Perspectives for Penning Trap Mass Measurements of Super Heavy Elements

- Introduction to Super Heavy Elements
- Production of SHE
- Mass determination of SHE
- Direct mass measurements for Z > 100 with SHIPTRAP
- Extending the reach towards SHE
- Conclusions

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Mass Measurements for Nuclear Physics

- Isospin Symmetry
- Pairing
- Exotic decays
- Fundamental Interactions

- Halos and Skins
- Stability of SHE

- Magic Numbers
- Evolution of Shell Structure

Proton Number Z

Neutron Number N

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Extending the Nuclear Chart at RIB Facilities

Chart of the Nuclides 1958

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Extending the Nuclear Chart at RIB Facilities

Chart of the Nuclides 2009

≈ 3000 known nuclides

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Super Heavy Elements

- how heavy can the elements be?
- location of the island of stability?
- structure of SHE?

stability due to shell effects
⇒ accurate binding energies needed

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Production of SHE

Exclusive access to nuclides with Z > 100 by fusion-evaporation reactions

- “cold” fusion: heavy ions on Pb and Bi targets
- “hot” fusion: \(^{48}\)Ca induced reactions on Actinide targets

- Heavy-ion accelerator to provide high-intensity stable beams at coulomb barrier energies
- thin targets \(\approx 0.5\) mg/cm\(^2\)
- Recoil separator to separate evaporation residues from primary beam in flight
GSI: Unique Combination for SHE Studies

ECR + UNILAC

Stable targets

Beam

Actinide targets

SHIP

TASCA

Chemistry

Radiochem. labs

SHIPTRAP

TASISpec

Chemical theory

Courtesy of Ch. E. Duellmann

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The UNIversal Linear ACcelerator – UNILAC

≈ 12 MeV/u for all elements
Beam intensity (on target) 0.5 - 4 μA_p
(25% duty cycle)
### SHIP:
- Separation time: 1 – 2 μs
- Transmission: 20 – 50 %
- Background: 10 – 50 Hz
- Det. E. resolution: 18 – 25 keV
- Det. Pos. resolution: 150 μm
- Dead time: 3 – 25 μs

≈ 5 MeV/u

0.1-1 MeV/u

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TASCA - a Gas-filled Separator for Chemistry and Physics

- Chemical investigations of the transactinide elements: one-atom-at-a-time chemistry
- Nuclear structure investigations
- Hot-fusion nuclear reaction studies

TASCA
TransActinide Separator and Chemistry Apparatus

Courtesy of Ch. E. Duellmann

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GSI: Elements 107 – 112

48Ca + X

X + 208Pb, 209Bi

proton number

neutron number

Courtesy of S. Hofmann
Results at FLNR Dubna

48Ca + X
X + 208Pb, 209Bi

85 chains
34 isotopes
5 new elements

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Key Results: growing $T_{1/2}$ and constant $\sigma$

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

$\sigma = 0.5 – 5 \text{ pb}$
Producing New Isotopes and Elements

Experiments with $^{248}\text{Cm}$ targets

$^{54}\text{Cr} + ^{248}\text{Cm} \rightarrow ^{302}120^*$

$\sigma = 30 \text{ fb} - 0.6 \text{ pb}$

for $BF = 7.0 - 8.3 \text{ MeV}$

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Knowledge of Masses for $Z > 100$

AME 2003

- no direct mass measurements for $Z > 92$
- some masses indirectly determined from $Q_\alpha$ values
- many masses extrapolated from systematic trends
• binding energy determines existence of SHE
• studies of the shell structure evolution $N = 152, 162$
• pin down endpoints of decay chains (Rf, Sg)
• studies of long-lived isomeric states
Mass Determination using Decay-links

\[ ^{270}_{\alpha} \text{Ds (Z=110)} \]

\[ ^{266}_{\alpha} \text{Hs} \]
\[ ^{262}_{\alpha} \text{Sg} \]
\[ ^{258}_{\alpha} \text{Rf} \]
\[ ^{254}_{\alpha} \text{No} \]
\[ ^{250}_{\alpha} \text{Fm} \]
\[ ^{246}_{\alpha} \text{Cf} \]
\[ ^{242}_{\alpha} \text{Cm} \]
\[ ^{238}_{\alpha} \text{Pu} \]

**Difficulties:**
- "incomplete" α-chains
- decays not between ground states
- uncertainties accumulate

F.P. Hessberger et al.,

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Direct Mass Measurements above $Z = 100$

Typical production rates at present facilities:

- 1 atom/s @ $Z=102$ ($\sigma \approx \mu b$)
- 1 atom/week @ $Z=112$ ($\sigma \approx pb$)

<table>
<thead>
<tr>
<th>Present reach of Penning Traps for RIBs</th>
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</thead>
<tbody>
<tr>
<td>Half-life</td>
</tr>
<tr>
<td>Rate of trapped ions</td>
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</table>

Requirements:

- energy matching of reaction products to trap's energy scale
- high efficiency to deal with very low production rates
- high cleanliness for low background
- stable and reliable operation over extended time
Penning Trap Basics in Brief

Axial motion:
harmonic oscillation in E-field
\[ \omega_z = \sqrt{\frac{qV_0}{md^2}} \]

Magnetron motion:
E x B drift
\[ \omega_\perp = \frac{\omega_z}{2} \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}} \]

Reduced cyclotron motion:
\[ \omega_\perp = \frac{\omega_z}{2} \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}} \]

in an ideal trap:
\[ \omega_c = \omega_\perp + \omega_\parallel = \frac{q}{m} B \]

invariance theorem:
\[ \omega_c^2 = \omega_\perp^2 + \omega_\parallel^2 + \omega_z^2 \]


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Cyclotron frequency measurement

**Step 1: Excite radial motion**

- \( E_\sim 1\text{meV} \equiv E_+ \sim 1\text{eV} \)

**Step 2: Convert \( E_{\text{rad}} \) into \( E_{\text{axial}} \), measure TOF**

- Inhomogeneous part of magnetic field

**Record TOF as function of excit. frequency \( \Rightarrow \) Resonance**

M. König et al., Int. J. of Mass Spectr. and Ion Proc. 142 (1995) 95

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**SHIPTRAP Setup**

0.1-1 MeV/u → ≈ 1 eV

**Gas Cell**
- SHIP ion beam
- Entrance window
- DC cage
- RF funnel
- Extraction RFQ
- Cooler and Buncher RFQ

**Buncher**
- Laser or surface ionization source

**Transfer**
- Quadrupole deflector
- Purification trap

**Penning Traps**
- Superconducting magnet
- Diaphragm
- MCP-detector
- Measurement trap

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Mass resolving power of $m/\delta m \approx 100,000$ in purification trap:

$\Rightarrow$ separation of isobars

Mass resolving power of $m/\delta m \approx 1,000,000$ in measurement trap:

$\Rightarrow$ separation of isomers
Direct Mass Measurements of $^{252-254}$No

Gateway to Superheavies

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• rate of incoming particles for $^{255}\text{Lr}$ only 0.3 ions/s

• First direct mass measurements in the region $Z > 100$

• $^{255}\text{Lr}$ nuclide with lowest rate ever measured in a Penning trap

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Mass determination of SHE

- Combine new, directly measured masses and α-decay spectroscopy
- Determine the masses of short-lived higher-Z nuclides

To be determined:
α-decay of $^{262}\text{Sg}$ (15%)
The Route to SHE

- **improve production rates**
  - increase primary beam intensities
    - improved ECR sources (28 GHz)
    - optimized cw accelerator for stable beams
    - target developments (compounds, cooling)

- **access to more neutron-rich nuclides**
  - hot-fusion reactions with actinide targets

- **higher sensitivity and efficiency**
  - detection system with single-ion sensitivity
  - next generation gas stoppers
Higher Intensities at GSI

New 28-GHz EZR Source:
- Higher charge state
- Higher intensity

Factor: 2 – 5

New RFQ Injector:
- Duty factor 25 % => 50 %
- Higher injection energy
- Higher acceptance

Factor: ≥ 2

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Optimized Accelerator for SHE Production

Superconducting continuous wave accelerator:

Energy MeV/u

- ECR source
- RFQ, 108 MHz
- IH DTL, 108 MHz
- CH DTL, supercond. 324 MHz
- QWR Cavities 108 MHz
- Debuncher

- 0.003
- 0.3
- 1.4
- 1.8
- 2.4
- 3.3
- 4.2
- 5.2
- 6.1
- 7.1

Design specifications
- DC beam
- $1 < A/q < 7$
- $E_{\text{beam}}$: 4-7.5 MeV/u
- $\Delta E_{\text{beam}} < \pm 3\text{keV/u}$

U. Ratzinger et al., Frankfurt University
W. Barth, L. Dahl et al., GSI

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The Route to SHE

increase sensitivity and efficiency

- (non-destructive) detection system with single-ion sensitivity
  → mass measurement with one ion only

- next generation gas stoppers:
  - cryogenic for highest cleanliness
  - RF carpet extraction systems
Coupling of TASCA and SHIPTRAP

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Conclusions

• Direct mass measurements for No, Lr region have been performed

• High-precision mass measurements of stopped rare isotopes with production rates of about 0.1 per second are possible today

• Opened the door for novel experiments with stopped heavy elements

• Technical developments and new techniques will pave the way to heavier elements

Thank you for your attention!
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