EuNPC Master class, 2015

"Basics of Precision Nuclear and Atomic Mass Measurements for Fundamental Studies"

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Content

Max Planck Institute for Nuclear Physics

Some useful literature

Books and review articles:

L.S. Brown and G. Gabrielse: Physics of a single electron or ion in a Penning trap; Rev. Mod. Phys. 58, 233 (1986)

G. Bollen: Traps for Rare Isotopes, Lecture Notes in Physics, 651, 169-210 (2004)

F.G. Major et al.; Charged Particle Traps, Volume I and II Springer, Vol. 37, Berlin (2005)

K. Blaum: High-accuracy mass spectrometry with stored ions, Phys. Rep. 425, 1-78 (2006)

J. Äystö: Overview of recent highlights at ISOL facilities, Nucl. Phys. A 805, 162c-171c (2008)

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.

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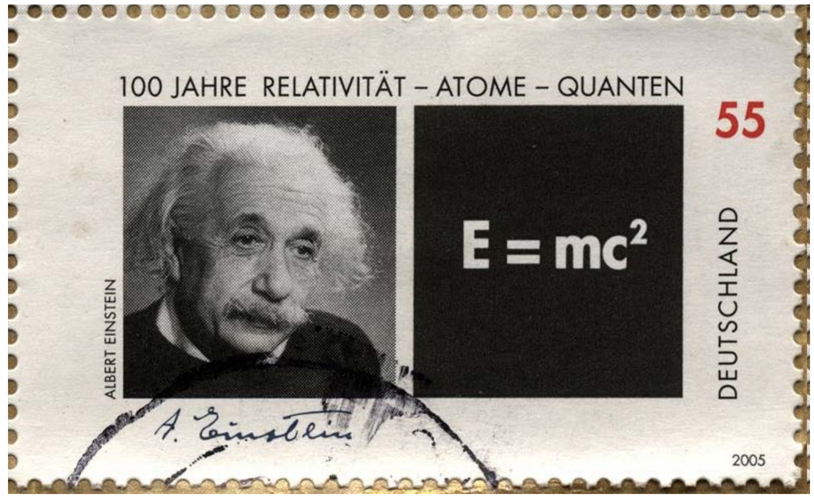
1 Atomic masses: Motivation

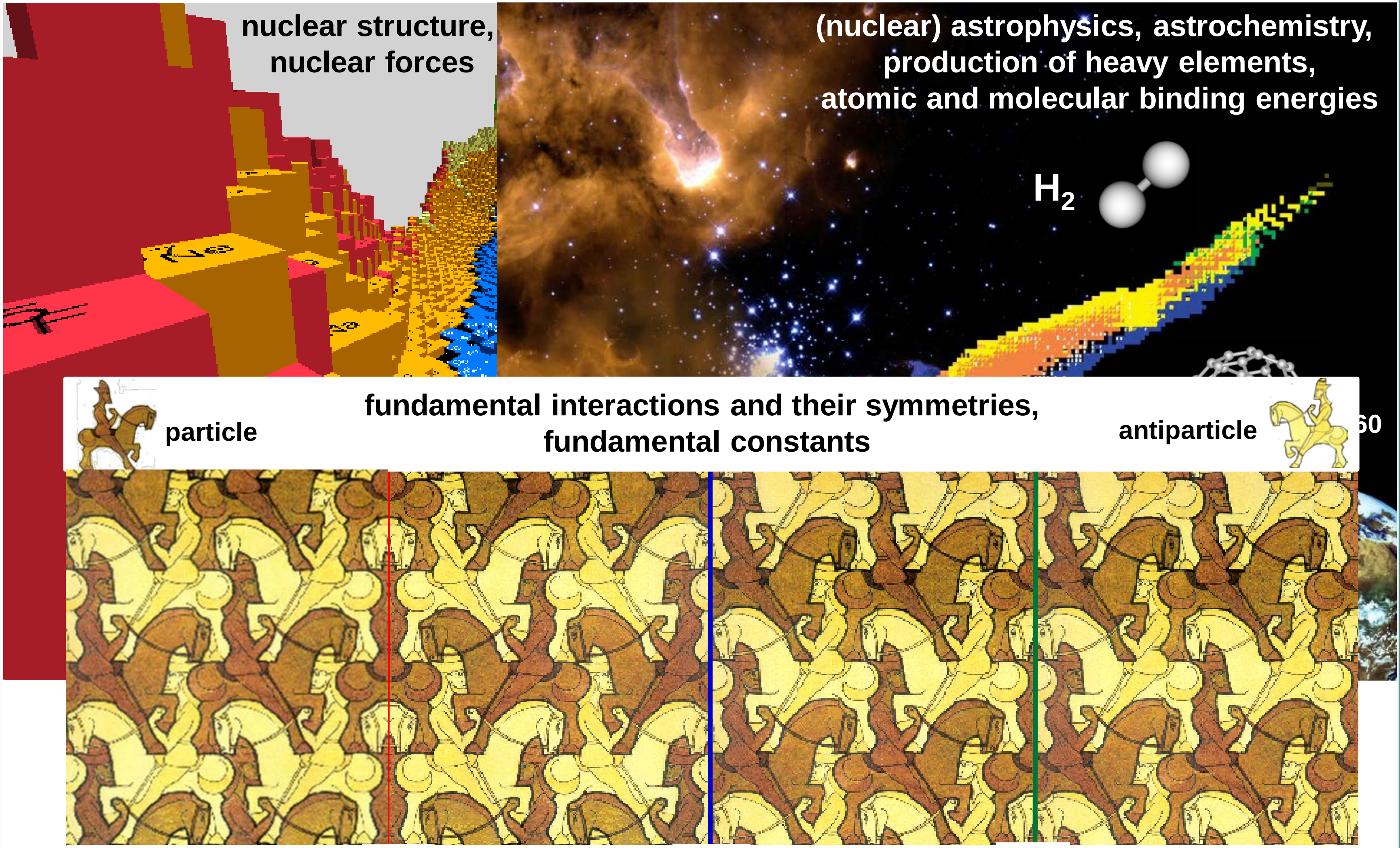


$$E = mc^2$$

$m_{n,p} \approx 1\ \mathrm{GeV}/c^2 = 1.000.000.000\ \mathrm{eV}/c^2$

$\approx 0{,}0000000000000000000000000017\ \mathrm{kg}$

Fields of applications

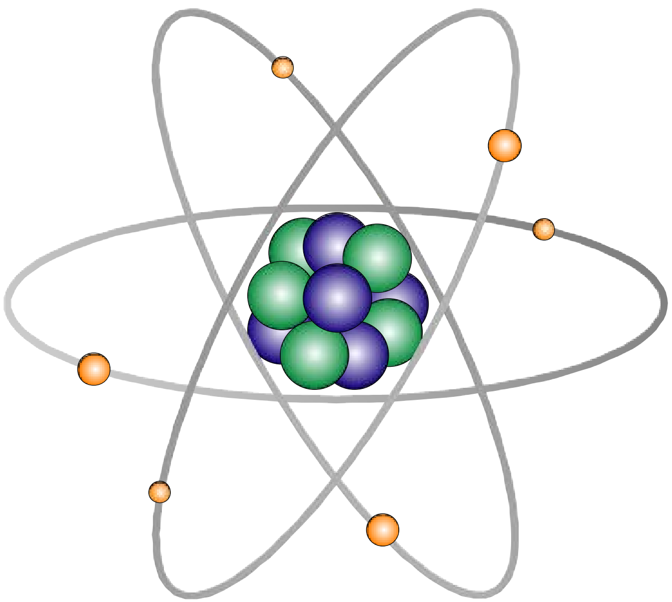


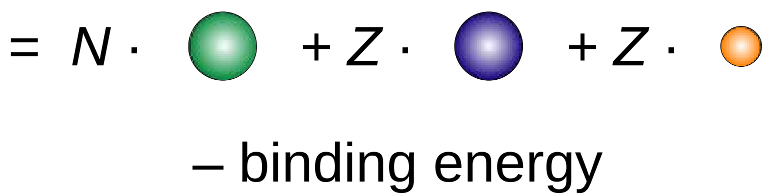
P **C** **T**

Credit to H.W. Wilschut.

Atomic and nuclear masses

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



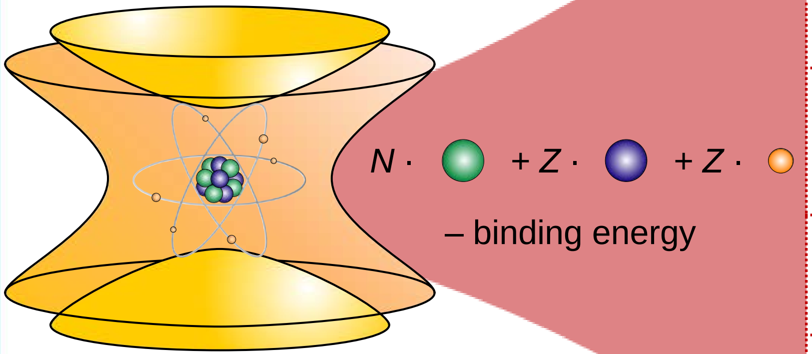


$$M_{\mathrm{Atom}} = N \cdot m_{\mathrm{neutron}} + Z \cdot m_{\mathrm{proton}} + Z \cdot m_{\mathrm{electron}} - (B_{\mathrm{atom}} + B_{\mathrm{nucleus}})/c^2$$

$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} - 10^{-8}$

Why measuring atomic masses?



Experimental setups

- General physics & chemis
- Nuclear structure physics
  - separat
- Astrophysics
  - separati
- Weak interaction studies
- Metrology - fundamenta
  Neutrino physics
- CPT tests
- QED in highly-charged ior
  - separation o

KATRIN-TRAP

CSRe/ESR

TRIGA-TRAP

ISOLTRAP/TITAN

SHIPTRAP

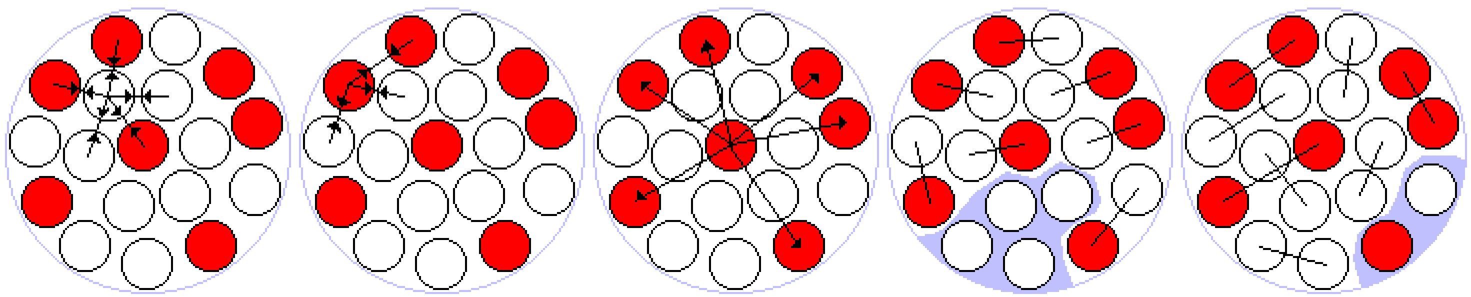
THe-TRAP

PENTA-TRAP

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

CERN **IMP/GSI** **MPIK** **TRIGA**

The liquid drop model



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

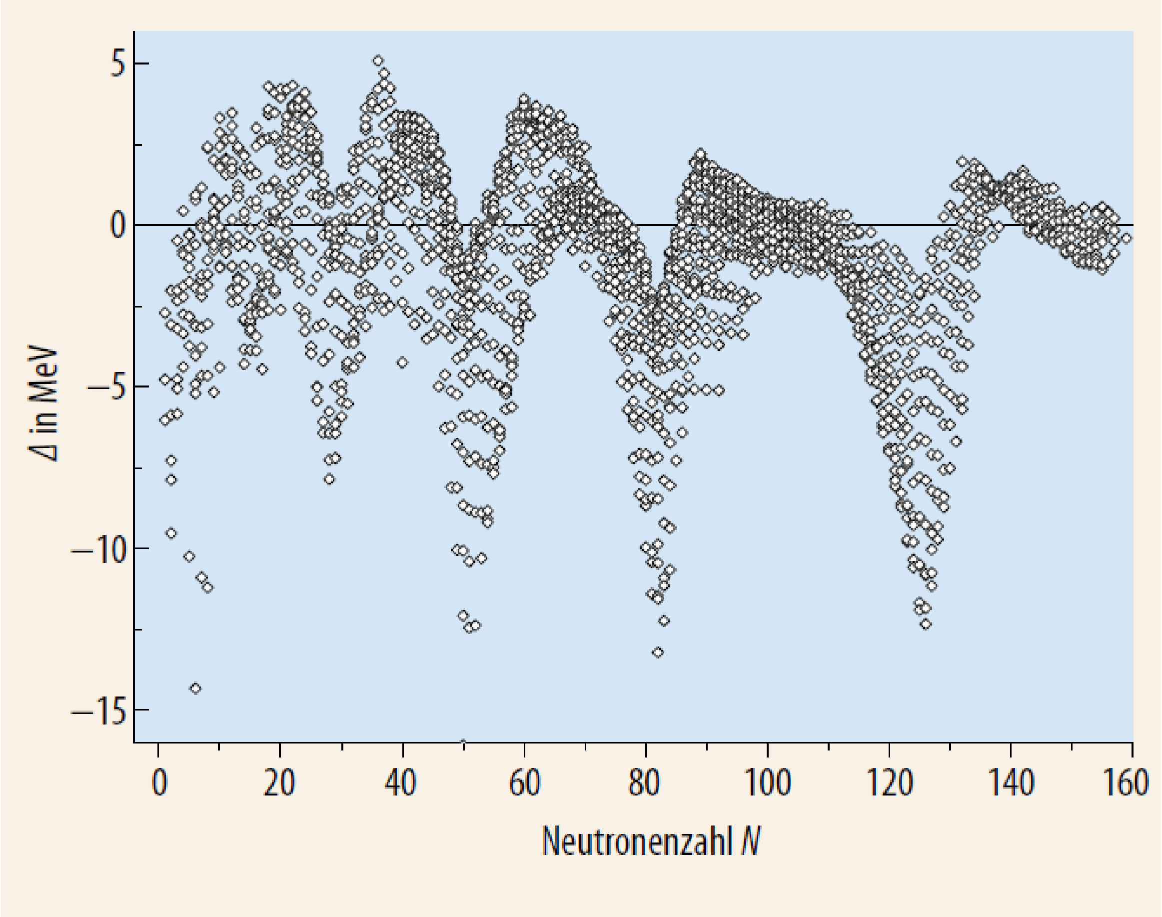
$A = N + Z$, neutron number N, proton number Z and elementary charge e

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

Symmetry: $I^2 = (N - Z)^2 / A^2$

C. F. v. Weizsäcker, Zeitschrift der Physik, 96, 431 (1935)

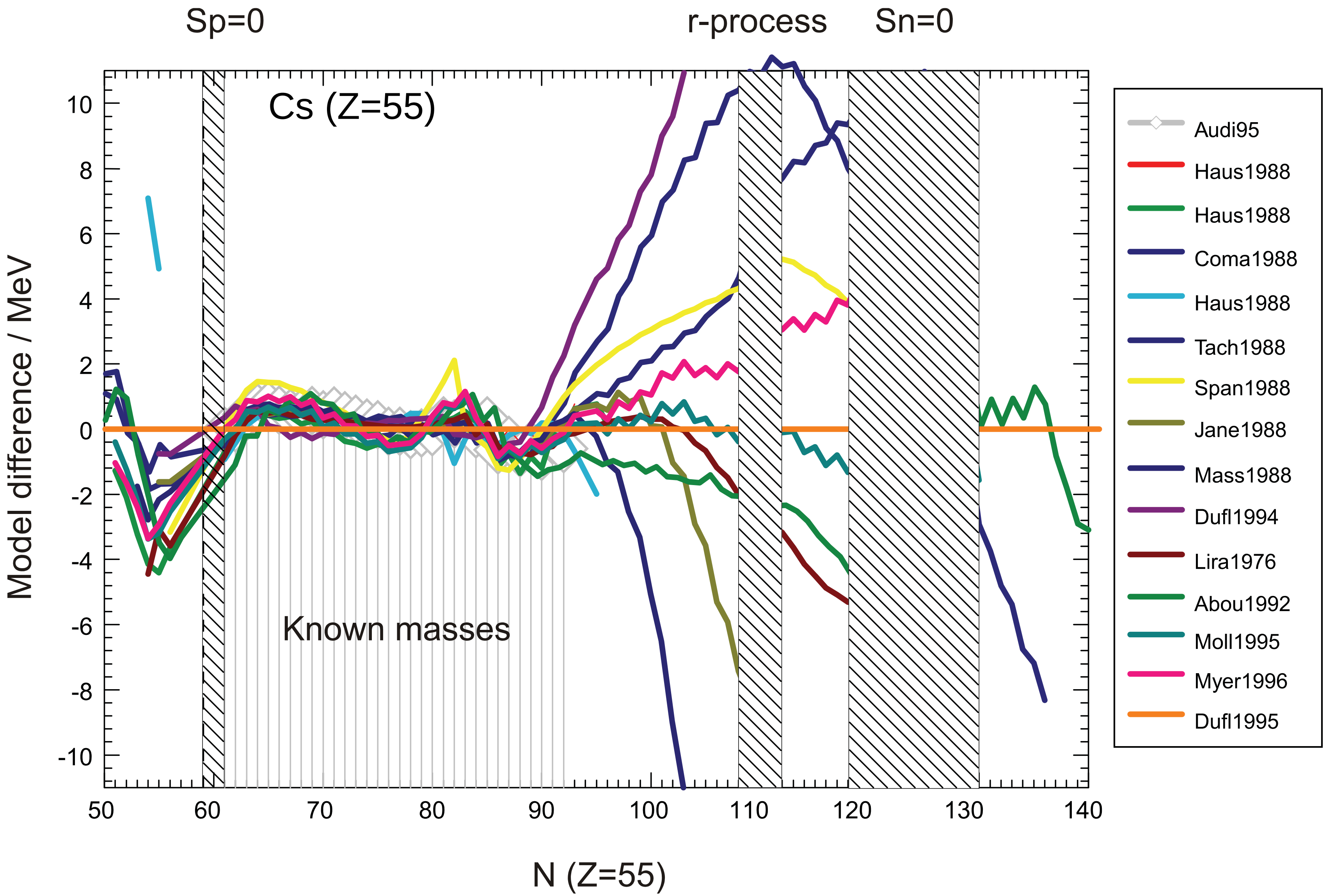
Comparison B_{nucl}: Theory-experiment



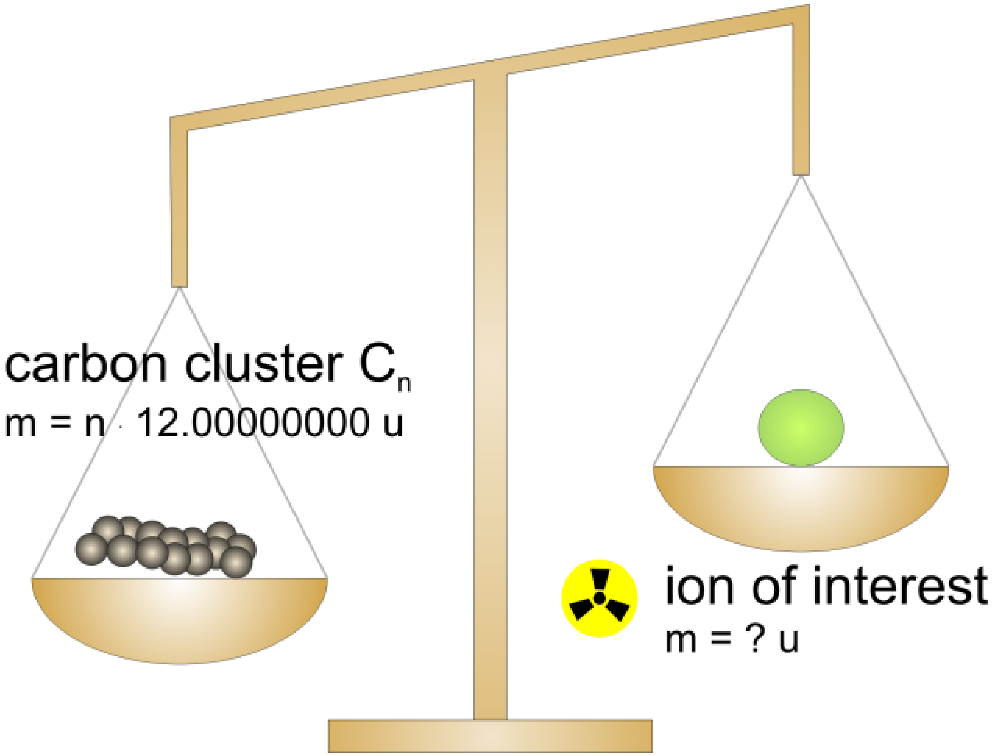
Nuclear structure effects like shell closures become visible.

1949: The shell model and magic numbers (Göppert-Mayer + Jensen).

Test of nuclear mass models



How to weigh an atom



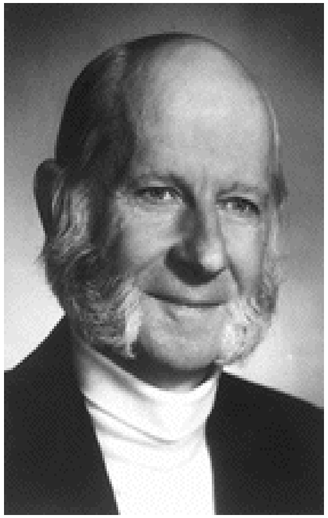
$\nu_{c,1}$

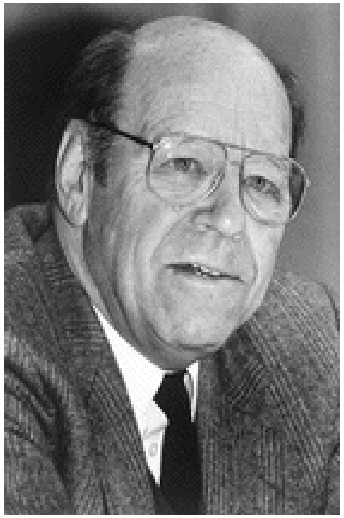
$\nu_{c,2}$ $\Rightarrow$ $\frac{\nu_{c,1}}{\nu_{c,2}}$

How to weigh atoms/ions?

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

Hans Dehmelt (1922 - ...)





Wolfgang Paul (1913 - 1993)

Nobel Prize in Physics in 1989 to

Hans Dehmelt und Wolfgang Paul

„for the development of the ion trap technique“.

Storage and cooling techniques

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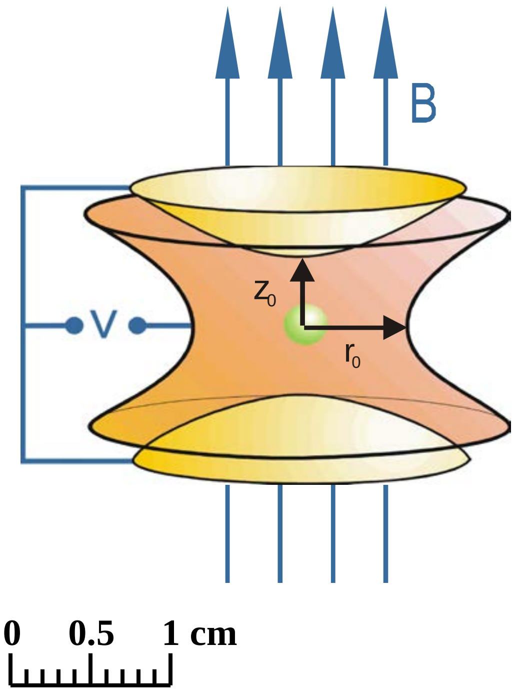
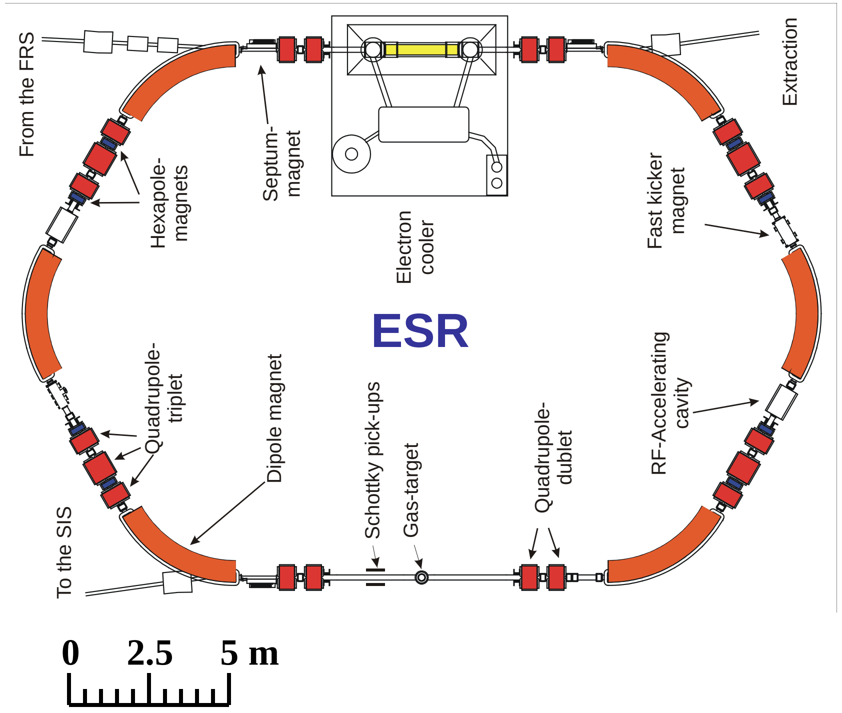
Penning trap



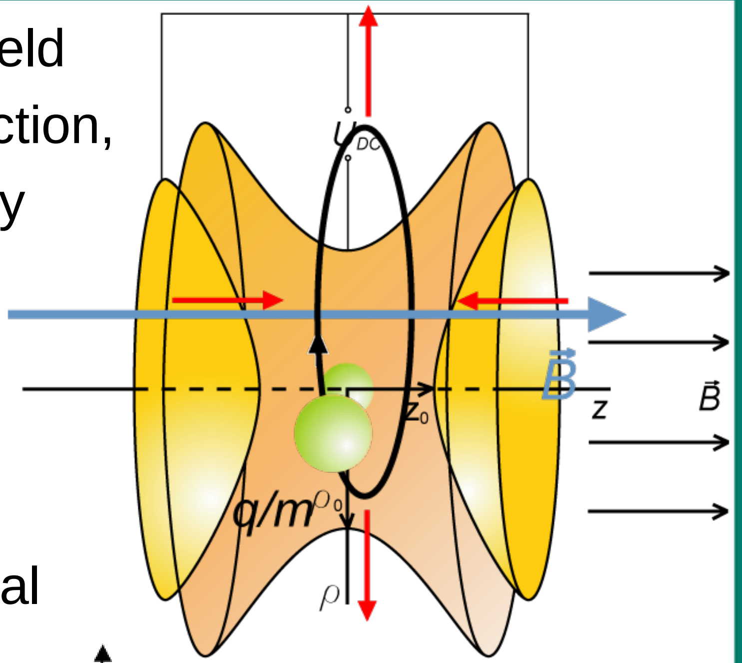
Storage ring



particles at nearly rest in space | **relativistic particles**

* ion cooling
* long storage times
* single-ion sensitivity
* 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

$$\omega_c = \frac{q}{m} B_z$$

→ bound in radial direction

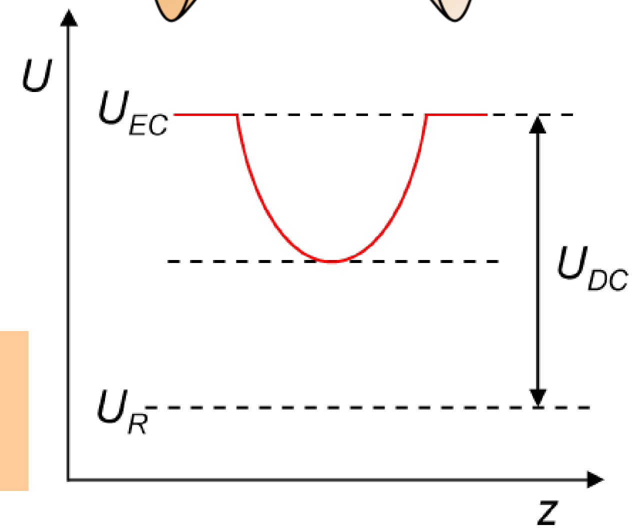
- Weak, electrostatic quadrupole potential

$$V(z,\rho) = \frac{U_{DC}}{2d^2}(z^2 - \tfrac{1}{2}\rho^2)$$

Geometry parameter $d^2 = \tfrac{1}{2}(z_0^2 + \frac{\rho_0^2}{2})$

- Equations of motion in 3D:

$$\vec{F} = -e_0(\vec{\nabla}\phi(r) + \vec{v} \times \vec{B}) + m\ddot{\vec{r}} = 0$$



Equation of motion in a Penning trap

plus Lorentz force:

$$\vec{F} = -e_0 \vec{\nabla}\phi(r) + \vec{v} \times \vec{B}$$

equation of motion:

$$\vec{F} = -e_0 \left(\vec{\nabla}\phi(r) + \vec{v} \times \vec{B}\right) + m\ddot{\vec{r}} = 0$$

axial oscillation

$$\frac{2e_0U_0}{md_0^2} \cdot z + m\ddot{z} = 0$$

$$\omega_z = \sqrt{\frac{2e_0U_0}{md_0^2}}$$

***z* or axial frequency**

radial oscillation

substitution:

$$u = x + iy$$

$$\omega_c = \frac{e_0}{m} B$$

$$u(t) = u_0 e^{-i\omega t}$$

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

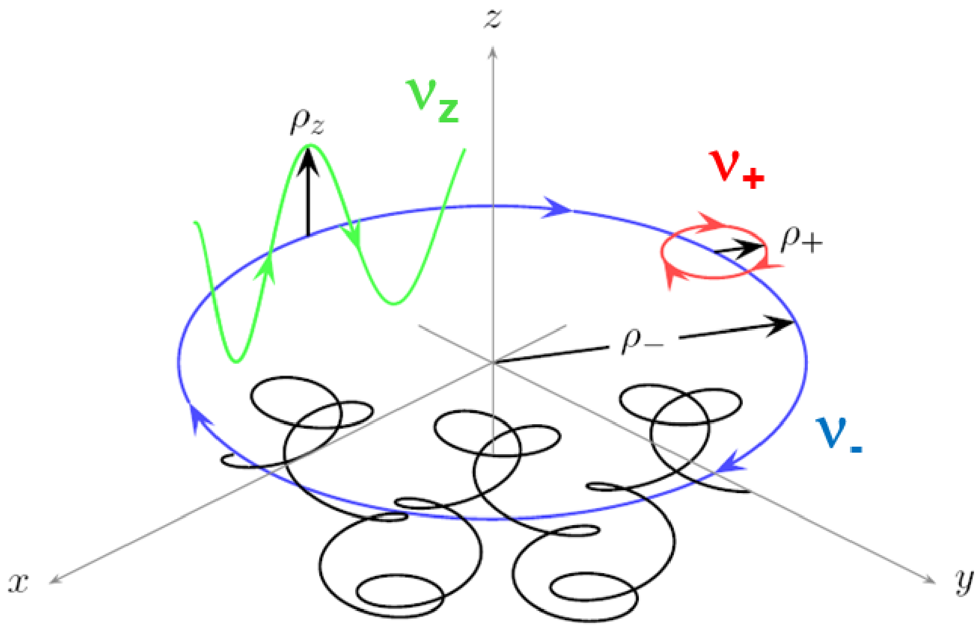
$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

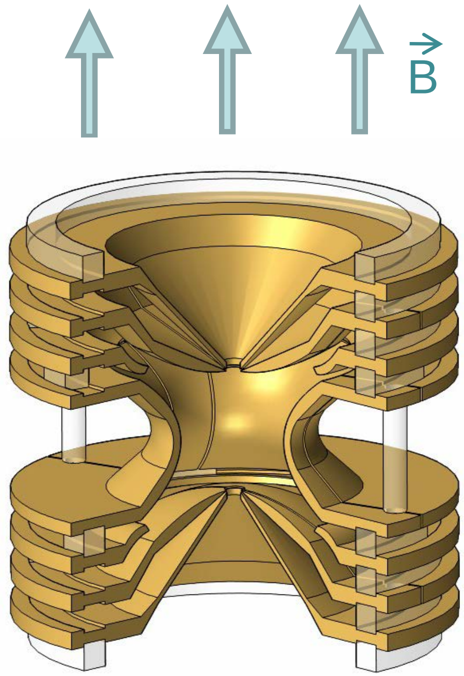
modified cyclotron frequency

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

magnetron frequency

Storage of ions in a Penning trap





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

$$\omega_c = qB/m$$

An ***invariance theorem*** saves the day:

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

$$\omega_c = \omega_+ + \omega_-$$

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986).
K. Blaum, Phys. Rep. 425, 1 (2006).

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