Precision Measurements of Very-Short Lived Nuclei Using an Advances Trapping System for Highly-Charged Ions

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Fields of Application

**Physics & Chemistry**
- Basic information required
- $\delta m/m \approx 1 \cdot 10^{-5}$
- Trap assisted decay spectroscopy

**Nuclear Physics**
- Nuclear binding energies, Q-values
- $\delta m/m \approx 1 \cdot 10^{-7}$

**Nuclear Structure**
- Shell closure, pairing, deformation, halos, isomers
- $\delta m/m \leq 1 \cdot 10^{-7}$

**Weak Interaction**
- Symmetry tests, CVC hypothesis
- $\delta m/m \leq 1 \cdot 10^{-8}$

**Astro-physics**
- Nuclear synthesis, r- and rp-process
- $\delta m/m < 1 \cdot 10^{-7}$

**Fundamental Properties**
- Tests of nuclear models and formulae
- $\delta m/m \leq 1 \cdot 10^{-7}$

**Exotic Nuclides**
- Weighing exotic nuclides
- Trap assisted laser spectroscopy

**Astrophysics**
- Nuclear synthesis, r- and rp-process
- $\delta m/m < 1 \cdot 10^{-7}$
Why trapping?

- effective use of rare species
- easy manipulation of trapped particles
- $q/m$-separation
- extended observation & manipulation time
- accumulation & bunching
- charge breeding
- polarization
- increase of luminosity

EFFICIENCY

ACCURACY

SENSITIVITY
The Electron Beam Ion Trap

**Principle**

- The trap: 
  - Axially: electron beam space charge
  - Longitudinally: electrodes

- Trap potential $U_t \approx 450 \text{ V}$

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>6 Tesla</td>
</tr>
<tr>
<td>Cathode radius</td>
<td>6.4 mm</td>
</tr>
<tr>
<td>Electron beam energy</td>
<td>30 keV</td>
</tr>
<tr>
<td>Electron beam current</td>
<td>5 A</td>
</tr>
<tr>
<td>Beam radius (80% current)</td>
<td>~50 µm</td>
</tr>
<tr>
<td>Electron flux</td>
<td>$3.4 \cdot 10^{23} \text{ cm}^{-2} \text{s}^{-1}$</td>
</tr>
<tr>
<td>Central current density</td>
<td>$1.1 \cdot 10^5 \text{ A/cm}^2$</td>
</tr>
<tr>
<td>Trap length</td>
<td>25 cm</td>
</tr>
<tr>
<td>Ionization time (Sn, q: 1→2)</td>
<td>0.16 µs</td>
</tr>
<tr>
<td>Axial oscillation period</td>
<td>16 µs</td>
</tr>
<tr>
<td>Total electron charges</td>
<td>$8 \cdot 10^{10}$</td>
</tr>
</tbody>
</table>
Charge Breeding Results

Results from ISOLDE (Courtesy of F. Wenander)
Principle of Penning Traps

Cyclotron frequency: \[ f_c = \frac{q}{2\pi m} \cdot B \]

PENNING trap
- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field

Typical frequencies
\( q = e, \ m = 100 \text{ u}, \ B = 6 \text{ T} \)
\[ f_+ \approx 1 \text{ kHz} \]
\[ f_- \approx 1 \text{ MHz} \]

\[ f_+ + f_- = f_c \]

\[ R = f_{\text{exc}} T_{\text{exc}} \]
Determine atomic mass from frequency ratio with a well-known reference mass
The Advantage of Taking Highly-Charged Ions

- much higher resolving power and accuracy
- saving in beam time requirement
The Goal

Precision measurements on short-lived nuclides.

NESR ion beam → RFQ cooler & buncher → EBIT charge breeder → m/q selection → Penning trap

10-100 times higher yield as everywhere else

1 – 50 times higher resolving power as compared to 1+

factor of 10 - 5000
shorter half-lives accessible
much higher resolving power and accuracy
saving in beam time requirement

$$\delta m/m < 1 \times 10^{-8} \text{ on isotopes with } T_{1/2} \approx 100 \text{ ms} \Rightarrow \text{perfect match with FRS LEB capabilities}$$
All known nuclides (masses measured or estimated)

In total: 3180 nuclides
Mass values available: 2228

NUSTAR: yield >100/s
In total: 2762 nuclides
Nuclides with a relative mass uncertainty of $\delta m/m \leq 10^{-7}$

In total: 1158 nuclides
Nuclides with a relative mass uncertainty of $\delta m/m \leq 10^{-8}$

In total: 181 nuclides

There is a huge potential for high-precision mass measurements.
Mass measurement programs worldwide

Conversion electron spectroscopy in a Penning trap:
- advantages: carrier-free sources:
  - no scattering, no energy loss
  - improved lineshape, peak/background
- first-time demonstrated at REXTRAP (ISOLDE)
  (Weissman et al., NIM A492 (2002) 451)
Perspectives of Trap Assisted Spectroscopy

- Perspective: development of new spectroscopic technique:
  - $\alpha$- and electron spectroscopy to determine the lifetimes of $2^+$ or $0^+$ states giving exp. access to quadrupole moments or E0 strength
  - population via $\alpha$ decay esp. in heavy nuclei: leads to the emission of low-energy 'shake-off' electrons: position-resolved detection measures the start position
  - measuring the direction of the $\alpha$ decay provides the momentum of the recoil nucleus
  - after its lifetime (typ. few 100 ps) the excited state decays via (L-) conversion, again shake-off electrons are emitted in the conversion process.
Results – Costs - Responsibilities

Expected results:
- Overall efficiency: 1-5%
- Maximum resolving power: 10E8
- Accessable half-life: 10 ms
- Relative mass uncertainty: 10E-9

Mainz, Greifswald, Jyväskylä, Stockholm: Penning trap system
GSI, Munich: RFQ cooler and buncher
Heidelberg, GSI, Livermore, Seattle:
Giessen, Mainz, Orsay: Detection system and electronics
Mainz, Munich: Trap assisted spectroscopy

Organisation and responsibilities

Cost estimates:
- Superconducting magnet (without traps and electronics): 300 kEUR
- EBIT: 500 kEUR
- RFQ cooler and buncher (without electronics): 200 kEUR
- Electronics (for traps and buncher): 200 kEUR
- Vacuum components (for highly-charged ions): 300 kEUR
- Off-line ion source with bender: 60 kEUR
- TOF-detector (with electronics): 20 kEUR
- FT-ICR detector (with electronics): 50 kEUR

SUM: 1.630 kEUR

MATS will be an advances trapping system for mass spectrometry, laser spectroscopy, and in-trap decay spectroscopy with highly-charged ions.
The MATS Collaboration

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Thanks a lot for your attention!