Introduction to nuclear and particle physics

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(tutorials)

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(lecture)

I. Physics of the atomic nucleus

2. A first view on nuclear properties
3. Nuclear Magnetic Momenta
4. Models of the nucleus
5. Nuclear Decays
6. Nuclear Fusion and Nuclear Fission
7. Mössbauer Effect
8. Nuclear Magnetic Resonance in medicine
9. Particle detection
10. Scattering processes
11. Nucleosynthesis

Some useful books

http://www.e12.physik.tu-muenchen.de/staff/profs/fabbietti.html.en

- Povh, Rith, Scholz, Zetsche:

  Particles and nuclei
  (Springer 1999)

- Krane:

  Introductory nuclear
  physics (Wiley & Sons 1987)

- Segre:

  Nuclei and particles
  (Benjamin 1965)

Perkins:

Introduction to high
energy physics
(Addison Wesley 1986)

- Halzen, Martin:

  Quarks and leptons
  (Wiley & Sons 1984)

- Kane:

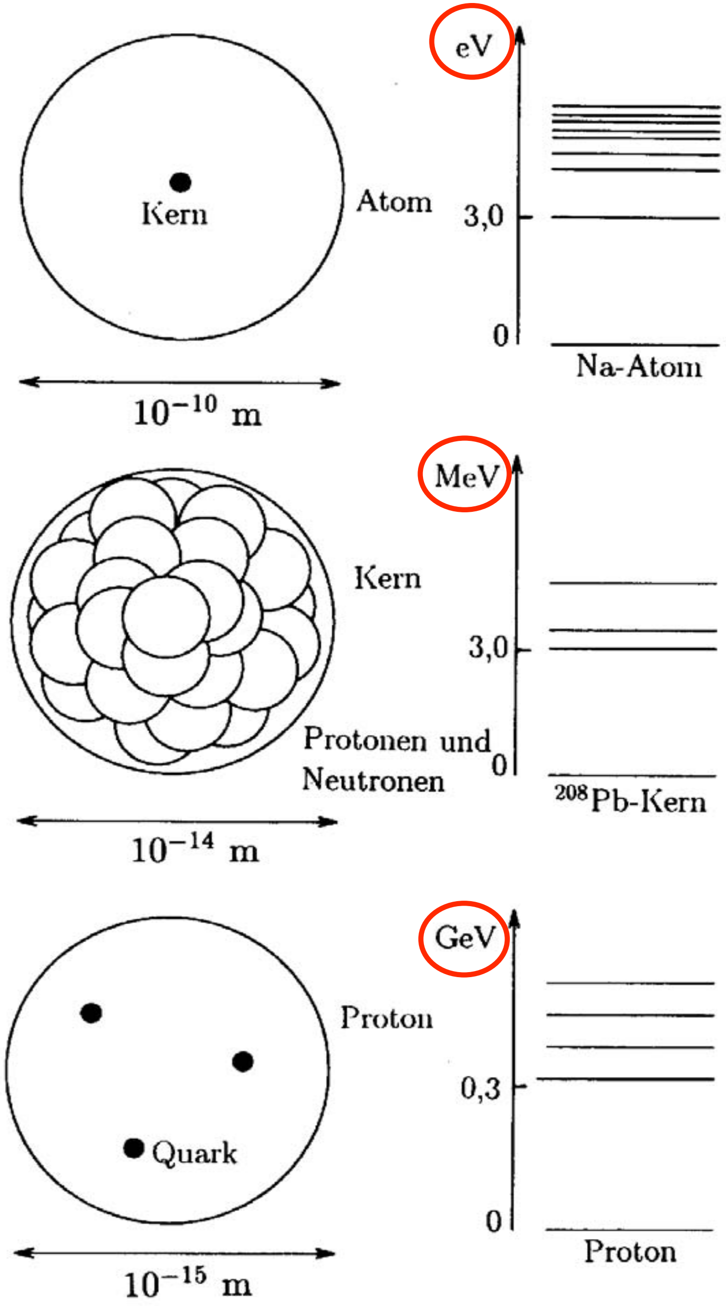
  Modern elementary
  particle physics
  (Addison Wesley 1987)

Particles Zoo

Generation:	I	II	III	Elektrische Ladung:
Quarks	**u** (m=5-10 MeV/c^2) *up*	**c** (m≈1,5 GeV/c^2) *charm*	**t** (m≈178 GeV/c^2) *top*	**+2/3**
	d (m=5-10 MeV/c^2) *down*	**s** (m≈150 MeV/c^2) *strange*	**b** (m≈5 GeV/c^2) *bottom*	**-1/3**
Leptonen	ν_e (m≈0)	ν_μ (m≈0)	ν_τ (m≈0)	**0**
	e (m=511 keV/c^2)	μ (m=106 MeV/c^2)	τ (m=1,77 GeV/c^2)	**-1**

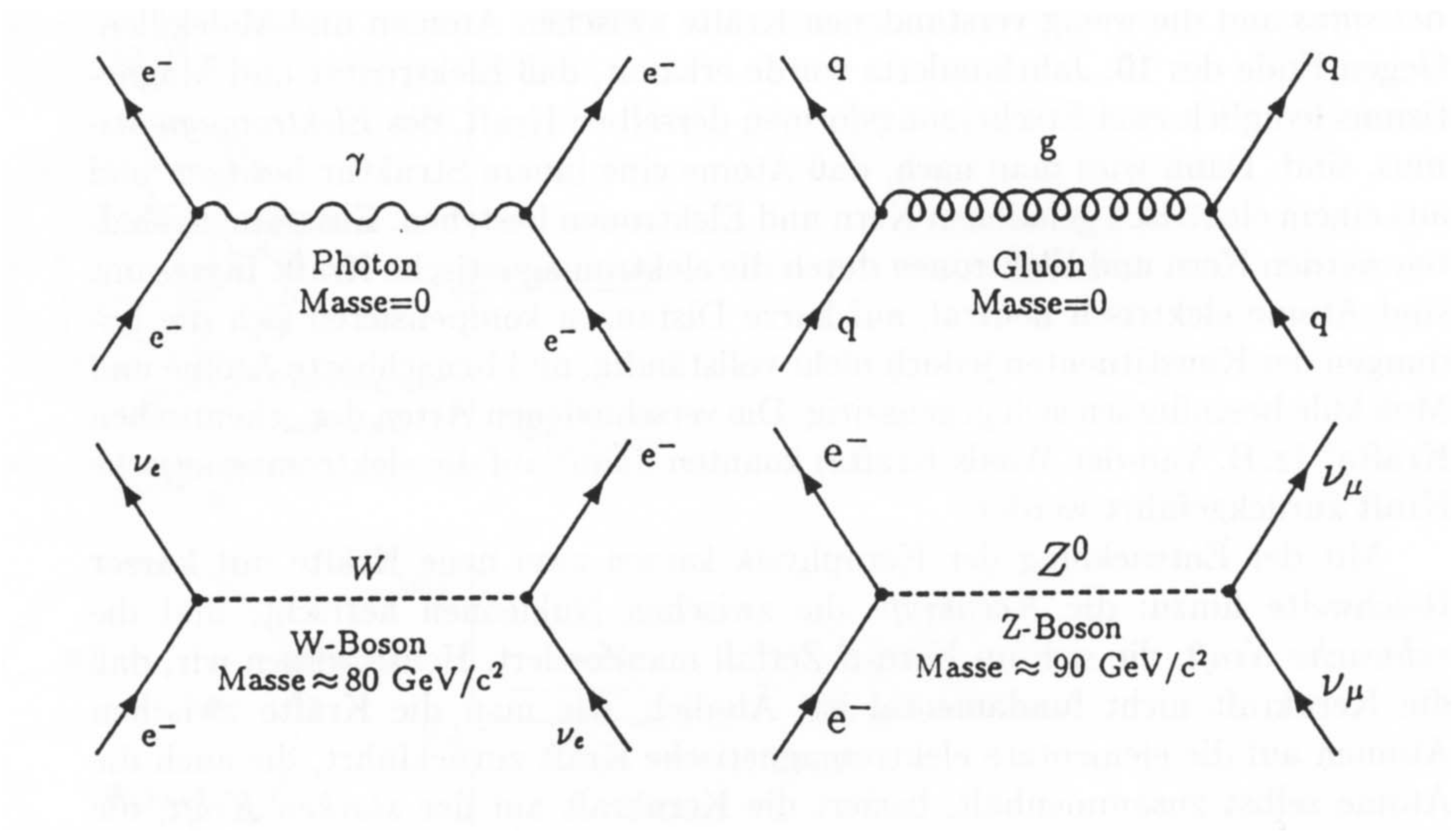
schwerer →

Systems, sizes: :Energy-spectra



Povh et al.,
„Particles & nuclei“

Fundamental interactions



Discovery of the electron

Joseph John Thomson 1897

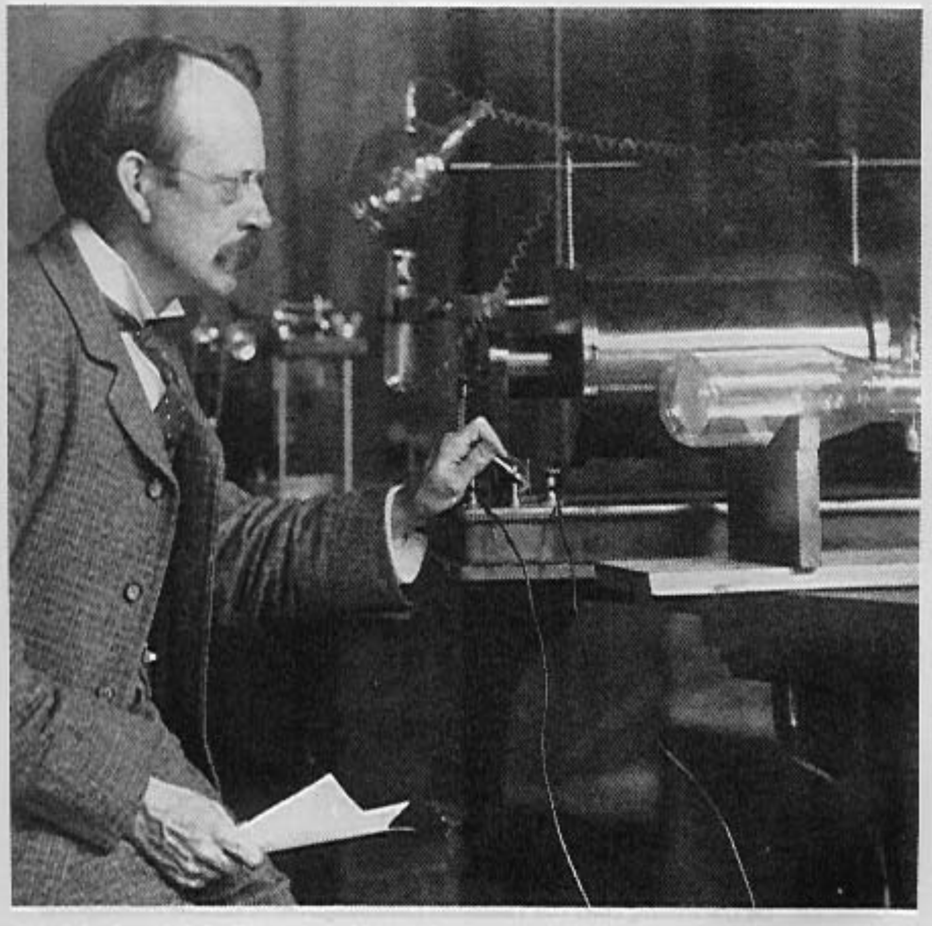


Abb. 1.5 **Joseph John Thomson (1856–1940), der für seine Untersuchungen des Elektrons und der Isotope berühmte englische Physiker. Er leitete als dritter Direktor das Cavendish-Laboratorium. Ein Foto im Maxwell-Hörsaal des Laboratoriums zeigt ihn bei der Betrachtung einer Kathodenstrahlröhre. Allem Anschein nach war Thomson etwas ungeschickt, aber er verstand die Möglichkeiten einer Apparatur sehr genau. (Cavendish-Laboratorium, Universität Cambridge)**

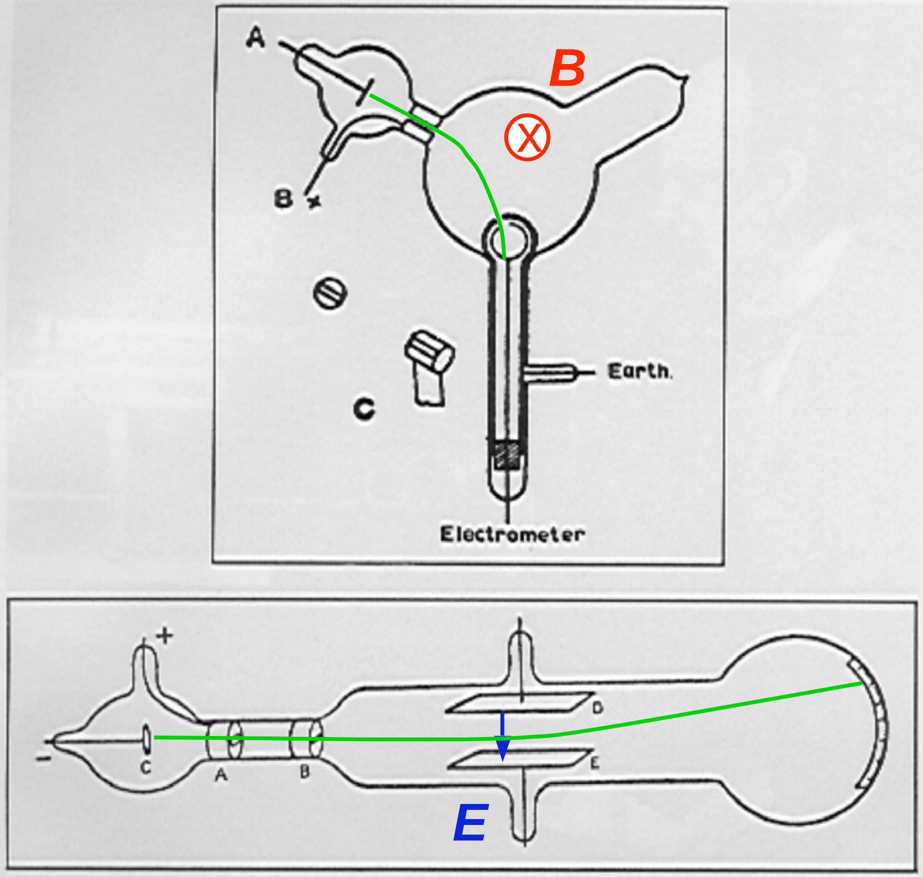


Abb. 1.6 **(a) Darstellung einer von Thomsons Entladungsröhren aus dem *Philosophical Magazine* (*44*, 293 [1897]). Die von der Kathode A erzeugten Elektronen können durch einen außen angebrachten Magneten abgelenkt und in einen Kollektor (Faraday-Käfig) geleitet werden, der an ein Elektrometer angeschlossen ist, das die Gesamtladung mißt. (b) Eine andere von Thomsons Entladungsröhren aus demselben Journal. Das von der Kathode C emittierte Strahlenbündel wird in A und B gebündelt und passiert zwischen D und E ein elektrisches Feld. Senkrecht dazu wird durch außerhalb der Röhre angebrachte Spulen ein Magnetfeld erzeugt.**

$$Q = Ne$$

$$W = \frac{N}{2} m v^2$$

Classically produces heat

$$B: \quad \frac{m v^2}{r_B} = e v B \quad \frac{m v}{e} = B r_B$$

$$\rightarrow \frac{2W}{Q B^2 r_B^2} = \frac{e}{m}$$

Independent from the cathode material and the gas sort

Discovery of „X-Strahlen“

Röntgen 1895

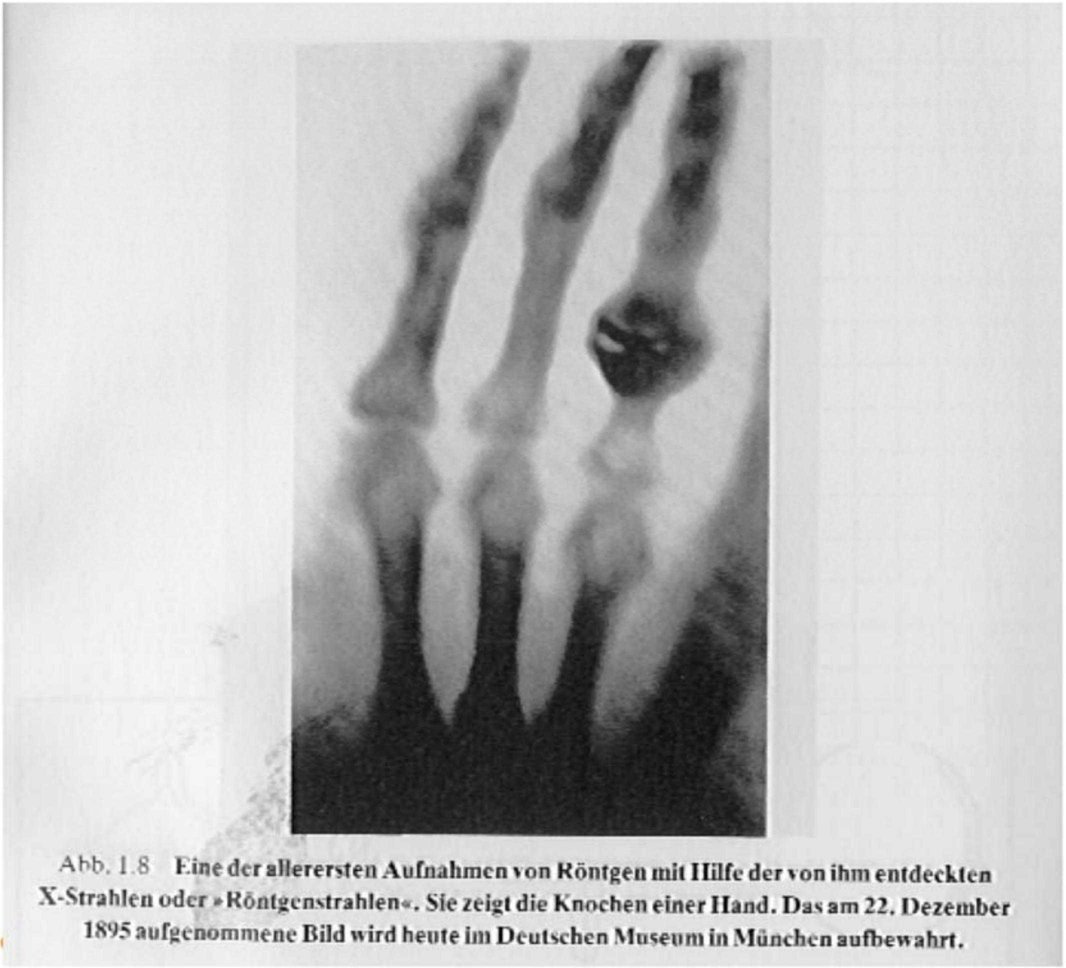
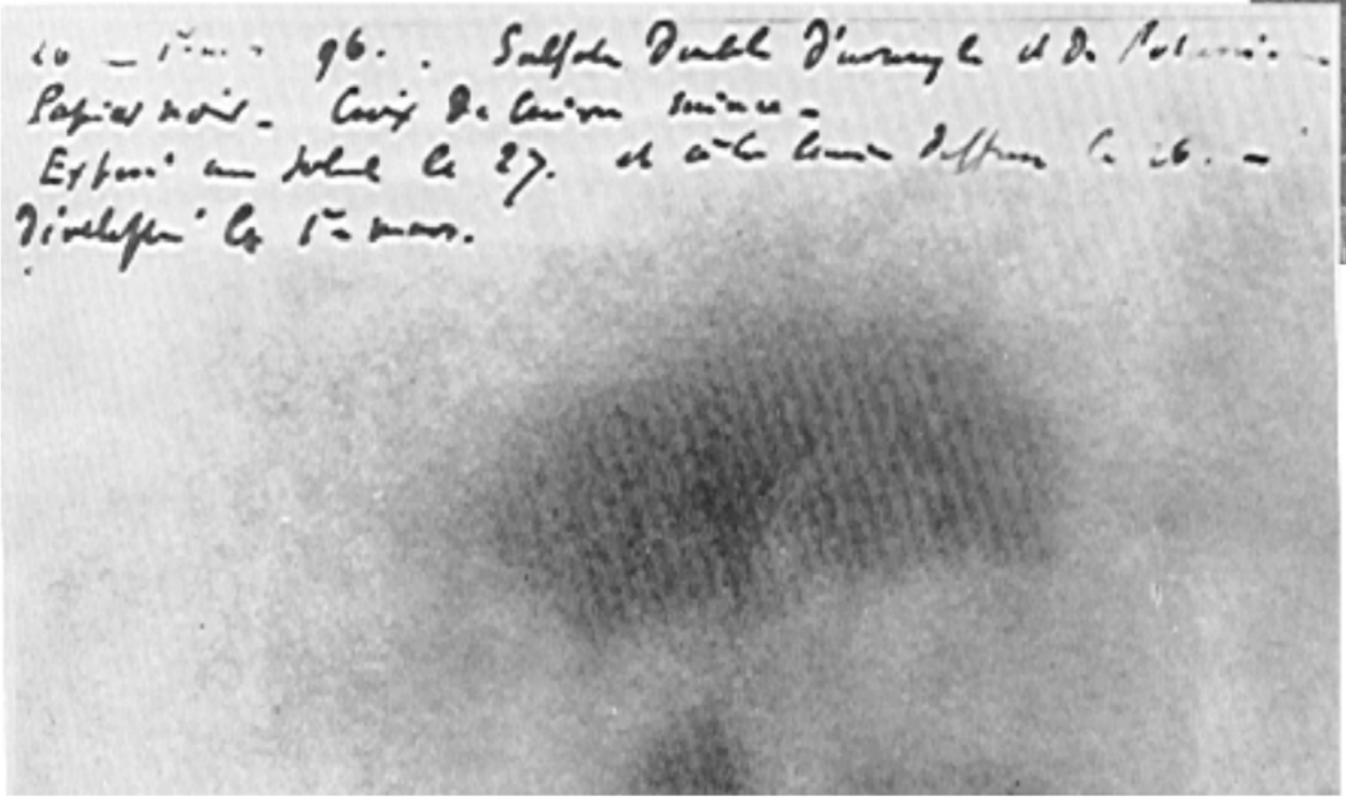
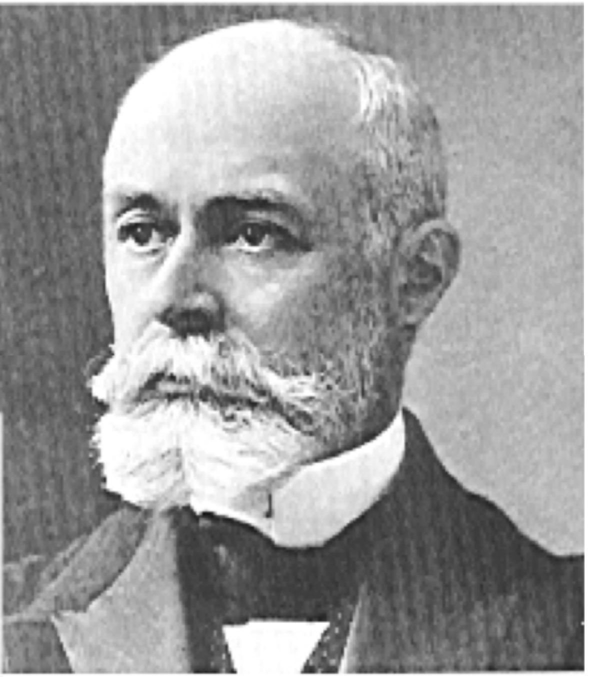


Abb. 1.8 Eine der allerersten Aufnahmen von Röntgen mit Hilfe der von ihm entdeckten X-Strahlen oder »Röntgenstrahlen«. Sie zeigt die Knochen einer Hand. Das am 22. Dezember 1895 aufgenommene Bild wird heute im Deutschen Museum in München aufbewahrt.

Discovery of radioactivity

Henri Bequerel 1896





Discovery of the atomic nucleus

Rutherford, Geiger, Marsden 1908 - 1913

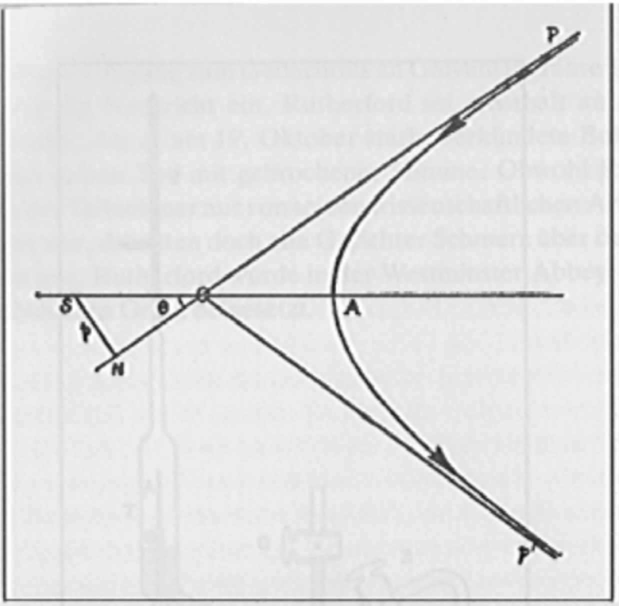


Abb. 6.2 **Die Bahn eines von einem Kern abgelenkten (*P* nach *P'*) α-Teilchens. Die Ablenkungen von α-Teilchen beim Durchgang durch eine dünne Metallfolie folgen dem Gesetz, das auf der Grundlage dieser Abbildung berechnet wurde. Damit wurde die Existenz eines geladenen Streuzentrums im Atom bewiesen, das später Kern genannt wurde. (Aus Rutherfords Artikel im *Philosophical Magazine 21*, 669 [1911])**

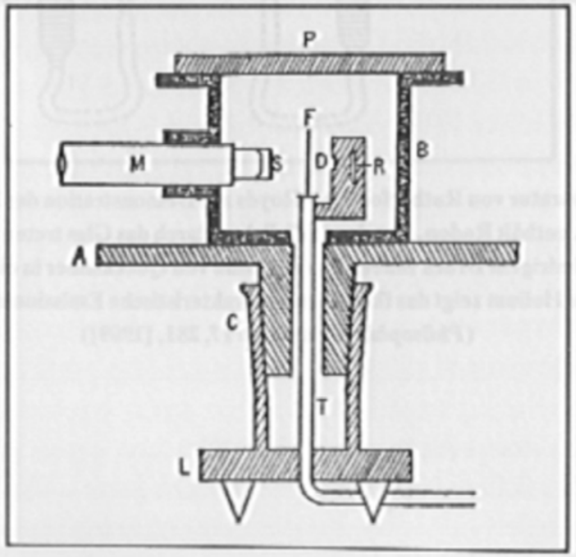


Abb. 6.3 **Die von H. Geiger und E. Marsden zur Untersuchung der Streuung von α-Teilchen benutzte Apparatur. R ist die α-Quelle, die sich in einem Bleibehälter im Vakuumgefäß B befindet. Ein dünner Strahl von α-Teilchen passiert den Spalt und trifft auf einen dünnen Metallstreifen F auf. Die den Streifen durchquerenden α-Teilchen erreichen den Fluoreszenzschirm S und werden im Mikroskop M beobachtet, das zusammen mit B und TF bewegt werden kann. (*Philosophical Magazine 25*, 604 [1913])**

Discovery of the proton as a product of a nuclear reaction

Ernest Rutherford 1919

$^{14}N+ \, ^{4}He \rightarrow \, ^{12}O + p$

A positive particle was created with larger range than ^{4}He

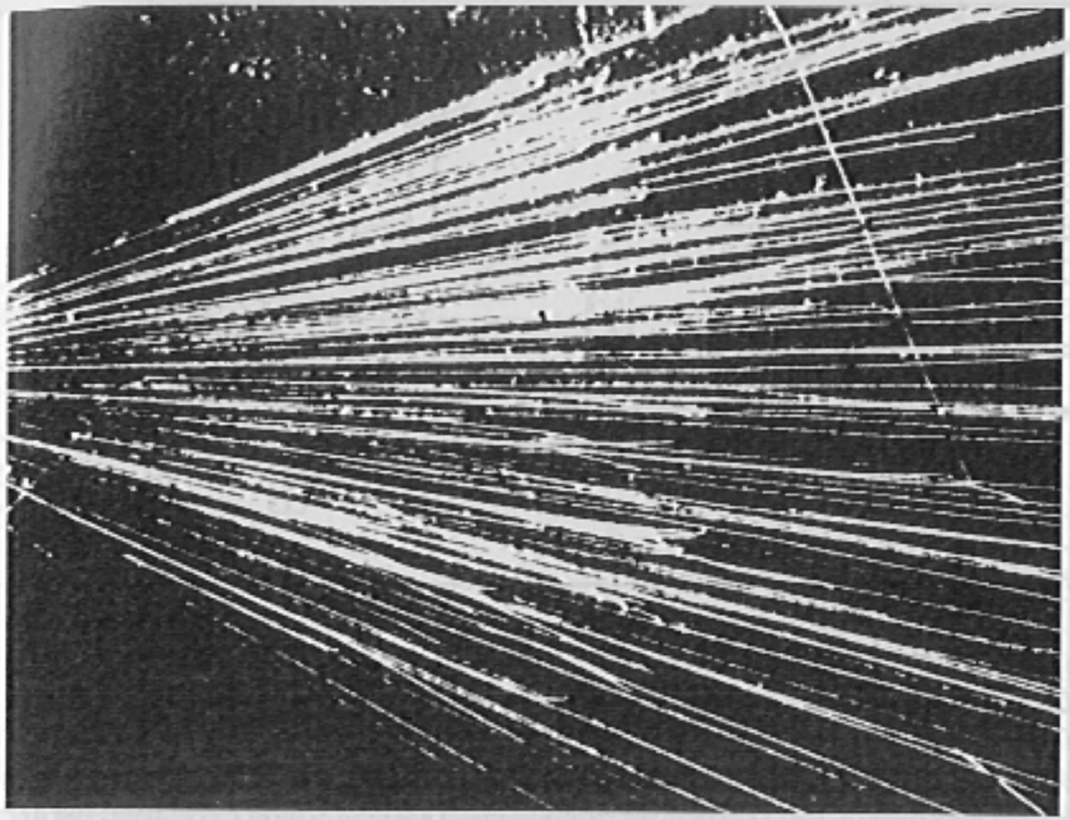
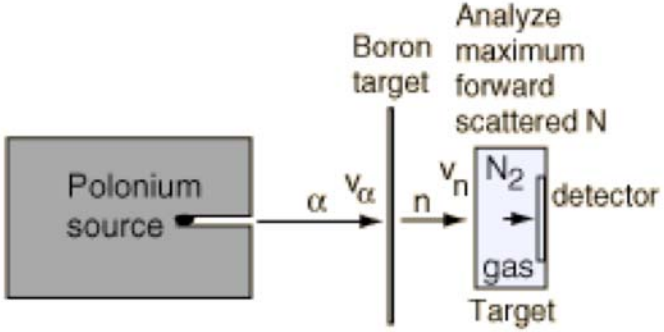


Abb. 6.5 Von Blackett beobachtete Zertrümmerung eines Stickstoffkerns in einer Nebelkammer. Die Quelle enthält $Pb^{212} + Bi^{212} + Po^{212}$ im radioaktiven Gleichgewicht und emittiert α-Teilchen mit zwei verschiedenen Reichweiten: 8,6 und 4,8 cm. Ein Teilchen mit der längeren Reichweite trifft auf einen Stickstoffkern und bricht ihn entsprechend der Reaktion ${}_7N^{14} + {}_2He^4 = {}_8O^{17} + {}_1H^1$ auf. Die längere quer verlaufende Spur stammt vom Proton, die andere ist die von ${}_8O^{17}$. (P. M. S. Blackett und D. Lea in *Proceedings of the Royal Society, London* 136, 325 [1932])

Discovery of the neutron

James Chadwick 1932



Analyze maximum forward scattered N

Boron target

Polonium source

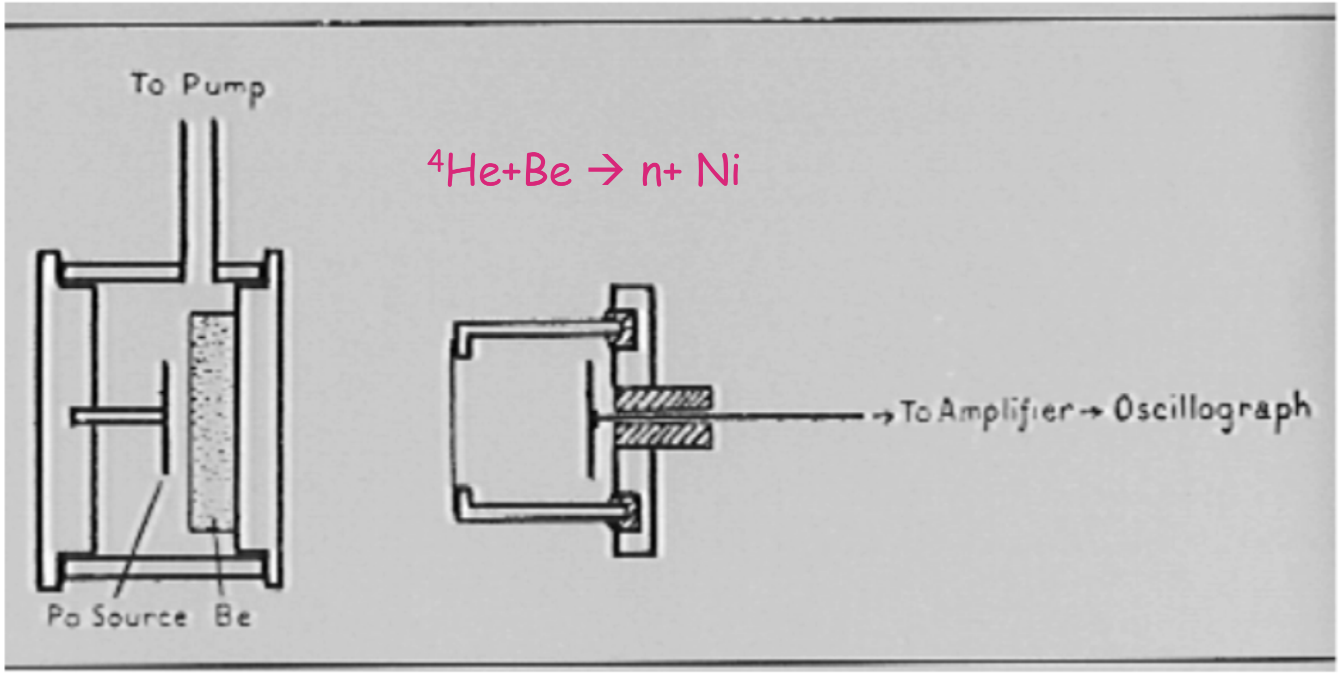
α v_α

n v_n

N_2 gas

Target

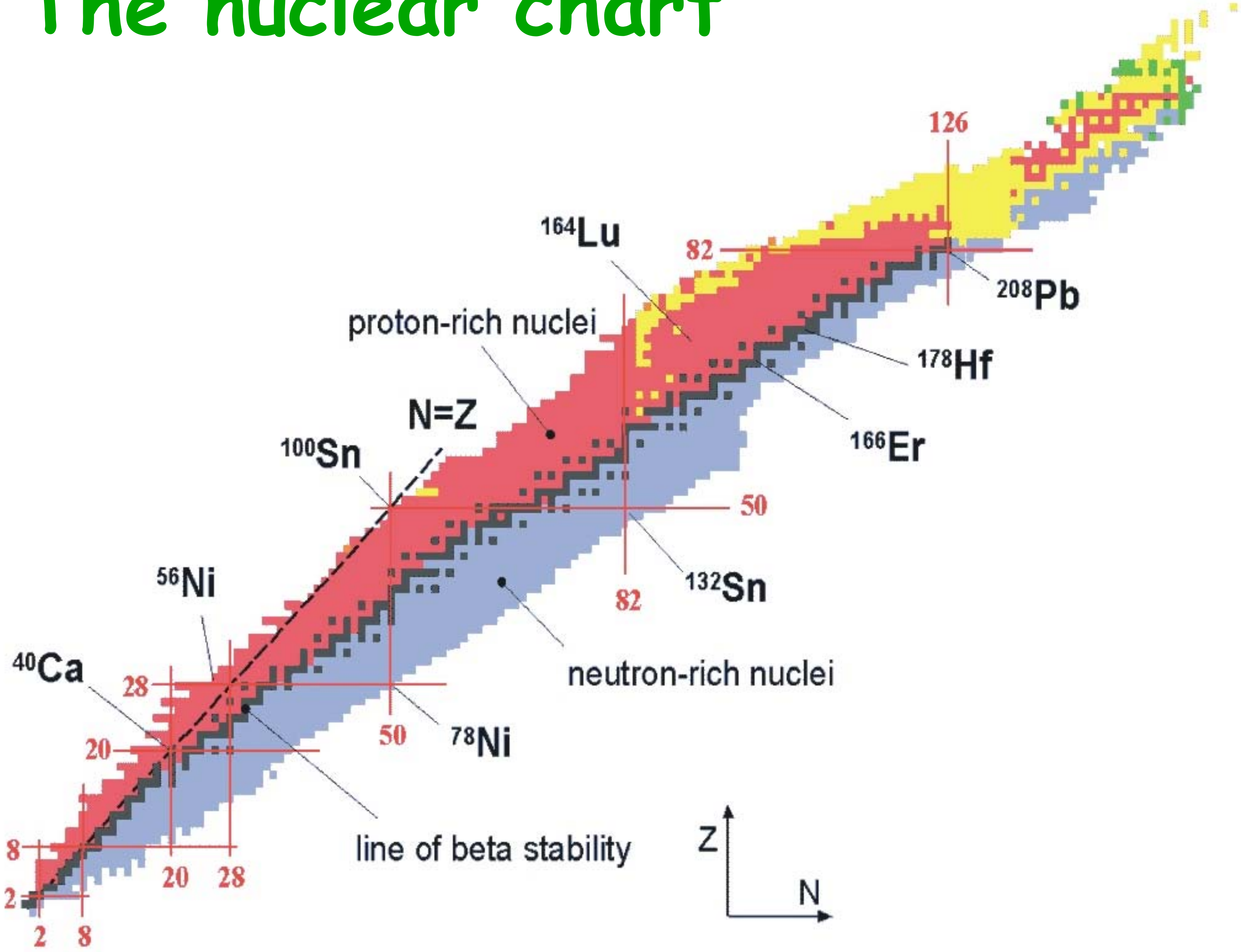
detector



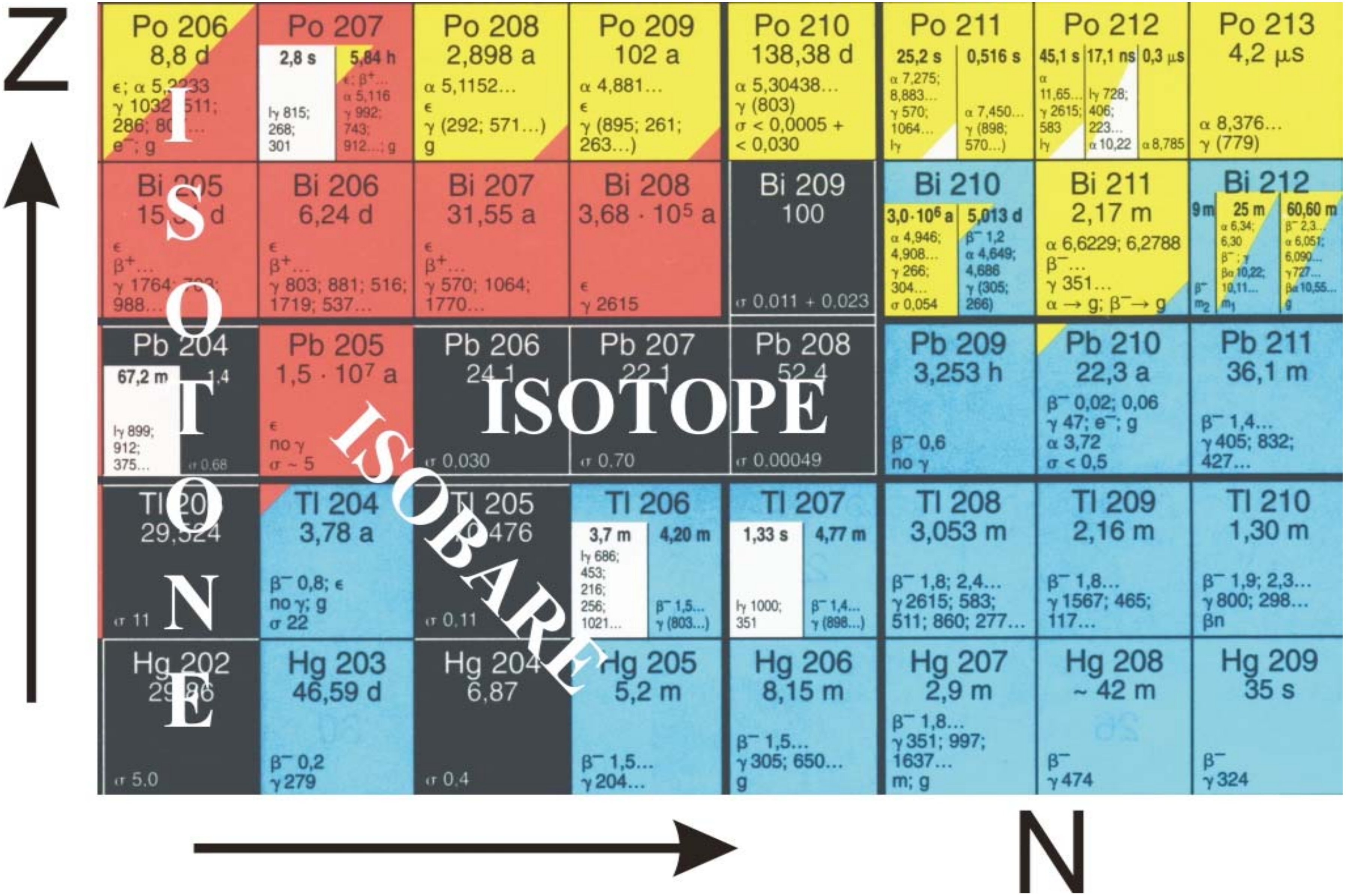
$^4He+Be \rightarrow n+ Ni$

n was detected measuring the recoil energy of the ejected nuclei.

The nuclear chart



Laura



Po 206 8,8 d ε; α 5,2233 γ 1032; 511; 286; 80[illegible]… e⁻; g	Po 207 2,8 s: Iγ 815; 268; 301 5,84 h: ε; β⁺…; α 5,116; γ 992; 743; 912…; g	Po 208 2,898 a α 5,1152… ε γ (292; 571…) g	Po 209 102 a α 4,881… ε γ (895; 261; 263…)	Po 210 138,38 d α 5,30438… γ (803) σ < 0,0005 + < 0,030	Po 211 25,2 s: α 7,275; 8,883…; γ 570; 1064…; Iγ 0,516 s: α 7,450…; γ (898; 570…)	Po 212 45,1 s: α 11,65…; γ 2615; 583; Iγ 17,1 ns: Iγ 728; 406; 223…; α 10,22 0,3 µs: α 8,785	Po 213 4,2 µs α 8,376… γ (779)
Bi 205 15[illegible] d ε β⁺… γ 1764; [illegible] 988…	Bi 206 6,24 d ε β⁺… γ 803; 881; 516; 1719; 537…	Bi 207 31,55 a ε β⁺… γ 570; 1064; 1770…	Bi 208 3,68 · 10⁵ a ε γ 2615	Bi 209 100 σ 0,011 + 0,023	Bi 210 3,0·10⁶ a: α 4,946; 4,908…; γ 266; 304…; σ 0,054 5,013 d: β⁻ 1,2; α 4,649; 4,686; γ (305; 266)	Bi 211 2,17 m α 6,6229; 6,2788 β⁻… γ 351… α → g; β⁻ → g	Bi 212 9 m: β⁻; m₂ 25 m: α 6,34; 6,30; β⁻; γ; βα 10,22; 10,11…; m₁ 60,60 m: β⁻ 2,3…; α 6,051; 6,090…; γ 727…; βα 10,55…; g
Pb 204 1,4 67,2 m: Iγ 899; 912; 375… σ 0,68	Pb 205 1,5 · 10⁷ a ε no γ σ ~ 5	Pb 206 24,1 σ 0,030	Pb 207 22,1 σ 0,70	Pb 208 52,4 σ 0,00049	Pb 209 3,253 h β⁻ 0,6 no γ	Pb 210 22,3 a β⁻ 0,02; 0,06 γ 47; e⁻; g α 3,72 σ < 0,5	Pb 211 36,1 m β⁻ 1,4… γ 405; 832; 427…
Tl 20[illegible] 29,524 σ 11	Tl 204 3,78 a β⁻ 0,8; ε no γ; g σ 22	Tl 205 [illegible]0,476 σ 0,11	Tl 206 3,7 m: Iγ 686; 453; 216; 256; 1021… 4,20 m: β⁻ 1,5…; γ (803…)	Tl 207 1,33 s: Iγ 1000; 351 4,77 m: β⁻ 1,4…; γ (898…)	Tl 208 3,053 m β⁻ 1,8; 2,4… γ 2615; 583; 511; 860; 277…	Tl 209 2,16 m β⁻ 1,8… γ 1567; 465; 117…	Tl 210 1,30 m β⁻ 1,9; 2,3… γ 800; 298… βn
Hg 202 29[illegible]6 σ 5,0	Hg 203 46,59 d β⁻ 0,2 γ 279	Hg 204 6,87 σ 0,4	Hg 205 5,2 m β⁻ 1,5… γ 204…	Hg 206 8,15 m β⁻ 1,5… γ 305; 650… g	Hg 207 2,9 m β⁻ 1,8… γ 351; 997; 1637… m; g	Hg 208 ~ 42 m β⁻ γ 474	Hg 209 35 s β⁻ γ 324

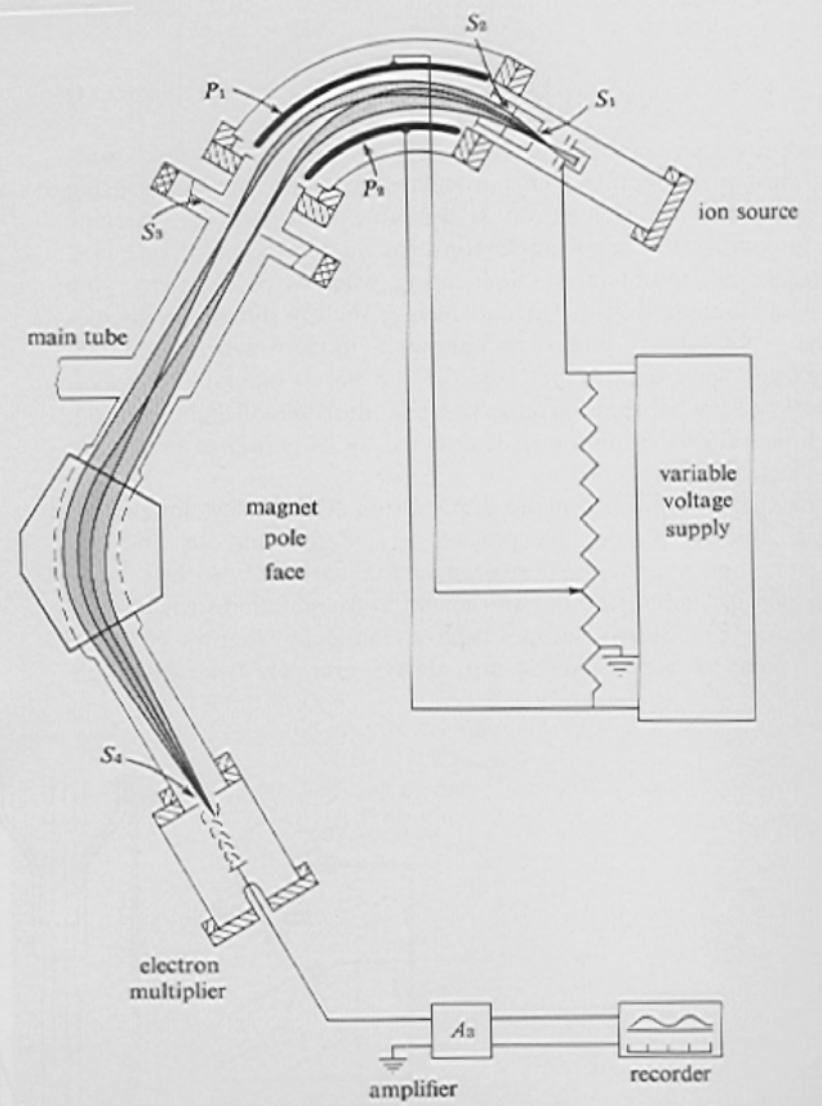
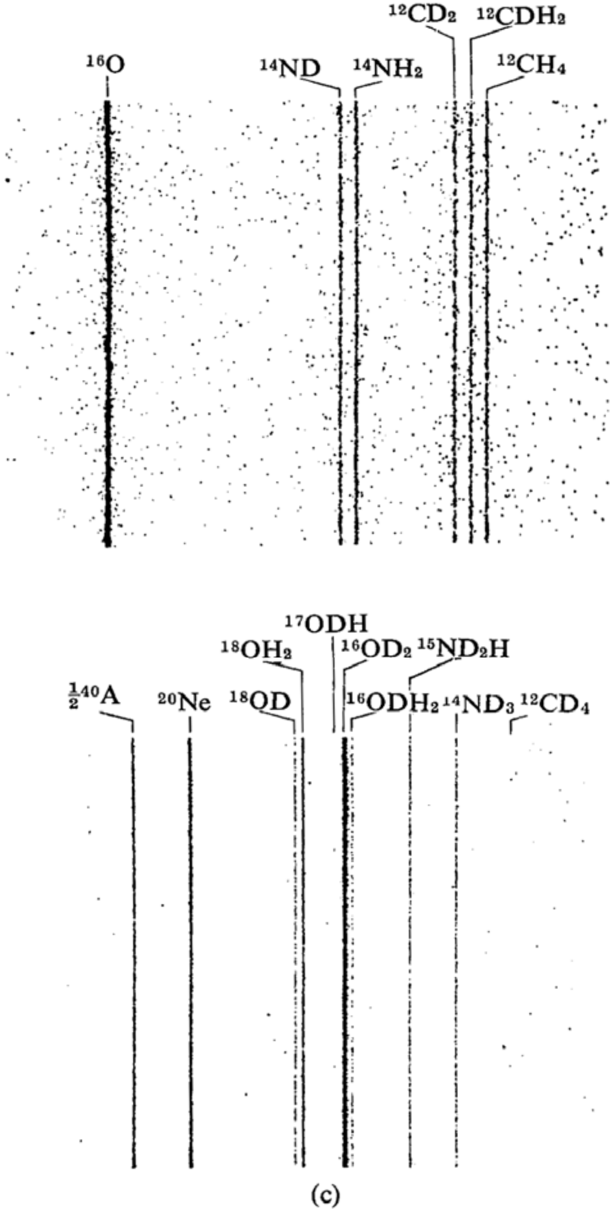


Figure 6-5 Mass spectrometer of Nier et al. The spectrometer focuses ions of a given mass; the focusing action is independent, within limits, of kinetic energy and of the entrance angle. Ions are produced in the ion source and accelerated by a voltage of about 40 kV. They are electrically deflected through an angle of 90° by a condenser P_1P_2 (radius 20 in.), and refocused on an electron multiplier by a magnetic field. The trajectories in the figure represent two beams of ions, of the same mass but different velocity and diverging from the source. The double-focusing action is demonstrated by the convergence of such beams at S_4. Two ions having a mass ratio m/m' and starting from rest follow exactly the same trajectory if all the voltages applied in the two cases are in the ratio $V'/V = m/m'$. Thus, measuring the ratio V'/V electrically for which two ions (e.g., CH_4^+, O^+) arrive at the same point gives their mass ratio. [Courtesy Prof. A. O. Nier.]



Segrè: Nuclei and Particles

How to measure nuclear mass?

Ion source + electric and magnetic field

$$F_{el} = qE = \frac{mv^2}{r_E} \rightarrow E_{kin} = \frac{mv^2}{2} = \frac{qEr_E}{2}$$

E= Energy Filter

$$F_{mag} = qvB = \frac{mv^2}{r_B} \rightarrow p = mv = qBr_B$$

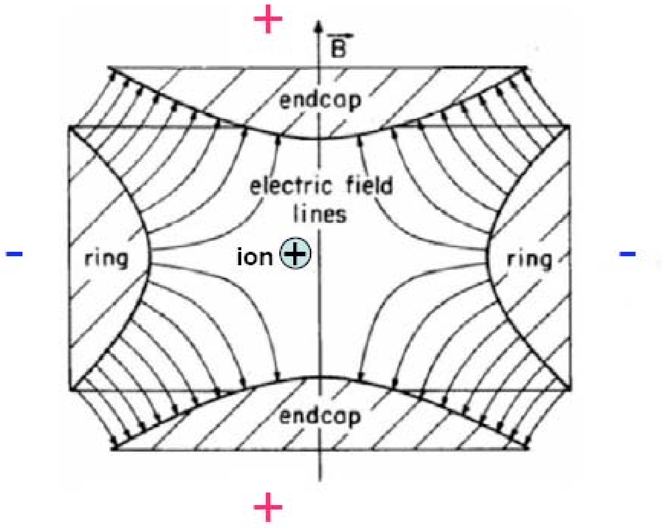
B= momentum filter

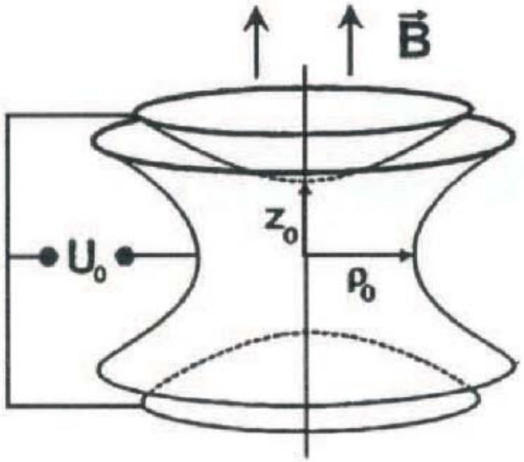
$$v = \frac{qBr_B}{m} \qquad \frac{q}{m} = \frac{Er_E}{B^2 r_B^2}$$

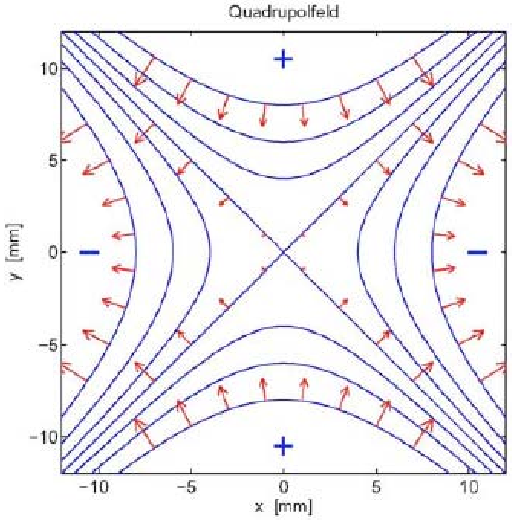
Mass Standard: 1u=1/2 m(^{12}C)= 931.49... MeV/c^2

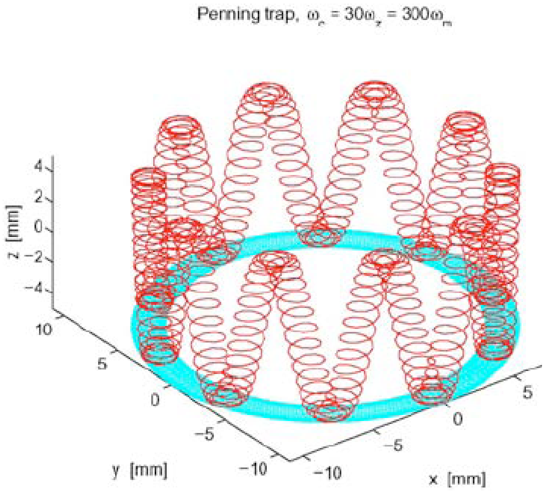
Penning Trap

Static electric quadrupole and static magnetic field

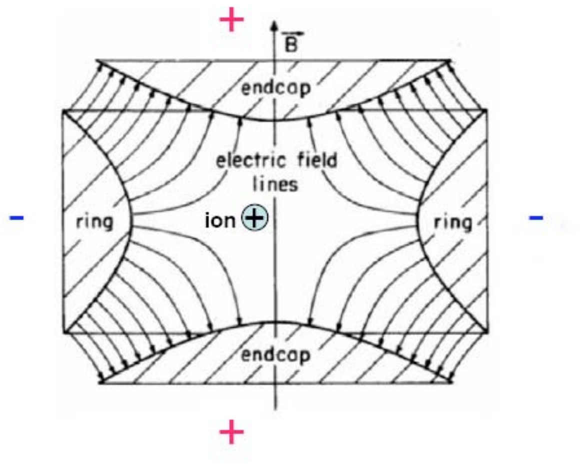


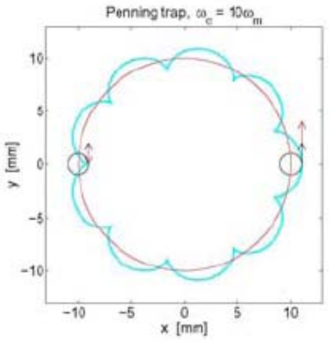


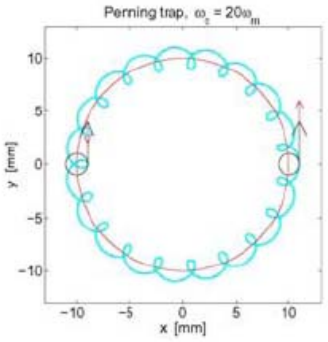




Harmonic Oscillation in z

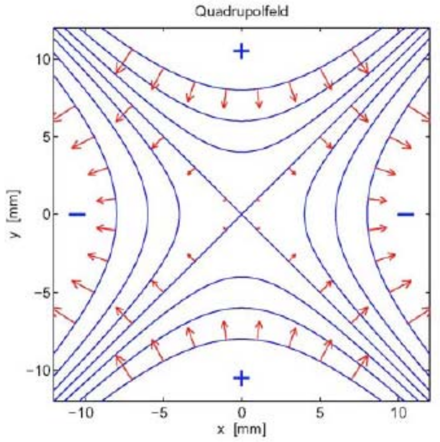






Cyclotron Motion +

Magnetron Motion

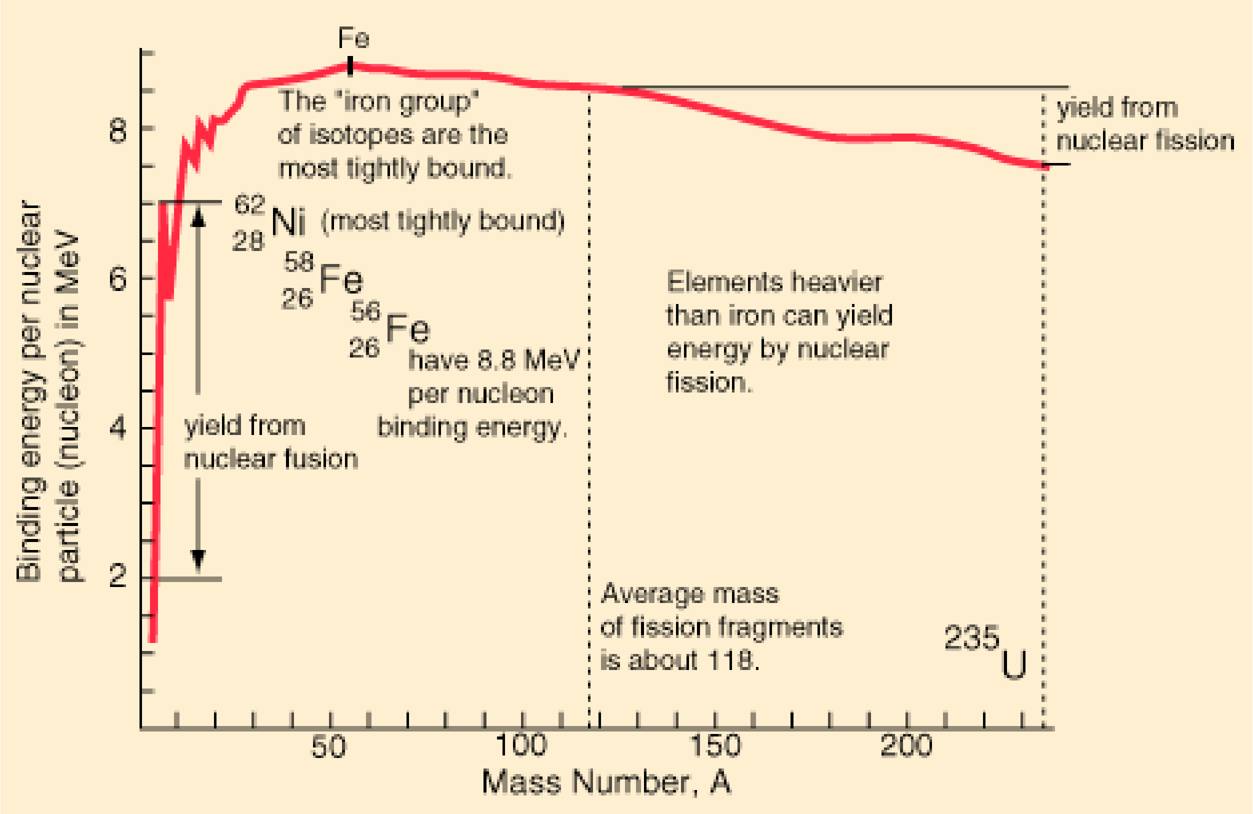


Cyclotron Frequency:

$$m\omega_c^2 r = \frac{q}{c} B\omega_c r \Rightarrow \omega_c = \frac{q}{m}\frac{B}{c}$$

Precise Measurement of e^-,p and Nuclear Masses

Nuclear binding energy per nucleon



Maximum @ A=60

BE roughly constant throughout most of the periodic table -->

Constant density of all nuclei? --> Liquid drop Model

Povh et al.,
„Particles and nuclei“

Liquid Drop Model

- Spherical dorp to minimize energy in absence of external forces
- $R \div 1/N^3$, N= Nr. of molecules in the drop
- a= Binding energy of each molecule to the drop
  Energy= 0 when the molecules are separated by large distances
  $E= -aN + 4\pi R^2 T$
- T: Surface tensionof the liquid -> $BE = aN - \beta N^{2/3}$ binding energy of the drop
- Given the energy Q of the drop on the surface $E = Q^2/(8\pi\varepsilon_0 R)$
  $B = aN - \beta N^{2/3} - \gamma Q^2/(N^{1/3})$

$$B(Z,A) = a_V A - a_S A^{\frac{2}{3}} - a_C \frac{Z^{1/2}}{A^{1/3}}$$

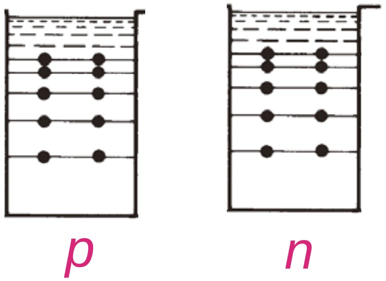
a_V : Volume Term

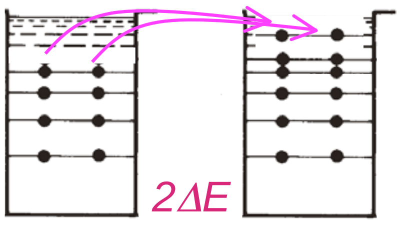
a_S : Surface Term

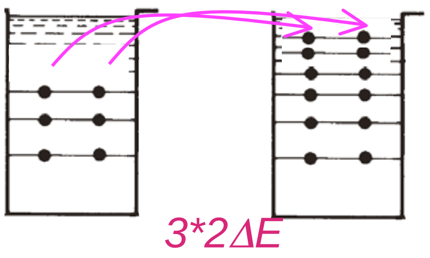
a_C : Coulomb Term

If we stick to this formula for a given A and B the maximum is found for Z=0
That means that something is missing in the formula

1. p and n are in two different potential wells. If DE is the energy needed to move 1 proton to the next energy level:







N-Z= 2, 4, 6
ΔE= 1 2 5 8..
E÷$(N-Z)^2$ $\Delta E/8$

The sign is determined by the fact that the Binding Energy is reduced by placing protons in the higher neutron orbitals

Asymmetry Term: $-a_A(Z-N)^2/A$

The spacing energy ΔE is inverse proportional to the well volume --> ΔE÷$1/A$

2 . 2p are always more bound than 1p --> Pairing Term
= 0 for odd nuclei
> 0 for even-even nuclei $a_P/A^{1/2}$
< 0 for even-even nuclei $-a_P/A^{1/2}$

$a_P \sim 12$ MeV

Total Binding Energy

$$B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} \begin{cases} +0 \\ \pm \dfrac{a_P}{A^{1/2}} \end{cases}$$

$$\underbrace{a_V = 15.5 MeV \quad a_S = 17.23 MeV \; a_C = 0.697 MeV \quad a_A = 23.285 MeV \; a_P = 12 MeV}_{found\ by\ fitting\ the\ data}$$

Contributions to the nuclear binding energy

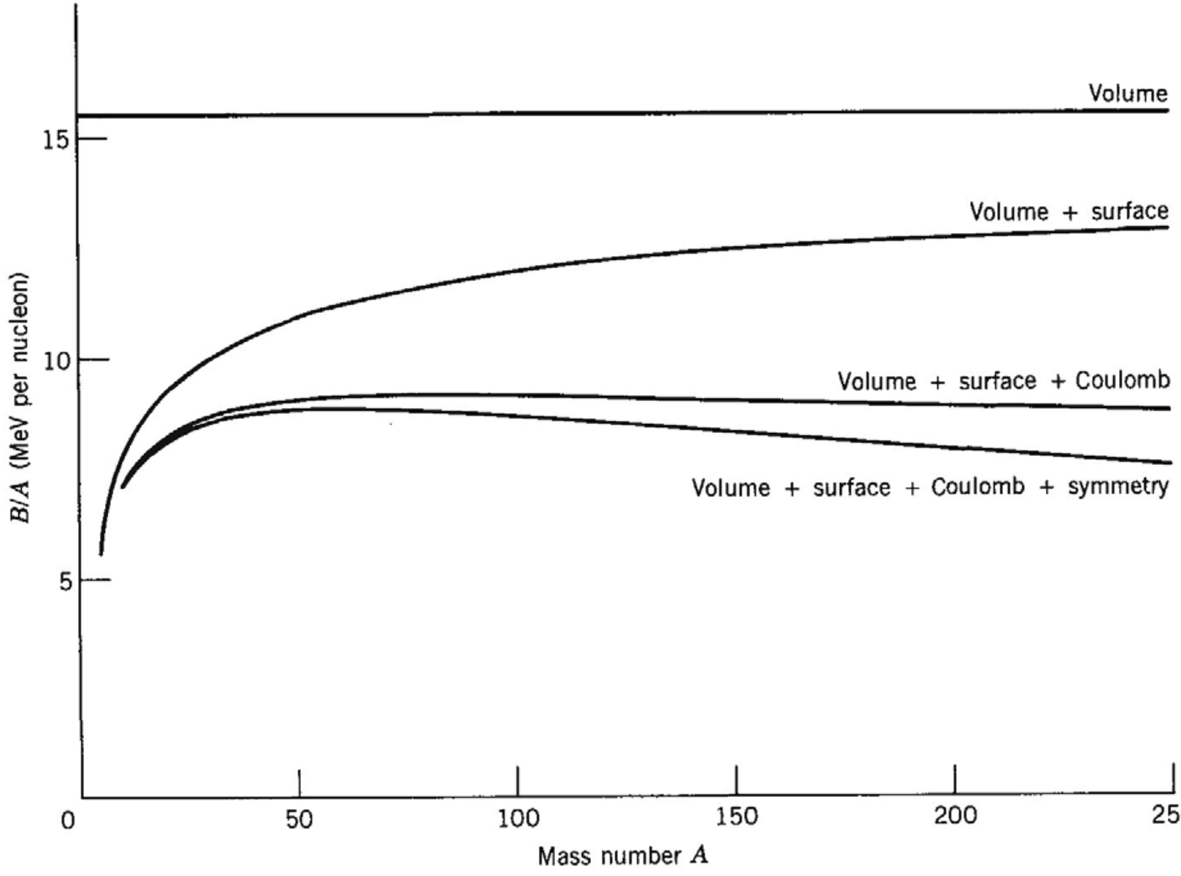
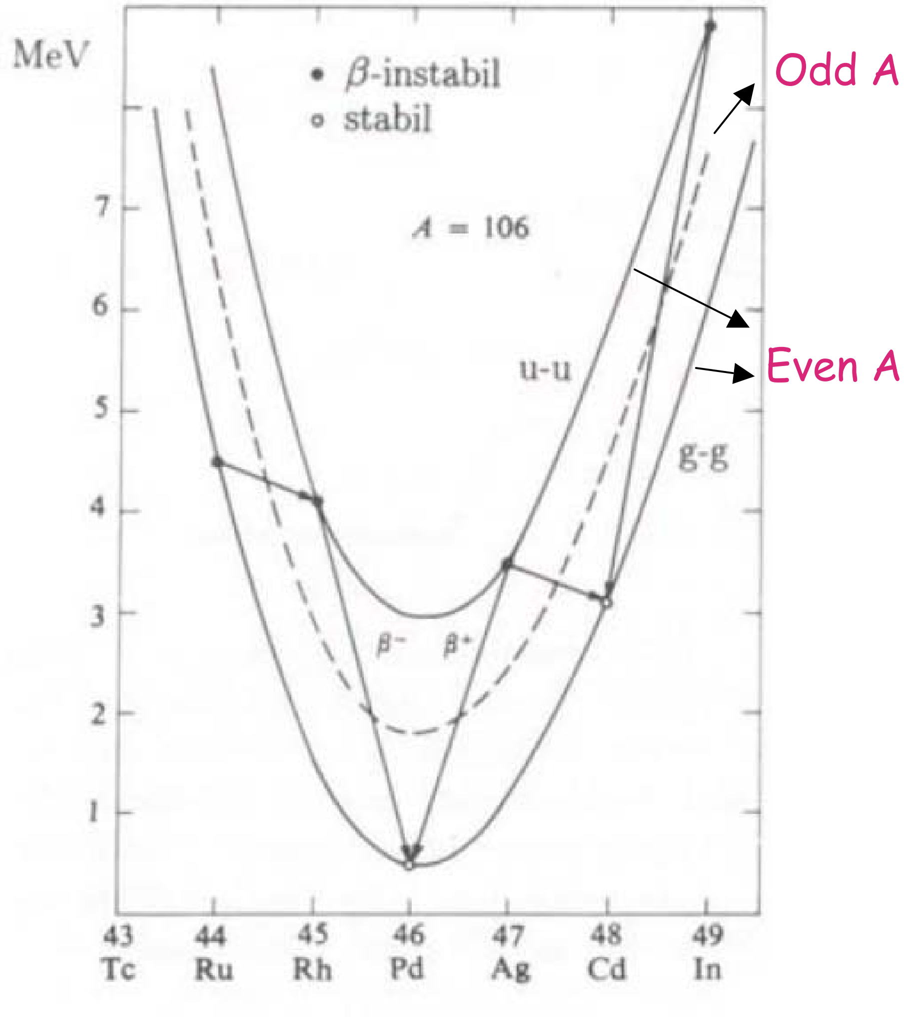


Figure 3.17 The contributions of the various terms in the semiempirical mass formula to the binding energy per nucleon.

Krane: Introductory nuclear physics



β^+decay :

$p \rightarrow n + e^+ + \nu_e$

β^-decay :

$n \rightarrow p + e^- + \underline{\nu}_e$