High-precision mass measurements for reliable nuclear-astrophysics calculations

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High-precision mass measurements for reliable nuclear-astrophysics calculations

Atomic masses of radionuclides

The ISOLTRAP experiment

Principle of mass measurement

Recent experimental results
Nucleosynthesis and r-process

s-process

Pb

82

50

Ni

Sn

fission in stars

neutrons

r-process

protons
courtesy: K. Blaum, H. Schatz
In total: 3180 nuclides
Measured masses: 2228

all nuclides

In total: 1158 nuclides

\[ \delta m/m < 10^{-7} \]

In total: 181 nuclides

\[ \delta \frac{m}{m} < 10^{-8} \]

In total: 24 nuclides

δm/m < 10^{-9}

Penning traps at accelerators

- operating facilities
- facilities under construction or test
- planned facilities
Production of radioactive nuclides at ISOLDE

- Spallation production of radioactive nuclides:
  - $^{238}\text{U} + \text{spallation}$
  - $^{208}\text{Fr}$

- Fragmentation production of radioactive nuclides:
  - $^{238}\text{U} + \text{fragmentation}$
  - $^{75}\text{Li}$

- Fission production of radioactive nuclides:
  - $^{238}\text{U} + \text{fission}$
  - $^{143}\text{Cs}$
Production of radioactive nuclides at ISOLDE
ISOLTRAP: Experimental setup

- Buncher
- Preparation trap
- Precision trap

2m
ISOLTRAP: Experimental setup

- **Bunching of the continuous beam**
- **Determination of cyclotron frequency** ($R = 10^7$)
- **Removal of contaminant ions** ($R = 10^5$)

- ISOLDE beam (continuous) 60 keV
- Stable alkali reference ion source
- RF trap
- HV platform
- 1st pulsed drift tube 2.8 keV ion bunches
- 2nd pulsed drift tube
- 100 eV ion bunches
- Preparation Penning trap $B = 4.7$ T
- Precision Penning trap $B = 5.9$ T

Principle of mass determination

\[ \nu_c = \frac{1}{2\pi} \frac{q}{m} B \]

measurement of cyclotron frequency

motional modes of ion stored in a Penning trap
Principle of mass determination

- Magnetron excitation
- Quadrupole excitation $\nu_{rf}$
- radial $\Rightarrow$ axial energy
- Time-of-flight (TOF)

Conversion of magnetron into cyclotron motion

- Passing B-field gradient after ejection

Diagram showing the trajectory of particles under the influence of a magnetic trap.
Principle of mass determination

Example: $^{85}\text{Rb}$ (900ms excitation duration)
**Principle of mass determination**

**mean TOF**

**TOF spectrum**

**Example:** $^{85}$Rb (900ms excitation duration)
Principle of mass determination

cyclotron frequency of "unknown" nuclide

\[ \nu_c = \frac{1}{2\pi} \frac{q}{m} B \]

cyclotron frequency of well-known nuclide

\[ \nu_{c,\text{ref}} = \frac{1}{2\pi} \frac{q}{m_{\text{ref}}} B \]

determination of mass ratio

\[ \frac{\nu_{c,\text{ref}}}{\nu_c} = \frac{m}{m_{\text{ref}}} \]
Stable alkali ions as mass references
Carbon clusters as mass references

K. Blaum et al., EPJ A 15, 245 (2002)

Mass measured at ISOLTRAP
Reference mass
Determination of the mass accuracy

Combined carbon cluster cross-reference measurements

Relative mass accuracy limit: \( (\frac{\delta m}{m})_{\text{lim}} = 8 \cdot 10^{-9} \)

**ISOLTRAP mass measurements in 2004-2005**

**Nuclides measured in 2004/2005**

- $^{126}$Xe, $^{136}$Xe
- $^{127,128,131-134}$Sn
- $^{118,120,122-124}$Cd
- $^{126}$Xe, $^{136}$Xe
- $^{127,128,131-134}$Sn
- $^{84}$Kr, $^{86-95}$Kr
- $^{35-38}$K, $^{43-46}$K
- $^{22}$Mg
- $^{21-22}$Na
- $^{17}$Ne, $^{19}$Ne
- $^{71-81}$Zn

<table>
<thead>
<tr>
<th>Highlights</th>
<th>Nuclide</th>
<th>Half-life</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{17}$Ne</td>
<td>109 ms</td>
<td>530 eV</td>
</tr>
<tr>
<td></td>
<td>$^{22}$Mg</td>
<td>3.86 s</td>
<td>270 eV</td>
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<tr>
<td></td>
<td>$^{35}$K</td>
<td>178 ms</td>
<td>530 eV</td>
</tr>
<tr>
<td></td>
<td>$^{81}$Zn</td>
<td>290 ms</td>
<td>3.45 keV</td>
</tr>
</tbody>
</table>
The mass of $^{22}$Mg

- 10 frequency ratios measured
- 16 relations included in $\chi^2$ adjustment

Solving the mass discrepancy of $^{22}$Mg

Ion yields at ISOLDE
Ion yields at ISOLDE

protons

neutrons

yield (ions/μC)

SC and PSB yields
courtesy: M. Turrion
ISOLDE target for Zn run

UC$_x$ target
RILIS

quartz transfer line

protons

courtesy: T. Stora et al.
Yields at ISOLTRAP

Zn

estimate for target/ion source
0.5%
Preliminary result for mass excess Zn

![Graph showing the difference in mass excess for Zn isotopes](image)

- Mass number A: 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81
- Difference mass excess (ISOLTRAP-AME2003) / keV
- Mean TOF / µs
- ν₀ - 1122161.85 Hz / Hz
- $^{81}\text{Zn}^+$
Ion yields at ISOLDE

protons

neutrons

yield (ions/μC)

SC and PSB yields

courtesy: M. Turrion
Decay in the buffer-gas-filled preparation trap

A novel idea: In-trap decay mass spectrometry

[Diagram showing decay processes]

- Make more radioactive species available
- Nearly simultaneous $\omega_c$ measurement of mother and daughter nuclei
- Test candidate: $^{37}\text{K} \rightarrow ^{37}\text{Ar}$

Elements/isotopes which are in principle not produced are accessible!
First application of in-trap decay mass spectrometry
Summary

• mass determination with a time-of-flight cyclotron resonance detection technique

limited by:

nuclide production rate above 100 s\(^{-1}\)
half-life (so far) over 65ms
systematic uncertainty limit:

\[
(\delta m/m)_{\text{lim}} = 8 \cdot 10^{-9}
\]

• so far mass measurements on more than 300 radionuclides at ISOLTRAP for tests of nuclear structure, mass models, a contributions to a CKM unitarity test, ...

• new techniques and development:
in-trap decay method, new ion sources and detector, magnetic field stabilization, new excitation schemes, ...
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