to $^{75}$Br. Having fitted six adjustable parameters of the effective interaction to ground state masses and the surface diffuseness, the nuclear RMS radii and the fission barriers of heavy nuclei come out very close to measurements without further parameter adjustments. The trend of the fission barriers for elements below about $Z = 88$ may be interpreted as evidence for the expected tendency of the congruence energy to double its value as the neck in the saddle-point shapes tends to zero. If this interpretation is confirmed, it will lend weight to the hypothesis that the term in nuclear binding energies proportional to $|N - Z|/A$ arises to a significant extent from the stronger interaction between 'congruent' nucleons, characterized by similar nodal structures of their wave functions.

A seventh (density-dependence) parameter in the effective interaction can be adjusted to ensure fair agreement with the measured energy-dependence of the optical model potential in the range from −70 MeV to 180 MeV.

The model is used to predict properties of nuclear and neutron matter (including their compressibilities). A table of some 9000 calculated ground state masses of nuclei up to $Z = 135$ has been prepared.

Neutron (open squares) and proton (solid squares) Thomas-Fermi chemical potentials for isotopes from $^{83}$Sn to $^{167}$Sn.

Footnotes and References

* LBL-36557 Submitted to Nuclear Physics.
Effects of Neutrino-Electron Scattering on Neutrino Transport in Type II Supernovae*

J.M. Smit, J. Cernohorsky, L.J. van den Horn, and Ch.G. van Weert†

We investigate the effects of neutrino-electron scattering on electron-neutrino transport during the collapse phase of a Type II supernova. Calculations of stationary state transport were performed on a 1.17 $M_\odot$ spherically symmetric infall model, with neutrino-electron scattering turned off and on. During the transport calculation the stellar background is kept fixed in time. In this manner we can isolate the effects of neutrino-electron scattering on neutrino transport alone.

We find that the inclusion of neutrino-electron scattering approximately doubles the emitted neutrino flux. Neutrino-electron scattering increases the rate at which energy and lepton number are transferred from the matter to the neutrinos. However, the transfer of entropy to the matter increases in a large part of the collapsing core. We also discuss the equilibration of the neutrinos.

Legendre Expansion of the Neutrino-Electron Scattering Kernel*

J.M. Smit and J. Cernohorsky†

The expansion of the neutrino-electron scattering rate in a Legendre series of the scattering angle is extended to include quadratic terms. This extension provides a considerable improvement of the 'fit' to the scattering rate. On the other hand, the effect of the quadratic terms on the neutrino transport during the infall phase of a Type II supernova is found to be negligible.

This is partly due to the specific state of the matter background and the shape of the neutrino spectra which suppress the phase space where the quadratic Legendre approximant could be significant. Furthermore, the intrinsic structure of the Boltzmann equation causes the suppression of (nearly) coherent scattering in the forward direction where the scattering rate deviates most from a linear approximation.

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Prompt Subsidence of a Protoneutron Star into a Black Hole*

N. K. Glendenning

A newly formed protoneutron star, prior to the loss of neutrinos, will consist of a charge-neutral mixture of neutrons, protons, electrons, muons and trapped neutrinos in the lowest energy state available under these circumstances. However, in a few seconds, the neutrinos will escape, enabling the interior of the star to find a lower energy. We study two possibilities: (1) A significant number of baryons will, through the weak interaction, convert to hyperons. (2) Hadronic matter may convert to quark matter in the interior where the pressure is high. In either case the resulting softer equation of state will not support as large a range of stars either in mass or baryon number. Therefore, beyond the baryon number of either of the above equilibrated sequences there is a significant range of baryon numbers and corresponding masses for protoneutron stars that possess no hydrostatically stable configurations after neutrino loss. They will subside into a black hole on the timescale of neutrino loss, about ten seconds, and after the processed material of the supernova has been ejected into the galaxy, contributing to the cosmic elemental abundances. The observation of the neutrino signal from SN1987A, but the absence of a pulsed signal or evidence of a neutron star in the light curve of the supernova remnant, suggest that in this case a supercritical protoneutron star may have been formed which collapsed to form a black hole subsequent to the neutrino emission. In any case, the processes described here presumably are responsible for the collapse of some protoneutron stars after the supernova explosion and neutrino signal, and may be relevant to any disparity in neutron star birthrates and type II supernova rates in the galaxy. Sequences of stellar masses as functions of baryon number are shown in Fig. 1. The sequences for n,p,e matter, representative of protoneutron stars for which hyperonization is delayed by the presence of trapped neutrinos, are shown by dotted lines. The solid dots mark the mass limit for the sequences. The cold evolved stable neutron stars are shown by the solid line and the last stable configuration is labeled H. Therefore protoneutron stars formed with baryon number between H and P have no stable configuration upon deleptonization and will collapse to a black hole. We see that the window for such a scenario is a substantial $1/2M_\odot$, and exceeds by about a factor five the window created by accretion induced collapse, whose time scale is much longer. It is important to note that the mechanism described does not alter the amount of processed material expelled by evolved massive stars into the universe to form the cosmic abundance of elements, but it impacts on the apparent discrepancy between neutron star and supernova remnant associations.

Fig. 1 Mass vs baryon number for protoneutron stars (n+p+e) and stable hyperonized stars (n+p+H+e). Window for prompt collapse is between H and P

*Astrophysical J. (in press)
Test of Free Precession of a Pulsar as an Alias for an Orbiting Planet*

N. K. Glendenning

The first planets outside the solar system were discovered recently in orbit around a pulsar. It seems most unlikely that this is a singular system; surely other pulsars with one or more planetary companions exist. Of course planets cannot be directly seen in such distant systems. What is observed is a modulation of the pulsar period, which is interpreted to be a doppler shift due to orbital motion of the pulsar. No doubt timing residuals will now be closely scrutinized for evidence of planets as companions to pulsars. That is the main motivation for this note. Because there is another possible cause of period modulation, - the free precession of an isolated pulsar. It is possible to confuse this with modulation by a single companion if the modulation is sinusoidal.

Our purpose here is quite simple; it is (1) to show that there are circumstances in which free precession of a solitary pulsar can mimic a single planetary companion, (2) to establish a relationship involving three observable quantities, the pulsar period, the modulation period, and its amplitude, that has to hold if free precession is occurring. If the relation is satisfied, then no definite conclusion concerning a planetary companion could be readily made. If the relation cannot be satisfied, then precession is ruled out, and one has clearer evidence for a planetary hypothesis.

The general expression for the time dependent frequency, \( \Omega(t) \), of the azimuthal angle of the magnetic axis, assuming only that the star's symmetry axis precesses with angular velocity \( \Omega \) and as a consequence spins about its symmetry (or reference) axis with angular velocity \( n \) is,

\[
\Omega(t) = \frac{d \Phi(t)}{dt} = \Omega + \frac{n \tan \gamma \sec \beta \cos(nt)}{\tan \beta + \tan \gamma \cos(nt)} \left\{ 1 + \left( \frac{\tan \gamma \sec \beta \sin(nt)}{\tan \beta + \tan \gamma \cos(nt)} \right)^2 \right\}^{-1}
\]

The modulation reduces to sinusoidal form if \( \tan \gamma \ll \tan \beta \). The angle between symmetry axis and angular momentum axis is \( \beta \) and between symmetry and magnetic axis, \( \gamma \). Then

\[
\Omega(t) \approx \Omega + \frac{n \tan \gamma}{\sin \beta} \cos(nt).
\]

From this time-dependent frequency, we can read, what, for a freely precessing pulsar, would be interpreted as its period, \( P = 2\pi/\Omega \), and its modulation period, \( P_m = 2\pi/n \) with \( P_m < < P \). Pulse arrival times would appear as if they were Doppler shifted by orbital motion with a companion! We deduce under general circumstances that

\[
|\Delta P| < \frac{P^2}{P_m}.
\]

This relation specifies the condition that three observables must satisfy so that precession can mimic the slow sinusoidal pulsar period modulation that might otherwise be attributed to the Doppler shift due to orbital motion.

---

A Possible New Class of Dense White Dwarfs∗
N. K. Glendenning, Ch. Kettner and F. Weber

Bodmer and Witten independently hypothesized that strange quark matter, an approximate equal mixture of u,d,s quarks, may be the absolute ground state of the strong interaction (rather than $^{54}$Fe). Even to the present day there is no unequivocal scientific basis on which one can either confirm or reject this hypothesis, - it remains a serious possibility of fundamental significance for rare but exotic phenomena.

If the hypothesis is true, then there could exist compact stars containing such matter. Strange stars, - the counterparts of neutron stars, - with central densities above nuclear saturation density, have been extensively discussed. Here we point out the possible existence of a new class of very dense white dwarfs whose stability is established solely by a strange quark core.

A strange quark star or core has a sharp edge of thickness defined by the range of the strong interaction. Alcock, Farhi and Olinto pointed out that the electrons, which neutralize the positive charge of strange quark matter and are bound to it by the Coulomb attraction, extend several hundred fermis beyond the edge, thus creating a dipole layer of very high voltage. It can support, out of contact with the core, ordinary matter, which it polarizes. The maximum density of such a ‘crust’ is limited by the neutron drip density, above which neutrons would gravitate to the strange core and be converted to quark matter. Of particular interest, as part of the continuum of equilibrium configurations of compact strange stars with nuclear crusts, there are stable strange dwarfs having densities of nuclear material as high as the neutron drip, - more than ten thousand times the central density of a typical $M = 0.6M_\odot$ white dwarf. They owe their stability solely to the quark core, without which they would lie on the unstable region of the sequence between white dwarfs and neutron stars.

In proposing the possible existence of a new type of star it is necessary to investigate the stability of these strange dense dwarfs to radial pulsations. We do this through the method of Chandrasekhar. For a metric of the form $ds^2 = e^{2\nu} dt^2 - e^{2\lambda} dr^2 - r^2 (d\theta^2 + \sin^2 \theta d\phi^2)$, the adiabatic motion of the star in its $n$'th normal mode, where $n = 0$ is the fundamental mode, is expressed in terms of an amplitude $u_n(r)$ by $\delta r(r, t) = e^\nu u_n(r) e^{i\omega_n t}/r^2$ which denotes small Lagrangian perturbations in $r$. The quantity $\omega_n(t)$ is the star’s oscillation frequency, which we want to compute. The eigenequation for $u_n(r)$ which governs the $n$'th normal mode, first derived by Chandrasekhar, has the Sturm-Liouville form

$$\frac{d}{dr} \left( \Pi \frac{du_n}{dr} \right) + \left( Q + \omega_n^2 W \right) u_n = 0,$$

where $\Pi, Q, W$ are radial functions of pressure and energy density obtained for a particular stellar model as a solution of the Oppenheimer-Volkoff equations. Unlike the continuum of hydrostatic equilibrium solutions for white dwarfs and neutron stars, between which there is a large gap in central density of many orders of magnitude for which there are no stable solutions, we find that the strange dwarfs are connected to strange compact stars (analogous to neutron stars) through a stable continuous domain of very light planetary-like objects with masses even lower than 1/10 Jupiter. They may be of interest as gravitational micro-lensing candidates. The heavier dwarfs in this continuous sequence have nuclear material at densities of up to $4 \times 10^4$ higher than that found in the typical $0.6M_\odot$ white dwarf and so constitute a possible new class of stars!

From Strange Stars to Strange Dwarfs*

N. K. Glendenning, Ch. Kettner and F. Weber

We determine all possible equilibrium sequences of compact strange-quark-matter stars with nuclear crusts, which range from massive strange stars to strange white-dwarf-like objects (strange dwarfs). The properties of such stars are compared with those of their non-strange counterparts, — neutron stars and ordinary white dwarfs. The main emphasize of this paper is on strange dwarfs, which we divide into two distinct categories. The first one consists of a core of strange matter enveloped within ordinary white dwarf matter. Such stars are hydrostatically stable with or without the strange core and are therefore referred to as ‘trivial’ strange dwarfs. This is different for the second category which forms an entirely new class of dwarf stars that contain nuclear material up to \( \sim 4 \times 10^4 \) times denser than in ordinary white dwarfs of average mass, \( M \sim 0.6 M_\odot \), and still about 400 times denser than in the densest white dwarfs. The entire family of such dwarfs, denoted dense strange dwarfs, owes its hydrostatic stability to the strange core. We have performed a stability analysis of the entire sequence using techniques devised by Chandrasekhar. One of the striking features of strange dwarfs is that the entire sequence from the maximum-mass strange star to the maximum-mass strange dwarf is stable to radial oscillations. The minimum-mass star is conditionally stable, and the sequences on both sides are stable. This contrasts with ordinary neutron stars and white dwarfs where there is a broad range of unstable configurations between them extending over a central density domain of five orders of magnitude. As a result, we find an expansive range of very-low-mass (planetary-like) strange-matter stars (masses even below \( \sim 10^{-4} M_\odot \) are possible) that arise as natural dark-matter candidates, which, if abundant enough in our Galaxy, should be seen in the gravitational microlensing searches that are presently being performed.

Fig. 1 Neutron star (NS) - white dwarf (wd) sequence, (solid line). Two strange star (SS) - strange dwarf (sd) sequences, for which the inner crust density of nuclear material has the indicated values (in g/m/cm\(^3\)). The higher value is the drip density. Vertical bars mark minimum mass stars. Crosses mark termination of the strange star sequences where the strange core shrinks to zero. At those points they become identical to ordinary white dwarfs.

*Astrophysics J. (in press)
Structure and Stability of Strange and Charm Stars at Finite Temperature*


The purpose of this work consists of a detailed investigation of the structure and stability of strange and charm stars at finite temperatures. It is found that temperatures $T \lesssim 50$ MeV modify the equation of state significantly only at energy densities that are close to $\sim 4B$, i.e., at small external bag pressures. The situation is different for the electrons since they are bound to the system by the electromagnetic interaction rather than the strong force, as is the case for the quarks. Correspondingly the electron density varies for temperatures in the range $0 \lesssim T \lesssim 50$ MeV between one and two orders of magnitude. A change of the density of electrons is accompanied by a change of their chemical potential, which, however, is smaller than $\lesssim 1$ MeV. As a consequence of the weak temperature dependence of the equation of state, the bulk properties of sequences of strange stars too exhibit only a weak dependence on temperature. The quark/lepton composition of quark-star matter is determined up to those densities at which even charm-quark states become populated. We find that this takes place at densities slightly larger than $10^{17}$ g/cm$^3$. In order to fulfill the condition of electric charge neutrality, there is only little need for electrons. Muons are completely absent in strange-star matter, and become populated only at densities larger than the threshold density of charm quarks.

Of crucial importance for the existence of nuclear crusts on the surfaces of bare strange stars is the existence of a Coulomb barrier associated with the difference of the electrostatic potential at the surface and the base of the crust. It is found that finite temperatures lead to a considerable reduction of the Coulomb barrier, which favors the tunneling of ions (atomic nuclei) bound in the nuclear crust toward the strange star surface. In fact, the electrostatic potentials at the surface of a hot strange star and at the base of its inner crust may even become equal at temperatures that are typical for newly formed pulsars, $T \sim (30 - 50)$ MeV. Thus, the Coulomb barrier, which prevents the ions in the crust from coming into contact with the star’s strange matter core, disappears and consequently conversion of confined baryonic matter into strange matter is not prohibited any longer. Therefore, we conclude that hot strange stars are unlikely to possess nuclear crusts as long as their temperatures are larger than about 5 MeV, depending on the value of the crust’s electrostatic potential at its base.

Another important topic of this investigation consists of performing a stability analysis of quark-matter stars against radial oscillations. It is found that the fundamental eigenmode passes through zero at the density of the most massive strange star. This eigenmode is positive at all densities smaller than this one. Thus, strange stars are stable against radial oscillations. The situation is different for all quark stars having central densities larger than the maximum-mass strange star. For all such configurations the fundamental mode is found to be unstable. More than that, going to higher and higher central star density leads to the successive excitation of higher-lying eigenmodes. We thus arrive at the very important conclusion that no quark-matter stars can exist in nature other than the hypothetical strange stars. Specifically, this rules out the possible existence of charm-quark stars.

---


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Strange-Matter Stars*
F. Weber, Ch. Kettner‡, M. K. Weigel,§ and N. K. Glendenning

This paper gives an overview of the properties of all possible equilibrium sequences of compact strange-matter stars with nuclear crusts, which range from strange stars to strange dwarfs. In contrast to their non-strange counterparts, neutron stars and white dwarfs, their properties are determined by two (rather than one) parameters, the central star density and the density at the base of the nuclear crust. This leads to stellar strange-matter configurations whose properties are much more complex than those of the conventional sequence. As an example, two generically different categories of stable strange dwarfs are found, which could be the observed white dwarfs. Furthermore we find very-low-mass strange stellar objects, with masses as small as those of Jupiter or even lighter planets. Such objects, if abundant enough, should be seen by the presently performed gravitational microlensing searches.

The following items are particularly noteworthy:

- The complete sequence of compact strange stars can sustain extremely rapid rotation and not just those close to the mass peak, as is the case for neutron stars!

- If the strange matter hypothesis is correct, observed white dwarfs should contain strange-matter cores in their centers. Their maximal possible baryon number compatible with hydrostatic stability is smaller than $A_{\text{core}} \lesssim 2 \times 10^{55}$!

- The masses and radii of stable strange stars with nuclear crusts lie in the ranges $10^{-4} \lesssim M_{\text{SS}}/M_{\odot} \lesssim 2$ and $2 \lesssim R_{\text{SS}}/\text{km} \lesssim 10^3$. Those of the strange dwarfs are given by $10^{-4} \lesssim M_{\text{sd}}/M_{\odot} \lesssim 1$ and $10^3 \lesssim R_{\text{sd}}/\text{km} \lesssim 10^4$. Thus, if the abundance of such stars in our Galaxy is sufficiently large enough, the presently performed gravitational microlensing experiments should see them all!

- Strange stars can possess nuclear crusts of thickness $\sim (1 - 10^{4})$ km! This will be of great importance for their cooling behavior (presently under investigation).

- Elsewhere (Ref. 1) we have shown that, in contrast to claims expressed in the literature, the moment of inertia of the crust on a strange star can account for both the observed relative frequency changes of pulsars (glitches) as well as the relative change in spin-down rate!


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Hadronic Matter and Rapidly Rotating Compact Stars*
F. Weber, Ch. Kettner, and N. K. Glendenning

In part one of this paper we introduce a representative collection of modern neutron-star-matter equations of state (pressure as a function of energy density, \( P(\epsilon) \)), which consists of relativistic field-theoretical equations of state and non-relativistic Schrödinger-based models that are derived for different assumptions about the physical behavior of super-dense matter (e.g. baryon populations, pion condensation, possible transition of baryon matter to quark matter at high densities).

Part two deals with the theoretical determination of the absolute limiting rotational periods of rapidly rotating neutron stars, i.e. the Kepler (or mass shedding) period, \( P_K \equiv 2\pi/\Omega_K \). The quantity \( \Omega_K \) denotes the Kepler frequency given by

\[
\Omega_K = \omega + \frac{\omega'}{2\psi'} + \epsilon e^{-\psi} \sqrt{\frac{\psi'}{\psi}} + \left( \frac{\omega'}{2\psi'} e^{\psi - \nu} \right)^2,
\]

which can only be evaluated self-consistently\(^2\) in combination with Einstein’s equation,

\[
\mathcal{R}^{\kappa\lambda} - \frac{1}{2} g^{\kappa\lambda} \mathcal{R} = 8\pi T^{\kappa\lambda}[\epsilon, P(\epsilon)].
\]

The Kepler periods computed for the above mentioned collection of nuclear equations of state are graphically depicted in Fig. 1. Our investigation predicts limiting periods for a \(~ 1.4 M_\odot\) pulsar in the range \( 0.7 \text{msec} \lesssim P_K \lesssim 1.2 \text{msec} \), depending on equation of state. Therefore, from this collection it appears that the observation of such a pulsar with a period that lies below \(~ 0.7 \text{msec} \) would be hard to reconcile with theories of dense hadronic matter. According to our present understanding of super-dense matter, plausible objects that would allow for such small rotational Kepler periods are hypothetical self-bound strange stars, made up of up-, down-, and strange-quark matter that is absolutely stable with respect to \(^{56}\text{Fe}\).

Fig. 1: Kepler period versus rotational neutron star mass. The labels attached to these curves refer to different models for the equation of state.\(^3,4\) Only pulsar periods \( P > P_K \) are possible, which is consistent with the pulsar periods known to date.

The properties of strange stars are discussed in the third part of this paper. It is found, for example, that strange stars can carry nuclear crusts of thickness ranging from \(~ 1 \text{km} \) to \(~ 10^3 \text{km} \), depending on mass and the density of the crust at its inner base. Furthermore the lightest stars of strange-star sequences can be several orders of magnitude less massive than the lightest stable object in the neutron star/white dwarf sequence.


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