“Basics of Precision Nuclear and Atomic Mass Measurements for Fundamental Studies”

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Motivation for precision mass data

How to weigh an atom

Nuclear structure studies

Astrophysics applications

Tests of fundamental symmetries
Some useful literature

Books and review articles:


K. Blaum et al.: Precision atomic physics techniques for nuclear physics with radioactive beams; Physica Scripta T152, 014017 (2013)
Characteristics of a (radioactive) nucleus

- Its weight
- Its size
- Its life-time/decay
- Its shape
- Its e.m. properties
- Its mood (state)

In recent years unique tools have been developed to determine experimentally and to describe theoretically these characteristics.
Atom masses: Motivation

\[ E = mc^2 \]

\[ m_{n,p} \approx 1 \text{ GeV/c}^2 = 1.000.000.000 \text{ eV/c}^2 \approx 0.000000000000000000017 \text{ kg} \]
Fields of applications

- (nuclear) astrophysics, astrochemistry, production of heavy elements, atomic and molecular binding energies
- nuclear structure, nuclear forces
- fundamental interactions and their symmetries, fundamental constants

Credit to H.W. Wilschut.
Atomic and nuclear masses

Masses determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.

\[ M_{\text{Atom}} = N \cdot m_{\text{neutron}} + Z \cdot m_{\text{proton}} + Z \cdot m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2 \]

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

\[ \delta m/m = 10^{-6} - 10^{-8} \]
Why measuring atomic masses?

Sources:
Accelerator or reactor based radioactive beam facilities and electron beam ion traps.

- CERN
- IMP/GSI
- MPIK
- TRIGA

Experimental setups
- KATRIN-TRAP
- CSRe/ESR
- TRIGA-TRAP
- ISOLTRAP/TITAN
- SHIPTRAP
- THe-TRAP
- PENTA-TRAP

General physics & chemistry
Nuclear structure physics
- separation
Astrophysics
- separation
Weak interaction studies
Metrology - fundamental constants
Neutrino physics
CPT tests
QED in highly-charged ions
- separation

$N \cdot +Z \cdot +Z \cdot$ – binding energy
The liquid drop model

\[ E_{B,Kern} / A = a_{Vol} + a_{Oberf} A^{-1/3} + \frac{3e^2}{5r_0} Z^2 A^{-4/3} + (a_{Symm} + a_{OberfSymm} A^{-1/3}) I^2 \]

\[ A = N + Z, \text{ neutron number } N, \text{ proton number } Z \text{ and elementary charge } e \]

Nuclear Radius: \[ R \approx r_0 A^{1/3} \]

Symmetry: \[ I^2 = (N - Z)^2 / A^2 \]

Comparison $B_{\text{nucl}}$: Theory-experiment

Nuclear structure effects like shell closures become visible.

1949: The shell model and magic numbers (Göppert-Mayer + Jensen).
Test of nuclear mass models

Cs (Z=55)

Model difference / MeV

Known masses

N (Z=55)
2 How to weigh an atom

carbon cluster $C_n$
\[ m = n \cdot 1.200000000 \text{ u} \]

ion of interest
\[ m = \text{? u} \]

\[ \nu_{C,1} \quad \nu_{C,2} \quad \frac{\nu_{C,1}}{\nu_{C,2}} \]
How to weigh atoms/ions?

By capturing and storing of ions and comparing with other masses!

Nobel Prize in Physics in 1989 to Hans Dehmelt und Wolfgang Paul „for the development of the ion trap technique“. 

Hans Dehmelt (1922 - ... ) 
Wolfgang Paul (1913 - 1993)
**Storage and cooling techniques**

- **Penning trap**
  - $0 \quad 0.5 \quad 1 \text{ cm}$
  -  

- **Storage ring**
  - $0 \quad 2.5 \quad 5 \text{ m}$
  -  

- **Particles at nearly rest in space**
  - *ion cooling*
  - *single-ion sensitivity*

- **Relativistic particles**
  - *long storage times*
  - *high accuracy*
The Penning trap

- Trapping of particle via motion in em field
- Strong homog. magnetic field in $z$ direction, particle moves with cyclotron frequency
  \[ \omega_c = \frac{q}{m} B_z \]
  \[ \rightarrow \text{bound in radial direction} \]
- Weak, electrostatic quadrupole potential
  \[ V(z, \rho) = \frac{U_{DC}}{2d^2} (z^2 - \frac{1}{2} \rho^2) \]
  \[ d^2 = \frac{1}{2} (z_0^2 + \rho_0^2) \]
- Equations of motion in 3D:
  \[ \vec{F} = -e_0 (\vec{\nabla} \phi(r) + \vec{v} \times \vec{B}) + m\vec{r} = 0 \]
Equation of motion in a Penning trap

**Equation of motion:**

\[ \mathbf{F} = -e_0 \nabla \phi(r) + \mathbf{v} \times \mathbf{B} \]

**Axial oscillation**

\[ \frac{2e_0 U_0}{md_0^2} \cdot z + m \ddot{z} = 0 \]

\[ \omega_z = \sqrt{\frac{2e_0 U_0}{md_0^2}} \]

**Radial oscillation**

substitution:

\[ u = x + iy \]

\[ \omega_c = \frac{e_0}{m} B \]

\[ i \omega_c \dot{u} - \frac{\omega_z^2}{2} u + \ddot{u} = 0 \]

\[ \omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}} \]

\[ \omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}} \]
Storage of ions in a Penning trap

The free cyclotron frequency is inverse proportional to the mass of the ions!

\[ \omega_c = \frac{qB}{m} \]

An invariance theorem saves the day:

\[ \omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2 \]


End of lecture 1

What did we learn?
1) Motivation for precision mass data
2) Liquid drop model and nuclear binding energy
3) Storage of charged particles
4) Penning trap technique

What comes next?
1) Manipulation of stored ions
2) Frequency measurement techniques
3) Experimental setup
4) Applications of precision nuclear mass data
   * Nuclear physics and astrophysics