High-precision Penning trap experiments for fundamental studies

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Content

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- Experimental setup and measurement procedure
- High-precision mass measurements
- High-precision $g$-factor measurements
- Summary
Part I

High-precision mass measurements
**Requirements for mass spectrometry**


High-accuracy mass measurements allow one to determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.

\[
B(Z,N) = [(N m_n + Z m_p + Z m_e - m(Z,N)] \cdot c^2
\]

- binding energy
# Requirements for mass spectrometry

High-accuracy mass measurements allow one to determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.

<table>
<thead>
<tr>
<th>K. B., Phys. Rep. 425, 1-78 (2006)</th>
<th>$\delta m/m$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General physics &amp; chemistry</strong></td>
<td>$\leq 10^{-5}$</td>
</tr>
<tr>
<td><strong>Nuclear structure physics</strong></td>
<td>$\leq 10^{-6}$</td>
</tr>
<tr>
<td>- separation of isobars</td>
<td></td>
</tr>
<tr>
<td><strong>Astrophysics</strong></td>
<td>$\leq 10^{-6}$</td>
</tr>
<tr>
<td>- separation of isomers</td>
<td></td>
</tr>
<tr>
<td><strong>Weak interaction studies</strong></td>
<td>$\leq 10^{-8}$</td>
</tr>
<tr>
<td><strong>Metrology - fundamental constants</strong></td>
<td>$\leq 10^{-9}$</td>
</tr>
<tr>
<td><strong>CPT tests</strong></td>
<td>$\leq 10^{-10}$</td>
</tr>
<tr>
<td><strong>QED in highly-charged ions</strong></td>
<td>$\leq 10^{-11}$</td>
</tr>
<tr>
<td>- separation of atomic states</td>
<td></td>
</tr>
</tbody>
</table>
**Precision: A brief history of mass spectrometry**

- **38Ca** ($T_{1/2} = 440$ ms)
- **28Si**

### Mass Uncertainty $\frac{\delta m}{m}$

- **Mass Spectrographs**
- **RF Spectrometers**
- **Reaction Q**
- **ion cloud**
- **single ion**
- **PTMS**

**m**($^{28}$Si)$= 27.976 926 532 6 \text{ u}$

$$\delta m = 0.000 000 001 9 \text{ u}$$

Rel. Precision $= 6 \times 10^{-11}$

**Distance Mainz-Seattle**

8000km ± 0.5mm

SMILETRAP, MIT-TRAP (now at FSU), Seattle-TRAP, Mainz-TRAP

CPT, ISOLTRAP, JYFLTRAP, LEBIT, SHIPTRAP

www.quantum.physik.uni-mainz.de/mats/
**Principle of Penning trap mass spectrometry**

**Cyclotron frequency:**

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

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

Typical frequencies

\[ q = e, \ m = 100 \, \text{u}, \ B = 6 \, \text{T} \]

\[ f_- \approx 1 \, \text{kHz} \quad f_+ \approx 1 \, \text{MHz} \]

Time-of-flight ion cyclotron resonance detection

(3) TOF measurement

(2) Energy conversion

(1) Excitation of the ion motion

Determine atomic mass from frequency ratio with a well-known “reference mass”.

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

\[
f_{c,\text{ref}} = \frac{m - m_e}{m_{\text{ref}} - m_e}
\]
Triple-trap mass spectrometer ISOLTRAP

F. Herfurth, et al., NIM A 469, 264 (2001)
K. Blaum et al., NIM B 204, 478 (2003)
Resolution and isolation of nuclear isomers

Isomerism in $^{68}$Cu:

- $^6_1\rightarrow 721.6\text{ keV}$
- IT 84%
- $^6_1\rightarrow \beta^- 16$
- $^6_1\rightarrow 16\%
- g: $T_{1/2} = 31.1\text{ s}$
- m: $T_{1/2} = 3.75\text{ min}$

as produced by ISOLDE

isolation of the $^1_1$ ground state

$^{68}$Zn

isolation of the $^6_1$ isomeric state

Applications

- Preparation of an isomerically pure beam
- Clear state-to-mass assignments
- Trap-assisted decay and laser spectroscopy

Applications: Nucleosynthesis studies

Questions addressed:
• Why is iron so much abundant than heavier elements such as gold?
• Why are there heavy elements at all and how did they come into existence?
• How can we explain the isotopic composition in the Universe?
**Determination of the $^{76}\text{Ge} \beta$-Decay Q-Value**

**Question:** Is there a $\nu$-less double $\beta$-decay?

**Reaction:** $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^- (+2\bar{\nu}_e ?)$

---

### Mass determination of $^{76}\text{Ge}$ and $^{76}\text{Se}$

- **$^{76}\text{Ge}$**
  - Measured deviation [ppb]
  - Ion charge state

- **$^{76}\text{Se}$**
  - Measured deviation [ppb]
  - Ion charge state

### Q-value of $^{76}\text{Ge}$ ($0\nu\beta\beta$):

- Measured deviations for $^{76}\text{Ge}$ and $^{76}\text{Se}$

**7-fold improvement of the Q-value ($\delta m/m = 1 \times 10^{-9}$)**

Performed at SMILETRAP (Stockholm)


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Isobaric Multiplet Mass Equation

Mass formula for multiplets of nuclear states with same mass and isospin

\[ M = a + bT_z + cT_z^2 + dT_z^3 \]

Commonly used quadratic form

\[ A = 33, \ T = \frac{3}{2} \] quartet:

- \[ ^{33}\text{Ar} \]
- \[ ^{33}\text{Cl} \]
- \[ ^{33}\text{S} \]
- \[ ^{33}\text{P} \]
Most stringent test of IMME (with $^{32,33}$Ar)

ISOLTRAP measurements 2003:
- $^{33}$Ar with $u(m) = 0.44$ keV
- $^{32}$Ar with $u(m) = 1.8$ keV

New status:
$A = 33$, $T = 3/2$ quartet: $d = -0.13(45)$ keV
$A = 32$, $T = 2$ quintet: $d = -0.11(30)$ keV

Recent results of fundamental studies

Population inversion of nuclear states and nuclear structure studies:


Why are there elements heavier than iron?


Are there scalar currents present in the Weak Interaction?


$V_{ud}$ – is unitarity violated in quark mixing?


$\rightarrow$ See talk by J. Hardy and I. Towner tomorrow
Future perspectives

We want to perform mass measurements on rarely produced heavy nuclides. (~1 particle per minute)

Need for:

- a non-destructive detection technique
- single-particle sensitivity
- a low-noise and cold environment
Non-destructive ion detection

Applications

- Mass measurements on heavy/superheavy rare elements
- Fast identification and effective use of stored ions

Operation of traps and electronics at **cryogenic** (4 K) temperature.

Status FT-ICR mass spectrometry

Precision Penning trap

- traps assembled
- 4K reached
- electronic testet
- ion trapping in progress

Single ion sensitivity (singly charged heavy ion)!

Cryogenic electronics


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Spectroscopy setup at the Mainz TRIGA reactor

In Collaboration with:
Klaus Eberhardt
Gabriele Hampel
Norbert Trautmann

Laser spectroscopy team:
Christopher Geppert
Jörg Krämer
Wilfried Nörtershäuser

and GSI Darmstadt

mass spectrometry
and
collinear laser spectroscopy
on transuranium elements (Np-Cf) and neutron-rich nuclides
Laser and mass spectroscopy at FAIR

- MATS
- LaSpec
- RFQ
dipole
- gas catcher

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Part II

High-precision $g$-factor measurements
The g – factor

relation between magnetic dipole moment and angular momentum

\[ \vec{\mu} = g_J \frac{|q|}{2m} \hbar \vec{J} \]

free lepton: \( g_s = g \)-factor of the spin
Measurement principle for a proton

Eigenmotions of the particle $\rightarrow$ cyclotron frequency

Zeeman splitting in the spin eigenstates $\rightarrow$ Larmor frequency

$$\omega_L = \frac{2\mu \cdot B}{\hbar} = g_p \frac{e}{2m_p} B$$

$$g_p = 2 \cdot \frac{\omega_L}{\omega_c}$$

$$\omega_c = \frac{e}{m_p} B$$

We aim for $\delta g/g < 10^{-9}$. 
**g-factor of the proton and the antiproton**

**Test of CPT invariance**
- Currently believed to hold
- CPT transforms particle into its antiparticle (P. Dirac 1928)

\[
g_p = 2 \cdot \frac{\omega_L}{\omega_c}
\]

\(\omega_c\): cyclotron frequency
\(\omega_L\): Larmor frequency

PDG: \(g_p = 2 \times 2.792847337(29)\)

With our double Penning-trap technique we aim for \(\delta g/g = 10^{-9}\).
Status of the (anti)proton g-factor experiment

Hybrid analysis trap

1 cm ± 1 μm

Manufactured at the Institute for Microtechnique Mainz (IMM).


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Penning traps are ideal tools to perform high-precision experiments for fundamental studies!

- Unitarity test of the CKM matrix:
  \[ \delta m/m < 10^{-8} \] for short-lived radionuclides
- Test of \( E=mc^2 \):
  \[ \delta m/m < 10^{-10} \] for \(^{32}\text{S}, \, ^{33}\text{S}\)
- Test of CPT invariance:
  \[ \delta g/g < 10^{-9} \] for proton and antiproton
- Test of bound-state QED
  \[ \delta g/g < 10^{-9} \] for hydrogen-like highly-charged ions
- Determination of fundamental constants:
  \( m_e, \, m_p, \, \alpha, \, N_a h, \, \mu, \) …

Thanks a lot for your attention.
The Helmholtz-Research-Group MATS

In collaboration with:

and the ISOLTRAP team

„Mass“-Team
M. Dworschak (PhD), G. Eitel (Dipl.), R. Ferrer (PhD),
S. George (PhD), J. Ketelaer (PhD), S. Nagy (PostDoc),
D. Neidherr (PhD), J. Repp (Dipl.), Ch. Smorra (Dipl.)

„g-Factor“-Team
S. Kreim (PhD), C. Rodegheri (PhD), S. Sturm (PhD),
B. Schabinger (PhD), S. Ulmer (PhD), A. Wagner (Dipl.)

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