Introduction to Nuclear Physics

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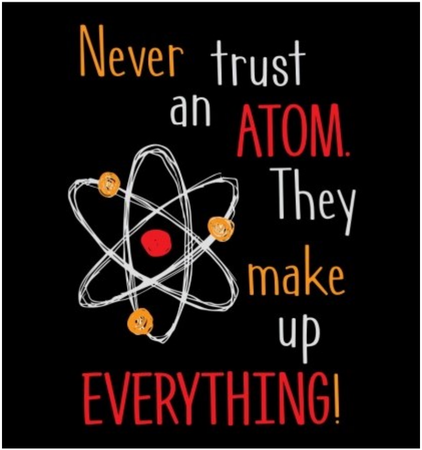
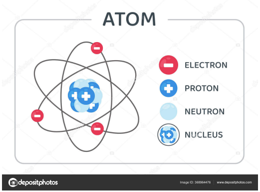
Introduction

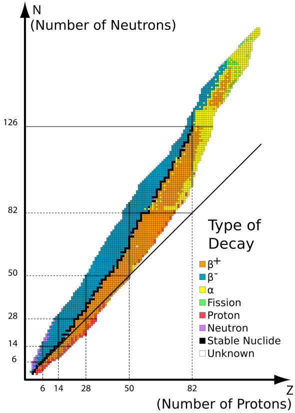


What are we made of- Revisit Basics



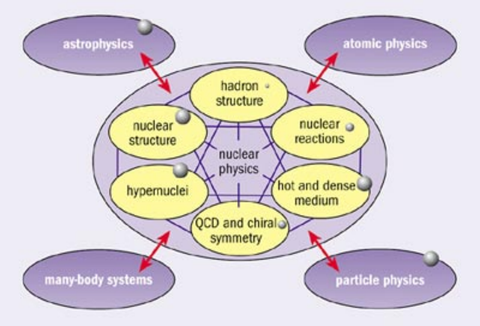
Discoveries

- Electron : J. Thomson, 1897
- Proton : Goldstein, 1986
- Neutron : J. Chadwick, 1932



Introduction

Nucleons, Isotopes, Isobars, Isotones, Isomers



300 Stable, 3000 Unstable, 7000 Predicted

Why Nuclear Physics

Key Problems

- Understanding nuclear processes that drive evolution of stars and galaxies and Universe
- Emergence of simple and regular patterns in complex nuclei
- Limits on nuclear existence: heaviest nucleus, maximum number of nuclei?
- Understanding nuclear structure
- Nucleon-Nucleon interaction arising from QCD
- Applications: Nuclear Energy, Medical Physics

Nuclear Physics: Timeline

1. 1896: Becquerel discovers X-rays, followed by 'uranic' rays
2. 1897: Rutherford: 'uranic' rays are mixture of positive and negative charges, α and β rays. Thomson discovers electron.
3. 1898: Curie couple observed 'uranic' rays from few other elements. Coins radioactivity.
4. 1899: P. Villard discovers gamma rays. Becquerel realises β rays are high energy electrons
5. 1906: Discovery of α particles
6. 1909: Rutherford'd gold foil experiment
7. 1915: Helium's mass deficit (1905: Einstein - $\mathrm{E} = \mathrm{m}c^2$)
8. 1930: Dirac's equation
9. 1931: Problem with beta decay, neutrino theorized
10. 1932: Neutron discovery, positron discovery

Properties of Nuclei

What will we discuss

1. Nuclear Mass
2. Radius and Density
3. Nuclear Charge
4. Binding Energy
5. Dipole Moment
6. Quadrupole Moment
7. Spin and Parity
8. Nuclear Force
9. Nuclear States

Properties of Nuclei

Mass and Size

mass of all protons plus neutrons
Size around 10^{-15}m

Radius, Density, Mass Distribution

- The density of all nuclei is approximately same, $10^{17}\frac{kg}{m^3}$
- $\mathrm{D} = \frac{\mathrm{M}}{4\Pi\mathrm{R}^3}$
- $\mathrm{R} = \mathrm{R_o}\mathrm{A}^{1/3}$
- This given the Volume $\propto A$

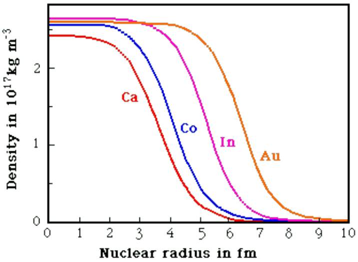
How or Why is the density almost constant

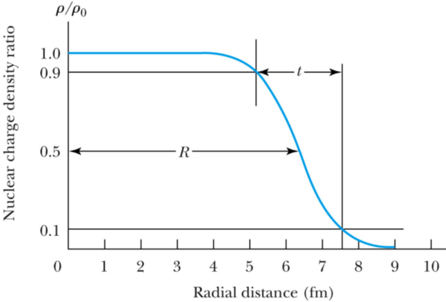
Will get there soon!

Properties of Nuclei

Nuclear MAss and Charge Distribution

- Charge and Matter radii are nearly equal
- Charge distribution also shows $A^{\frac{1}{3}}$ dependence
- This happens because the coulomb repulsion tends to push the protons outwards

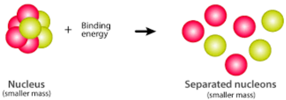




Properties of Nuclei

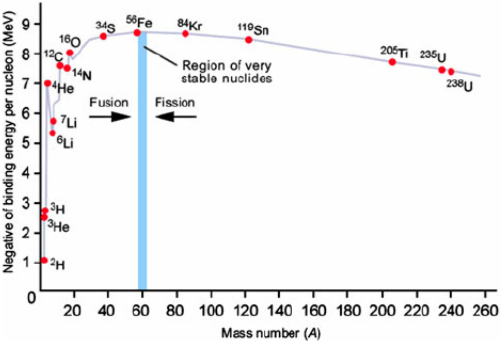
Binding Energy and Mass defect

- If Mass of Nuclei is M,
- While the sum of mass of nucleons is A,
- The $M < A$;
- and $A - M = \Delta m$
- Or Zm_p + Nm_n - $M_A = \Delta m$
- Binding energy $= \Delta mc^2$



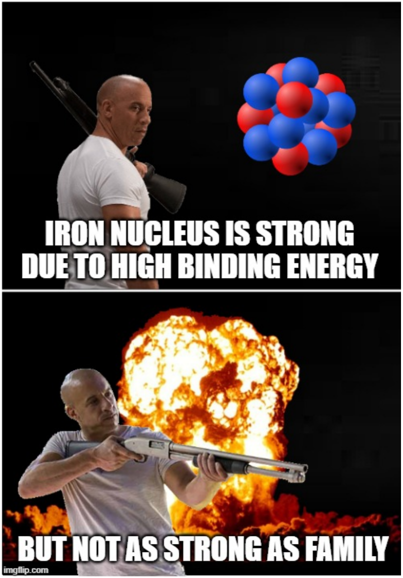
- Evidently, more the B.E, more stable is the nuclei

Binding Energy Per Nucleon



Binding energy per nucleon = B.E/A
Energy required to release a nucleon

Properties of Nuclei



Properties of Nuclei

Nuclear Spin and Parity

- Total angular momentum of nucleus is represented by its Spin-I
- Even-Even: Zero Spin, even parity
- Odd A: spin is equal to half integer
  and parity is -1^{l})
- Odd-Odd: Integral Spin, and parity depends on angular momentum of the unpaired proton and neutron.

Neutrons and Protons tend to pair up in such a way that the pair has 0 spin and parity equal to 1.

Properties of Nuclei

Dipole Moment

- Arises from the spin of protons and neutrons
- $\mu = \mathrm{g} \, \frac{e}{2m_p} \mathrm{I}$

Neutron Magnetic Moment

- $\mathrm{g} =$ 5.5856947
- $\mu =$ -1.9130418

Proton Magnetic Moment

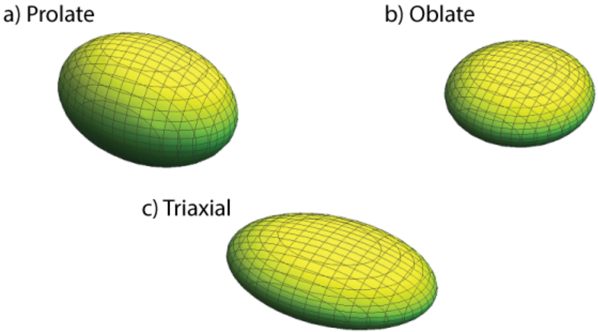
- $\mathrm{g} =$ -3.8260837
- $\mu =$ 2.7928456

Properties of Nuclei

Quadrupole Moment

Shape of nuclei are not entirely spherical. They are influenced by the quadrupole moment.

- Classically: Q $= \int \rho(3z^2 - r^2)dV$
- Quantum Mechanics: Q $= \frac{3k^2 - I(I+1)}{(I+1)(2I+3)} Q_0$

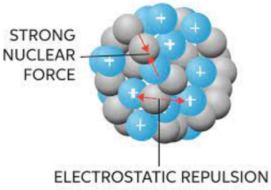


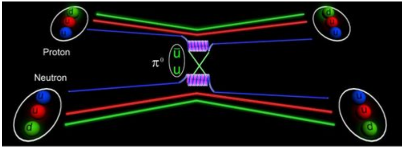
Nuclear Force

Residual color force

Properties

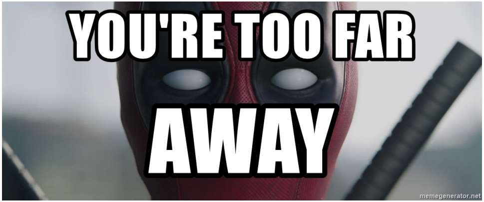
- Bind the Nucleons together
- Very Short Range (1 fm)
- Repulsive at inter-nucleonic distances- 0.5fm
- Mediated by mesons (pions)
- Not a central force
- Spin dependent
- Charge Independent



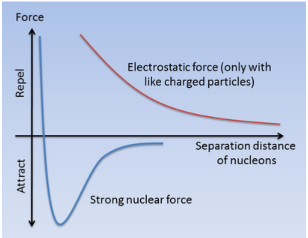


Nuclear Saturation: Far, then Forgotten

Almost all nucleons



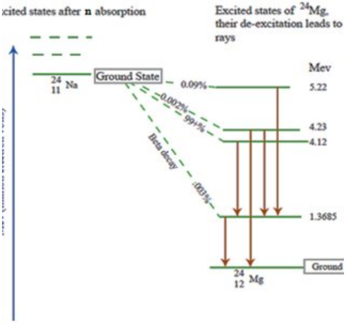
Nuclear Saturation arises due to an interplay between the attractive nuclear force and repulsive coloumbic interactions



Nuclear States- Isomers

There is one ground state and several excited states

- Characterized by half-life
- Decay modes and probabilities
- Excitation energies
- Nuclear Spin and Parity



Nuclear Models

Nuclear Models

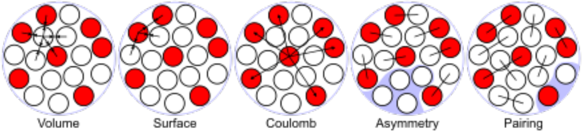
Shell Model
Liquid Drop Model

For explaining the stability, occurrences and behaviour of nuclei and to mathematically predict the binding energies, reactions, decay channels etc

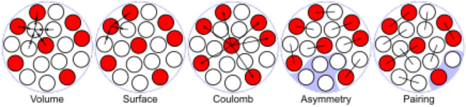
Liquid Drop Model

Facts

- Constant density
- Molecules too close: Repulsion
- Molecules too far: No attraction
- Assumes that liquid drop has uniform distribution of positive charge
- A liquid drop changes shape in presence of forces



Liquid Drop Model



- $\mathrm{R} = \mathrm{R_o A^{1/3}}$
- Volume : $\mathrm{V} \propto \mathrm{A}$
- Surface: $\mathrm{S} \propto \mathrm{A}^{2/3}$: distribution at surface
- Cuolomb: $\mathrm{S} \propto \frac{\mathrm{Z(Z-1)}}{\mathrm{A}^{1/3}}$: proton repulsion
- Symmetry: $\frac{\mathrm{(N-Z)^2}}{\mathrm{A}}$: Neutrons and protons
- Pairing: $\frac{1}{\mathrm{A}^{1/2}}$: Pauli exclusions

Binding Energy: Semi Empirical Mass Formula

$$\mathrm{B.E} = a_v \, \mathrm{A} - a_s \, \mathrm{A}^{2/3} - a_c \, \frac{\mathrm{Z(Z-1)}}{\mathrm{A}^{1/3}} - a_a \, \frac{\mathrm{(N-Z)^2}}{\mathrm{A}} + \delta \, \frac{1}{\mathrm{A}^{1/2}}$$

Liquid Drop Model

Properties Well explained by Liquid-drop model

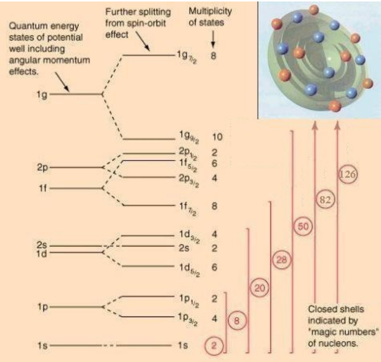
Radioactivity: Fission

Binding energies of most nuclei

Shell Model

- Based on the Pauli Exclusion principle and analogous to electronic shell model.
- Tries to explain the stability of nucleus based on the 'magic number' of nucleons that fill different energy levels

- Shells of protons and neutrons are treated separately
- The nuclear potential considered is something in between of square well and harmonic oscillator potential.



Shell Model

Properties explained by shell model

- Increase in Binding energy at predicted magic number values
- Explains Spin and parity of nuclear ground states
- Nuclear magnetic moment

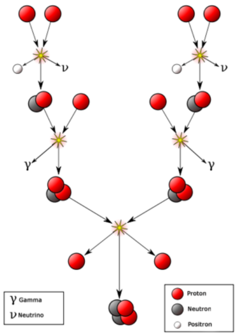
Nuclear Fusion

Proton-Proton fusion in Sun

- Formation of deuterium
- Then Helium-3
- Helium 4 and Berrylium-6

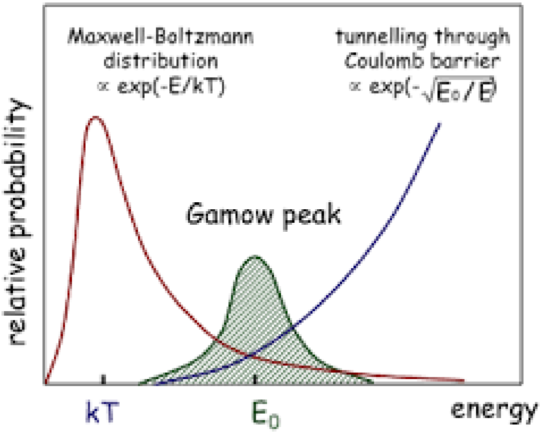
Energy

- Formation of Helium-4 from 4 protons with a mass deficit (0.7% of mass)
- 3.8 x 10^{26} Joules of energy/second

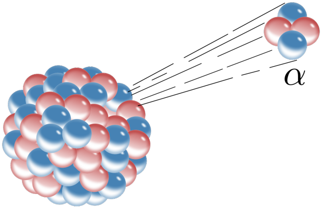


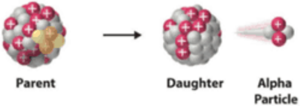
Fun-Fact: Gamow Window

How probable is the fusion of two protons inside Sun?



Alpha Decay





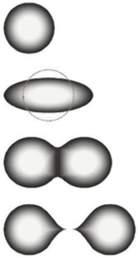
$$^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He + 4.78\ MeV$$

How it occurs

- The alpha is exists and is trapped inside a nucleus
- It has a finite probability to tunnel through the coulombic barrier
- Considering the height of the potential barrier the half life of the decay can be derived.

Nuclear Fission

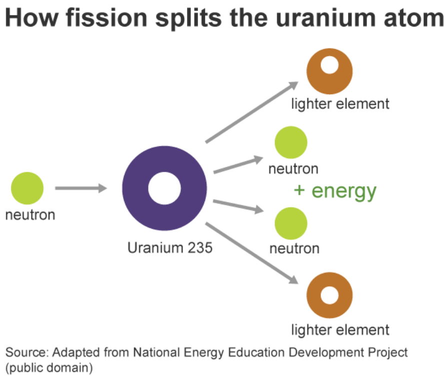
- An unstable Nucleus splits into two or more smaller nuclei
- Its a different process compared to quantum tunneling processes like alpha decay or proton emission.
- Fission can either be spontaneous or induced(shooting neutrons for eg.)



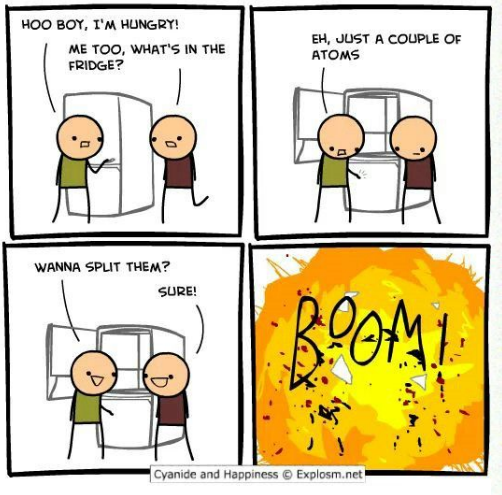
How it Occurs

- Requires some amount of initial energy that can overcome the nuclear force and deform the nucleus
- The electromagnetic repulsion takes over after some critical separation length

Nuclear Fission



Fission


HOO BOY, I'M HUNGRY!
ME TOO, WHAT'S IN THE FRIDGE?
EH, JUST A COUPLE OF ATOMS
WANNA SPLIT THEM?
SURE!
BOOM!
Cyanide and Happiness © Explosm.net

The End

Of course, we are not experts, but okay