Nuclear Structure Revealed by High-Precision Mass Measurements at SHIPTRAP / GSI

Michael Block
GSI Darmstadt
Helmholtz-Institut Mainz
Institut für Kernchemie Johannes Gutenberg Universität Mainz
Nuclear Shells: Magic Numbers in SHE?

[Graph showing neutron number N vs. proton number Z for different models (SkP, SLy6, SkI3, SkI4, NL3, NL-Z2)]
Nuclear Shells: Magic Numbers in SHE?
high-precision mass measurements provide
- accurate absolute binding energies to map nuclear shell effects
- anchor points to fix decay chains

Studies the nuclear structure evolution

Benchmark theoretical nuclear models
SHIPTRAP Setup

\[ \approx 50 \text{ MeV} \rightarrow \approx 1 \text{ eV} \rightarrow \approx 1 \text{ keV} \]

- Gas Cell
  - SHIP ion beam
  - Entrance window
  - Extraction RFQ
  - DC cage
  - RF funnel

- Buncher
  - Surface ion source

- Transfer
  - Quadrupole deflector
  - Purification trap

- Penning Traps
  - Diaphragm
  - Measurement trap

- Detector
  - Superconducting magnet
  - MCP detector (ToF)
SHIPTRAP Setup

≈ 50 MeV ➞ ≈ 1 eV ➞ ≈ 1 keV

Gas Cell
- SHIP ion beam
- Entrance window
- Extraction RFQ
- DC cage
- RF funnel

Buncher
- Surface ion source
- Quadrupole deflector

Transfer
- Purification trap

Penning Trap
- Silicon box
- Focussing tube
- Measurement trap

TRAPSPEC
- Cluster- and Clover-type Ge detectors
Direct mass measurements with SHIPTRAP

$^{206}\text{Pb}(^{48}\text{Ca},2n)^{252}\text{No}$
$^{207}\text{Pb}(^{48}\text{Ca},2n)^{253}\text{No}$
$^{208}\text{Pb}(^{48}\text{Ca},2n)^{254}\text{No}$
$^{208}\text{Pb}(^{48}\text{Ca},1n)^{255}\text{No}$

$^{209}\text{Bi}(^{48}\text{Ca},2n)^{255}\text{Lr}$
$^{209}\text{Bi}(^{48}\text{Ca},1n)^{256}\text{Lr}$

E. Minaya Ramirez et al., Science 337, 1183 (2012)
Masses of even-even $N-Z = 48$ and $N-Z = 50$ Nuclei

$\Delta m^2$ / MeV

$\Delta m^2(\text{exp}) - \Delta m^2(\text{theo})$ / MeV

Atomic Number

Atomic Number

Möller et. al. [MöN95] Kuora et al. [KoT05] Myers et al. [MyS96] Smolanczuk et al. [SmS95a]
Direct Mapping of Nuclear Shell Effects in the Heaviest Elements

\[ \delta_{2n}(N,Z) = 2B(N,Z) - B(N-2,Z) - B(N+2,Z) \]

**Experimental**
- Muntian (mic-mac)
  - Z=114 N=184
- Möller FRDM
  - Z=114 N=184
- TW-99
  - Z=120 N=172
- SkM*
  - Z=126 N=184
SHIPTRAP: Probing the Strength of Shell Effects

\[
\delta^2_{2n}(N,Z) = 2B(N,Z) - B(N-2,Z) - B(N+2,Z)
\]
Probing the Strength of Shell Effects @ $N = 152$
TRIGA-SPEC Setup in Mainz

J. Ketelaer et al., NIM A 594, 162 (2008)
Accurate mass measurements with keV precision on long-lived actinides

- provide anchor points
- cross check masses obtained by other techniques
- Next: mass measurements of $^{250-251}$Cf, $^{249}$Bk

Upgrades and Combinations

- Novel experiments
  - trap-assisted decay spectroscopy
  - laser spectroscopy (gas cell, gas jet, trap)
  - gas phase chemistry

- Increase efficiency and sensitivity
  - novel measurement schemes (PI-ICR)
  - single-ion mass measurements (FT-ICR)
    - TRIGA-TRAP, TRAPSENSOR
  - cryogenic gas cell
CryoCell Setup

Advantages compared to 1st generation gas cell:

- Larger stopping volume and Coaxial injection of reaction products
- Higher cleanliness due to cryogenic operation
- Larger gas density at a lower absolute pressure

C. Droese et al. NIM B 338, 126 (2014)
**Advantages compared to 1st generation gas cell:**

- Larger stopping volume and Coaxial injection of reaction products
- Higher cleanliness due to cryogenic operation
- Larger gas density at a lower absolute pressure

C. Droese et al. NIM B 338, 126 (2014)
Phase Imaging Ion Cyclotron Resonance (PI-ICR)

- position resolution: 70 µm
- active diameter: 42 mm

Delay-Line Detector by Roentdek GmbH

Position sensitive detector
Phase Imaging Ion Cyclotron Resonance (PI-ICR)

Independent Measurements of Eigenfrequencies $\nu_+$ and $\nu_-$

Determination of the spatial distribution

Radial excitation

Radial excitation followed by a phase accumulation time

$\phi + 2\pi n = 2\pi \nu t$

$\Delta \nu = \frac{\Delta \phi}{2\pi t} = \frac{\Delta R}{\pi t R}$
position-sensitive delayline detector (RoentDek GmbH DLD40)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active diameter</td>
<td>42 mm</td>
</tr>
<tr>
<td>Channel diameter</td>
<td>25 µm</td>
</tr>
<tr>
<td>Open area ratio</td>
<td>&gt;50 %</td>
</tr>
<tr>
<td>Position resolution</td>
<td>70 µm</td>
</tr>
<tr>
<td>Max. B-field</td>
<td>a few mT</td>
</tr>
<tr>
<td>Time resolution</td>
<td>~ 10 ns</td>
</tr>
</tbody>
</table>

image of magnetron motion ($G \approx 20$)
PI-ICR vs. ToF-ICR in experiment

10-hour measurements

\[ \delta[M^{124}\text{Xe} - M^{124}\text{Te}] \sim 300 \text{ eV} \]

\[ \delta[M^{132}\text{Xe} - M^{131}\text{Xe}] \sim 70 \text{ eV} \]

Gain in Precision \( \sim 4.5 \) !!!
Dreams for future applications

Isomerism in

$^{68}\text{Cu}$

$^6_i - 721.6 \text{ keV}$

$1^+$

$\beta^- 84\%$

$\beta^- 16\%$

$^0_i$

$^{68}\text{Zn}$

$g$: $T_{1/2} = 31.1 \text{ s}$
$m$: $T_{1/2} = 3.75 \text{ min}$

$E_{\text{exc}} \approx 700 \text{ keV}$
$m/\Delta m = 10^6$

$E_{\text{exc}} \approx 100 \text{ keV}$
$m/\Delta m \approx 10^7$ needed

$E_{\text{exc}} \approx 10 \text{ keV}$
$m/\Delta m \approx 10^8$ needed

$70^\circ$ phase difference

Dreams for future applications

Isomerism in $^{68}\text{Cu}$:

- $^{68}\text{Cu}$: $E_{\text{exc}} \approx 700$ keV
- $^{68}\text{Zn}$: $E_{\text{exc}} \approx 100$ keV
- $^{68}\text{Cu}$: $E_{\text{exc}} \approx 10$ keV

- $6^-$ phase difference

$m/\Delta m \approx 10^6$ needed
$m/\Delta m \approx 10^7$ needed
$m/\Delta m \approx 10^8$ needed

Neutrino mass determination via $\beta$/EC decay

Beta transitions between nuclear ground states with very low Q-values

- $\beta^-$-decay of $^3$H; Q-value $\approx 18.6$ keV
  - KATRIN
- $\beta^-$-decay of $^{187}$Re; Q-value $\approx 2.47$ keV
  - MARE
- EC in $^{163}$Ho; Q-value $\approx 2.55$ keV
  - ECHO HOLMES
$\beta^-$ decay endpoint measurement

\[ \text{Const. offset } \sim m^2(\nu_e) \]
\[ := \sum_i |U_{ei}|^2 m_i^2 \]

$m_\nu = 0 \text{ eV}$
$m_\nu = 1 \text{ eV}$

$\sim 2 \times 10^{-13}$

G. Drexlin, V. Hannen, S. Mertens, and C. Weinheimer
$^{187}\text{Re}-^{187}\text{Os}$ mass difference measurement

- Large discrepancy between measurements by proportional counters and micro-calorimeters

SHIPTRAP results $^{187}\text{Re}/^{187}\text{Os}$ mass difference

pattern 1: "magnetron-motion phase"

(a) center

$\alpha_{\text{mag}}$

$t = 700$ ms

magnetron

pattern 2: "cyclotron-motion phase"

(b) center

$\alpha_{\text{cyc}}$

$t = 700$ ms

cyclotron

number of detected ions

max

$Q_{\text{SHIPTRAP}} = 2492(30)(15)\text{ eV}$

4-hour measurement
Large discrepancy between measurements by proportional counters and micro-calorimeters

SHIPTRAP result confirms latest micro-calorimeter results

**TRAPSpec: Trap-assisted Spectroscopy**

Idea: Penning traps as high resolution mass separator for nuclear decay spectroscopy

**benefit:**
- selection of a particular state feasible
- Well-defined conditions
- Detailed nuclear structure information in one go

D. Rudolph et al.
TRAPSPEC – decay studies of $^{213}$Ra

D. Rudolph al., GSI Scientific Report, NUSTAR-SHE-08, 177 (2009)

F.P. Hessberger et al. EPJA 30, 551 (2006)
Penning trap mass spectrometry provides masses even radionuclides with unprecedented precision compared to other techniques.

High-precision mass measurements allow investigating nuclear structure effects even in the heaviest elements.

Increased resolving power and higher precision of novel PI-ICR method opens the door for applications in fundamental physics.

Technical and methodical improvements will extend the reach towards more exotic nuclides with lower production rates.

SHE research at GSI is being integrated into FAIR and will remain an important topic in the future (cw linac).

Thank you for your attention!