Nuclear and Radiation Physics (PHY2005)

Lecture 1

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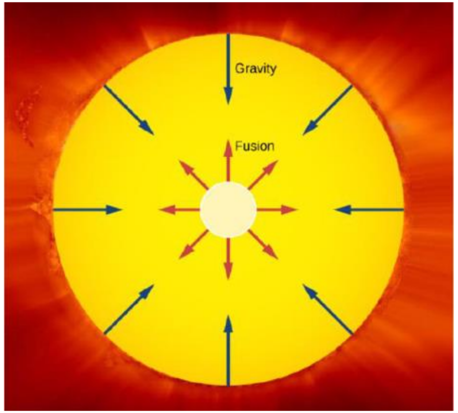
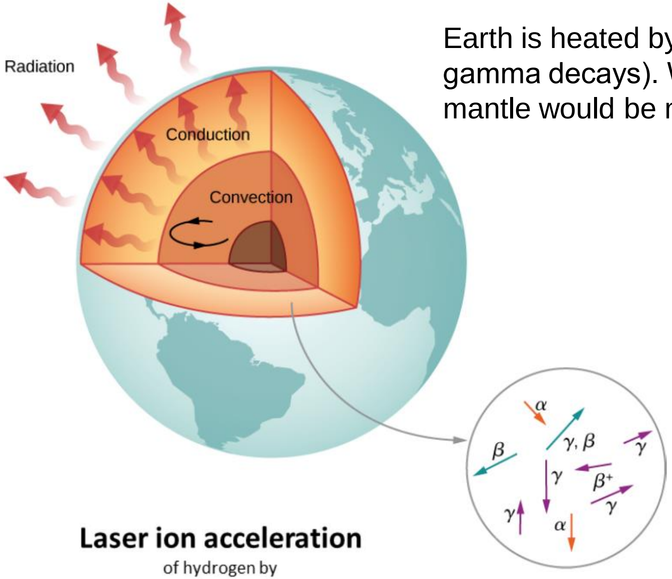
Motivations
Nuclear and radiation physics

The Sun produces energy by fusing hydrogen into helium at the Sun's core. Outward Pressure (thermal plasma): Sun expansion. Inward pressure (gravity): Sun contraction.

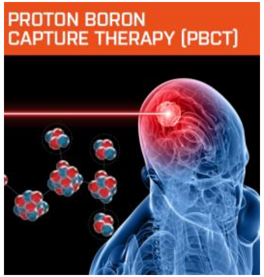


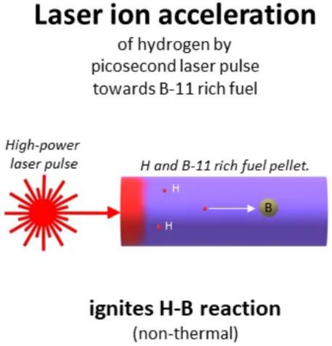


Earth is heated by nuclear reactions (alpha, beta, and gamma decays). Without these reactions, Earth's core and mantle would be much cooler than it is now.

Nuclear Power Plants uses a nuclear fission reactor to generate electricity

$p^{11}B$ nuclear fusion (neutron-less) for applications in "Energy" and "Cancer Therapy"





Preliminaries

OBJECTIVES AND OUTCOMES

- Knowing the terminology and notation of nuclear physics
- Understanding physical reasoning behind model**s** of the nucleus
- Understanding processes such as radioactive decay, fission, fusion
- Becoming aware of applications of nuclear physics in science, technology, and medicine

SYLLABUS

1. Nuclear Properties
2. The Inter-Nucleon Potential
3. Nuclear Models
4. Nuclear Decays and Reactions
5. Interaction of Radiation with Matter
6. Applications of Nuclear Physics

MATERIAL & SUGGESTED READING

1. "Nuclear and Radiation Physics" (***Notes by D. Margarone, 2021-2022***)
2. "Introductory Nuclear Physics" (*K.S. Krane, Wiley*)
3. "Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles"
   (*Eisberg and Resnick, Wiley 2nd Edition*)
4. Material on "advanced topics" *(beyond our core content)*

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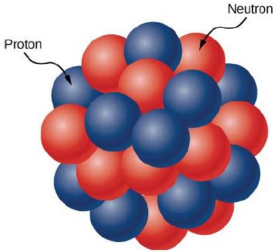
Ernest Rutherford

"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."
[*Recalling in 1936 the discovery of the nucleus in 1909, when some alpha particles were observed instead of travelling through a very thin gold foil were seen to rebound backward, as if striking something much more massive than the particles themselves. He won the Nobel Prize in Chemistry for this discovery*.]"

***"All science is either physics or stamp collecting**."*



- ✓ Nuclear forces between protons and neutrons are known
- ✓ BUT, no unique comprehensive theory of nuclei able to explain their properties based on nuclear forces acting between their protons and neutrons

Static nuclear properties

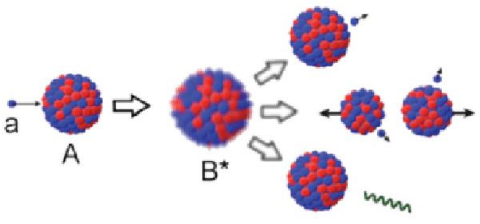
- electric charge
- binding energy
- angular momentum
- parity
- magnetic dipole and electric quadrupole moments
- characteristic energy of excited states: ~ 1 MeV (~ *1 eV for atoms*)

Dynamic nuclear properties

- decay
- fission
- fusion

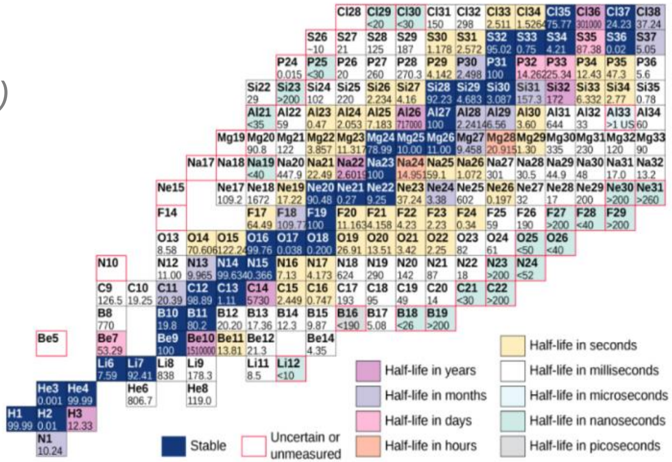
$$a + A \rightarrow B + b$$

Nuclear reactions (general case)



$$^{4}He + {}^{14}N \rightarrow {}^{17}O + {}^{1}H$$

First artificial nuclear reaction (Rutherford 1919)



Stable and unstable nuclei

$$(K_a + m_a c^2) + m_A c^2 = (K_B + m_B c^2) + (K_b + m_b c^2)$$

Conservation of total relativistic energy

Nuclear shape

- mean radius *(rms)*
- skin thickness *(90% →10%)*

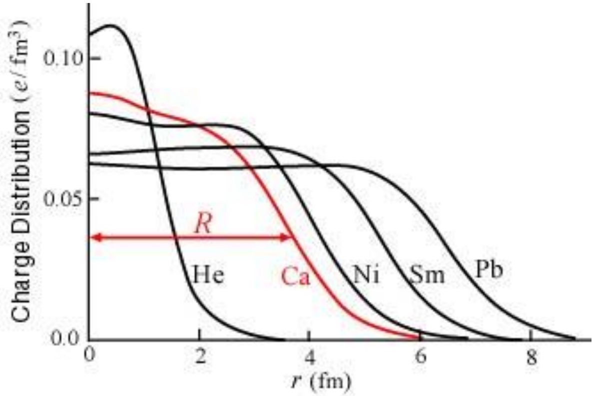
Nuclear Radius

- distribution of nuclear charge – protons (*high-energy electron scattering*)
- distribution of nuclear matter – protons & neutrons *(high-energy alpha-particle scattering)*
- mass radius and charge radius agree with each other within ~ 0.1 fm
- nucleus is not a hard sphere
- central nuclear charge density nearly constant for all nuclei:

$$\frac{A}{\frac{4}{3}\pi R^3} \sim const \quad \Rightarrow \quad \boxed{R = R_0 A^{1/3}}$$

Empirical mean radius formula ($R_0 \approx 1.2$ fm)

- charge density drops to zero over a certain distance: *skin thickness ~ 2.3 fm (90% → 10%)*



Radial charge distribution of several nuclei

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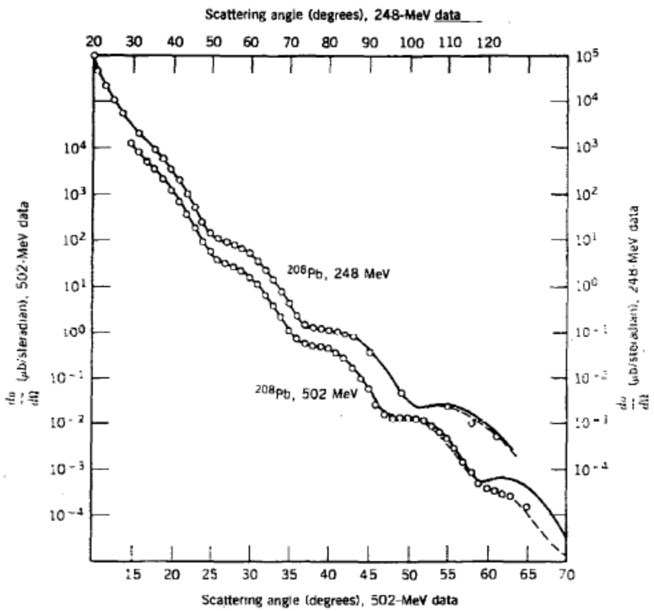
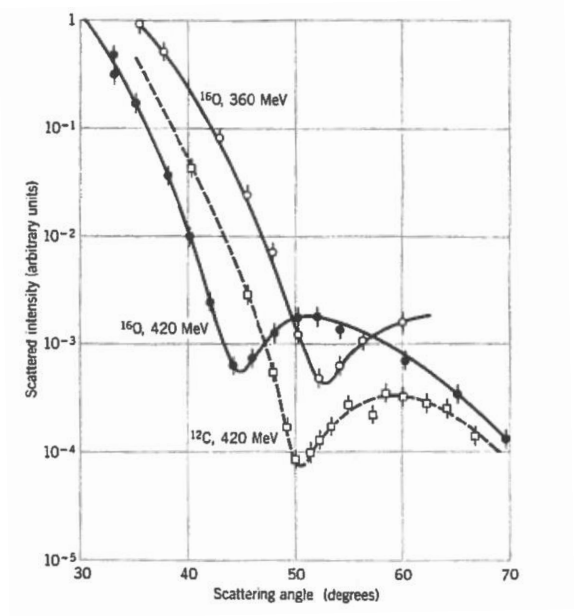
1.2. Nuclear Radius & Density II (elastic scattering)

$$\theta = sin^{-1}\left(\frac{1.22}{D}\right)$$

D: nucleus diameter





Elastic electron scattering (several minima in the diffraction pattern)

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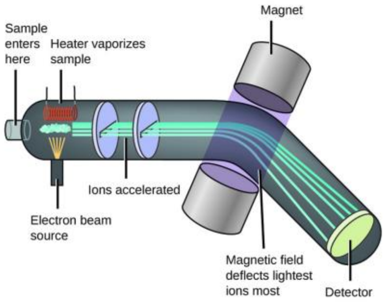
1. Nuclear Properties

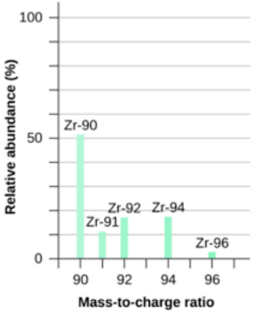
1.3. Mass & Abundance of Nuclei

Mass spectrometry

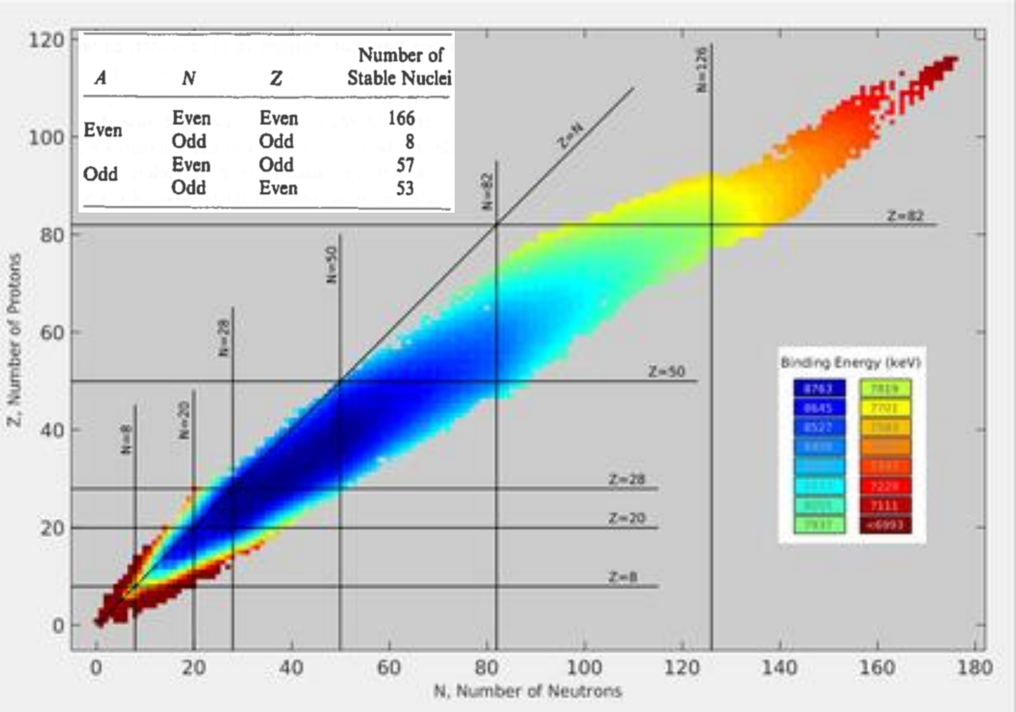
- measurement of <u>nuclear mass</u> with high precision *($\sim 10^{-6}$)* by isotope separation
- measurement of relative <u>abundance</u> of various isotopes *(current)*

- $A = Z + N$
- low Z → Z ~ N
- high Z → N > Z *(Z/A ~ 2/5)*





Schematic of a mass spectrometer



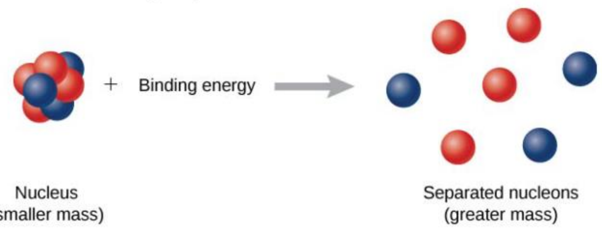
The Segre' chart

Binding energy definition

- amount of energy released in forming the nucleus *(mass defect)*: $B = \Delta m\, c^2$

- difference in mass energy between a nucleus ${}^{A}_{Z}X_{N}$ and its constituents *Z* protons and *N* neutrons:

$$\boxed{B = \left[Zm({}^{1}H) + Nm_N - m({}^{A}X)\right]c^2}$$



A few remarks

- the masses are often expressed in MeV *(mass-energy mc²)* and typically we deal with atomic masses

- the masses are generally given in atomic mass units, thus it is convenient to include the unit conversion factor: *1 u = 1.66x10⁻²⁷ kg = 931.50 MeV/c²*

Neutron separation energy:

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

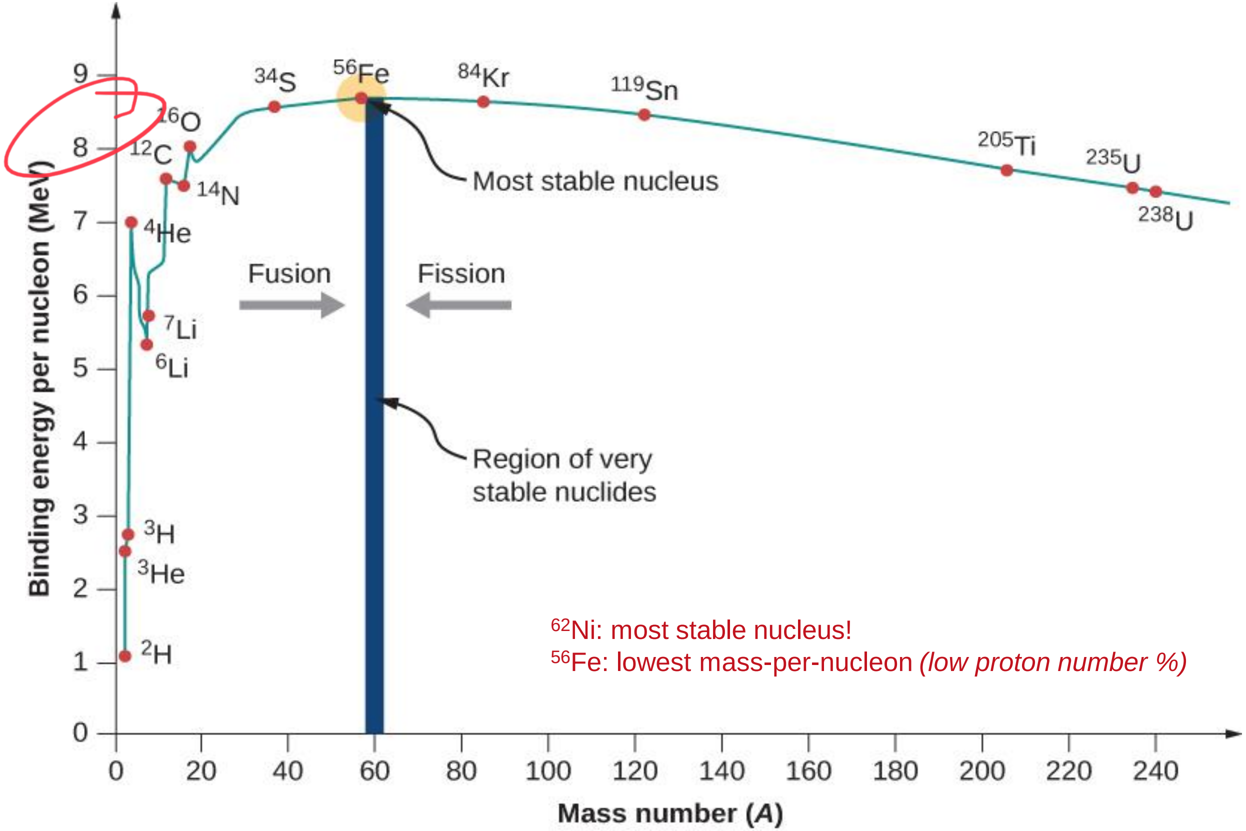
Proton separation energy:

$$S_p = B({}^{A}_{Z}X_N) - B({}^{A-1}_{Z-1}X_N) = \left[m({}^{A-1}_{Z-1}X_N) - m({}^{A}_{Z}X_N) + m({}^{1}H)\right]c^2$$

Additional remarks

- the average binding energy per nucleon, B/A, is relatively constant *(~ 8 MeV/u)* except for very light nuclei *(2.2 MeV for ^{2}H)*

- maximum stability *(most tightly bound nuclei): A ~ 60*



^{62}Ni: most stable nucleus!

^{56}Fe: lowest mass-per-nucleon *(low proton number %)*

Derivation of binding energy formula

$$\boxed{B = \left[Zm(\,^{1}H) + Nm_N - m(\,^{A}X)\right]c^2}$$

- mass energy nucl.

$$m_{nucl}c^2 = m_A c^2 - Z m_e c^2 + \cancel{\sum_{i=1} B_i}$$

~ eV ~ keV

- binding energy nucl. $^{A}_{Z}X_{N}$:

$$B = \left\{Z m_p + N m_N - \left[m(^{A}X) - Z m_e\right]\right\}c^2$$

$$= \left[Z\, m(^{1}H) + N m_N - m(^{A}X)\right]c^2$$

Calculate the binding energy per nucleon of an α-particle (^{4}He)

$$B = \left[Zm(\,^1H) + Nm_N - m(\,^AX)\right]c^2$$

$m(^4He) = 4.002602$ u; $m(^1H) = 1.007825$ u; $m(n) = 1.008665$ u
1 u = 931.50 MeV/c^2

$$B = \left(2\,m(^1H) + 2\,m_N - m(^4He)\right]c^2 =$$

$$= (2 \times 1.007825 + 2 \times 1.008665 - 4.002602)\,\underline{\underline{u}}\,c^2$$

$$= 0.030378 \times 931.5\,\mathrm{MeV}/\cancel{c^2}\,\cancel{c^2} = \underline{28.3\,\mathrm{MeV}}$$

$$\frac{B}{A} = \frac{28.3}{4} = 7.07\,\frac{\mathrm{MeV}}{\mathrm{nucl.}}$$