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FUTURE PROGRAMS WITH HIGH ENERGY NUCLEI AT THE BERKELEY BEVALAC *

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ABSTRACT

Experiments with relativistic nuclear beams which will provide new data on nucleus-nucleus collisions at Bevalac energies over the next one or two years are summarized. A brief description of each experiment and its goals are presented. In addition, future improvements to the Bevalac Facility are discussed.

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INTRODUCTION

In my previous talk\(^1\) I reviewed existing data on high energy nucleus-nucleus collisions. These data were obtained over the period extending from 1972-73 up to the present. In this talk I will present a brief summary of experiments that are either presently on the Bevatron floor or will be within the next few months. This will include a brief description of each experiment and its motivation. It is hoped that by providing such a summary, interested experimentalists and theorists in this area of physics investigation will know what can be expected from each program and perhaps provide comments of value to the appropriate experiment.

Besides the summary of the upcoming experimental program, I will devote a brief portion of this talk to a description of future machine developments which are of importance to the long term goals of the nuclear science program at the Bevalac.

"NEAR FUTURE" EXPERIMENTAL PROGRAM

In this section I will be describing the "near future" experimental program at Berkeley. This will include descriptions of experiments which are presently set up and running, as well as those which will be placed in operation over the period of the next six to nine months (up to about Spring 1977). These experiments can be expected to provide new data on nucleus-nucleus interactions over the available energy range of \(-150-2100\) MeV/nucleon at the Bevalac. These experiments cover a wide range of phenomena, such as projectile fragmentation, pion production, photon production, light-ion elastic scattering and polarization, electron capture by relativistic nuclei, phenomena arising from central collisions, and applications to problems in astrophysics. With each description a list of the experimental group is included.

(1) Projectile Fragmentation: Heckman/Greiner Group (LBL/UCSSL)

This group has been actively involved with projectile fragmentation measurements including studies of the fragmentation of C, N, O, Ne and Ar projectiles at 1.05 and 2.1 GeV/nucleon. Some of these results were discussed in my first lecture\(^1\). The group, sometimes in collaboration with others, is involved in second generation projectile fragmentation experiments including the following:

(A) Heavy Ion Fragmentation, Low Mass Targets and High Mass Beams: Greiner, et al.\(^2\)

An extension of earlier single-particle inclusive projectile fragmentation studies on nuclear targets (Be and above) to light liquid targets (H\(_2\), D\(_2\), He). Data from light targets will be used to see if the "factorization" of production cross-sections still holds and whether fragment momentum distributions are similar to those found for heavier targets. In addition, they...
will be using heavier projectiles (including $^{56}$Fe). This experiment will be installed in late 1976 or early 1977, and should have preliminary results by summer 1977.

(B) Heavy Ion Fragmentation, Multi-particle Inclusive Spectra: Lindstrom, et al.

This experiment represents an extension of their earlier single-particle fragmentation measurements, to a study of several final state fragments. Using a variety of beam projectiles ($^4$He, $^7$Li, $^{12}$C, $^{14}$N, $^{16}$O) at 1.05 and 2.1 GeV/nucleon, an improved spectrometer system will be used to measure the angular distribution and multiplicities of secondaries, in association with a fragment with $Z \geq 2$. Particles within $50^\circ$ of the beam will be measured. A range of targets from CH$_2$ to Pb will be used to measure the dependence on target mass. By studying 2-body processes (e.g., $^{16}$O + $^{15}$N + p) they hope to obtain information on correlations to better understand the fragmentation process. Recently, there have been speculations about $^{12}$C's in nuclei. A study of a 3-body final state like

$$^{16}$O $\rightarrow ^{15}$C + $^\Lambda$ + p

could provide useful information on this question. This experiment will be set up by early 1977 and should provide preliminary results by summer 1977.

(C) Coulomb Dissociation of Relativistic $^{16}$O and $^{15}$O: Berman, et al.

This experiment will make use of the high resolution spectrometer of Lindstrom et al. It has been observed that the coulomb field plays a major role in those fragmentation events in which only a single nucleon is removed. This experiment will continue studies on coulomb dissociation. Provided that earlier conclusions on the coulomb contribution are correct, a second phase will employ the spectrometer to study reactions such as $^{16}$O + p + $^{15}$N, in order to extract the virtual photon-weighted cross-sections as a function of the photon-excitation energy (accuracy of $1 - 2$ MeV). In effect, they hope that for single
nucleon removal fragmentation events the interaction essentially sees only the virtual photon field of the target nucleus. Thus, they would in effect have a “photon target” as shown below:

\[ \text{effective target} \]
\[ 1^0 + \gamma + N + p \]

heavy target

This experiment will be running in early 1977 and should have preliminary data by summer 1977.

(1) **Target-Projectile Correlation Test:** Rasmussen, et al.

This experiment will be one of the first to look for correlations between large target excitation and projectile fragmentation. The experiment will search for coincidences between a known \( \gamma \)-ray from the target and a fragment in an upstream solid state counter (at 0°). This experiment should provide an unambiguous test of whether heavy ion reactions at about 1 GeV/nucleon reside in asymptopia (so that limiting fragmentation holds, implying independence of processes on target nucleus) by checking for the lack of correlations between projectile fragments and \( \gamma \)-rays from target excitation. The experiment will be set up by fall 1976 and will be completed before the end of 1976.

(2) **Light Ion Projectile Fragmentation and Pion Production:** Steiner, et al.

An extension of earlier work on fragmentation and pion production performed at a fixed laboratory angle of 2.5°: This experiment is designed to measure the following:
Incident projectile energies are 0.4, 1.05, and 2.1 GeV/nucleon. A variety of targets are used (Be, C, Cu, Pb). Primary objectives are to test the validity of the hypothesis of projectile limiting fragmentation and to learn from the abundance and momentum and angular distributions of fragments more about the grouping and momentum distributions of constituents in the nucleus. This experiment has been taking data and will be completed in the fall of 1976. Preliminary results should be available by late 1976 or early 1977.

(3) Single Diffractive Dissociation of Complex Nuclei: Zinnober et al. (LRL)

Measurement of the single-particle inclusive cross-section, etc., for $A + p \rightarrow p + x (A = p, ^{12}C)$ and $x$ is the "missing mass" ($M = M_{p} - M_{A}$; $0.03 \, \text{GeV}$). Momentum transfer range $0.03 - 0.05 \, \text{GeV}$. This experiment inverts the traditional role of beam (heavy projectile) and target (proton). Goals of experiment are two-fold. First, the data will be used to test multiple scattering models. Secondly, it has been pointed out that Mueller-Regge asymptotics might be applied to systems of large baryon number $A$ at lower energies than required for small $A$. If true, then questions of pomeron dominance, factorization and the value of the triple pomeron vertex might be answered with heavy ions at Bevalac energies. The experiment has completed data-taking and is presently in analysis stage.

(4) Multipion Production from High-Z Collisions: Cork et al. (LRL/UCSL)

If superdense nuclear matter is produced in heavy ion collisions, a possible by-product would be large numbers of pions. This experiment will use a multi-annelled water Cerenkov counter to detected charged pions produced at angles $150^\circ$ by a Pb target. Pion multiplicities will be determined. Experiment is set up and should be taking data with an Ar beam by early 1977.
(5) Electromagnetic Radiation from Relativistic Heavy Ion Collisions: TOSAB Collaboration, Rasmussen et al.

This group has been active in γ-ray measurements in heavy ion collisions. Inclusive measurements have ranged from photon energies of a few kilovolts (atomic x-rays) to over 100 MeV (presumably from γ decay). Initial work has been concerned with detecting known nuclear levels in hopes of obtaining more dynamical information on projectile fragmentations and target excitation reactions. These experiments are now complete and analysis of data continues. Future directions include detection of photons from 70. Particular attention will be paid to central collisions, where one expects many pions (neutral and charged) to be created. Data relevant to this is not expected until mid-1977.

(6) Studies of Particle Production and Fragmentation in the LBL Streamer Chamber; Poe, et al. (U.C. Riverside/LBL)

This group has recently demonstrated that heavy ion interactions can be successfully studied in a conventional streamer chamber. The streamer chamber is an ideal device with large solid angle and multi-track efficiency which can be used to survey nucleus-nucleus interactions. Four targets (LiH, NaF, BaI2, Pb3O4) located inside the chamber have been exposed to a high energy argon beam. By the end of this year, exposures with carbon and argon beams each at 400 MeV/nucleon and 2.1 GeV/nucleon will be completed. This will allow systematic studies of the dependence of particle production on projectile type, energy and target material. Initial emphasis will be placed on charged particle multiplicities, pion production and light particles emitted backwards in the laboratory.

(7) Study of Large Momentum Transfer in Target Fragmentation: Poskanzer/Guthrod Group (LBNL/GSI/Marburg)

This group has been measuring the energy (<200 MeV/n) and angular distribution (30°-150° in lab) of fragments from a uranium target bombarded by proton, alpha and neon beams at 250, 400 and 2100 MeV/nucleon. Most recent work has involved single particle distributions for p, d, 3H and He fragments. Multiplicity data in association with these fragments has been taken and is being analyzed for any evidence of phenomena which could be associated with such things as nuclear shock waves or other effects of increasing the nuclear density in central collisions. Data will be ready for publication in late 1976. Future studies involve detection of heavier mass fragments with essentially the same apparatus. Interest continues for studying large energy and momentum transfer processes.
Light Ion Elastic Scattering and Polarization Measurements: Ito et al. (UCLA/LBL/UC Davis)

This group has developed a single-arm spectrometer system for measuring light ion elastic scattering. Scattering angles of $0 \leq \theta_{\text{scatt}} \leq 15^\circ$, and scattered momenta of $p/z = 6 \text{ GeV/c}$ are detected by this system. Experiments on $p^4\text{He}$ and $^4\text{He} p$ elastic scattering have been finished. Data were taken at the following energies:

- $p^4\text{He}$: 3.5 GeV/c ($0.15 \leq t \leq 0.62$); 5.75 GeV/c ($0.15 \leq t \leq 2.2$)
- $^4\text{He} p$: 1.7 GeV/c ($0.1 \leq t \leq 0.5$); 0.95 GeV/c ($0.15 \leq t \leq 0.83$)

These data will be used to test multiple scattering theories over a large range of incident energies and momentum transfer. In addition, the group is interested in possible correlation effects in light nuclei that can be probed with such measurements. To provide more complete information on the scattering amplitude, polarization data is required. An experiment in collaboration with U.C. Davis group will be setting up to measure the polarization in $^4\text{He} p$ scattering by use of a polarized target. The experiment should be taking data early in 1977.

Measurements of Light Fragment Spectra Produced in Nucleus-Nucleus Collisions: Igo et al. (UCLA/LBL)

Using their single-arm spectrometer (see (8) above) in association with an array of 33 lucite Cerenkov counters spanning $360^\circ$ in azimuthal angle, measurements of light fragment spectra and fast particle ($r \approx 0.7$) multiplicities are underway. The fragments result from the collisions of a heavy projectile (e.g. Ar) with a light target (e.g. Be). If particles are emitted at preferred angles (as speculated for particles arising from shock waves), they will be emitted fast at forward angles in the kinematics of this experiment. Preliminary data exists for C and Ar projectiles. Finally running will occur in earlier 1977. This experiment is designated 317H.

Measurements of Transverse Momenta of Fragments Emitted After Nucleus-Nucleus Head-On Collisions: Nagamiya et al. (LBL)

This experiment is designed to look at head-on collisions of nearly equal masses. It is hoped that such collisions will result in highly compressed nuclear matter, possibly leading to such things as shock waves. A spectrometer in association with symmetrically placed counters will be employed to isolate head-on collisions. Single-particle inclusive spectra for pions and light nuclear fragments ($p, d, ^3\text{H}, ^3\text{He}, \alpha$) will be obtained for $20^\circ < \theta_{\text{frag}} < 70^\circ$. 

- Light Ion Elastic Scattering and Polarization Measurements: Ito et al. (UCLA/LBL/UC Davis)
- Measurements of Light Fragment Spectra Produced in Nucleus-Nucleus Collisions: Igo et al. (UCLA/LBL)
- Measurements of Transverse Momenta of Fragments Emitted After Nucleus-Nucleus Head-On Collisions: Nagamiya et al. (LBL)
and 100 GeV/nucleon. The apparatus is presently being set up, with initial data taking to occur in late 1976 or early 1977. Preliminary data available by mid-1977.

(11) Production of Light Particles Near 180° from Nucleus-Nucleus Collisions: L. Schroeder et al. (LBL)

Extensive studies of single-particle spectra at forward angles have been made at the Bevatron/Bevalac Facility. In contrast, the region of particle production at backward angles and at high energies has barely been touched. This experiment will measure the energy and momentum spectrum of light particles (\( K^*, p, d, ^3H, ^3He, \)) produced in the backward direction (180°) by nucleus-nucleus collisions. Primary emphasis will be placed on the meson spectra with the capability of measuring pions up to 1.2 GeV. A spectrometer consisting of a dipole magnet and a quadrupole doublet will be used in conjunction with scintillation counters to detect the particles produced at 180°. dE/dx and TOF measurements will be used for particle identification. Results of these measurements will be compared for their dependence on: incident projectile (p, \( ^4\)He, Ne, Ar), incident energy (1.05 and 2.1 GeV/n), and target material (Be, C, Cu, Pb). Data from this experiment will provide a systematic survey of particle production (at the highest energy) in the backward direction. The experiment will be set up in early 1977 and preliminary data should be available in mid-1977.


Many heavy ion-induced reactions at cyclotron energies (up to 20 MeV/n) have shown results that require further study at higher energies. There is also some existing Bevalac work that could be clarified by additional results at lower energy. Especially interesting are studies of "Quasi-elastic scattering" reactions to the low lying continuum, including excitation of giant multipoles, which may provide a mechanism for observed projectile fragmentation results. To this end, a low energy (50-250 MeV/n) beam preparation channel and spectrometer of modest proportions has been proposed. It is anticipated that this facility would be adapted to experiments suggested by outside users and would be especially suitable for beams made available by a proposed line-item modification of the Bevalac. Set up for this facility is planned to begin in mid-1977. Some early data (without benefit of facility) may be taken at energies of 100-250 MeV/n in early 1977.

(13) A Study of 2-Body Fragmentation Modes of Light Nuclei: Kirk et al.† (Louisiana State University)

An experiment to study the diffractive dissociation of nuclear projectiles is presently set up with data taking to begin in the fall of 1976 and extend into early 1977. Studies of 2-body fragmentation modes (e.g. \( ^6\)Li \( \rightarrow d + \alpha \), \( ^6\)Li \( \rightarrow ^3H + ^3He \)) will be used to provide data to test nuclear cluster models.
Outgoing fragment rigidities will be <150 MeV/c. Incident projectiles will include \( ^6\text{Li}, ^{12}\text{C}, ^{16}\text{O} \). Measurements will be made at two energies to study their dependence on energy as well as on target material. If limiting fragmentation holds, one anticipates that these 2-body final states would be independent of projectile energy and target material.

(14) **Production of Neutrons by High Energy Heavy Ions:** Schimmerling et al.\(^{(1)}\) (LBL/Kent State University)

Until recently, no experiment has been set up to measure neutron production at the Bevalac Facility. This experiment will measure the energy (>100 MeV) and angular (0 \( \leq \theta \leq 30^\circ \)) distributions for neutrons produced in the collisions of heavy ion beams (at energies of 250-1000 MeV/nucleon) with various targets. During early 1977 neutron detector efficiencies will be measured, with production data to start in the summer of 1977.

(15) **Atomic Charge Exchange Cross Sections of High Energy Heavy Ions:** Raisbeck et al.\(^{(15)}\) (CNRS/LBL/UCSSI)

The purpose of this experiment is to measure the atomic electron capture and loss cross-sections of high energy heavy ions. These cross sections are of fundamental importance for understanding the basic mechanism of electron transfer reactions at relativistic energies. The results are also of great interest for predicting the behavior of certain isotopes in cosmic rays - those that decay by pure (nuclear) electron capture. A high energy heavy ion beam (having nuclear charge \( Z \) and mass \( A \)) will be passed through a thin target, and the ratio \( (Z-1)^+/A/Z^+/A \) in the exiting beam will be measured with a magnetic spectrometer. Measurements will be made to determine the dependence of these ratios on target thickness, on projectile and target nuclear charge and on energy in the region from 0.25 to 2.1 GeV/nucleon. Beams of \( ^{12}\text{C}, ^{20}\text{Ne}, \) and \( ^{40}\text{Ar} \) on a variety of targets will be studied. Data on C and Ne beams has been taken, the remainder of the running will be completed by late 1976.

(16) **Other Experiments**

In addition to the counter and streamer chamber experiments described, a variety of irradiations of visual detectors (emulsions, lexan detectors, Ag-Cl detectors) have been undertaken. Table 1 summarizes the nature and status of these irradiations.
TABLE I

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Detector</th>
<th>Beam/Energy</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lord et al. 21</td>
<td>Loaded emulsion</td>
<td>Kr, 2.1 GeV/n</td>
<td>To be run</td>
</tr>
<tr>
<td>Herbert et al. 22</td>
<td>Pb-loaded emulsion</td>
<td>Ar or Kr, 2.1 GeV/n</td>
<td>To be run</td>
</tr>
<tr>
<td>Otterlund et al. 23</td>
<td>Emulsion with embedded wires</td>
<td>Fe or Kr, 250 MeV/n and 2.1 GeV/n</td>
<td>To be run</td>
</tr>
<tr>
<td>Price et al. 24</td>
<td>Lexan</td>
<td>Ne, 2.1 GeV/n</td>
<td>Finished, data being analyzed</td>
</tr>
<tr>
<td>Schopper et al. 25</td>
<td>Ag-Cl</td>
<td>He to Kr, 0.1-2.1 GeV/n</td>
<td>Several exposures completed, run continuing</td>
</tr>
<tr>
<td>O'Sullivan et al.</td>
<td>Lexan</td>
<td>Ne, 2.1 GeV/n</td>
<td>To be run</td>
</tr>
</tbody>
</table>

Radio-chemical and γ-ray scanning techniques are also used on targets irradiated with heavy ion beams. Not all of the accelerator time goes to Nuclear Science experiments. Approximately 1/3 of the time is devoted to Biology and Medicine experiments. Basic research on the effects of heavy ion irradiation is being made, with the eventual goal of clinical applications. The wide range of nuclear projectiles makes the Bevalac an ideal place for calibrating the response of cosmic ray detectors to various heavy ions. A large number of experimental groups have calibrated their detectors before flying them in either balloons or satellites. From 100-300 hours/year have been devoted to these calibrations. By the end of 1976, either Fe or Kr should be accelerated. These ions will be of enormous use to cosmic ray physicists.

FUTURE MACHINE DEVELOPMENTS

Two major improvements are presently planned which will substantially extend the capabilities of the Bevalac. The first consists of the installation of a new liner inside the Bevatron's present vacuum chamber. This will improve the pressure from its present 3-5 x 10⁻⁷ torr to around 10⁻⁹ torr. This reduction in pressure will allow the acceleration of much heavier ions and by accelerating lower charge states, allows experimental programs with beams as low as 50 MeV/nucleon. A third injector added to the SuperHILAC will also be required to obtain heavier beams (Pb or U). Fig. 1 compares the capabilities of the present facility (SuperHILAC and Bevalac) with those of the proposed
Funding from ERDA has been requested for FY 1973. An additional request to ERDA is for the funding of a new Heavy Ion Spectrometer System (HISS). HISS features a large solid angle, large magnetic volume, with good energy and spatial resolution. The proposal calls for a superconducting dipole (2 meter diameter and up to 1 meter gap) and quadrupoles. The superconducting aspect should help save power. A central justification for HISS lies in the fact that it will serve as a basic facility for carrying out new generations of physics experiments at the Bevalac. HISS is designed to operate with heavy-ion beams of 250 MeV/nucleon to 2.1 GeV/nucleon and typical resolutions of

\[ \frac{d\sigma}{dp} \sim 10^{-3} \]

Funding is requested for FY 1978.

CONCLUSIONS

The experimental program at the Bevalac is now evolving from its initial round of survey experiments, to a series of second and third generation experiments. While single-particle inclusive studies were the dominant theme for the initial experiments, the trend is toward experiments involving the detection of two or more fragments in the final state. These experiments should provide new keys to unraveling the dynamics of nucleus-nucleus interactions at relativistic energies.
REFERENCES

1. L.S. Schroeder, "Particle Production in Nucleus-Nucleus Collisions at Berkeley", invited talk given at the Topical Meeting on Multiparticle Production on Nuclei at the International Centre for Theoretical Physics, Trieste, Italy (June, 1976).


4. Collaboration of B. Berman (Lawrence Livermore Laboratory) and members listed in Ref. 2, Exp. 350H.


6. Collaboration of the TOSABE group (Tokyo University, Osaka University, and Berkeley) with members of Ref. 2. For complete list of TOSABE Group see Ref. 11.


8. A. Zingher, A. Clark, B. Holley, D. Keefe, L. Kerth, R. Morgado, M. Richardson and L. Schroeder (LBL), Exp. 209H.


10. B. Cork, F. Bieser, D. Greiner, D. Keefe, P. Lindstrom (LBL/UCSSL), Exp. 271H.


13. A. Poskanzer, J. Gosset, W. Meyer, G. Westfall (LBL), H. Gutbrod (RSI), A. Sandoval, and R. Stock (Univ. of Marburg), Expt. 284H.

14. G. Igo, M. Nasser, G. Geaga, H. Spinka, M. Gazzaly, J. McClelland, A. Sagle, P. Oillataguerre (UCLA), J. Carroll, V. Perez-Mendez, E. Whipple, S. Evans (LBL), Exp. 168, 314H. For the polarization measurements the UCLA/LBL group is collaborating with members of the UC Davis group (Brady, King, Johnson, and Harrison), Exp. 341H.


17. D. Hendrie, L. Schroeder, D. Scott (LBL), Expt. 352H.


21. J. Lord, L. Kirkpatrick (University of Washington), P. Katzer (Western Washington State College), Expt. 234H.

22. J. Hebert, C. Hebert (University of Ottawa), A. Van Ginneker (FNAL), Expt. 240H.

23. I. Otterlund, B. Andersson, K. Kristiannson, and B. Lindkvist (University of Lund), Expt. 259H.


25. E. Schopper, H. Baumgartd, J. Schott, E. Obst (University of Frankfurt), Expt. 307H.

26. D. O'Sullivan, A. Thompson, C. O'Ceallaigh (Dublin Institute for Advanced Studies), Expt. 335H.

Fig. 1 Comparison of the present (lower graph) and future (upper graph) capabilities of the SuperHILAC and Bevalac in terms of projectile mass and energy.
Time averaged current in particles /second

Proposed facility

Present facility

Fig. 1