Lawrence Berkeley National Laboratory
Recent Work

Title
Proceedings of Workshop on the Physics using compound nucleus separators, Berkeley, CA, April 10-12, 1997

Permalink
https://escholarship.org/uc/item/6v69x2ps

Author
Gregorich (Editor), Ken

Publication Date
1997-04-12
Proceedings of the Workshop on the Physics Using Compound Nucleus Separators
Ernest Orlando Lawrence
Berkeley National Laboratory
April 10–12, 1997

Kenneth E. Gregorich, Editor
Nuclear Science Division
April 1997
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
Workshop on the Physics Using Compound Nucleus Separators

Kenneth E. Gregorich, Editor

Nuclear Science Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California, Berkeley, California 94720 USA

Lawrence Berkeley National Laboratory
April 10-12, 1997
Conference 9704-118

This work was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.
Workshop on the Physics Using Compound Nucleus Separators  
Lawrence Berkeley National Laboratory  
April 10-12

<table>
<thead>
<tr>
<th>Time</th>
<th>Presenter</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thursday April 10, Morning Session</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9:00 AM</td>
<td>Lee Schroeder</td>
<td>Welcome</td>
</tr>
<tr>
<td></td>
<td>Paul Fallon</td>
<td>Workshop Introduction</td>
</tr>
<tr>
<td></td>
<td>Victor Ninov</td>
<td>World's Compound Nucleus Separators</td>
</tr>
<tr>
<td>10:05 AM</td>
<td>BREAK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ken Gregorich</td>
<td>BGS Design and Capabilities</td>
</tr>
<tr>
<td></td>
<td>Paul Fallon</td>
<td>GFS Design Goals</td>
</tr>
<tr>
<td>12:00 PM</td>
<td>LUNCH</td>
<td></td>
</tr>
<tr>
<td><strong>Thursday April 10, Afternoon Session (Jim Waddington)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:00 PM</td>
<td>Witek Nazarewicz</td>
<td>Theory: Drip-line to Super-Heavies</td>
</tr>
<tr>
<td></td>
<td>Monique Bernas</td>
<td>Fission of Relativistic Nuclei</td>
</tr>
<tr>
<td>3:30 PM</td>
<td>BREAK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phil Woods</td>
<td>RDT and Proton Emitters</td>
</tr>
<tr>
<td></td>
<td>Ken Toth</td>
<td>Short Lived Particle Emitters</td>
</tr>
<tr>
<td>5:05 PM</td>
<td>END</td>
<td></td>
</tr>
<tr>
<td><strong>Friday April 11, Morning Session (Peter Armbruster)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9:00 AM</td>
<td>Peter Möller</td>
<td>The Stability of Superheavy Elements and the Valleys that get us there!</td>
</tr>
<tr>
<td></td>
<td>Sigurd Hofmann</td>
<td>Population and Identification of Superheavy Elements</td>
</tr>
<tr>
<td></td>
<td>Matthias Schädel</td>
<td>Hot Fusion: Results and Prospects</td>
</tr>
<tr>
<td></td>
<td>General Discussion</td>
<td></td>
</tr>
<tr>
<td>11:00 AM</td>
<td>BREAK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>I-Yang Lee</td>
<td>The 8Pi at the BGS Focal Plane</td>
</tr>
<tr>
<td></td>
<td>Michael Hass</td>
<td>Electromagnetic Studies at the Focal Plane</td>
</tr>
<tr>
<td></td>
<td>Andreas Türler</td>
<td>BGS as a Preseparator for Chemical Studies</td>
</tr>
<tr>
<td>12:30 PM</td>
<td>LUNCH</td>
<td></td>
</tr>
<tr>
<td><strong>Friday April 11, Afternoon Session (David Fossan)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:00 PM</td>
<td>Rauno Julin</td>
<td>Merits and Limitations of RDT with RITU</td>
</tr>
<tr>
<td></td>
<td>Peter Butler</td>
<td>Gamma+Electron Spectroscopy A&gt;220</td>
</tr>
<tr>
<td></td>
<td>Denis McNabb</td>
<td>Search for SD in light Actinides</td>
</tr>
<tr>
<td>3:20 PM</td>
<td>BREAK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bill Gelletly</td>
<td>A Birds Eye View of Nuclei Near N=Z</td>
</tr>
<tr>
<td></td>
<td>Mike Carpenter</td>
<td>Gamma-Ray Spectroscopy Beyond the Proton Drip Line for N&gt;82 and Z&lt;82</td>
</tr>
<tr>
<td></td>
<td>Matt Devlin</td>
<td>Channel Selection with Charge Particle Detector Arrays</td>
</tr>
<tr>
<td></td>
<td>Cyrus Baktash</td>
<td>Spectroscopy and Channel Selection Near the Proton Drip Line. General Discussion</td>
</tr>
<tr>
<td>5:40 PM</td>
<td>END</td>
<td></td>
</tr>
<tr>
<td><strong>Saturday April 12, Morning Session</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9:30 AM</td>
<td>INFORMAL DISCUSSION / OPEN QUESTIONS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BGS - Physics/Design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GFS - Physics Design</td>
<td></td>
</tr>
<tr>
<td>12:00 PM</td>
<td>END</td>
<td></td>
</tr>
</tbody>
</table>
Victor Ninov
Lawrence Berkeley National Laboratory
World’s Compound Nucleus Separator

- Why we need Recoil Separators
- Demands for a Recoil Separator
- Principle of Kinematic Separation
- Velocity Separators
- Gas-Filled Separators
- Mass Separators
(16,18O,4n) - REACTIONS WITH ACTINIDE TARGETS

HI, 1n - REACTIONS WITH Pb- and Bi-TARGETS

64Ni-, 70Zn- Projectiles

CROSS SECTION / nb

10^{-4} 
10^{-3} 
10^{-2} 
10^{-1} 
10^{0} 
10^{1} 
10^{2} 
10^{3}

ATOMIC NUMBER

100 102 104 106 108 110 112 114
4n-REACTIONS

- $\nabla C + (U\ldots Cm)$
- $\square N + (Am\ldots Cf)$
- $\circ O + (U\ldots Cf)$
- $\triangle Ne + (U\ldots Cm)$
- $\diamond Mg + (U)$
Ground-State Shell-Correction Energies

\[ \beta_2 \approx 0.00 \]
\[ \beta_4 \approx -0.04 \]

\[ \beta_2 = 0.22 \]
\[ \beta_4 = -0.06 \]

Neutron Number

\( \bullet : (\text{Ti}-\text{Kr}) + \text{^{208}Pb} \rightarrow (Z=104-118) \)

\( \bullet : (\text{O}-\text{Ti}) + \text{^{248}Cm} \rightarrow (Z=104-118) \)

\[ \square \square : \text{Known nuclei, } \alpha \text{ decay, fission} \]

\[ \square : \text{Investigated compound nuclei} \]
Cross Section Systematics for Production of Heavy Elements

$I^{10-30}_4 8\text{Ca} \cdot 208\text{Pb}, 209\text{Bi}$ In-Reactions

Extrapolations

$\frac{(N-Z)}{2} = 3, 4, 5, 6$

$\sigma / \text{cm}^2$

Element number

48Ca
50Ti
54Cr
58Fe
62Ni
64Ni
70Zn
76Ge

102 104 106 108 110 112 114 116

1 nb
1 pb
Demands for a Recoil Separator

- luminosity should be as high as possible
- mass resolving power as large as possible
- separation time as short as possible
- angular and momentum acceptance as large as possible
- yield of separated nuclei not dependent on their chemical properties
Principle of Kinematic Separation

\[ p_{\text{proj.}} = p_{\text{cn}} \]

eg. complete fusion

\[ v_{\text{cn}} = \frac{m_{\text{proj.}}}{m_{\text{proj.}} + m_{\text{tar.}}} \cdot v_{\text{proj.}}. \]

\[ v_{\text{cn}}, E_{\text{cn}} < v_{\text{proj.}}, E_{\text{proj.}}. \]

\[ B\rho = \frac{m \cdot v_{\text{cn}}}{q} \quad \text{for} \quad v_{\text{cn}} B \]

separation of \( cn \) and projectiles in a \( B \)-field is in principle possible

**Problem:** \( q \)-distribution
Velocity Filters

Magnetic field:

$$\vec{F}_{\text{magn.}} = q \cdot (\vec{v} \times \vec{B})$$

Electric field:

$$\vec{F}_{\text{el.}} = q \cdot \vec{E}$$

combined B- and E- fields:

$$F_{\text{tot.}} = q(E + v \cdot B) \quad \text{for} \quad \vec{E} \neq \vec{B}$$

$$F_{\text{tot.}} = 0 \quad \text{for} \quad v = \frac{E}{B}$$

$$F_{\text{tot.}} \neq 0 \quad \text{for all other velocities}$$

- complete separation of the cn from the projectiles
- collection of all charge states of the cn
- stigmatic focusing
- high transport efficiency

- small angular acceptance
- velocity dispersion in the focal plane
2.1 Layout of the recoil separator showing its main components.
### Operating parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum particle current</td>
<td>$5 \times 10^{12}$/s</td>
</tr>
<tr>
<td>Target thickness</td>
<td>100-500 $\mu$g/cm$^2$</td>
</tr>
<tr>
<td>Accepted angle</td>
<td>$52 \times 52$ mrad$^2$</td>
</tr>
<tr>
<td>Solid angle</td>
<td>2.7 msr</td>
</tr>
<tr>
<td>Accepted velocity range</td>
<td>10%</td>
</tr>
<tr>
<td>Transport efficiency</td>
<td>10-70%</td>
</tr>
<tr>
<td>Overall background rejection</td>
<td>$10^7$-$10^{12}$</td>
</tr>
<tr>
<td>Quadrupole apertures</td>
<td>75 mm</td>
</tr>
<tr>
<td>High voltage maximum</td>
<td>600 kV</td>
</tr>
</tbody>
</table>

**Diagram:**

- Target wheel
- Lenses
- Electric Field
- Dipole
- Beam stop
- 7.5° Dipole
- TOF Detectors
- Si Detectors
- \(\gamma, x\)-Ray Detectors

**SHIP 1994**
Table 1: Parameters of the ion-optical system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular acceptance</td>
<td>±3°</td>
</tr>
<tr>
<td>$E/E$</td>
<td>±10°</td>
</tr>
<tr>
<td>$q/q$</td>
<td>±10°</td>
</tr>
<tr>
<td>$p/p$</td>
<td>±5°</td>
</tr>
<tr>
<td>Transport time</td>
<td>$3 \times 10^{-6}$ s</td>
</tr>
<tr>
<td>Distances between:</td>
<td></td>
</tr>
<tr>
<td>Target and first triplet</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Target and first condenser</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Target and second triplet</td>
<td>7 m</td>
</tr>
<tr>
<td>Target and detectors</td>
<td>12 m</td>
</tr>
<tr>
<td>Effective length of quadrupole lenses</td>
<td>35 cm</td>
</tr>
<tr>
<td>Particle radius</td>
<td>10 cm</td>
</tr>
<tr>
<td>Maximum field gradient</td>
<td>10 T/m</td>
</tr>
<tr>
<td>Effective length of first and third condensers</td>
<td>47 cm</td>
</tr>
<tr>
<td>Effective length of second condenser</td>
<td>82 cm</td>
</tr>
<tr>
<td>Distance between plates</td>
<td>15 cm</td>
</tr>
<tr>
<td>Maximum value of electric field strength</td>
<td>20 keV/cm</td>
</tr>
<tr>
<td>Target diameter</td>
<td>1 cm</td>
</tr>
</tbody>
</table>
Gas-Filled Separators

magnetic field region filled with dilute gas

Bohr's approximation

\[ \bar{q} = \frac{v}{v_0} \cdot Z^{1/3} \]
\[ v_0 = \frac{c}{137} \]
\[ B \rho \approx \frac{A}{Z^{1/3}} \]

first order:
- independent of \( c_n \)-velocity
- separates \( c_n \) from projectiles according to their difference in \( B \rho \)

reality:

\[ \bar{q} = Z \cdot (1 - c_1 \cdot e^{-c_2 \cdot \frac{v}{v_0} \cdot Z^{1/3}}) \]

Problems:
- \( q \) is a complex function of \( v, Z \)
- shows fluctuations depending on the atomic shell structure of \( c_n \)
往来校正器(HECK)

- operable under 0° - 150°
- wide angular acceptance
- wide velocity acceptance
- wide charge acceptance
- high efficiency
- dependant on chemical properties of the recoils
- difficult calibration
- "weak" mass resolution
RITH / Jyväskylä
now combined with TESSA
Combination of two Separators

$^{151}$Ho + $^{152}$Er

High-resolution mode

- m/q focusing

$m/\Delta m = 130 \pm 12$

m/q-focussing mode or charge focussing mode
m/q-dispersion minimized
ER focussed onto the detector (3 charges)
Recoil Separators are Useful Tools

- Radiative, stable beam
- Cluster, plasma
- Target
- Recoil separator
- Charged particle, fission fragment, detectors
- SI-Detectors for recoils, α and fission
- Gamma detectors
- RFQ ion guide, cooler trap, precision trap
Ken Gregorich
Lawrence Berkeley National Laboratory
Gas-filled Separator Operating Principles

Gas-Filled Separator Advantages

- **average charge state**: Recoils experience many charge-changing collisions, taking on a well-defined average charge state.
- **velocity independent**: Average charge is proportional to velocity, making the magnetic rigidity independent of velocity (charge from unit acceleration).
- **lower beam rigidity**: By velocities, scattered projectiles, and transfer products all have lower potential rigidity than compound nucleus recoils.
- **target cooling**: Since the separator is filled with gas, a smaller He can be flowed past the target to give better cooling (higher beam current).
- **larger acceptance**: The BGS has a larger angular acceptance than other compound nucleus separators.

Disadvantages

- **scattering in gas**: Scattering in the gas and charge-changing collisions between the gas and nuclei increase the transit time and complicate target design.
- **windows**: Scattered neutrons are necessary to detangle the separator field, leading to some scattering to high transparency.

vacuum recoils

beam

gas-filled recoils

beam
88-INCH CYCLOTRON FACILITY
Berkeley Gas-Filled Separator

A World-Class Facility:
High-Intensity Beams from the 88
Large Angular Acceptance
Large Bending Angle
Large Momentum Acceptance
Samll Cross Sections
Asymmetric Reactions
Better Separation
High Effic., Thick Tgts.

Present Status:
3-D B-Field Simulations Have Been Colpleted
Full Monte-Carlo Simulations of Trajectories are Running
Magnet System Construction is Under Way
Vacuum System and Target Area are Being Designed
Data Acquisition Work has Begun
Magnets & Vacuum Chamber Installation Scheduled for August
First Experiments Planned for Late 1997

Early Heavy Element Experiments with the BGS:
\( ^{248}\text{Cm}(^{26}\text{Mg},4n)^{270}\text{Hs} \) at the center of \( N=162 \) \( Z=108 \) shell
\( ^{238}\text{U} (^{36}\text{S}, 4n)^{270}\text{Hs} \) what are the \( \alpha- \) and SF-halflives?

\( ^{248}\text{Cm}(^{48}\text{Ca},4n)^{292}\text{116} \) spherical superheavies, do they exist?
\( ^{244}\text{Pu}(^{48}\text{Ca},4n)^{288}\text{114} \) 100 times better sensitivity

\( ^{209}\text{Bi}(^{24}\text{Mg},3n)^{230}\text{Am} \) electron capture-delayed fission
\( ^{209}\text{Bi}(^{28}\text{Si},3n)^{234}\text{Bk} \) with \( Q_{EC} > \) fission barrier

\( ^{238}\text{U} + ^{86}\text{Kr} \) binary transfer to produce new neutron-rich nuclides: BGS followed by chemistry
Comparison of Separators for Unslowed Compound-Nucleus Recoils

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SASSY I</td>
<td>DQhQv</td>
<td>±3°</td>
<td>11.0 msr</td>
<td>22°</td>
<td>2.2 Tm</td>
<td>4.0 m</td>
<td>0.67 cm/_%</td>
</tr>
<tr>
<td>SASSY II</td>
<td>DvQhDv</td>
<td>±3°</td>
<td>11.0 msr</td>
<td>55°</td>
<td>2.2 Tm</td>
<td>2.5 m</td>
<td>0.74 cm/_%</td>
</tr>
<tr>
<td>RITU</td>
<td>QvDQhQv</td>
<td>±2.8°</td>
<td>9.5 msr</td>
<td>25°</td>
<td>2.2 Tm</td>
<td>4.7 m</td>
<td>1.00 cm/_%</td>
</tr>
<tr>
<td>DUBNA</td>
<td>DQhQv</td>
<td>±2.9°</td>
<td>10.2 msr</td>
<td>22°</td>
<td>3.1 Tm</td>
<td>4.3 m</td>
<td>0.92 cm/_%</td>
</tr>
<tr>
<td>HECK</td>
<td>DQhQv</td>
<td>±2.8°</td>
<td>9.5 msr</td>
<td>30°</td>
<td>2.2 Tm</td>
<td>3.4 m</td>
<td>0.75 cm/_%</td>
</tr>
<tr>
<td>SHIP</td>
<td>vel. filter</td>
<td>±1.8°</td>
<td>3.9 msr</td>
<td>n/a</td>
<td>n/a</td>
<td>12. m</td>
<td>0.22 cm/_% (v)</td>
</tr>
<tr>
<td>FMA</td>
<td>QQEDEQQ</td>
<td>±2.5°</td>
<td>8.0 msr</td>
<td>-20 +40 -20</td>
<td>1.1 Tm</td>
<td>8.2 m</td>
<td>1.00 cm/_%</td>
</tr>
<tr>
<td>BGS</td>
<td>QvDHD</td>
<td>±6.1°</td>
<td>45.0 msr</td>
<td>70°</td>
<td>2.5 Tm</td>
<td>4.6 m</td>
<td>2.00 cm/_%</td>
</tr>
</tbody>
</table>
\[ ^{40}\text{Ca} + ^{40}\text{Ca} \rightarrow ^{77}\text{Zr} + 3n \]

- \( E_{Zr} = 96-98 \text{ MeV} \)
- \( \text{TGT} = 2.0 \text{ cm} \times 0.5 \text{ cm} \)
- \( Phe = 2 \text{ mBar} \)
- \( MAP = 3.0 \text{ mBar} \)
- \( S_{X} = 0.65 \)
- \( S_{G} = 0.56 \)
- \( S_{F} = 0.56 \)

\( 0 \times \text{LEN} = 0.03 \text{ cm} \)

\( 4 \times \text{LEN} = 0.25 \text{ cm} \)
\[ i := 1.24 \]
\[ Z_i := 5.1 \]
\[ A_i := Z_i^2 + 0.0045(Z_i)^2 \]

\[ v_0 = 2.189 \times 10^6 \text{m sec}^{-1} \]
\[ q := 1.602 \times 10^{-19} \text{coul} \]
\[ \text{MeV} := 1.602 \times 10^{-13} \text{joule} \]
\[ \text{AMU} := 1.66 \times 10^{-27} \text{kg} \]

\[ j := 1.13 \]
\[ v_j := j \cdot v_0 \]

\[ q_{SAS} := Z_i \left[ 1 - 1.04 \cdot e^{-0.91 - (Z_i)^{0.66667}} \right] \]
\[ q_{SLO} := 0.394 \cdot v_j \cdot Z_i^{0.33333} + 1.65 \]
\[ q_{i,j} := \begin{cases} \text{if} (q_{SLO_i,j} > q_{SAS_i,j}, q_{SLO_i,j}, q_{SAS_i,j}) \\ \text{if} \left(\frac{v_j}{v_0} > 4.0, q_{SAS_i,j}, q_{i,j}\right) \end{cases} \]
\[ B_{p_i,j} := \frac{A_i \cdot \text{AMU} \cdot v_j}{q_{i,j} \cdot q^2} \begin{cases} \text{tesla} \cdot \text{m} \\ \text{sec}^{-1} \end{cases} \]

\[ E/A = 0.025 \begin{array}{cccccccccccccc}
0.099 & 0.223 & 0.397 & 0.621 & 0.894 & 1.216 & 1.589 & 2.011 & 2.483 & 3.004 & 3.575 & 4.196 \\
0.099 & 0.153 & 0.217 & 0.294 & 0.328 & 0.364 & 0.402 & 0.441 & 0.481 & 0.522 & 0.565 & 0.607 \\
1.016 & 0.277 & 0.329 & 0.353 & 0.38 & 0.41 & 0.441 & 0.474 & 0.508 & 0.543 & 0.58 & 0.618 & 0.656 \\
1.028 & 0.392 & 0.419 & 0.438 & 0.462 & 0.488 & 0.517 & 0.547 & 0.579 & 0.611 & 0.645 & 0.68 & 0.716 \\
0.349 & 0.5 & 0.504 & 0.519 & 0.54 & 0.564 & 0.591 & 0.619 & 0.649 & 0.68 & 0.712 & 0.745 & 0.779 \\
0.428 & 0.601 & 0.588 & 0.598 & 0.616 & 0.638 & 0.662 & 0.689 & 0.718 & 0.747 & 0.778 & 0.81 & 0.843 \\
0.505 & 0.698 & 0.672 & 0.676 & 0.69 & 0.71 & 0.733 & 0.759 & 0.786 & 0.814 & 0.844 & 0.875 & 0.906 \\
0.583 & 0.798 & 0.756 & 0.753 & 0.764 & 0.782 & 0.803 & 0.827 & 0.853 & 0.881 & 0.909 & 0.939 & 0.97 \\
0.66 & 0.9 & 0.84 & 0.831 & 0.838 & 0.853 & 0.872 & 0.895 & 0.92 & 0.947 & 0.975 & 1.004 & 1.034 \\
0.737 & 1.006 & 0.926 & 0.908 & 0.911 & 0.924 & 0.942 & 0.963 & 0.987 & 1.013 & 1.04 & 1.068 & 1.098 \\
0.814 & 1.108 & 1.013 & 0.988 & 0.985 & 0.995 & 1.011 & 1.031 & 1.053 & 1.078 & 1.105 & 1.132 & 1.161 \\
0.891 & 1.207 & 1.101 & 1.065 & 1.059 & 1.066 & 1.08 & 1.098 & 1.12 & 1.144 & 1.17 & 1.197 & 1.225 \\
1.517 & 1.994 & 1.81 & 1.737 & 1.677 & 1.653 & 1.646 & 1.651 & 1.662 & 1.677 & 1.697 & 1.719 & 1.742 \\
1.842 & 2.396 & 2.334 & 2.108 & 2.01 & 1.964 & 1.944 & 1.939 & 1.944 & 1.954 & 1.97 & 1.988 & 2.01 \\
\end{array} \]
Paul Fallon
Lawrence Berkeley National Laboratory
Quad Triplet + Wien Filter

Recoil $B_p = 0.8 T_m$

Quad Tesla

<table>
<thead>
<tr>
<th>Quad</th>
<th>Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Angular Acceptance $\sim +/- 6^\circ$

$\Delta p = +/- 10\%$

$\Delta v = +/- 25\%$

$\Delta q = 1.3$

Efficiency: 30-70\%
GFS
Gammasphere Fusion Separator
(FRAGMENT)
(GAS FILLED SOLENOID)
1. Reduce Background

- **Fission**
  \( A > 190 \)
  - Rich Variety of Shapes/Collective Excitations
  - Weak Structures in \( \sim 1 \text{mb} \) Channel.
    - Superdeformation: \( \text{Pb} \rightarrow \text{U} \)
    - Octupole Deformations
    - Hyperdeformations!

- **Mass Identification**
  **Decay Tagging:** Identify the Nucleus via \( p, \alpha \)-decay energies.

- **Gamma Identification**
  **Gate on the gamma-ray, look at centroid of “recoil-peak” at the focal plane:**

2. **Doppler Correction**
   (a) Determine the recoil angle
   (b) Correct the Doppler shift
    » Significant Improvement in Resolving Power
AIM: Collect "all" recoils from a fusion-evaporation reaction originating from the target position of gammasphere.

**Design Goals**
- Large Acceptance/Transmission
- Good Beam Rejection
- Recoil (Mass) Identification
- Doppler Correction

**Constraints**
- Fit with/within Existing Gammasphere Frame
- COST

Accept +/- 7 degree Recoil Cone
Beam Rejection: $10^7$

GAS FILLED

- Focus "all" Charge States
- Velocity Compensation
- Low Resolution
Devices Studied:

History: (Al Ghiorso) Considered GAS SYSTEMS.

Two "Element" Design:
1. Focus Products
2. Dispersive (Reject Beam)

<table>
<thead>
<tr>
<th>Focussing</th>
<th>Dispersive</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUADS (Cu-Fe/ Per.)</td>
<td>DIPOLE</td>
</tr>
<tr>
<td>SOLENOID</td>
<td>DIPOLE</td>
</tr>
</tbody>
</table>
Quad + Dipole

(1) Gammasphere

(2) Gammasphere

Permanent

Solenoid + Dipole

(1) Gammasphere

(2) Gammasphere

3.5m
**Solenoid Only**

1 Silicon Array and/or 2 “x,y,z Tracking” Information

(i) 
Gammasphere

![Diagram](image)

(ii) 
Gammasphere

![Diagram](image)

- x,y position > slope, “intercept” of recoil ray

2m
Gas Filled Solenoid + Gammasphere
(Early Layout)
Average Beam and Recoil Rigidities in Carbon and He Gas

- Beam (Carbon)
- Recoil (Carbon)
- Beam (Gas)
- Recoil (Gas)
Reconstruct Ion Path

- Extract \((X,Y,Z)_1\) \((X,Y,Z)_2\) - \(\Theta,\Phi\)
- Doppler Correct.
- Reduce/Remove Solenoid's Aberrations
Determining the Recoil Cone Angle

- Track recoil - obtain exit angle.
- Reconstruct emitted angle.
  \[ \Delta \phi = 40^\circ \quad \Delta \theta = 1^\circ \]

Effect on Resolving Power for \( \gamma^4 \) (0.5mg/cm\(^2\) Targets)

![Graph showing increase in resolving power for different targets](image-url)
Summary

• Tapered S.C. Solenoid - Technically Feasible
  - Design Review (OK), Vendors willing to bid.
  - Beam Rejection OK for $\Delta \beta \rho \sim 30\% \ (20\%)$
  - Resolution $\sim 10\%$

• No Gas Option.
  - Solenoid?
  - Quads (perm) + Wien Filter
Witek Nazarewicz
Oak Ridge National Laboratory/University of Tennessee
- BGS physics
- GFS physics

Probing the effective Hamiltonian

Effective forces for heavy nuclei

- Density dependence
- Effective mass
- Spin-orbit
- Range

Superheavy elements
Heaviest elements & actinides
Proton emitters

Extrapolation properties
Global comparison of $S_{2n}$

- Exp
- Syst
- FRDM
- HFB+SkP

Neutron Number

Global comparison of $S_{2n}$

Fig. 3. Comparison of the neutron drip lines obtained with three mass formulae. The curves indicate the position in the $(N, Z)$ plane of the last even isotope stable against two neutrons emission.


Energy density mass formula

→ Vanishing of shell effects at $N=28, 50,$ and $82$

→ Importance of $M^*$
How well can HF do for known $\alpha$-decay chains?

Table 6
Calculated and experimental values of $Q_\alpha$ for the $^{264}$Mt $\rightarrow$ $\cdots$ $^{248}$Fm $\alpha$-decay chain

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>HF+SkP</th>
<th>HF+SLy7</th>
<th>WS</th>
<th>exp $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{264}$Mt</td>
<td>10.82</td>
<td>10.81</td>
<td>11.11</td>
<td>10.80</td>
</tr>
<tr>
<td>$^{260}$Nh</td>
<td>10.16</td>
<td>10.21</td>
<td>10.12</td>
<td>9.92</td>
</tr>
<tr>
<td>$^{256}$Rf</td>
<td>9.63</td>
<td>8.77</td>
<td>9.18</td>
<td>8.95</td>
</tr>
<tr>
<td>$^{252}$No</td>
<td>9.04</td>
<td>7.97</td>
<td>8.51</td>
<td>8.55</td>
</tr>
</tbody>
</table>

$^a$ Ref. [41].
S. Ciwick et al.

HF + SkP + S-pairing (LN)
HF + SLy7 + S-pairing (LN)
WS

\( ^{310}126_{184} \)

**neutrons**

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4p(_{1/2} )</td>
</tr>
<tr>
<td>3f(_{5/2} )</td>
</tr>
<tr>
<td>4p(_{3/2} )</td>
</tr>
<tr>
<td>2h(_{9/2} )</td>
</tr>
<tr>
<td>3f(_{7/2} )</td>
</tr>
<tr>
<td>1k(_{17/2} )</td>
</tr>
<tr>
<td>1j(_{13/2} )</td>
</tr>
<tr>
<td>2h(_{11/2} )</td>
</tr>
<tr>
<td>4s(_{1/2} )</td>
</tr>
<tr>
<td>3d(_{3/2} )</td>
</tr>
<tr>
<td>3d(_{5/2} )</td>
</tr>
<tr>
<td>2g(_{7/2} )</td>
</tr>
<tr>
<td>1j(_{15/2} )</td>
</tr>
<tr>
<td>2g(_{9/2} )</td>
</tr>
<tr>
<td>1i(_{11/2} )</td>
</tr>
<tr>
<td>3p(_{1/2} )</td>
</tr>
<tr>
<td>3p(_{3/2} )</td>
</tr>
<tr>
<td>2f(_{5/2} )</td>
</tr>
<tr>
<td>1i(_{13/2} )</td>
</tr>
<tr>
<td>4p(_{1/2} )</td>
</tr>
<tr>
<td>3f(_{5/2} )</td>
</tr>
<tr>
<td>4p(_{3/2} )</td>
</tr>
<tr>
<td>2h(_{9/2} )</td>
</tr>
<tr>
<td>3f(_{7/2} )</td>
</tr>
<tr>
<td>1k(_{17/2} )</td>
</tr>
<tr>
<td>1j(_{13/2} )</td>
</tr>
<tr>
<td>2h(_{11/2} )</td>
</tr>
<tr>
<td>4s(_{1/2} )</td>
</tr>
<tr>
<td>3d(_{3/2} )</td>
</tr>
<tr>
<td>3d(_{5/2} )</td>
</tr>
<tr>
<td>2g(_{7/2} )</td>
</tr>
<tr>
<td>1j(_{15/2} )</td>
</tr>
<tr>
<td>2g(_{9/2} )</td>
</tr>
<tr>
<td>1i(_{11/2} )</td>
</tr>
<tr>
<td>3p(_{1/2} )</td>
</tr>
<tr>
<td>3p(_{3/2} )</td>
</tr>
<tr>
<td>2f(_{5/2} )</td>
</tr>
<tr>
<td>1i(_{13/2} )</td>
</tr>
</tbody>
</table>

SkP  SLy7  SW
$^{310}_{126}^{184}$

Protons

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>4s$_{1/2}$</th>
<th>3d$_{3/2}$</th>
<th>3d$_{5/2}$</th>
<th>2g$_{7/2}$</th>
<th>1j$_{15/2}$</th>
<th>2g$_{9/2}$</th>
<th>1i$_{11/2}$</th>
<th>3p$_{1/2}$</th>
<th>3p$_{3/2}$</th>
<th>2f$_{5/2}$</th>
<th>1i$_{13/2}$</th>
<th>2f$_{7/2}$</th>
<th>1h$_{9/2}$</th>
<th>3s$_{1/2}$</th>
<th>2d$_{3/2}$</th>
<th>1h$_{11/2}$</th>
<th>2d$_{5/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\[ \hat{\mathcal{H}} = \hat{\mathcal{H}}_{\text{ws}} + \hat{\mathcal{H}}_{\text{s.o.}} + \left\{ V_{\text{coul}} - V_{\text{coul}(0)} \right\} x_{\text{coul}} + V_{\text{coul}(0)} \]
$^{288}$I$^{	ext{118}}$: SkP 2.8  SLY7 8.6  WS 0.9 μs
$^{280}$I$^{	ext{114}}$: 1.3  3.8  1.4 μs
Alpha energies assigned to the decay chain of $^{277}112$
Nuclear Structure in the Actinides

very large deformations super-, hyper-

multiphonon states

large deformations, shape coexistence

low-energy octupole and dipole modes

Shell model

Physics Division ORNL/Dept. of Physics UT
$S_{2p}/\text{MeV}$ vs. $N$ for $\text{HF} + \delta + LN$.
S. Cwiok et al.

HF + $S + LN$ (with odd-$T$ terms)

E/MeV

-1.0
-0.6
-0.2
0.2
0.6
1.0

$11/2^{-} \{v^+1115/2\}$
$9/2^{+} \{v^+1111/2\}$
$7/2^{+} \{v^-12d_{9/2}\}$
$3/2^{+} \{v^-12g_{7/2}\}$
$1/2^{+} \{v^-13d_{5/2}\}$
$9/2^{-} \{v^-11j_{15/2}\}$

$249$Pu
$251$Pu

$9/2^{+} \{v^+12g_{9/2}\}$
$7/2^{+} \{v^+12g_{7/2}\}$
$1/2^{+} \{v^+13d_{5/2}\}$
$11/2^{-} \{v^-11j_{15/2}\}$
Figure 2
Proton emitters

\[ \ln \frac{2}{T_{1/2}} \propto \left( \frac{Z e^2}{R_c - Q_{p,\text{nuc}}} \right)^{-1/2} \exp(-2G_{ji}) \]

\[ G_{ji} = \sqrt{2m/\hbar^2} \int_{R_a}^{R_c} dr \sqrt{V_{ji}(r) + V_{\text{Coul}}(r) + V_l(r) - Q_{p,\text{nuc}}} \]

\[ E_p = (1233 \pm 3) \text{ keV} \]

\[
\begin{array}{c|c}
T_{1/2} & \text{ms} \\
0 & 3 \\
2 & 26 \\
5 & 81 \\
\hline
(85 \pm 10) & \text{(Exp.)} \\
\end{array}
\]

\[ ^{151}\text{Lu}(11/2^-) \rightarrow ^{150}\text{Yb}(0^+) \]
Very narrow resonances: $\Gamma \sim 10^{-22} \text{ - } 10^{-15} \text{ MeV}$

$^{147}\text{Tm}$

$d_{3/2}, Q=1139 \text{ keV}$

$log(|\psi|)$

$r (\text{fm})$
\[ t_{1/2} = \frac{1}{S_p} \frac{\hbar}{\nu} \ln 2 \]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>( Q_p ) (keV)</th>
<th>orbit</th>
<th>( t_{1/2,p} )</th>
<th>( S_p^{\exp} )</th>
<th>( S_p^{\text{th}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{109}_{53}\text{Mo} )</td>
<td>829 ± 4</td>
<td>( 1d_{5/2} )</td>
<td>(100 ± 5) ( \mu s )</td>
<td>(10 ± 1) ( \mu s )</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>( ^{113}_{55}\text{Cm} )</td>
<td>977 ± 4</td>
<td>( 1d_{5/2} )</td>
<td>(17 ± 2) ( \mu s )</td>
<td>(0.540 ± 0.06) ( \mu s )</td>
<td>0.032 ± 0.005</td>
</tr>
<tr>
<td>( ^{149}_{69}\text{Tm} )</td>
<td>1071 ± 3</td>
<td>( 0h_{11/2} )</td>
<td>(2.8 ± 1.2) ( s )</td>
<td>(2.6 ± 0.2) ( s )</td>
<td>0.9 ± 0.7</td>
</tr>
<tr>
<td>( ^{149}_{69}\text{Tm} )</td>
<td>1132 ± 4</td>
<td>( 1d_{3/2} )</td>
<td>(360 ± 40) ( \mu s )</td>
<td>(210 ± 20) ( \mu s )</td>
<td>0.58 ± 0.06</td>
</tr>
<tr>
<td>( ^{151}_{71}\text{Lu} )</td>
<td>1255 ± 3</td>
<td>( 0h_{11/2} )</td>
<td>(130 ± 150) ( ms )</td>
<td>(60 ± 5) ( ms )</td>
<td>0.5 ± 0.4</td>
</tr>
<tr>
<td>( ^{157}_{73}\text{Tb} )</td>
<td>947 ± 7</td>
<td>( 2s_{1/2} )</td>
<td>(300 ± 110) ( ms )</td>
<td>(220 ± 60) ( ms )</td>
<td>0.74 ± 0.34</td>
</tr>
<tr>
<td>( ^{151}_{75}\text{Re} )</td>
<td>1214 ± 6</td>
<td>( 2s_{1/2} )</td>
<td>(370 ± 40) ( \mu s )</td>
<td>(190 ± 30) ( \mu s )</td>
<td>0.51 ± 0.10</td>
</tr>
<tr>
<td>( ^{161}_{75}\text{Re} )</td>
<td>1338 ± 7</td>
<td>( 0h_{11/2} )</td>
<td>(325 ± 44) ( ms )</td>
<td>(86 ± 14) ( ms )</td>
<td>0.27 ± 0.06</td>
</tr>
<tr>
<td>( ^{165}_{77}\text{Ir} )</td>
<td>1733 ± 7</td>
<td>( 0h_{11/2} )</td>
<td>(350 ± 70) ( \mu s )</td>
<td>(100 ± 10) ( \mu s )</td>
<td>0.29 ± 0.07</td>
</tr>
<tr>
<td>( ^{165}_{77}\text{Ir} )</td>
<td>1086 ± 6</td>
<td>( 2s_{1/2} )</td>
<td>(110 ± 15) ( ms )</td>
<td>(36 ± 7) ( ms )</td>
<td>0.33 ± 0.08</td>
</tr>
<tr>
<td>( ^{167}_{77}\text{Ir} )</td>
<td>1261 ± 7</td>
<td>( 0h_{11/2} )</td>
<td>(7.5 ± 1.9) ( s )</td>
<td>(2.0 ± 0.4) ( ms )</td>
<td>0.27 ± 0.09</td>
</tr>
<tr>
<td>( ^{171}_{79}\text{Au} )</td>
<td>1718 ± 6</td>
<td>( 0h_{11/2} )</td>
<td>(2.22 ± 0.29) ( ms )</td>
<td>(0.35 ± 0.04) ( ms )</td>
<td>0.16 ± 0.03</td>
</tr>
</tbody>
</table>
Phil Woods
Edinburgh University
Holistic Studies Beyond the Proton Drip-Line

- (near) ground-state properties of proton unbound nuclei
- structure of excited states of proton unbound nuclei - the development of Recoil Decay Tagging, RDT
The Proton Drip Line
from $Z=69-83$
Proton Spectroscopic Factors

for \( 82 > Z > 64 \)

\[
S_j^{\text{exp}} = \frac{t_{1/2}^\text{calc}}{t_{1/2}^\text{exp}}
\]

\[
S_j^{\text{theory}} = \frac{P}{9} - \text{D. Kurath}
\]

Low seniority shell model calculation

\( P = \text{number of proton hole pairs in daughter relative to } Z=82 \text{ shell} \)

\( \text{eg } P = \frac{1}{4} \text{ for } ^{177}\text{Tl} \)
SPECTROSCOPIC FACTORS FOR PROTON RADIOACTIVITY

- $h_{11/2}$
- $d_{3/2}$
- $s_{1/2}$

$S = P/9$
beam γ-ray detection

Primary Beam

Implant of nucleus - Obtain \((x, y, E_0, t_0)\)

DSSD

Recoil Decay Tagging
RDT

PRC51, 78 (1995)

ZPA 325, 197 (1986)

Recoiling nuclei dispersed according to \(A/q\)

Subsequent radioactive decay of implanted nucleus - Obtain \((x, y, E_1, t_1)\)

\(300 \mu m\)
First observation of in-beam \( \gamma \)-rays from a ground-state \( \beta \)-emitter! \( \sigma_{^{109}I} \sim 3 \mu b \)
$^{54}Fe + ^{92}Mo \rightarrow ^{146}Er^*$

$^{141}Ho \ p$-decay!

April 2, '97

EDF Run 14 Sum 2,842

$^{149}Tb \rightarrow \Delta E \ 4\ h

17 \ h\m
360

150 \ 0\min

425 \ 7\ mins$
Ken Toth
Oak Ridge National Laboratory
STUDY OF Pb, Po, Pt & Emitters
NEAR THE DRIP LINE

FMA

$^{18}$Kr., Mo Beams
Incident on
Zn and Mo Targets.

$^{180, 181, 182}$Pb.
$^{166, 167, 168}$Pt.
$^{190, 191}$Po.

Also,
$^{186-189}$Bi.
MASS DIFFERENCES (MASSES)

HALF-LIVES
α-DECAY RATES

STRUCTURE INFORMATION (SHELLS)

\[ \begin{align*}
Z &= 82 \text{ STABILITY MIDWAY BETWEEN } N = 126 \text{ AND } \\
N &= 82.
\end{align*} \]
\[ \alpha \text{ - Decay Reduced Width:} \]
\[ \delta^2 = \frac{\lambda h}{P} \]

"\( \lambda \)" is decay constant.
"\( P \)" is penetrability factor.

\( \delta^2 \approx \) transition probability, where dependence of decay rate on \( E_x, Z, A \), has been removed.

5-wave \( \alpha \)-decay transitions:
\( \text{gr. state} \rightarrow \text{gr. state of e-e nuclei} \).
$^{92}\text{Mo} + ^{90}\text{Zr}$

$E(^{92}\text{Mo}) = 422\text{MeV}$

\[ \text{ENERGY (keV)} \]

\[ \text{COUNTS} \]
(a) All Alphas, t<2 ms
(b) Gated with M 166
(c) Cor. with $^{162}$Os
HRIBF Recoil Mass Spectrometer

Momentum Separator
(P/Q)

Target

Beam

Mass Separator
(A/Q)

ED1

Q4 Q5

Q2

Q1

S1

S2

D2

D1

Q3

Fingers

ED2

D3

Q6 Q7

Focal Plane

Inverse reactions
High rigidity beams (K=100)
Excellent beam rejection (>10^{12})
Excellent mass separation (M/ΔM=450)
Large energy acceptance
Large solid angle
Large A/Q acceptance
Sigurd Hofmann
GSI
Hexadecapole Deformation $\varepsilon_4$

$\lambda_n = 36.60, a_n = 0.80$ fm

$^{272} \text{I}^{10}$

Single-Neutron Energy (MeV)

Spheroidal Deformation $\varepsilon_2$
\[ S. Cwiok et al. 1996 \]

**Diagram Description**

- Two graphs are shown, each labeled with 'SkP' and 'SLy7', representing different potential energy surfaces.
- The graphs show a series of data points and lines that indicate various isotopes and their properties.
- The isotopes are numbered from 162 to 184, with specific lines and markers indicating different values.

**Notes**

- The heaviest isotopes range from 118 to 128.
- The beam used is 86Kr to 110Po.

**Data Points**

- 267/110: \( 3 \, \text{m/s} \)
- 269/110: \( 170 \, \text{m/s} \)
- 271/110: \( 11 \, \text{m/s} \)
- 273/110: \( 76 \, \text{m/s} \)
- 277/112: \( 7 \, \text{m/s} \)
- 283/114
- 290/116
SHIP 94

- Target wheel
- Lenses
- Electric Field
- Magnets
- Beam stop
- 7.5 deg Magnet
- TOF Detectors
- Si-Detectors
- γ-Detectors

Projectiles
\( \alpha-\alpha \) correlated particles for \( ^{208}\text{Pb}(^{58}\text{Fe},\text{ln})^{265}\text{Pb} \)
\((^{50}\text{Ti} \text{ and } ^{58}\text{Fe}) + (^{208}\text{Pb})\)

- Bass-barrier
- \(\text{CN}=^{258}104\)

Graph showing cross-section in barns versus \(E^* / \text{MeV}\), with peaks for 1n, 2n, and 3n emissions. The nucleus \(^{266}108\) is indicated at higher \(E^*\) values.
Neutron Number vs. Proton Number diagram showing various isotopes and decay chains. The decay chains are labeled with Greek letters and numbers, indicating different half-lives and isotopes. The diagram includes elements such as Fm, No, and others with specific proton and neutron numbers.
Fusion Initiated by Transfer (FIT)

$^{64}\text{Ni} + ^{208}\text{Pb} \rightarrow ^{272}\text{110}$

$E_{\text{CM,exp}} = 236.2$ MeV

$E^*_{\text{exp}} = 10.2$ MeV
Ground-State Shell-Correction Energies

**a) Z=110**

beam: stable \[ {^{60}\text{Ni}} {^{62}\text{Ni}} {^{64}\text{Ni}} {^{66}\text{Ni}} {^{68}\text{Ni}} {^{70}\text{Ni}} {^{72}\text{Ni}} \] + \[ {^{208}\text{Pb}} \]

Möller (FRDM) Sobiczewski

**b) Z=112**

beam: stable \[ {^{64}\text{Zn}} {^{66}\text{Zn}} {^{68}\text{Zn}} {^{70}\text{Zn}} {^{72}\text{Zn}} {^{74}\text{Zn}} {^{76}\text{Zn}} \] + \[ {^{208}\text{Pb}} \]

Sobiczewski Möller (FRDM)

**c) Z=114**

radioactive beam: stable \[ {^{66}\text{Ge}} {^{68}\text{Ge}} {^{70}\text{Ge}} {^{72}\text{Ge}} {^{74}\text{Ge}} {^{76}\text{Ge}} {^{78}\text{Ge}} \] + \[ {^{208}\text{Pb}} \]

Sobiczewski Möller (FRDM)
Participants

Peter Armbruster
Helmut Folger
Fritz-Peter Heßberger
Sigurd Hofmann
Rudo Janik
Matti Leino
Gottfried Münzenberg
Viktor Ninov
Andre Popeko
Stefan Saro
Hans-Jochen Schött
Christelle Stodel
Alexander Yeremin

Institutes:

GSI Darmstadt
JINR Dubna
University Bratislava
University Jyväskylä
Matthias Schädel
GSI
HOT FUSION: RESULTS AND PROSPECTS
- HOT FUSION IN HEAVY ELEMENT RESEARCH -

Matthias Schädel, GSI, Darmstadt

Regions of Interest - Paths to enter

"Cold -" vs. "Hot - Fusion"
- borderline or transition region
  - characteristica
  - differences
  - regions of nuclei
    - $\sigma (Z)$ - dependence

Important Special Aspects
- $\Gamma_n/\Gamma_f$
  - fission times
  - pre - equilibrium particle emission

Alternative Approaches
- ($\alpha x n$) - reactions

Workshop on Gas - Filled Separators, Berkeley, April 10-12, 1997
FUSION

"hot"

\[ ^{232}_{90}\text{Th} \rightarrow ^{254}_{99}\text{Es} + ^{13}_{6}\text{C} \rightarrow ^{48}_{20}\text{Ca} \]

"cold"

\[ ^{208}_{82}\text{Pb}, ^{209}_{83}\text{Bi} + ^{50}_{22}\text{Ti} \rightarrow ^{86}_{36}\text{Kr} \]

"alternative"

\[ ^{154}_{62}\text{Sm} \rightarrow ^{160}_{64}\text{Gd} \]
$^{22}_{10}\text{Ne}$ $^{248}_{96}\text{Cm}$ FUSION $^{270}_{106}\text{Sg}$ $^{265}_{106}\text{Sg}$

5 x 10$^{15}$ PROJECTILES ON TARGET 5 x 10$^{8}$ COMPOUND NUCLEI 1 ATOM
Do we understand "HOT FUSION"?

I. Semi-empirical approaches (educated guesses)

e.g., fusion-evaporation codes like HIVAP:

Parameters

Masses
- particle separation energies
- shell effects, \( S = M_{\text{exp}} - M_{LD} \)

Fission barriers \( B_f = B_{fLD} - S \)

Level densities \( \rho(E, J) \approx \exp[2(aE_J)^{1/2}] \)
\( a = â\{1 + f(E)S/E\} \)
\( f(E) = 1 - \exp(-E/E_d) \)

Damping constant \( E_d = 18 \text{ MeV} \)

II. Empirical descriptions

\( \Rightarrow \) No! We can describe it
HIVAP "without" fusion barrier
Projectile energy / MeV

Cross section / nb

HIVAP calculations

- experimental data

\( ^{248}\text{Cm}(^{15}\text{N},4n)^{259} \)

\( ^{249}\text{Bk}(^{15}\text{N},4n)^{260} \)

\( ^{249}\text{Cf}(^{15}\text{N},4n)^{260} \)

\( ^{249}\text{Cf}(^{18}\text{O},4n)^{263} \)
$^{16,18}O$-Projectiles

$^{208}Pb, ^{209}Bi$-Targets

Cross section / nb

Fissility, $x_m$

PRODUCT Z

$^*$ 100-103
$\Delta$ 104
$\Box$ 105
$\nabla$ 106
$\bigcirc$ 107-109
$\bigtriangleup$ 110
$\bigtriangledown$ 111
$\blacklozenge$ 112
Cold – and Hot Fusion: Common Feature?!

Important,
i.e., mainly determining the $\sigma(Z)$-dependence, is only the fission competition in the evaporation of the last neutron.

"Second order " effects:

- fusion hindrance in cold fusion.
- fission competition in the evaporation of the first neutrons in hot fusion.

$(\Gamma_n/\Gamma_f \approx 0.5)$

BUT:

This is in contradiction to calculations which indicate a strong influence of fusion hindrance for Pb-based systems.
Fission Competition, Time Scales, and Pre-Equilibrium Reactions


$^{22}\text{Ne}, ^{26}\text{Mg}, ^{27}\text{Al}, ^{31}\text{P on } ^{232}\text{Th}, ^{236}\text{U, } ^{238}\text{U} (^{22}\text{Ne, } ^{8}\text{n}) ^{252}\text{No}$

"... conclude that ... the main losses in the yields of transcurium ER formed in heavy ion "hot" fusion reactions arise at the final steps of the deexcitation cascades."

"... qualitative conclusion that fission does not play decisive role in their formation, at least, at the first step of the deexcitation process."

for evaporation of 6n, 7n, 8n (E* 40 MeV)

leading to $^{242}\text{Cf}, ^{248}\text{Fm, }^{250}\text{Md, }^{252}\text{No: } \Gamma_n/\Gamma_{tot} \approx 0.5$ !

i.e., 50 % survival probability for each step, or

"only" f = 10-20 loss for 4n-evaporation.

---

![Graphs](image-url)
\[ ^{208}\text{Pb} + ^{70}\text{Zn}, \approx 1 \text{ pb} \]

\[ ^{238}\text{U} + ^{34}\text{S} + ^{36}\text{S}, \approx 3 \text{ pb} \]

\[ ^{244}\text{Pu} + ^{34}\text{S} + ^{36}\text{S}, \approx 0.3 \text{ pb} \]

\[ ^{248}\text{Cm} + ^{22}\text{Ne}, \approx 0.3 \text{ nb} \]

\[ ^{238}\text{U} + ^{26}\text{Mg}, \approx 1 \text{ nb} \]

\[ ^{244}\text{Pu} + ^{22}\text{Ne}, \approx 3 \text{ nb} \]
EVAPORATION RESIDUES

TARGETS

\(^{208}\)Pb, \(^{209}\)Bi

\(^{232}\)Th

\(^{238}\)U

\(^{244}\)Pu

\(^{248}\)Cm

\(^{254}\)Es

PROJECTILES

\(^{50}\)Ti ..... \(^{82}\)Se

\(^{18}\)O ..... \(^{48}\)Ca

CHANNEL

1n

4n

3n

2n

\(^{48}\)Ca

48 Ca

178 - 180

\(N\)

\(\text{ISI Darmstadt Nuclear Chemistry Group}\)
$E^*\left(\frac{296}{116_{180}}\right) = 16 - 40 \text{ MeV}$

48 Ca + 248 Cm

1: SASSY
2: SHIP
3-8: CHEMISTRY

The $^{48}$Ca - Path

Nuclear Chemistry Group
(αxn)-REACTIONS


7.1 10.5 MeV/u $^{12}$C, $^{11}$N, $^{16}$O on $^{197}$Au, $^{209}$Bi:
E. $θ$, $σ$ of $α$-particles measured:

"... direct projectile breakup reactions occur in interactions between the projectile and the surface of the target nucleus and, thus, involve the larger impact parameter. These reactions would then leave residual nuclei that are excited to energies considerably below the excitations involved in the full compound nucleus reactions."


$^{215}$Cm+$^{18}$($α$3n)$^{259}$No discovered


$^{239}$Pu($^{12}$C,$α$2n)$^{215}$Cf measured

factor $≈$ 5–10 higher $σ$ than 4n- and 3n-channel


$^{219}$Cf($^{12}$C,$α$1n)$^{256}$No measured

factor $≈$ 10 higher $σ$ than 4n-channel

H. Bruchertseifer et al., JINR P 7-80-666 (1980)

$^{176}$Lu($^{22}$Ne,$α$2n)$^{191}$Au measured

broad excitation function
$^{12}C + ^{249}Cf \rightarrow ^{261}Rf^*$

Relative cross section

Energy (MeV)


$\alpha 2n$  
$\alpha 3n$  
$\alpha 4n$  
$\alpha n$

$^{250}Fm$  
$^{254}No$  
$^{255}No$  
$^{253}No$  
$^{256}No$  
$^{257}Rf$

$\alpha x n - EVR?$  
or transfer products?
WHAT'S NEEDED

Targets (facilities, expertise, new technologies):

\[ ^{232}\text{Th}, ^{236,238}\text{U}, ^{242,244}\text{Pu}, ^{248}\text{Cm}; - ^{249}\text{Bk}, ^{254}\text{Es}. \]

Beams (intense):

\[ ^{18}\text{O}, ^{22}\text{Ne}, ^{26}\text{Mg}, ^{30}\text{Si}, ^{40}\text{Ar}, \text{ and } ^{34,36}\text{S}, ^{48}\text{Ca}. \]

Techniques:

* Recoil separators with large angular and momentum acceptance (gas-filled or not), and a good suppression of near-target transfer products.

* Sensitive radiochemical techniques; high separation factor, fast

Reaction Studies:

more dedicated studies in the region of highly fissile nuclei; e.g. \( E_\alpha, \Theta_\alpha \) in coincidence with heavy-element EVR.

Motivated young scientists, support (financial) from authorities, and support from THEORY!
I-Yang Lee
Lawrence Berkeley National Laboratory
Delayed $\gamma$-ray, $\tau > 1 \mu$sec

- isomeric states
- following $\alpha$, $\beta$, or $p$-decay

- N=Z nuclei
  - n-p pairing
  - Single particle states near $^{100}$Sn

- $\beta$-decay
  - Low spin, high excitation energy states
  - Order to chaos

- Proton activity
  - From excited states
  - To excited states
Compton Shielded Ge detector

Number of detectors $N = 20$
Source to Ge distance $= 15 \text{ cm}$
Solid angle $\Omega = 0.0076 \%$
Peak efficiency $\epsilon_p = 0.15 \ (1.33 \text{ MeV})$

Total efficiency $N \Omega \epsilon_p = 0.023$
Peak-to-total $= 0.55$
Resolving power $= 1000$

one detector at closest distance $\Omega \epsilon_p = 0.015$
Event Rate = 3000

8-π at BGS

Rate (events/second)

Mγ

1-fold

2-fold

3-fold
8-π at BGS

Raw Ge Rate = 10 k

1-fold

2-fold

3-fold

Rate (event/sec)

Mγ
### Counting Rate

**Cross section** = 1 µb  
**Target thickness** = 1 mg/cm² (A=100)  
**Beam intensity** = 1 pµA  
**BGS efficiency** = 30%  

**Focal plane event rate = 30 /sec**

<table>
<thead>
<tr>
<th>$M_\gamma$</th>
<th>Raw Ge singles rate</th>
<th>total clean rate</th>
<th>$\gamma$</th>
<th>$\gamma - \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1 /sec</td>
<td>5.7/sec</td>
<td>0.45/sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>490 k/day</td>
<td>39 k/day</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2 /sec</td>
<td>10.2/sec</td>
<td>1.76/sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>880 k/day</td>
<td>152 k/day</td>
<td></td>
</tr>
</tbody>
</table>
8π array at BGS

Counting Rate

Cross section = 1 b
Target thickness = 1 mg/cm² (A=100)
Beam intensity = 1 µA
BGS efficiency = 80%

Focal plane event rate = 3 × 10⁷/sec

Raw Ge single rate < 10 k/sec

<table>
<thead>
<tr>
<th>Mγ</th>
<th>event rate</th>
<th>total clean rate</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>γ</td>
<td>γ−γ</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.1 × 10⁵/sec</td>
<td>59.2 k/sec</td>
<td>4.7 k/sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5115 M/day</td>
<td>406 M/day</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.6 × 10⁵/sec</td>
<td>54.4 k/sec</td>
<td>9.3 k/sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4700 M/day</td>
<td>804 M/day</td>
<td></td>
</tr>
</tbody>
</table>
$8\pi$ efficiency for extended source

Source-Ge distance = 15 cm
Selection of Weak Decay Channel

\[ \alpha-, \ p- \text{decay} \]
\[ \text{Energy specific} \]
\[ \text{RDT} \]

Isomeric \( \gamma- \text{decay} \)

\[ \beta- \text{decay} \]
\[ \text{Energy nonspecific} \]
\[ \text{Long lived} \]
\[ \text{\( \gamma \)-ray multiplicity} \]
\[ \text{\( \gamma \)-ray sum energy} \]
\[ \text{moving tape select lifetime} \]
Arrived at LBNL on 4/3/97 from Chalk River.

In storage at Buildings 51 and 88.

To operate at BGS requires:

Supporting structure.

Liquid nitrogen filling system.

Cables.
Structure Studies of Isomers and Ground States with

LBL Gas-Filled-Magnets

Michael Hass
Department of Particle Physics
The Weizmann Institute

Gamma-decay studies of isomers 
$^{182}$Os(I=K=25)

- Quadrupole moments (*signs*) of high-spin isomers.
- Magnetic moments of ground states in mirror nuclei (f-shell).

ADVANTAGES

1) High transmission efficiency
2) Short transit time!!
3) "Good" beam-products separation
\(^{182}\text{Os (I=K=25)}\)

- Decay-path, and in particular a branch from K=25 to gs\(_b\)(K=0), established; but **ONLY very partially**.
- Magnetic moment measured \([g=+.425(8)]\)
- Quadrupole moment measured \([|Q|=4.2(2) \text{ eb}]\)

Picture of "tunneling in the \(\gamma\)-plane" still unsettled.
$^{182}\text{Os} \ (K=I=25)$

- $\tau = 216 \ \text{ns}$

- $^{150}\text{Nd}(^{36}\text{S},4n)^{182}\text{Os}$ at $E(^{36}\text{S})=160 \ \text{MeV}$
  $\Rightarrow v/c[\text{recoils}]=0.6 \ \text{cm/ns}$
  $\Rightarrow$ For GEM length of 200 cm,
  $t(\text{flight})=350 \ \text{ns}.$
  $\Rightarrow$ about 20% $K=25$ isomers reach fp.
  Timing at the fp with \textit{individual} nuclei.

Previous experiments at Daresbury:

\[\text{\rule{0.5\textwidth}{0.5mm}}\]

\[200 \ \text{ns}\]

$I=\sim 1-2 \ \text{pnA}$ and timing with the pulsed beam.

- Particular and immediate aim:
  level scheme below isomer

Similar considerations also for measuring sign-of-Q. for this case and others as well.
a. The experimental set-up (shown for the $^{144}$Gd case).

b. Ratio functions (eq.2) for polarized $^{144}$Gd($10^+$) isomers:

$$R(t) = \frac{Y(0^\circ, t) - Y(90^\circ, t)}{Y(0^\circ, t) + Y(90^\circ, t)} = \frac{3}{4}A_{22} \sum S_{n1}^{22} \cos(n\omega_0 t)$$

$$R(t) = \frac{Y_a(t) - Y_b(t)}{Y_a(t) + Y_b(t)} = -\frac{3}{2}\mu_e F_L \sum S_{n1}^{12} \sin(n\omega_0 t)$$
The pxf detector is for initial identification and diagnostic purposes. It is then replaced by the tilted-foil apparatus and MCP. r counters are placed at the focal-plane area.
$^{92}\text{Mo}^{8+}$ decay

$^{13}\text{Na}^{+} \xrightarrow{\text{coinc.}} \text{MCP detector}$

at local plane of RMS - Rochester

$t (\text{transit}) \approx 1 \mu s$ ! (only $\approx 4\%$ remain)

$\tau = 290 \text{ ms}$

Counts/channel

Channel #
Magnetic Moments of Mirror Nuclei

**Isoscaler component:**
\[
\mu(M_T) + \mu(-M_T) = \mu_0[1+(g_n + g_p - 1)<S_z>] = 2 \mu(T=0)
\]

**Isovector Component:**
\[
\mu(M_T) + \mu(-M_T) = \mu_0[<\Sigma\tau_3(k) i_z(k)> + (g_p-g_n-1)<\Sigma\tau_3(k)s_z(k)>]M_T
\]

Connected to Gamow-Teller Strength

Picture complete for \( T=1/2 \) nuclei in the s-d shell. Virtually nothing is known about \( T=3/2 \) nuclei and \( T=1/2 \) in the f shell.
• Schematic figure of the ISOLDE setup on the HV platform.
• The inset shows the tilted-foil and beta-NMR geometry.

\[ E = 480 \text{ keV} \quad ^{23}\text{Mg} \]
RESULTS OF AUG. '96 RUN
$^{23}\text{Mg}(l=3/2^+, \tau=16 \text{ s})$

$\rho \approx 1.5\%$

$\eta = 0.533(6)$

Sum of all points removed from resonance and without RF.
FMA/ANL '97

$^{32}$S + $^{12}$C $\rightarrow ^{43}$Ti $\rightarrow$ 1-shelf?

Need high rate!
Andreas Türler
Paul Scherrer Institute
Why chemical studies?
Chemical separator systems
Why combine a physical with a chemical separator?
Chemistry in the gas phase:
  Prospects for chemical studies $Z=107$ to 109
  Future developments in gas phase chemistry
  A proposal for a 108 chemistry experiment in 3 years from now
Periodic Table of the Elements

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2</td>
<td>Li</td>
<td>Be</td>
<td>Na</td>
<td>Mg</td>
<td>Al</td>
<td>Si</td>
<td>P</td>
<td>S</td>
<td>Cl</td>
<td>Ar</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>K</td>
<td>Ca</td>
<td>Sc</td>
<td>Ti</td>
<td>V</td>
<td>Cr</td>
<td>Mn</td>
<td>Fe</td>
<td>Co</td>
<td>Ni</td>
<td>Cu</td>
<td>Zn</td>
</tr>
<tr>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>Rb</td>
<td>Sr</td>
<td>Y</td>
<td>Zr</td>
<td>Nb</td>
<td>Mo</td>
<td>Tc</td>
<td>Ru</td>
<td>Rh</td>
<td>Pd</td>
<td>Ag</td>
<td>Cd</td>
</tr>
<tr>
<td>37</td>
<td>38</td>
<td>39</td>
<td>40</td>
<td>41</td>
<td>42</td>
<td>43</td>
<td>44</td>
<td>45</td>
<td>46</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td>Cs</td>
<td>Ba</td>
<td>La</td>
<td>Hf</td>
<td>Ta</td>
<td>W</td>
<td>Re</td>
<td>Os</td>
<td>Ir</td>
<td>Pt</td>
<td>Au</td>
<td>Hg</td>
</tr>
<tr>
<td>55</td>
<td>56</td>
<td>57</td>
<td>58</td>
<td>59</td>
<td>60</td>
<td>61</td>
<td>62</td>
<td>63</td>
<td>64</td>
<td>65</td>
<td>66</td>
</tr>
<tr>
<td>Fr</td>
<td>Ra</td>
<td>Ac</td>
<td>Pm</td>
<td>Sm</td>
<td>Eu</td>
<td>Gd</td>
<td>Tb</td>
<td>Dy</td>
<td>Ho</td>
<td>Er</td>
<td>Tm</td>
</tr>
<tr>
<td>87</td>
<td>88</td>
<td>89</td>
<td>90</td>
<td>91</td>
<td>92</td>
<td>93</td>
<td>94</td>
<td>95</td>
<td>96</td>
<td>97</td>
<td>98</td>
</tr>
<tr>
<td>57</td>
<td>58</td>
<td>59</td>
<td>60</td>
<td>61</td>
<td>62</td>
<td>63</td>
<td>64</td>
<td>65</td>
<td>66</td>
<td>67</td>
<td>68</td>
</tr>
<tr>
<td>La</td>
<td>Ce</td>
<td>Pr</td>
<td>Nd</td>
<td>Pm</td>
<td>Sm</td>
<td>Eu</td>
<td>Gd</td>
<td>Tb</td>
<td>Dy</td>
<td>Ho</td>
<td>Er</td>
</tr>
<tr>
<td>89</td>
<td>90</td>
<td>91</td>
<td>92</td>
<td>93</td>
<td>94</td>
<td>95</td>
<td>96</td>
<td>97</td>
<td>98</td>
<td>99</td>
<td>100</td>
</tr>
<tr>
<td>Ac</td>
<td>Th</td>
<td>Pa</td>
<td>U</td>
<td>Np</td>
<td>Pu</td>
<td>Am</td>
<td>Cm</td>
<td>Bk</td>
<td>Cf</td>
<td>Es</td>
<td>Fm</td>
</tr>
<tr>
<td>101</td>
<td>102</td>
<td>103</td>
<td>104</td>
<td>105</td>
<td>106</td>
<td>107</td>
<td>108</td>
<td>109</td>
<td>110</td>
<td>111</td>
<td>112</td>
</tr>
</tbody>
</table>

Lanthanides

<table>
<thead>
<tr>
<th>57</th>
<th>58</th>
<th>59</th>
<th>60</th>
<th>61</th>
<th>62</th>
<th>63</th>
<th>64</th>
<th>65</th>
<th>66</th>
<th>67</th>
<th>68</th>
</tr>
</thead>
<tbody>
<tr>
<td>La</td>
<td>Ce</td>
<td>Pr</td>
<td>Nd</td>
<td>Pm</td>
<td>Sm</td>
<td>Eu</td>
<td>Gd</td>
<td>Tb</td>
<td>Dy</td>
<td>Ho</td>
<td>Er</td>
</tr>
<tr>
<td>89</td>
<td>90</td>
<td>91</td>
<td>92</td>
<td>93</td>
<td>94</td>
<td>95</td>
<td>96</td>
<td>97</td>
<td>98</td>
<td>99</td>
<td>100</td>
</tr>
<tr>
<td>Ac</td>
<td>Th</td>
<td>Pa</td>
<td>U</td>
<td>Np</td>
<td>Pu</td>
<td>Am</td>
<td>Cm</td>
<td>Bk</td>
<td>Cf</td>
<td>Es</td>
<td>Fm</td>
</tr>
<tr>
<td>101</td>
<td>102</td>
<td>103</td>
<td>104</td>
<td>105</td>
<td>106</td>
<td>107</td>
<td>108</td>
<td>109</td>
<td>110</td>
<td>111</td>
<td>112</td>
</tr>
</tbody>
</table>

Actinides
Heavy Elements

$Z \geq 104$

Physics
- Nuclear properties:
  - Decay mode: $\alpha$, EC, SF
  - Half lives?
  - Branching ratios?
  - Nuclear structure?
  - Deformations?
  - Reaction mechanism?

Better understanding of the influence of shells on stability and structure of heavy elements

Chemistry
- Chemical properties:
  - Group?
  - Electronic structure?
  - Influence of relativistic effects?
  - Stability of compounds?
  - Single atom chemistry?

Better understanding of the fundamental principles governing the periodic table

Separator

SHIP, BGS

OLGA, ARCA, SISAK
<table>
<thead>
<tr>
<th>Nickname</th>
<th>OLGA</th>
<th>ARCA</th>
<th>SISAK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affiliation</td>
<td>PSI Villigen University of Bern FZ Rossendorf</td>
<td>GSI Darmstadt University of Mainz TU Dresden</td>
<td>Chalmers University University of Mainz University of Oslo</td>
</tr>
<tr>
<td>Separation time</td>
<td>$\geq 3 \text{ s}$</td>
<td>$\geq 10 \text{ s}$</td>
<td>$\geq 1 \text{ s}$</td>
</tr>
<tr>
<td>Separation principle</td>
<td>gas - solid chromatography</td>
<td>extraction or ion exchange chromatography</td>
<td>liquid - liquid extraction</td>
</tr>
<tr>
<td>Operation principle</td>
<td>continuous</td>
<td>batch wise</td>
<td>continuous</td>
</tr>
<tr>
<td>Chemical yield</td>
<td>$\equiv 60 %$</td>
<td>$60 - 80 %$</td>
<td>$60 - 80 %$</td>
</tr>
<tr>
<td>Decontamination from actinides</td>
<td>$\equiv 10^3$</td>
<td>$\equiv 10^4$</td>
<td></td>
</tr>
<tr>
<td>Detection system</td>
<td>Wheel (ROMA, MG) Tape system</td>
<td>Counting chambers</td>
<td>Liquid scintillation flow through cells</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>$70 %$</td>
<td>$70 %$</td>
<td>$\equiv 100 %$</td>
</tr>
<tr>
<td>Smallest detected cross section</td>
<td>$\equiv 50 \text{ pb}$</td>
<td>$\equiv 250 \text{ pb}$</td>
<td>$&gt; 5 \text{ nb}$</td>
</tr>
<tr>
<td>Transactinides studied</td>
<td>104, 105, 106</td>
<td>104, 105, 106</td>
<td></td>
</tr>
</tbody>
</table>
OLGA ↔ Dubna Gas Filled Separator

Beam Energy: 121, 128 MeV
Beam Dose: $4.6 \times 10^{17}$
Targets: 950, 690 μg/cm$^2$
$^{265}\text{N}_{\text{Sg}} = 24.1$ (260 pb)
$^{265}\text{Sg}$ decay chains = 5
Overall efficiency = 2.1 %

Beam Energy: 121 MeV
Beam Dose: $6 \times 10^{18}$
Target: 240 μg/cm$^2$
$^{265}\text{N}_{\text{Sg}} = 910$ (260 pb)
$^{265}\text{Sg}$ decay chains = 4
Overall efficiency = 0.5 %

OLGA is factor 4 more efficient!
(Compared to beam dose even factor 16!)

01.04.97
Schematic of a gas-jet device

Gas - supply

He, Ar
1-3 l/min
p = 1-3 bar

Particle generator

salt
oven
spark discharge

Target chamber
Reaction products
Transport capillary
Stainless steel, polyethylene
ϕ, 1-3 mm; l ≤ 700 m
Disadvantages of Gas Jet Transport Systems

- Strong fluctuations in gas-jet yield (10 - 60%)
- Varying performance of aerosol generators
- Yield dependence on beam intensity and possibly beam structure (DC ↔ macropuls)
- Relatively long transport times (≥ seconds)
- No separation from unwanted reaction products
- Aerosol material interferes with desired clean chemical conditions
- High gas flow rates (≥ 1 l/min He)
Example: Dubna Gas Filled Separator

Separation Factor: Transferproducts $10^4 - 10^5$

$^{22}\text{Ne}(^{248}\text{Cm}, 5n)^{265}\text{106}$

$^{34}\text{S}(^{238}\text{U}, 5n)^{267}\text{108}$

Example: OLGA

Separation Factor: Actinides: $10^3 - 10^4$; Pb, Bi, Po: $0 - 10^1$

$^{18}\text{O}(^{249}\text{Bk}, 5n)^{262}\text{105}$

Problem: Target Impurities (Pb $\rightarrow$ Bi, Po, Ra, Ac) !!!
Why combine a physical with a chemical separator?

Chemistry profits from:
Good separation of transfer products from target impurities.
Fast and reliable transport.
Will allow special chemical environment (e.g. pure O₂)

Physics profits from:
Enhanced separation factors for separation from actinides with
$T_{1/2} \geq 1$ s. Especially interesting for enhancing separation from
long-lived SF activities.
BGS + Chemistry = $10^7$-$10^9$
## Production cross sections and predicted decay modes, decay energies, and half-lives for elements Z=107-109 suitable for chemistry experiments

<table>
<thead>
<tr>
<th></th>
<th>Q_α (MeV)</th>
<th>T_1/2(s)</th>
<th>Q_α (MeV)</th>
<th>T_1/2(α)(s)</th>
<th>T_1/2(EC)(s)</th>
<th>Q_α (MeV)</th>
<th>T_1/2(EC)(s)</th>
<th>Cross section (pb)</th>
<th>Extrapolated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ns (Element 107)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22Ne(249Bk, 5n)266Ns</td>
<td>n.a.</td>
<td>n.a.</td>
<td>8.82</td>
<td>377</td>
<td>&gt;100</td>
<td></td>
<td></td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>22Ne(249Bk, 4n)267Ns</td>
<td>8.94</td>
<td>63</td>
<td>8.47</td>
<td>2475</td>
<td>&gt;100</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td><strong>Hs (Element 108)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26Mg(248Cm, 5n)269Hs</td>
<td>n.a.</td>
<td>n.a.</td>
<td>8.84</td>
<td>632</td>
<td>&gt;100</td>
<td>9.34</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36S(238U, 5n)269Hs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26Mg(248Cm, 4n)270Hs</td>
<td>9.44</td>
<td>5</td>
<td>8.69</td>
<td>168</td>
<td>&gt;100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36S(238U, 4n)270Hs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>136Xe(136Xe, 1n)271Hs</td>
<td>n.a.</td>
<td>n.a.</td>
<td>8.82</td>
<td>745</td>
<td>&gt;100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mt (Element 109)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25Mg(249Bk, 5n)269Mt</td>
<td>9.60</td>
<td>0.6</td>
<td>9.62</td>
<td>3</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26Mg(249Bk, 5n)270Mt</td>
<td>n.a.</td>
<td>n.a.</td>
<td>9.53</td>
<td>12</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26Mg(249Bk, 4n)271Mt</td>
<td>9.45</td>
<td>1.6</td>
<td>9.30</td>
<td>27</td>
<td>39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

# Chemical systems suitable for gas chromatographic studies

<table>
<thead>
<tr>
<th>Element</th>
<th>103</th>
<th>104</th>
<th>105</th>
<th>106</th>
<th>107</th>
<th>108</th>
<th>109</th>
<th>110</th>
<th>111</th>
<th>112</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Chloride</td>
<td>(X)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Oxychloride</td>
<td>(X)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(X)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxide</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydroxide</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

01.04.97
Future Developments in Gas Phase Chemistry

Improvements in the chemistry:
For the chemistry of element 107, 108 and 109 the hydroxides and the oxides are best suited for a gas chromatographic separation:
- Good separation from actinides
- Good separation from early transactinides 104, 105 and 106
- Good separation from Pb and Bi and probably also Po (compared to chloride and oxychloride chemistry).

Improvements in the current detection system:
Tape system with thin foils and movable detectors
- 80% detector efficiency
- lower background compared to wheel
- α - recoil technique: measurement of interesting samples in low background environment
⇒ With these improvements we should be able to perform a first chemical separation of element 107

However:
⇒ The low production cross sections of elements 108 and beyond require better separation factors than what can be accomplished with chemistry alone!

Improvements in the transport system:
Replace aerosol gas-jet with chromatography column coupled directly to the BGS!:
- Transport time ≈ 1 μs !
- Transport yield = 10% - 40%
- Separation from unwanted reaction products (transfer products with target and target impurities)
- Clean chemical conditions (no aerosol material)
- Remote controlled chemistry inside the cave
Using the BGS in combination with thermochromatography for a chemical separation of \(^{269}\)\(^{108}\)O.
Chemical Separation of $^{269}\text{108O}_4$ using the BGS as preseperator

108 Experiment:

- **Half-life:** $^{269}\text{108} T_{1/2} = 10 \text{ s}$
- **Production reaction:** $^{26}\text{Mg} (^{248}\text{Cm}, 5n) ^{269}\text{108}$; Cross section $= 10 \text{ pb}$
- **Production rate:** 8.4 / day (0.5 mg/cm$^2$ target, 0.5 pA beam)
- **Separator Efficiency:** 20%
- **Chemical Yield:** 80%
- **Detection Efficiency:** 80%
- **Overall Efficiency:** 12.8 %
- **Detection Rate:** 1 / day

**Test experiment**

- **Test experiment:** $^{171}\text{OsO}_4$
- **Production reaction:** $^{24}\text{Mg} (^{152}\text{Gd}, 5n) ^{171}\text{Os}$
- **Half-life:** $^{171}\text{Os} T_{1/2} = 8.2 \text{ s}$, $E_\alpha = 5.24 \text{ MeV}$

Determine Chemical Yield
Check if Detector Setup works

**Results:**

**Chemistry:** Adsorption enthalpy of $^{108}\text{O}_4$ on Si surface
Relative volatility compared to lighter homologs

**Physics:** Determine possible SF-branch
Disadvantage of thermochromatography:
No half-life measurements possible for $^{108}$ nuclide
unless the separator can provide a start signal (TOF ?)
Rauno Julin  
University of Jyväskyla
Isotopes found with RITU
JUROSPHERE + RITU
GAS-FILLED SEPARATOR
FOR HEAVY-ELEMENT STUDIES

IN VACUUM

\[ B_0 = \frac{mv}{q} \]

\[ q = \frac{v}{v_0} 2^{1/3} = \text{mean charge} \]

\[ B_0 \propto A^{1/3} \]

\[ \Rightarrow \text{charge > focusing } \]

HIGH TRANSMISSION!

IN GAS

MAGNETIC FIELD REGION (with gas)

\( \sim 1 \text{mbar He} \)
RECOIL-DECAY TAGGING METHOD

R. S. Simon, 2 P A325 (6) 197
E. Paul, P R C57 (45) 78
RITU
focal plane
recoil distribution

80 mm

35 mm

⇒ granularity ~100
Focal Plane Si-Detector Spectrum

From

\[ 160 \text{Dy} + ^{36}\text{Ar} \rightarrow ^{176}\text{Po} + \alpha \]

\[ ^{176}\text{Po} \rightarrow ^{176}\text{Bi} + \alpha \]
Recoil gated η-tagged γ-rays
from $^{160}$Dy ($^{36}$Ar, 4m) $^{192}$Po

$\sim 7\mu$b!
EVEN $^{84}\text{Po}$ YRAST LEVELS

($+$ some low-spin levels)

\( E (\text{MeV}) \)

10\(^+\)

9\(^-\)

12\(^+\)

11\(^-\)

$\gamma^2$

MIDSHHELL

A

N

192 194 198 202 206 210
Total Alpha Spectrum

from $^{36}_{\text{Ar}} + ^{144}_{\text{Sm}} \rightarrow ^{180}_{\text{Hg}}$ *

- 50 hrs Data

~ 50 hrs Data

Energy/MeV

Escape Alphas

172Os

176Pt

175Pt

174Pt

173Pt

177Au

176Au

178Pt

178Hg

177Hg

6.75 MeV

176Hg
\[ ^{36}\text{Ar} + ^{144}\text{Sm} \rightarrow ^{180}\text{Hg}^* \rightarrow \]

Recoil gated \( \gamma \)-rays

2p2m ch. dominant

RDT with \( ^{196}\text{Hg} \) L's (\( t_\frac{1}{2} = 16\text{ms} \))

4m channel \( \sim 2\mu\text{B} \)
RDT $\eta$

with $^{176}\text{Hg}$ $\alpha$'s

Sum of gates

/usr2/mhm/sub/gate*0.5+0.0
/usr2/mhm/sub/gate scaled by 0.5
$^{63}\text{Cu} + ^{112}\text{Sn} \rightarrow ^{175}\text{Au}$

Diagram showing recoils.
RITU

GAS-FILLED SEPARATOR
FOR FUSION EVAP. RECOILS

+ high transmission (<50%)
+ simple to operate
+ perfect beam dump (<10⁻²)
+ inexpensive
+ target cooling

- no A and Z selection
  (without add. detectors)
- symmetric reactions (so far ⁶³Cu + ¹⁰⁶Cd)
Si strip
\[ X, Y \]

PPAC
\[ X, Y \ (\sim \Delta E, t) \]

Prompt \( \gamma \) - Recoil

Recoil - \( \beta \)

\( \beta \) - delayed \( \gamma \)
First observation of excited states in $^{192}$Po

University of Jyväskylä, Department of Physics, P.O. Box 35, 40351 Jyväskylä, Finland

R. G. Allatt, P. A. Butler, P. T. Greenlees, and R. D. Page
Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool, L69 3BX, United Kingdom
(Received 13 September 1996)

$\gamma$-rays following the $^{160}$Dy($^{36}$Ar,$4n$)$^{192}$Po reaction have been identified by employing a high-transmission gas-filled separator in recoil decay tagging measurements. The deduced level scheme reveals a flattening of the energy systematics, when going towards the neutron midshell indicating that the deformed intruder structures have become yrast. [S0556-2813(96)50212-8]
Peter Butler
University of Liverpool
AND e- SPECTROSCOPY

A \geq 220

1. Octupoles
   CN reactions - U
   Deep inelastic - Rn, Ra etc

2. SD and HD
   e- coincidences
   \gamma coincidences
transfer reactions
$\sigma \lesssim 1 \text{mb}$

CN reactions
$\sigma \sim 10 \text{mb}$

OR

Transf., W. Nazarewicz et al
$\sigma \sim 10 \text{mb}$  Nucl. Phys. A429 (1984) 269
The image contains a diagram labeled "Nuclear Reactions." It shows three plots of intensity versus mass numbers (192, 202, 212, 222) for different reactions:

1. $^{136}$Xe + $^{232}$Th
2. $^{86}$Kr + $^{232}$Th
3. $^{56}$Fe + $^{232}$Th

The plots indicate intensity on a logarithmic scale, with markers for various elements such as Th, Ra, Rn, Po, Pb, Hg, Pt, and Os, and a note for the octupole.
112 MeV $^{208}$Pb ($^{22}$Ne, $4n$) $^{226}$U

$\sigma \sim 5 \mu b$

DORIS + RITU ($\Upsilon_{\omega}$)

12 hour run

Gate on

$E_\alpha = 7.93 - 8.06$ MeV

($^{222}$Th + $^{219}$Ra)

7.32 MeV $^{223}$Th

7.57 MeV $^{226}$U

230 counts

Gate on

$E_\alpha = 7.52 - 7.62$ ($^{226}$U)

3$\gamma$ rays

176

186

214 (keV)

62 counts Total

$^{224}$U: $\sigma \sim 1 \mu b$

JUROSHPHERE EXPT SCHEDULED

21 April - 4 May 1997
SUMMARY OF RESULTS SO FAR

(J.F.C. Cocks et al.
Phys Rev Lett. April 1997)

1. \( I_x \) (-ve parity) - \( I_x \) (+ve parity)
   = 3 Octupole vibration
   218, 220, 222 Rn
   228 Ra
   228, 230, 232, 234 Th
   \( \rightarrow 0 \) Octupole Deformed
   222, 224, 226 Ra
   (224), 226 Th

#2. \( D_0 \) remains constant with spin

Dip seen at 224 Ra
- shell cancellation
DEEP INELASTIC REACTIONS

$E \sim 15-20\% \text{ above Coulomb barrier}$

Require $d\Omega \sim 1\text{sr}$ (at least 100m)

$\Delta p \sim 15\%$

$\%$ of products $\sim 5-10\%$

$\therefore \Delta \bar{v}/\bar{v} \sim 1\%$

$\Delta Z/Z \sim 1\%$

$\Delta A/A \sim 0.5\%$

GFS requires dipole etc.

fragment
\[
E_{\text{def}} \ (\text{MeV})
\]

\[
\begin{align*}
\text{SD} & \quad \text{HD} \\
& \quad \text{Ra} \\
& \quad \text{Th} \\
& \quad \text{U}
\end{align*}
\]

\[
\begin{align*}
\beta_2 & \sim 0.5-0.6 \\
\beta_2 & \sim 0.8-0.9 \\
\beta_3 & \sim 0.4
\end{align*}
\]

\[
\begin{array}{cccccccc}
130 & 132 & 134 & 136 & 138 & 140 & 142 & 144 \\
\end{array}
\]

\[
N
\]
$<m'_e> = 6$

$Z = 92$

$\sigma = 50\text{mb}$

$\frac{\Gamma_{e^-}}{\Gamma_{tot}} = 0.1$

$\text{(GB)}$

$\sigma = 10\mu\text{b}$

$\frac{\Gamma_{e^-}}{\Gamma_{tot}} = 1.0$

$\text{(SD)}$

$\sigma = 1\text{b}$

$\frac{\Gamma_{e^-}}{\Gamma_{tot}} = 0.05$

$\epsilon_{e^-}$

$0.05 \quad 0.10 \quad 0.15 \quad 0.20 \quad 0.25$

$\text{e}^- \text{ triples rate } / \text{hour}$

$\text{SACRED}$
P. A. Butler et al.
NIM A381 (1996) 433
$^{208}\text{Pb}(^{18}\text{O}, 4\text{n})^{222}\text{Th}$  \(\sigma \sim 15\text{mb}\)

Spectrum from Electron-Electron Matrix gated on $^{183}\text{L} (2^+ \rightarrow 0^+)$
SACRED electron array

![Diagram of SACRED electron array with main coils, HV, target, detector, and beam paths.]

OR

GAMMASPHERE

high x-fold detection

Reactions

CN reactions are:

1. $^{18}O + ^{208}Pb \rightarrow ^{222}Th$
2. $\alpha + ^{232}Th \rightarrow ^{230,232}U$
3. $\alpha + ^{238}U \rightarrow ^{237,239}Pu \quad T_{\text{if}} \sim \mu s$

$\alpha$-induced reactions have a strong linear dependence on the target thickness.
1. DO NOT NEGLECT TRANSFER PRODUCTS

2. DO NOT NEGLECT CONVERSION ELECTRONS
Bill Gelletly
University of Surrey
OUTLINE

1. INTRODUCTION
   Why study $N=Z$ nuclei?
   How can we study $N=Z$ nuclei?

2. STUDIES WITH FUSION-EVAPORATION REACTIONS
   Mirror Nuclei
   Isospin Mixing
   Shape changes along $N=Z$ line
   n-p pairing

3. FUTURE OF FUSION-EVAPORATION REACTION STUDIES

4. STUDIES WITH FRAGMENTATION REACTIONS
   Nature of Experiments
   New Isotopes
   Gamma-gating and Identification of Isomers
   $^{74}\text{Kr}$
   Future Studies
Why study $N = Z$ nuclei?

1. Up to $^{100}\text{Sn}$ neutrons and protons fill the same shells
2. Strong dependence of deformation on $Z$, $N$ and angular momentum
3. Co-existence of prolate, oblate and triaxial shapes
4. Evidence of n-p pairing
5. Mirror pairs at high spin
6. Astrophysical rp-process passes this way

Successfully studied by:

1. Beta-decay following spallation
2. Heavy ion fragmentation
3. Gamma rays from fusion - evaporation reactions
Single Particle Levels as fn. of $\beta_2$ from WOODS-SAXON CRANKING CALCULATION.

$\beta_2(\beta_1)$

Spherical

NAZAREWICZ et al.

$e_r$ (MeV)

$\beta_2$ (Prolate $\beta = 0.4$)
• rp-process path lies close to the $N=Z$ line.
• At every stage there is competition between (p,$\alpha$) and $\beta$-Decay.
• $2p$ capture is important.
• Inter alia we require:
  - Masses: As, Se, Br, Rb
  - $\beta$-Decay: Zr, Ru, Pd, Cd
\[ ^{49}\text{Mn} / ^{49}\text{Cr} \text{ Mirror Pair} \]

\[ ^{12}\text{C} \left( ^{40}\text{Ca}, p2n \right) ^{49}\text{Mn} \]

\[ 16\text{ESS} + \text{Daresbury Rec. Sep.} \]

\[ \begin{array}{cccccc}
6056 & 19/2^- & 5965 \\
4446 & 9/2^- & 52 & 3 & 4368 & 4219 \\
4250 & 17/2^- & 52 & 3 & 4368 & 4219 \\
3189 & 15/2^- & 31 & 40 & 3191 \\
2481 & 13/2^- & 44 & 9 & 2500 \\
1542 & 11/2^- & 42 & 4 & 1563 \\
1059 & 9/2^- & 60 & 9 & 1084 \\
261 & 7/2^- & 31 & 100 & 272 \\
0 & 5/2^- & 100 & 0 & 0 \\
\end{array} \]

- Charge Independence
- Collective
- G. Martinez-Pinedo et al. - Full pf shell model
\[ ^{49}\text{Mn from } ^{28}\text{Si on } ^{24}\text{Mg [PEX]} \]

C. O'Leary, M. Bentley (Staffordshire) et al.

- PEX Array.
Plot of level energy difference with spin for mirror pair

Mn49 and Cr49

\[
\text{Ex[Mn] - Ex[Cr] (keV)}
\]

Spin (J)

\[
1.5 \quad 3.5 \quad 5.5 \quad 7.5 \quad 9.5 \quad 11.5 \quad 13.5 \quad 15.5
\]

\[
-50.0 \quad 0.0 \quad 50.0 \quad 100.0
\]

\[
\text{\[49Cr} \quad \text{\[49Mn}
\]

Protons align.

\[\Delta V_c - \text{Negatwi}\]

Neutrons align.

\[\Delta V_c - \text{Zero}\]
In self-conjugate nuclei, E1 transitions between T=0 states are forbidden by isospin selection rule.
E1 Transitions between $T=0$ states are forbidden
• B A BROWN, J.Phys G8 (1982) 679

• We need 3 things:

  - Relative position of lowest T=0 and T=1 states of each spin involved.

  - \( \langle J, T=1 \mid V_c \mid J, T=0 \rangle \)

  - Anticipated strength of non-retarded E1 matrix element \( \langle 5^- \mid E_1 \mid 4^+ \rangle \)

• Position of lowest T=1, \( T_z=0 \) state we get from masses of isobars corrected for n-p mass difference and Coulomb shifts. Calc\(^N \) gives \( J^{\pi}=0^+ \) at 4.85(20 MeV). The 4\(^+ \) and 5\(^- \) states are then at 3.34 MeV and 2.97 MeV.

• Strength we get from unperturbed p-h states in \( A=63 \) and 65

• E1 strength = 1.0\(^{+0}_{-0.5} \) W.U. from average over \( A=56-74 \)

CRUDELY

\[ \text{Mixing amplitudes} \sim 1.2\% \]
Fig. 1 High spin states in the self-conjugate nucleus $^{74}$Rb [7]

- EUROCAM I + Recoil separator
  - ad PEX + Charged Particle Ball.
- $4^+ - 2^+ - 0^+$ sequence resembles sequence in $^{74}$Kr ($T_z = +1$)
  - g.s. is $T = 1$.

Cranking calc. with residual np-interaction.
- At $\hbar \omega / G = 0.2$ lowest $T = 1$, odd spin branch comes $T = 0$, even spin Routhian.
$^{10}$ Be ($^{10}$Ne, $2n$) $^{14}$N (CHAMBER)
Gated on $A = 84$ Gamma Rays

540 keV $^{84}$ Zr

444 keV $^{84}$ Mo

295 keV $^{84}$ Nb

Gamma ray intensity ($I_\gamma$)

$\Delta E$ (Channel number)
1 **Increased Efficiency** - $2n$ channel

EUROBALL/GAMMASPHERE - 10% FMA - 10%

In principle we can do spectroscopy up to Zr/Mo

2 **Selection by charged particle detector array**

Allows use of ($\alpha 2n$) channel

Improvement with EURQBALL - $5 \times 10^3$

but it depends on cleanliness of target

3 **Recoil Decay Tagging**

Here we use subsequent radioactive decay to identify source of $\gamma$-rays

4 **Radioactive beams**

(a) $^{12}\text{C}(^{54}\text{Fe}, 2n)^{64}\text{Ge}$

155 MeV

640(70)\(\mu\)b

(b) $^{40}\text{Ca}(^{34}\text{Ar}, 2p2\alpha)^{64}\text{Ge}$

130 MeV

50 mb
$^{40}_{Ca} (^{40}_{Ca}, 2\alpha)^{72}_{Kr}$

$^{36}_{Sr} + ISIS$

G. de Angelis et al.
(To be published)
$^{54}$Fe ($^{28}$Ar, 2n $^{90}$Ru $\rightarrow$ 120-125 MeV

$\gamma$/e $\sim$

A$^{14}$Be $\sim$ 1.0 \% efficiency.

- Sufficient $\Delta Z$ resolution - statistics required.
- Improved - Channel Plates not PPAC - Increased $\gamma$.
RECOIL DECAY TAGGING METHOD

TARGET BEAM

RECOIL

FMA

PPAC

DSSD

\(\text{GAMMA-RAY DETECTED}\)

\(\text{MIa MEASURED}\)

\(\text{RECOIL IMPLANTED IN DSSD PIXEL (X , Y)}\)

\(\text{ALPHA OR PROTON DECAY OCCURS IN PIXEL (X , Y)}\)

- Prompt \(\gamma\)-rays correlated with M/Q and (X , Y) position of recoil in DSSD
- Decay proton or alpha identifies nucleus that emitted the \(\gamma\)-rays
$^{71}$Kr/$^{71}$Br - Surrey/Daresbury/Valencia/Legnaro/Liverpool/Jyvaskyla

**JUROSPHERE** (gammas)

PIN (protons)

**PPAC** and **DSSD** record arrival of recoil

- $^{40}$Ca ($^{36}$Ar, αn)$^{71}$Kr - 105 MeV - $\sigma = 60$ µb

**JUROSPHERE - $\varepsilon = 1\%$**

RITU separates beam from recoils

DSSD has 2304 pixels

- $^{71}$Kr - 100 ms, $^{70}$Br - 80 ms
- $\beta^+$ decay correlated with gammas at target
- 1000 counts in 5 days
- Beam — 80 MeV, 150 pA
- Target — 1.6 mg cm⁻²
- Pb to shield BGO from collimators and beam dump
- Al foil to stop beam hitting LEDA.
- Beam dump 2 m away.
Data from 90° detectors except (c) where 45° detectors are included.

- a) Dominated by $e^+e^-$ but Compton suppression worked
HOW DO YOU MAKE N~Z NUCLEI?

(A) SOFTLY.......Heavy-Ion Fusion-Evaporation

\[ E_b \approx \text{Coulomb Barrier} \approx 4 \text{ MeV/A} \]

2n out channel for heavy N=Z upto 96-Cd


(B) BANG!!!! Fragmentation Reactions

\[ E_b \approx 50 \text{ MeV/A} \]

Many channels
Need LISE3 to id all recoils
(\approx 200 \text{ N,Z combinations})
$^9$K$_r$ (65 MeV/nu) + $^{120}$Ni

Michigan State University
National Superconducting Cyclotron Laboratory
A1200 Isotope Separator

K$_{1200}$ Cyclotron

Isotope Identification

Flight Time

$\Delta E$
SPECIFIC RESEARCH GOALS

2) Structure of N~Z Nuclei With Radioactive Ion Beams.

(a) Along the N=Z Line Using Projectile Fragmentation.
Nuclear collision causes beam to **fragment**.

Fragments form a **SECONDARY BEAM** of r-active nuclei.
These can be selected and separated by their A and Z eg.

\[
T_z = 1 \quad 1/2 \quad 0 \quad -1/2
\]

\[
\downarrow \quad \downarrow \quad \downarrow \quad \downarrow
\]

\[
\text{Ru} \quad \text{Mo} \quad \text{Zr} \quad \text{Y} \quad \text{Sr}
\]

\[
\text{Time of Flight (A/Z)}
\]

Defines the **limits** of nuclear stability ...
very imp. for nucleosynthesis and creation of the elements above A=56
Identify recoils using LISE3 $+$ Si stack

Measure delayed gamma-rays using Clover $+$ Leps detector

Total Gamma-efficiency for 4 clovers and 1 clover Leps $= 15\%$ for 1.33 MeV gamma-ray
First identification of $^{77}$Y, $^{79}$Zr, $^{83}$Mo and $^{87}$Ru.....

isomeric spectroscopy across the N=Z line is possible......

(Evidence of new isomeric decays in $T_z=0$, $^{82}$Nb and $^{86}$Tc).
'GRZYWACZ PLOT' TO ID ISOMERS

92-Mo @ 60 MeV/A on Ni target at GANIL

(a) all

(b) gammas

Tz = 3/2, 1, 1/2

time of flight (A/Q)

---

(2) γ-gated

Tz = 1

(2) γ-gated

Tz = 1/2

(c) all

(d) all

---

energy loss

energy loss

counts

counts
a) \( \gamma \)-ray spectrum within 4 ps.

\[ \text{Gamma rays gated on the first 4 us} \]

\[ \text{Time gated on 101, 144, and 246 keV gammas} \]

\[ \text{c. Chandler et al. - to be published} \]
SHAPE COEXISTENCE IN KRYPTON-74

\[ E (\text{keV}) \]

Counts

Energy (keV)

Counts

Ph x-rays

Counts

Counts

Time (ns)

\[ \tau \approx 30 \text{ ns} \]

4\(^+\)

556\(^+\)

\[ 0^+ \]

\[ \sim 30 \text{ ns} \]

2\(^+\)

<120 keV

456

1461

511

100 300 500 700

3500 3000 2500 2000 1500 1000 500 0

200 600 1000 1400 1600

25 20 15 10 5 0

35 30 25 20 15 10 5 0

\[ 0^+ \]

\[ 2^+ \]

\[ 4^+ \]
A. More efficient X-ray arrays.
B. 1) Improved Recoil Mass Separators.
2) Recoil Decay Tagging < $\alpha$- and $\beta$-decay
3) Charged Particle / Neutron arrays
4) Inner balls - $E_X$(Total) vs. Fold
5) Isomer Tagging
6) X-rays and Conversion electrons etc.
C. $\beta^+$/EC Decay
D. Radioactive Beams
   - CoulEX / Transfer
   - Fusim - evaporation
Mike Carpenter
Argonne National Laboratory
Y-Ray Spectroscopy Beyond the Proton Drip Line for 
$N > 82$ and $Z < 82$

(Oasis for proton and alpha radioactivity)

Current Results
Gammasphere + FMA
Gammasphere + GFS

RDT!
Proton Rich Compounds

Proton emitters

Neutron

Proton
Gammasphere + FMA

Conditions:  Beam current = 3pNa
Run Time = 5 days
Target:  A~100  0.5mg/cm²

Expected yield in $^2\rightarrow^0$ transition for

<table>
<thead>
<tr>
<th>σ</th>
<th>$\sigma$-ROT</th>
<th>$\sigma$-FMA*</th>
<th>$\sigma$-FMA*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$b</td>
<td>200,000</td>
<td>18,000</td>
<td>44,000</td>
</tr>
<tr>
<td>$\mu$b</td>
<td>200</td>
<td>18</td>
<td>44</td>
</tr>
<tr>
<td>100$\mu$b</td>
<td>20</td>
<td>~2</td>
<td>~4</td>
</tr>
</tbody>
</table>

For GFS  50% transmission + 2x target thickness = x10

$^*$  $^4-^2$ transitions in coincidence with $^2\rightarrow^0$ transitions (90%)

$^{(100\%)}$
<table>
<thead>
<tr>
<th>Quantum Number</th>
<th>Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0⁺</td>
<td>176⁻¹⁷⁶Hg, 178⁻¹⁷⁸Hg</td>
</tr>
<tr>
<td>0⁺</td>
<td>18⁰⁻¹⁸⁰Hg, 18²⁻¹⁸²Hg</td>
</tr>
<tr>
<td>0⁺</td>
<td>18₄⁻¹⁸⁴Hg, 18⁶⁻¹⁸⁶Hg, 18⁸⁻¹⁸⁸Hg, 1⁹₀⁻¹⁹⁰Hg</td>
</tr>
<tr>
<td>2⁺</td>
<td>6¹⁻⁶¹₃, 2⁺⁻⁵⁵₈</td>
</tr>
<tr>
<td>2⁺</td>
<td>4⁺⁻⁷₀₆, 4⁺⁻⁶¹₄, 4⁺⁻⁶₅₃</td>
</tr>
<tr>
<td>2⁺</td>
<td>2⁺⁻⁴₃₄, 2⁺⁻³₅₂, 2⁺⁻³₆₇, 2⁺⁻⁴⁰₅, 2⁺⁻⁴₁₃, 2⁺⁻⁴₁₆</td>
</tr>
<tr>
<td>4⁺</td>
<td>6⁻¹⁻⁶⁺, 10⁻¹⁻¹⁰₀₅, 4⁺⁻¹₀₄₂</td>
</tr>
<tr>
<td>6⁺</td>
<td>8⁻¹⁻¹₅₈₉, 8⁺⁻¹⁺₁₇₃₅, 6⁺⁻¹⁺₁₇₇₃</td>
</tr>
<tr>
<td>8⁺</td>
<td>10⁺⁻¹⁺₁₈₄₈, 10⁺⁻¹⁺₁₉₀₂</td>
</tr>
<tr>
<td>10⁺</td>
<td>12⁺⁻¹⁺₂₂⁰₂, 12⁺⁻¹⁺₂₂₅₆</td>
</tr>
<tr>
<td>10⁺</td>
<td>12⁺⁻¹⁺₂₄₅₃</td>
</tr>
<tr>
<td>10⁺</td>
<td>12⁺⁻¹⁺₂₄₅₅</td>
</tr>
<tr>
<td>12⁺</td>
<td>12⁺⁻¹⁺₂₇₁₃</td>
</tr>
<tr>
<td>(6⁺) 1369</td>
<td>6⁺⁻¹⁺₁₃₄₈, 6⁺⁻¹⁺₁₃₆₀, 6⁺⁻¹⁺₁₄₁₂</td>
</tr>
<tr>
<td>(4⁺) 1369</td>
<td>4⁺⁻¹⁺₁⁰₁₃, 6⁺⁻¹⁺₁⁰₃₂, 6⁺⁻¹⁺₉₄₇, 6⁺⁻¹⁺₉₉₄</td>
</tr>
<tr>
<td>(2⁺) 61₃</td>
<td>2⁺⁻¹⁺₅₅₈, 2⁺⁻¹⁺₄₃₄, 2⁺⁻¹⁺₃₅₂, 2⁺⁻¹⁺₃₆₇, 2⁺⁻¹⁺₄₀₅, 2⁺⁻¹⁺₄₁₃, 2⁺⁻¹⁺₄₁₆</td>
</tr>
<tr>
<td>(6⁺) 19₂₀</td>
<td>8⁺⁻¹⁺₁₇₄₄</td>
</tr>
<tr>
<td>(4⁺) 19₂₀</td>
<td>10⁺⁻¹⁺₁₉₁₃, 10⁺⁻¹⁺₁₈₄₈, 10⁺⁻¹⁺₁₉₀₂</td>
</tr>
<tr>
<td>(2⁺) 61₃</td>
<td>4⁺⁻¹⁺₇₀₆, 4⁺⁻¹⁺₆¹₄, 4⁺⁻¹⁺₆₅₃</td>
</tr>
<tr>
<td>(0⁺)</td>
<td>17⁰⁻¹₇₆Hg, 1⁰⁻¹₇₈Hg, 1⁰⁻¹₈⁰Hg, 1⁰⁻¹₈₂Hg, 1⁰⁻¹₈⁴Hg, 1⁰⁻¹₈₆Hg, 1⁰⁻¹₈₈Hg, 1⁰⁻¹₉₀Hg</td>
</tr>
</tbody>
</table>
Proton Emitter

Predicted Proton Emitter

<table>
<thead>
<tr>
<th>83</th>
<th>Bi</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>Pb</td>
</tr>
<tr>
<td>79</td>
<td>Tl</td>
</tr>
<tr>
<td>176 177 178 179 180 181 182</td>
<td></td>
</tr>
<tr>
<td>Hg</td>
<td></td>
</tr>
<tr>
<td>174 175 176 177 178 179 180</td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td></td>
</tr>
<tr>
<td>92 94 96 98 100 102</td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td></td>
</tr>
</tbody>
</table>

\[ ^{78}\text{Kr} + ^{103}\text{Rh} @ 340, 360 \text{ and } 380 \text{ MeV} \]

Theoretical Calculations
Predict Variety of Shapes in Light Hg and Pb Isotopes

RDT on $^{156}$Hf

$\alpha$-Decays in DSSD

$^{156m}$Hf

$^{156}$Hf

$T_{1/2} = 25 \text{ ms}$

D. Seweryniack et al.

N. (Edinburgh, York, Maryland)
13 experiments from \( A=24 \) to \( 226 \)

40 scientists from 13 countries

**Mass Gated**

- C14.06  W. F. Mueller  179Au first results
- L11.07  G. J. Lane  110Sb intruder bands

**RDT**

- C14.03  M. P. Carpenter  \( 103\text{Rh}(78\text{Kr},\text{pxn})176-179\text{Hg} \)
- L11.09  D. Seweryniak  \( 102\text{Pd}(58\text{Ni},2p2n)156\text{Hf} \)

**Ion Chamber Gated**

- K7.05  J. Schwartz  \( 12\text{C}(16\text{O},a)24\text{Mg} \) High-spin states
- N7.10  M. P. Carpenter  \( 12\text{C}(58\text{Ni},X)Y \longrightarrow 40\text{Ca}(Y,X)Z \) Development of secondary reactions

... and much more to come

Studies of \( N=Z \) nuclei: 62Ga, 88Ru, 92Pd

New regions of deformation: 200Rn, 204Ra

First observation of excited states in other nuclei using the RDT method
RECOIL DECAY TAGGING METHOD

TARGET → RECOIL → FMA → PPAC → DSSD

10^{-12} - 10^{-9} s → 0.5 - 2.0 \mu s → 30 ns → 20 \mu s - 5 s

- Reaction occurs
- Gamma-ray detected
- M/Q measured
- Recoil implanted in DSSD pixel (X, Y)
- Alpha or proton decay occurs in pixel (X, Y)

Prompt \gamma-rays correlated with M/Q and (X, Y) position of recoil in DSSD

Decay proton or alpha identifies nucleus that emitted the \gamma-rays
PROTON RADIOACTIVITIES

- PROTON EMITTERS FOUND AT ANL
- PREVIOUSLY Known PROTON EMITTERS

Fr
At
Bi
Tl
Au
Ir
Re
Ta
Lu
Tm
Ho
Tb
Eu
Pm
Pr
La
Cs
I
Sb
Channel selection with charged-particle detector arrays

Talk given at the Workshop on the Physics of using Compound-Nucleus Separators
LBNL

M. Devlin
April 11, 1997
Design goals of charged-particle detector arrays

High efficiency
High degree of segmentation
Good particle identification
Able to handle high count rates
Low particle detection energy thresholds
Low total mass
Properties of the Microball

- It consists of 95 CsI(Tl) scintillators with Si photodiode readout arranged in 9 rings covering 96% of $4\pi$

- It resolves and identifies charged particles with 80-95% efficiency

- It provides the charged particle energies

- It selects the exit channels with high efficiency

- It allows precise Doppler corrections to be made from the measurement of the recoil direction that improve substantially the energy resolution

For the $^{58}\text{Ni}(^{29}\text{Si},\alpha2p)$ reaction channel the FWHM goes from 24.0 to 6.5 keV at 2.0 MeV!

- It improves the peak to background by factors of 4-10 depending on the channel.
48 MeV alphas on Au

Channel Number
Slow ->

Channel Number
Fast ->

p punchthrough

p, d, t, \(^{3}\text{He}\), \(^{4}\text{He}\)
\( ^{28} \text{Si} + ^{56} \text{Ni} \) @ 130 MeV

\[ \begin{align*}
\alpha^{2 \rho} \\
\gamma \rho \\
\text{total}
\end{align*} \]
$^{88}\text{Sr}$ yрастное спектральное распределение:

- **A) No MB**
- **B) α2p gated**
- **C) Recoil corrected**

Если $p/b = 0.4$, то $\gamma = 1.3$ и $\eta = 4.5$. Ед. измер. $E_\gamma$ (кэВ).
The diagrams depict histograms labeled '3pν', '3p', and '5d' with corresponding quantiles.

For '3pν':
- Quantile: 13.1-44915

For '3p':
- Quantile: 18.6-36893

For '5d':
- Quantile: 20.7-276

The x-axis is labeled 'X' and the y-axis ranges from 0 to 50000.
$k_Y$, $H_Y$, $E^*$ gating

- 137 MeV $^{31}$P + $^{58}$Ni = $^{89}$Tc$^*$→

- 18% in $^{85,86}$Zr the 3p particle gate
  - with 12% as $^{85}$Zr+3pn, and 2.0% as $^{86}$Zr+3p
  - The Yrast SD was 2.8% of the $^{86}$Zr or 0.056% of the total

- After gating by $k_Y \geq 17$
  - 90% of the 3pn+$^{85}$Zr was removed
  - 35% of the total $^{86}$Zr was lost
  - and only 25% of the SD was lost

- In the end the SD was 0.042% of total and 4.0% of 3p, but only 2% of the initial background remained
Gammasphere + Microball

83 HPGe - Hevimets Removed

$^{28}\text{Si} + ^{40}\text{Ca}$ at $E_{\text{lab}} = 125$ MeV - 4 protons detected
Figure 2
D. Rudolph et al., Synthetische F= 1 (80 region)
$^{58}\text{Ni} + ^{58}\text{Ni} @ 250$ MeV

$E_\gamma$ (keV)

Counts

3pn gated

3p gated

$CS + MB + n$ detectors

J.F. Smith, D.R. LaFosse, et al.
\[
\begin{align*}
\text{GS + MB} & \quad \frac{\sigma}{<200 \mu b} \\
(\text{some spectroscopy}) & \\
\text{(high spin spectroscopy)} & \quad \leq 0.1 \text{ mb} \\
\text{GS + MB + neut} & \quad <50 \mu b \\
\text{SD (\geq 1\%) of a 1\% channel} & \\
\text{MB suppresses fission for p+n and n+n reactions} & \quad \text{in light and moderate mass nuclei}
\end{align*}
\]
Cyrus Baktash
Oak Ridge National Laboratory
Spectroscopy and Channel Selection
Near Proton-Drip Line

Cyrus Baktash
ORNL
**Important Considerations in the Choice of Tools and Techniques:**

- **Objectives:**
  - New isotope/element production, decay studies:
    - High beam intensities
    - Gamma spectroscopy
    - Few pna of beam

- **Reactions:**
  - Transfer and DIC (grazing angle) \( n\text{-rich} \)
  - Compound nucleus (forward angles) \( p\text{-rich} \)
  - Evaporation particles may be used for tagging

- **Partial Cross section:**
  - Determines requisite selectivity
    \[
    \begin{cases}
      \sim 50 \text{ mb} \\
      \sim 5 \text{ mb}
    \end{cases}
    \]

- **Count-rate requirements:**
  - A function of beam intensity and cross section;
  - Determines requisite efficiency

**Tools:**

- **Magnetic Recoil Separators**

- **Ge arrays, charged-particle det., n-det., (H,K) at the target position**

- **Recoil Mass Separators (RMS)**

  - **Focal-Plane detectors:**
    - Ionization chamber, X and \( \gamma \)-det. for Z-sel.;
    - DSSD;
    - Recoil-Decay (p, \( \alpha \), isomers) Tagging
    - Others (decay scheme)
Outline

Experiences from:

1. GS + 1st Ball $A \approx 80$ SD
2. GS + 1st Ball + n $A \approx 60$ $N = Z \leq 30$
   $N = Z \geq 40$
3. RMS + Aux. det
4. Summary

Pro. d emitters
Radioactive Ion Beams
Figure 6. Spectra of the yrast SD band in $^{149}$Gd when one, two, three, four and five coincidence requirements (gates, fold two corresponds to one gate) are demanded from a gate list of 10 transitions. The data are taken from Eurogam I (a) and Eurogam II (b) [31]. No background has been subtracted from these spectra.
- $A \approx 80$
- Charged-particle evaporation dominates
- Typically $\geq 20$ exit channels

Microball:
- Channel selection
- Better resolution $\Rightarrow$ improved RP
Reaction $^{28}\text{Si} + ^{58}\text{Ni}$ at 130 MeV

GAMMASPHERE (57) plus MICROBALL

$2.5 \times 10^9$ particle-γγγ events

Relative Cross-Sections (%)

<table>
<thead>
<tr>
<th></th>
<th>CN</th>
<th>Mo</th>
<th>Nb</th>
<th>Zr</th>
<th>Y</th>
<th>Sr</th>
<th>Rb</th>
<th>Kr</th>
<th>Br</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>81</td>
<td>82</td>
<td>83</td>
<td>84</td>
<td>78</td>
<td>79</td>
<td>80</td>
<td>81</td>
<td>82</td>
</tr>
<tr>
<td>0.001</td>
<td></td>
<td>0.40</td>
<td>0.58</td>
<td>0.10</td>
<td>0.02</td>
<td>0.28</td>
<td>0.03</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>79</td>
<td>80</td>
<td>81</td>
<td>82</td>
<td>77</td>
<td>78</td>
<td>80</td>
<td>79</td>
<td>80</td>
</tr>
<tr>
<td>0.02</td>
<td>0.28</td>
<td>0.03</td>
<td>0.77</td>
<td>0.005</td>
<td>0.05</td>
<td>1.1</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>77</td>
<td>77</td>
<td>78</td>
<td>79</td>
<td>76</td>
<td>77</td>
<td>78</td>
<td>78</td>
<td>79</td>
</tr>
<tr>
<td>0.09</td>
<td>0.14</td>
<td>0.30</td>
<td>1.1</td>
<td>0.005</td>
<td>0.05</td>
<td>1.1</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>75</td>
<td>74</td>
<td>75</td>
<td>76</td>
<td>77</td>
<td>78</td>
<td>78</td>
<td>78</td>
<td>79</td>
</tr>
<tr>
<td>0.21</td>
<td>0.01</td>
<td>0.05</td>
<td>0.05</td>
<td>0.005</td>
<td>0.05</td>
<td>1.1</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.05</td>
<td>0.05</td>
<td>1.1</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

| 38   | 39 | 40 | 41 | 42 | 43 | 44 |    |    |    |
Forking
(Also in $^{81}$Sr & $^{87}$Nb)

$^{83}$Zr
Liquid Scintillator n-det.  Microball

PID vs Fast \( \frac{\text{Fast}}{\text{Slow}} \) ratio
Figure 1: Experimental relative cross-sections [%] of the reaction $^{36}$Ar + $^{28}$Si at 136 MeV beam energy deduced from the thin target GAMMASPHERE experiment. The total cross section amounts to $\sigma_{\text{tot}} \approx 1000$ mb and the uncertainties reach from 5 % (strong channels) to 20 % (weak channels). The proposed reaction $^{24}$Mg + $^{40}$Ca leads to the same compound nucleus $^{64}$Ge.
2\alpha n \text{ and } 2882 \text{ keV gated}

(a)

(b)

(c)

\begin{align*}
\text{Intensity} & \quad \text{Intensity} & \quad \text{Intensity} \\
0 & \quad 200 & \quad 3 \cdot 10^5 \\
10 & \quad 0 & \\
200 & \quad 0 & \\
3000 & \quad 0 & \\
E_\gamma \text{ (keV)} & \\
1000 & \quad 1017 & \quad 2882 \\
2000 & \quad 866 & \\
3000 & \quad \text{(peak)} & \\
\end{align*}

\text{\textsuperscript{55}Ni}

\text{\textsuperscript{55}Co}
Fig. 1. Total Energy Plane contour plot for all events in which 3 protons were detected. The real 3p events are cleanly separated from the contaminating four-particle channels.

Fig. 2. Portion of the γ-spectra produced by a) gating on 3 detected protons, and b) setting a gate around the real 3p region of the 3p gated Total Energy Plane (Fig. 1).
Heavier $N=Z$; $< 10 \mu b \Rightarrow$ Requires High Selectivity

- Mass separator
- * Z-selector

Recall that $G_S + \mu_B$ Ball was not good enough, it remains to be seen if addition of n detector would help.
HRIBF Recoil Mass Spectrometer

Momentum Separator
(P/Q)

S1 S2 D2 Q4 Q5
D1 Q3
Target

Mass Separator
(A/Q)

ED1 D3 ED2 Q6 Q'7
Achromat
Focal plane

Inverse reactions
High rigidity beams (K=100)
Excellent beam rejection (>10^{12})
Excellent mass separation (M/ΔM=450)
Large energy acceptance
Large solid angle
Large A/Q acceptance
$^{58}\text{Ni} + ^{60}\text{Ni} @ 220 \text{ MeV}$

$M/\Delta M = 450$
Target Position Detectors

- 6 @ 90°
- 2 @ 155°
- 2 @ 132° (not shown)
- 4 @ 120°
- 8 @ 59°

Materials:
- Aluminum
- Lead
- 25% HPGe
- Clover
- CsI
- Fast Plastic/Inverted Si Neutron Detectors
HRIBF Recoil Mass Spectrometer

Momentum Separator
\((P/Q)\)

Mass Separator
\((A/Q)\)

Target
11 Clover Ge
12 Duet Ge (25%)
Hyball (CsI + Silicon)
NE-213 Array

PSAC
Strip Detectors
Tape System
Pair Spectrometer
Ion Chamber (\(Z\)-Information)
Isomer Catcher

\(E_{\text{pho}} \approx 4.7\)
### Selectivity

#### a) Total

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>51</th>
<th>50</th>
<th>49</th>
<th>48</th>
<th>47</th>
<th>46</th>
<th>45</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td>161</td>
<td>337</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>235</td>
<td>525</td>
<td>938</td>
<td></td>
<td></td>
<td>1688</td>
<td>409</td>
<td>308</td>
<td>2673</td>
</tr>
<tr>
<td>54</td>
<td>824</td>
<td>349</td>
<td>13</td>
<td>497</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>315</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### b) Mass

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>51</th>
<th>50</th>
<th>49</th>
<th>48</th>
<th>47</th>
<th>46</th>
<th>45</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>62</td>
<td></td>
<td></td>
<td>152</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### c) 1p Microball

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>51</th>
<th>50</th>
<th>49</th>
<th>48</th>
<th>47</th>
<th>46</th>
<th>45</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9</td>
<td></td>
<td>29</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>142</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>7</td>
<td>15</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### d) 2n n-detector

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>51</th>
<th>50</th>
<th>49</th>
<th>48</th>
<th>47</th>
<th>46</th>
<th>45</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
<td></td>
<td>1.6</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Improvement:**

- **Total**: 10/20,000
- **Microball**: 9/329 (improvement: 55)
- **Microball + RMS**: 3/20 (improvement: 300)

**Improvement:**

- **Total**: 3/217
- **Microball**: 0.1/4.2 → 47
- **Microball + RMS**: 0.03/0.3 → 2000
Table 1: Detection Efficiency of Ancillary Systems Separately and Combined for a Typical RIB Experiment

<table>
<thead>
<tr>
<th>Distinct Residues</th>
<th>( \varepsilon^c )</th>
<th>( % ) Yield</th>
<th>Enhancement</th>
<th>F.O.M.</th>
<th>( \xi \times \text{selectivity} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>23</td>
<td>1.00</td>
<td>0.05</td>
<td>not applicable</td>
<td>not applicable</td>
</tr>
<tr>
<td>RMS</td>
<td>3</td>
<td>0.30</td>
<td>1.4</td>
<td>28</td>
<td>8.4</td>
</tr>
<tr>
<td>HB</td>
<td>15</td>
<td>0.90</td>
<td>2.7</td>
<td>54</td>
<td>48.6</td>
</tr>
<tr>
<td>NW</td>
<td>4</td>
<td>0.01</td>
<td>2.4</td>
<td>48</td>
<td>0.2</td>
</tr>
<tr>
<td>RMS + HB</td>
<td>3</td>
<td>0.27</td>
<td>15</td>
<td>300</td>
<td>81.0</td>
</tr>
<tr>
<td>RMS + NW</td>
<td>1</td>
<td>0.0030</td>
<td>100.0</td>
<td>2000</td>
<td>6.0</td>
</tr>
<tr>
<td>HB + NW</td>
<td>4</td>
<td>0.0090</td>
<td>10</td>
<td>200</td>
<td>1.8</td>
</tr>
<tr>
<td>RMS + HB + NW</td>
<td>1</td>
<td>0.0027</td>
<td>100.0</td>
<td>2000</td>
<td>5.4</td>
</tr>
</tbody>
</table>

a) Values calculated from a statistical model calculation for the \(^{40}\text{Ca}(^{64}\text{Ga},p2n)^{101}\text{Sn}\) reaction at a beam energy of 235 MeV. The total fusion cross section is calculated to be 341 mb.

b) The number of reaction channels which survive the gating conditions.

c) Efficiency of the auxiliary detection system(s) in place. See Appendix B for discussion.

d) Percentage yield of the \(^{101}\text{Sn}\) channel with respect to the total channels within the gating conditions.

e) Enhancement of the relative yield of the \(^{101}\text{Sn}\) channel with respect to its ungated relative yield.

f) The Figure Of Merit (F.O.M.) for the detector, which is equivalent to the efficiency of the detector multiplied by the enhancement it provides for \(^{101}\text{Sn}\).

g) The values with no ancillary detector gating.

h,i,j) The values for the Recoil Mass Separator (RMS), the Hybrid Ball (HB), and the Neutron Wall (NW), respectively.
Summary

(1) No universal solution.
   → need as many tools as possible
   → use the most selective technique (inefficient)
      to establish few X-rays
   → go to the setup with best F.O.M. to build level scheme

(2) Guidelines:
   - $\sigma \leq 10^4 \text{ pb}$  high-fold $X$ (SD vs $A=150$)
   - $\sigma \leq 10 \text{ pb}$  \text{GS} + $\mu$-Ball (SD vs $A=80$)
   - $\sigma \leq \mu$-b  \text{GS} + $\mu$-Ball + N (N = 2 ≤ 36)
   - $\sigma \leq \mu$-b  mass separators + Z-selectors
   - $\sigma \leq 0.1 \text{ pb}$  (N = 2 ≥ 36)
      RDT

(3) For $\sigma \leq \mu$-b, use Radioactive Ion Beams
   - gain in $\sigma$ is offset by reduced beam intensity
   - But partial $\mu$ improves, especially RMS-based
     Techniques would work again.
GFS

1) A. of mass resolution

- In lo-res. mode (gas filled), would help reduce countrate in DSSD, and hence dead time:
  - Readout time $\sim 10^{-5}$
  - Countrate $\sim 10^5 \gg 1$

Also, less hit/pixel helps shorten the recovery time

- In Hi-res. mode (mass-separator), would be nice to achieve $\sim 1:150$

2) Countrates & physics

with 100% transmission eff., 10% e+ photo for G5:

- 1 Count/day/nb/few pna

  Can get 50 counts in 5 days $\Rightarrow$ 10nb

$\Rightarrow Z = 10^4$; Few levels
Karl-Heinz Schmidt
GSI
FISSION OF EXOTIC NUCLEI

Experiments performed at GSI by:

C. Böckstiegel, H.-G. Clerc, A. Grewe, M. de Jong
A. Junghans, J. Müller, S. Steinhäuser
IKDA, TH Darmstadt, Germany

M. Pfützner
University of Warsaw, Poland

J. Benlliure, A. Heinz, K.-H. Schmidt, B. Voss
GSI Darmstadt, Germany
FISSION OF EXOTIC NUCLEI

Limitations of conventional techniques

The secondary-beam facility of GSI

A fission experiment with exotic beams
  Experimental set-up
  Excitation mechanism

Results
  Z yields and TKEs in bimodal fission
  New insight into pair breaking in fission

Perspectives
Illustration of present knowledge on low-energy fission
max. 10 MeV above the fission barrier

○ measured mass distributions
(n,f) (sf) etc.
Our knowledge of low-energy fission relies on a very limited number of fissioning systems.

Difficulties to populate states close to the fission barrier:

- spontaneous fission restricted!
- $(n,f)
- $(\gamma,f)$
- $(d,pf)$ etc.

need stable or long-lived nuclei!

New options by the use of secondary beams?
238U (1 AGeV) + Pb
calculated cross sections
(A. Junghans)
Isotopical separation at the fragment separator (FRS)

Beam monitor
Scintillators

Projectiles $^{238}\text{U}$ (1 A·GeV) $10^7$ s$^{-1}$

Target

Degrader

Identified secondary beam $10^3$ s$^{-1}$

Protactinium

Position at S2 [mm] Mass number
Low-energy fission
max. 10 MeV above the fission barrier

✿✿ Charge distributions measured with secondary beams

○ measured mass distributions (n,f) (sf) etc.
Fission in inverse kinematics at relativistic energies:

excitation mechanisms

nuclear, $E^* \approx 30 \text{ MeV} \times \Delta A$

electromagnetic, $E^* \approx 12 \text{ MeV}$
Setup for the fission experiment

Method:
- electromagnetic excitation → fission
  (fission after nuclear contact is suppressed)

Features:
- forward focusing (almost 100% detection efficiency)
- excellent Z resolution
- kinematic analysis

Results:
- Z yields total kinetic energies
- Z response (sec. beam $^{226}$Th)

![Graph showing Z response of fission fragments](image)
Excitation mechanism:

- electromagnetic interaction
  - Excitation of the giant resonances (dipole-, quadrupole-)
  - 11 MeV mean excitation energy (FWHM = 5 MeV)

Multichance fission of $^{234}\text{U}$ after e.m. excitation

- $\approx 3$ barn excitation cross section
- 3 g lead target $\rightarrow \approx 1\%$ e.m. fission

Charge yields (e.m. induced bimodal fission)

Relative strength of the 2 fission modes

- 221Th
- 227Th
- 234U

M.G. Itkis, $E^* = 26$ MeV
$D_Z(Z + 1.5) = (-1)^{Z+1} \left[ \ln(Y(Z+3)) - 3\ln(Y(Z+2)) + 3\ln(Y(Z+1)) - \ln(Y(Z)) \right] / 8$
$D_2^*(Z+1.5) = (-1)^{Z+1} \left[ (\ln Y(Z+3) - 3\ln Y(Z+2) + 3\ln Y(Z+1) - \ln Y(Z)) / 8 \right]$
Prediction based on single-particle excitations

\[ P_L = \frac{Z_L}{Z_{CN}} \]
Perspectives

Secondary beams make short-lived nuclei available for low-energy fission studies.

Challenge to develop adequate experimental techniques for the new specific conditions.

A new door for fission studies is open and will give new life to this unique research field on large-amplitude collective motion.
CONCLUSION

Transition from symmetric to asymmetric fission around $A = 226$ systematically mapped

Weights of modes governed by $A$

Compact asymmetric mode around $N = 82$
observed for all nuclei

First determination of superfluid component in symmetric mode (10% to 15%)

First systematic observation of even-odd structure for odd-$Z$ fissioning nuclei
($Z$ even-odd effect in the presence of unpaired protons!)

Evidence that pair breaking occurs in an early stage of fission
(not during snapping-in at scission)