PHYS 3050
Nuclear Physics

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Room 135
OMB

Course Information

- Textbook: *Introductory Nuclear Physics* by Krane
- Other books: Ashby & Miller, Meyerhof, Livingston, Rohlf, Bowler, Burcham ….
- Assessment:

Mid-Session Exam 50 min. 20%

Final Exam 2 hrs 60%

2 Assignments 20%

- Lecture notes are on the Web page (including previous course notes, courtesy of O. Sushkov)
- www.phys.unsw.edu.au etc

Topics

1. Properties of nuclei (Radii, Mass, Binding Energy)
2. Properties of nuclear states (Spin, parity, magnetic and electric quadrupole moments)
3. Nuclear Models: Liquid-drop model
4. Fermi-gas model
5. Shell model
6. Collective model
7. Decay processes (α, β, γ)
8. Reactions (fission, fusion)
9. Elementary Particles, interactions and decays
10. The Standard Model

History

1895 Röntgen – X-rays

Fig. 2.7 *Röntgen's first X-ray photograph of a human shows the hand of his wife with the ring she was wearing.*

Close et al. 2.7

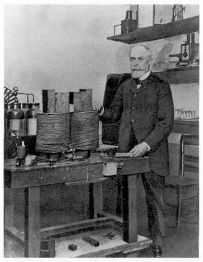


Fig. 2.9 *Henri Becquerel (1852–1908).*

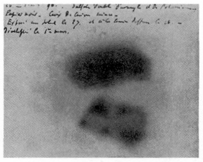
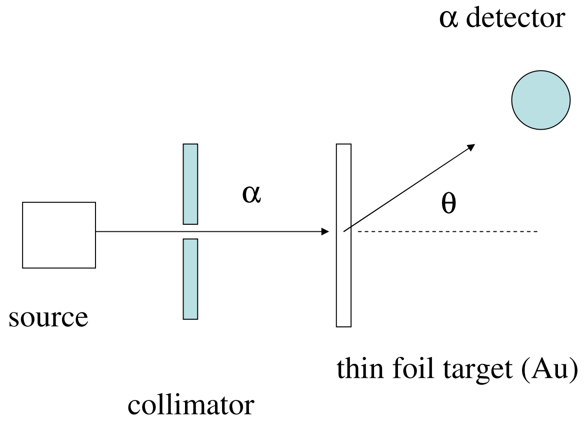


Fig. 2.10 *Becquerel's first evidence for radioactivity. These blurred images were formed on a photographic plate left for a few days under some uranium salts in a drawer, in February 1896.*

Close et al. 2.9, 2.10

1896 Becquerel - radioactivity
1897 Thomson - electron
1898 Curies – radium
1909 Rutherford – nucleus

Rutherford Scattering



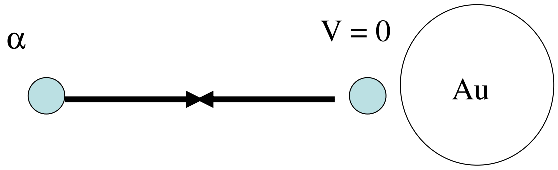
Count the number of scattered α particles as a function of scattering angle.

Atom is electrically neutral.

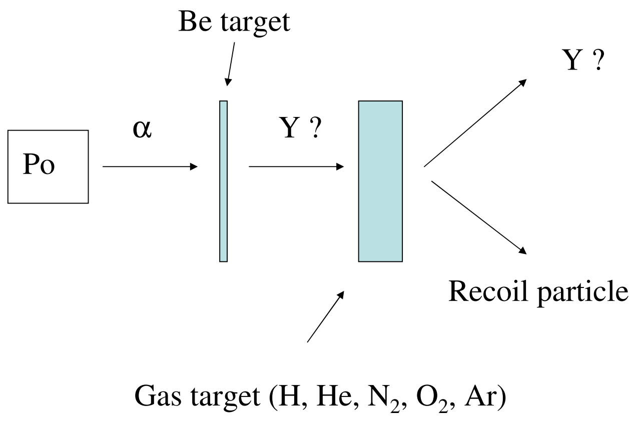
Must be a very small nucleus with almost all of the mass and all of the + charge (proton).

Rutherford

- Coulombic repulsion between the α-particle (2+) and the Au nucleus (79+)
- Let initial KE of α = PE at closest approach distance r
- KE (α) = 8 MeV
- Therefore, r = 2.8 x 10^{-14} m
- r = 28 fm = 28 fermi



Neutron - Chadwick



- 1932.
- The mystery particle (Y) has ~ proton mass but no charge
- The Neutron.

Nuclear properties

- 'atomic mass' = A
- 'atomic number' = Z = number of protons (+) = number of electrons (–)
- A–Z = number of neutrons (no charge) = N
- e.g. ^{238}U.
- A = 238 and U has Z = 92 protons. Therefore, 146 neutrons.

Terminology

- Nucleon: proton or neutron
- Nuclide: nucleus uniquely specified by N & Z
- Isoto**p**es: nuclides with the same Z (protons)

e.g. ^{235}U and ^{238}U

- Isoto**n**es: nuclides with the same N (neutrons)

e.g. ^{2}H (d) and ^{3}He

- Isobars: nuclides with the same A
- Atomic mass unit (u)

1 u = 1.66 x 10^{-27} kg ≡ 931.5 MeV/c^2

Z vs N curve (Segré chart)

- Light nuclei: N ~ Z
- Heavy N > Z

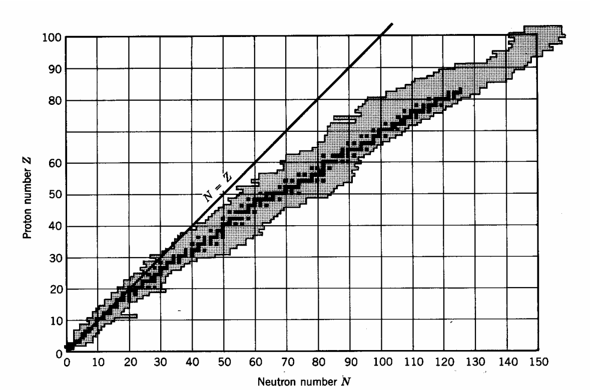


Figure 1.1 Stable nuclei are shown in dark shading and known radioactive nuclei are in light shading.

Krane 1.1

Properties of proton and neutron

	Proton	Neutron
Charge	+1	0
Mass (u)	1.007276	1.008665
Spin	½	½
Magnetic moment (μ_N)	+2.7928	–1.9128

Nuclear magneton = 5.05 x 10^{-27} J/T

Neutron has a moment but its charge = 0

Nuclear size

- Scattering experiments show that the nuclear radius is

$$r = r_o A^{1/3}$$

$$r_o \approx 1.2\ fm$$

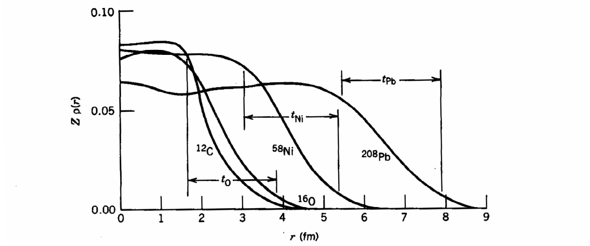


Figure 3.4 The radial charge distribution of several nuclei determined from electron scattering. The skin thickness *t* is shown for O, Ni, and Pb; its value is roughly constant at 2.3 fm. The central density changes very little from the lightest nuclei to the heaviest. These distributions were adapted from R. C. Barrett and D. F. Jackson, *Nuclear Sizes and Structure* (Oxford: Clarendon, 1977), which gives more detail on methods of determining ρ(*r*).

Krane 3.4

- The density of nuclei is approximately constant

$$\rho \propto \frac{A}{r^3}$$

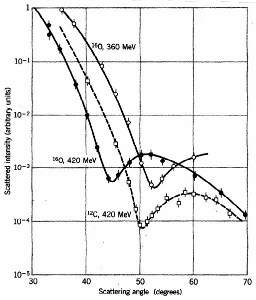
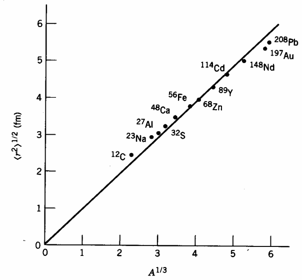


Figure 3.1 Electron scattering from ^{16}O and ^{12}C. The shape of the cross section is somewhat similar to that of diffraction patterns obtained with light waves. The data come from early experiments at the Stanford Linear Accelerator Center (H. F. Ehrenberg et al., *Phys. Rev.* **113**, 666 (1959)).

$$r \propto A^{1/3}$$

electron-scattering
Diffraction

Krane 3.1



Krane 3.5

Binding energy

- Nucleus (A, Z, N) has Z protons and N neutrons

- The mass difference springs from the energy gained in bringing the nucleons into their mutual potentials

$$\Delta = \left(m_{nucl.} - A\right) c^2$$

- This is the binding energy

$$B.E. = \left(m_{nucl.} - Zm_p - Nm_n\right) c^2$$

Binding energy

- e.g. ^{16}O (Z = 8 and N = 8)

$M_p = 938.280$ MeV/c^2
$M_n = 939.573$ MeV/c^2
$M_e = 0.511003$ MeV/c^2

$$8M_p + 8M_n + 8M_e = 15026.912\ MeV / c^2$$

$$Atomic\ \ Mass = 15.994915\ u$$

$$= 15.994915 \times 931.502$$

$$= 14899.295\ \ \text{MeV/c}^2$$

$$\Delta M = 15026.912 - 14.899.295$$

$$= 127.617\ MeV / c^2$$

$$= 7.976\ MeV / c^2\ \ per\ \ nucleon$$

Mass Defect (Δ)

- e.g. ^{16}O (Z = 8 and N = 8)

$$\Delta = \left(m_{nucl.} - A\right) c^2$$

$$\Delta = (M - A)c^2$$

$$= (15.994915 - 16)c^2$$

$$= -0.005085\ c^2\ MeV$$

$$= -0.005085 \times 931.502 = -4.737\ \ \text{MeV}$$

Separation Energy

- Neutron Separation Energy = energy to remove one neutron from nucleus

$$= B\left({}^{A}_{Z}X_{N}\right) - B\left({}^{A-1}_{Z}X_{N-1}\right)$$
$$= \left[m_{(A-1)} + m_n - m_A\right]c^2$$

$$e.g.\ {}^{16}_{8}O_{8} = \begin{pmatrix} 15.003065 + 1.00866501 \\ -15.994915 \end{pmatrix} c^2$$

$$= 0.016815\ c^2$$

$$= 15.6632\ MeV$$

Binding energy

$$\frac{B}{A}(MeV)$$

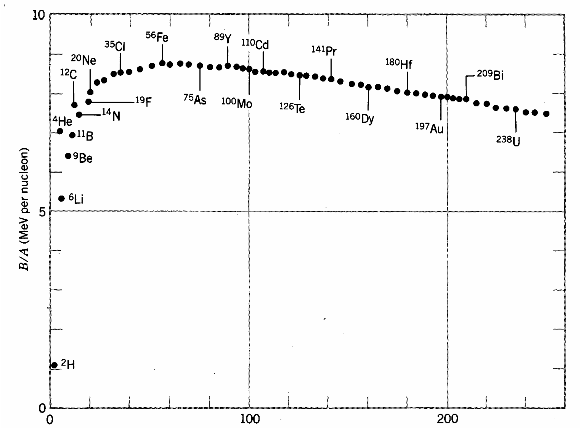


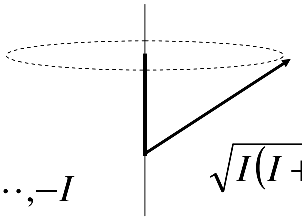
Figure 3.16 The binding energy per nucleon.

A

Krane 3.16

Nuclear Angular Momentum

- For many applications, the nucleus behaves as a single entity with an angular momentum *I*
- *I* is referred to as the nuclear 'SPIN'
- Can include both orbital and spin angular momentum



$$m_I\hbar$$
$$m_I = +I, +(I-1), \cdots, -I$$

$$\sqrt{I(I+1)}\hbar$$

$2I+1$ values

- p and n are fermions $s = \frac{1}{2}$
- Orbital angular momentum is an integer $l = 0, 1, 2\cdots$
- The total angular momentum of a nucleus is the vector sum of the intrinsic spin and orbital angular momentum of its nucleons

j-j coupling (A > 10)

$$\vec{I} = \sum_i \left(\vec{l}_i + \vec{s}_i\right) = \sum_i \vec{j}_i$$

L-S coupling (A < 10)

$$\vec{I} = \vec{L} + \vec{S}$$
$$\sum_i \vec{l}_i = \vec{L} \quad \& \quad \sum_i \vec{s}_i = \vec{S}$$

- Nuclei with an even number of nucleons (even-A) have

  I = integer

- Nuclei with an odd number of nucleons (odd-A) have

  I = half-integer

- Even-Z, even-N nuclei have $I = 0$
- A consequence of nucleon pairing
- In odd-A nuclei, the nuclear spin is (predominantly) that of the odd nucleon (p or n)
- Odd-Z, odd-N nuclei have

$$\vec{I} = \vec{j}_p + \vec{j}_n$$

- Coupling of the angular momenta of the 'extra' p and 'extra' n.
- Ground state is usually that with

  $s_p \,\&\, s_n$ parallel

Parity

- Nucleons and nuclei have a parity associated with their wavefunctions

$$\vec{r} \rightarrow -\vec{r}$$

$$\psi(-\vec{r}) = +\psi(\vec{r}) \qquad \text{EVEN (P = +1)}$$

$$\psi(-\vec{r}) = -\psi(\vec{r}) \qquad \text{ODD (P = −1)}$$

- Nuclear states e.g. $I^\pi = 2^+$
- Parity operator

$$P\psi(\vec{r}) = \psi(-\vec{r})$$

$$|\psi(r)|^2 = |\psi(-r)|^2$$

Parity

- A wavefunction in a central potential

$$\psi(r,\theta,\phi) = R(r)\underset{\nearrow}{Y_{lm}}(\theta,\phi)$$

Spherical Harmonics

$$\vec{r} \rightarrow -\vec{r} \quad \text{equivalent to} \quad \begin{cases} \theta \rightarrow \pi - \theta \\ \phi \rightarrow \pi + \phi \end{cases}$$

$$Y_{lm}(\theta,\phi) \rightarrow (-1)^l \, Y_{lm}(\theta,\phi)$$

$$P\psi(r,\theta,\phi) = (-1)^l \, \psi(r,\theta,\phi)$$

Parity

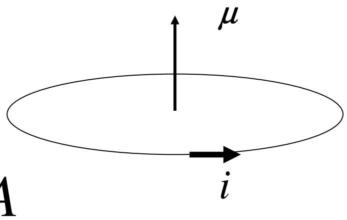
- The parity of a single nucleon is

$$\pi = (-1)^l$$

The intrinsic parities of free nucleons are

$$\pi_p = \pi_n = +1$$

Magnetic dipole moment



$$\mu = iA$$

Relate to angular momentum $\vec{\mu} = \frac{e\hbar}{2m}\vec{l}$

$$m_e \rightarrow \mu_B$$ “Bohr Magneton”

$$m_p \rightarrow \mu_N$$ “Nuclear Magneton”

Atomic moment >> Nuclear moment

$$\frac{m_p}{m_e} = 1837$$

Nuclear g-factors

Angular momentum → Magnetic moment

$$\vec{\mu}_l = g_l \mu_N \vec{l}$$

Gyromagnetic ratio

$g_l = 1$ proton

$g_l = 0$ neutron

$$\vec{\mu}_s = g_s \mu_N \vec{s}$$

$s = \frac{1}{2}$ for protons and neutrons

Expect $g_s = 2$ for elementary (Dirac) charged particles

$$g_s \approx \begin{cases} 5.5857 & \text{proton} \\ -3.8261 & \text{neutron} \end{cases}$$

- The neutron has a magnetic moment but its charge is ZERO !
- The g-factors of protons and neutrons are NOT equal to 2
- Suggests nucleons are NOT elementary – some “internal structure”