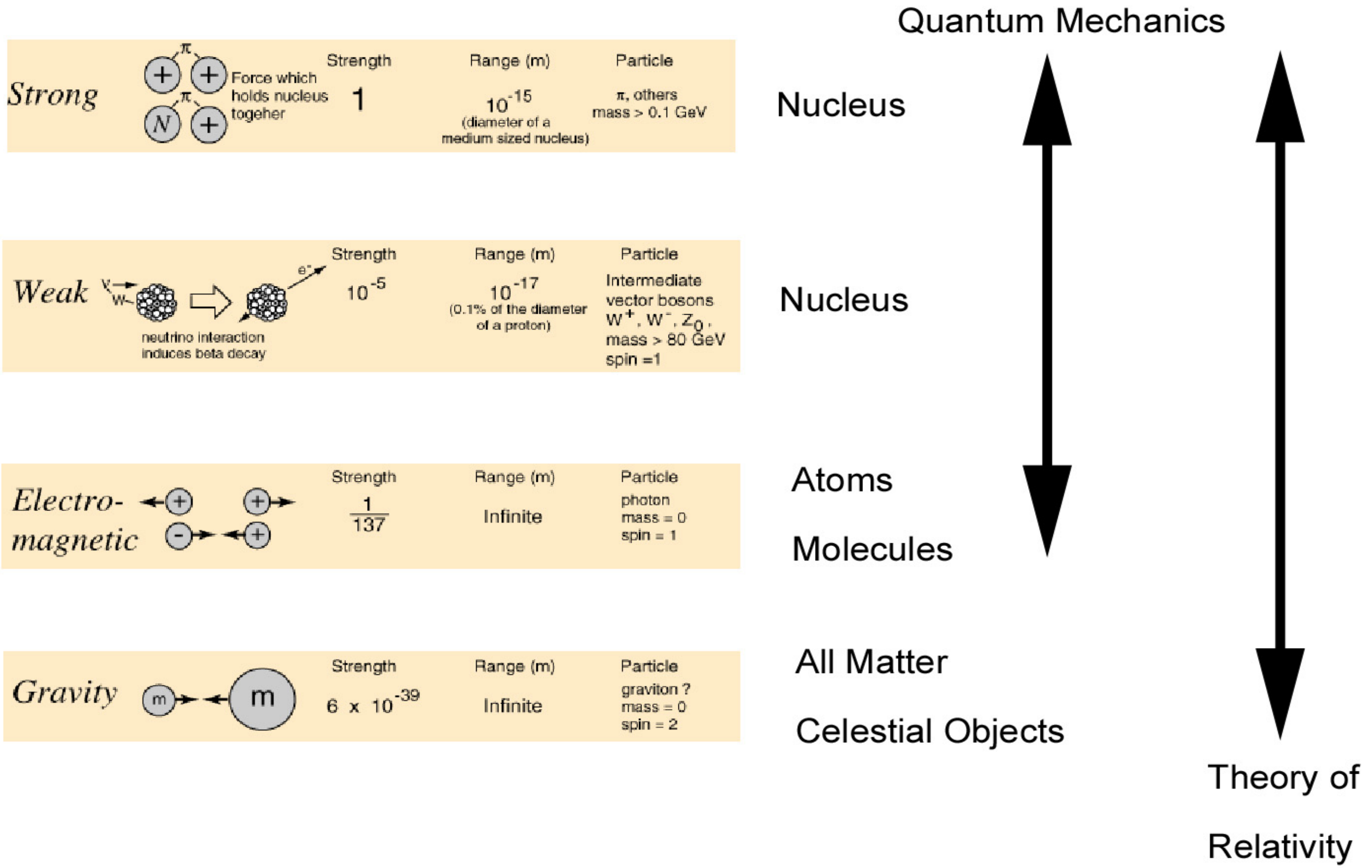
Fundamental Forces of Nature



		Strength	Range (m)	Particle	
Strong	Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	π, others mass > 0.1 GeV	Nucleus
Weak	neutrino interaction induces beta decay	10^{-5}	10^{-17} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1	Nucleus
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1	Atoms Molecules
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2	All Matter Celestial Objects

Quantum Mechanics

Theory of

Relativity

Nuclear Physics

Nuclear Physics comprises the study of:

- The general properties of nuclei
- The particles contained in the nucleus
- The interaction between these particles
- Radioactivity and nuclear reactions
- Practical applications of nuclear phenomena:
    - Medical radio-isotopes (imaging & therapy)
    - Magnetic Resonance Imaging (MRI)
    - Identification of materials (NAA, AMS)
    - Dating of materials
    - Power generation (fusion and fission)
    - Weapons of mass destruction (WMD)

Properties of Nuclei

Every atom contains at its center an extremely dense, positively charged nucleus, which is much smaller than the overall size of the atom, but contains most of its total mass.

The nucleus is made of protons and neutrons
  Protons have positive electric charge
  Neutrons have no electrical charge

$$^{16}_{8}\mathrm{O} \equiv {}^{A}_{Z}\mathrm{O}$$

Z = number of protons (atomic number)
N = number of neutrons
A = Z+N (mass number)

Isotopes of an element have the same number of protons but different number of neutrons. Isotopes have similar chemical properties, and different physical properties.

Isotope	**A**	**Z**	**N**	**Atomic Mass (u)**	**Abundance**
${}^{12}_{6}C$	12	6	6	12.000000	98.90%
${}^{13}_{6}C$	13	6	7	13.003355	1.10%

[The chemical atomic weight of carbon is 12.011 u]

Isotope	**A**	**Z**	**N**	**Atomic Mass (u)**	**Abundance**
${}^{14}_{6}C$	14	6	8	14.003242	Radioactive

[${}^{14}_{6}C$ decays by β^- emission with Half-Life 5730 y]

Nuclear Size and Mass

The radii of most nuclei is given by the equation:

$$R = R_0 \, A^{1/3}$$

R: radius of the nucleus, A: mass number, $R_0 = 1.2\text{x}10^{-15}$ m

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The mass of a nucleus is given by:

$$m = A\,u$$

$u = 1.66\ldots\text{x}10^{-27}$ kg (unified mass unit)

Nuclear Density

${}^{56}_{26}\mathrm{Fe}$ is the most abundant isotope of iron (91.7%)

$$R = 1.2\mathrm{x}10^{-15}\ \mathrm{m}\ (56)^{1/3} = 4.6\mathrm{x}10^{-15}\ \mathrm{m}$$

[Compare with inter-atomic separations $\approx 0.1\mathrm{x}10^{-9} - 0.3\mathrm{x}10^{-9}$ m]

$$V = 4/3\ \pi\ R^3 = 4.1\mathrm{x}10^{-43}\ \mathrm{m}^3$$

$$m = (56)\ 1.66\mathrm{x}10^{-27}\ \mathrm{kg} = 9.3\mathrm{x}10^{-26}\ \mathrm{kg}$$

$$\rho = m / V = 2.3\mathrm{x}10^{17}\ \mathrm{kg/m}^3$$

[Compare with the density of solid iron $\approx 7\mathrm{x}10^3\ \mathrm{kg/m}^3$]

Since: $m = A\ u$ and $R = R_0\ A^{1/3}$

$$\rho = m / V = u / (4/3\ \pi\ R_0^{\ 3}) \approx \text{constant}$$

All nuclei have approximately the same density

Nuclear Binding Energy

The total rest energy of the separated nucleons is greater than the rest energy of the nucleus.

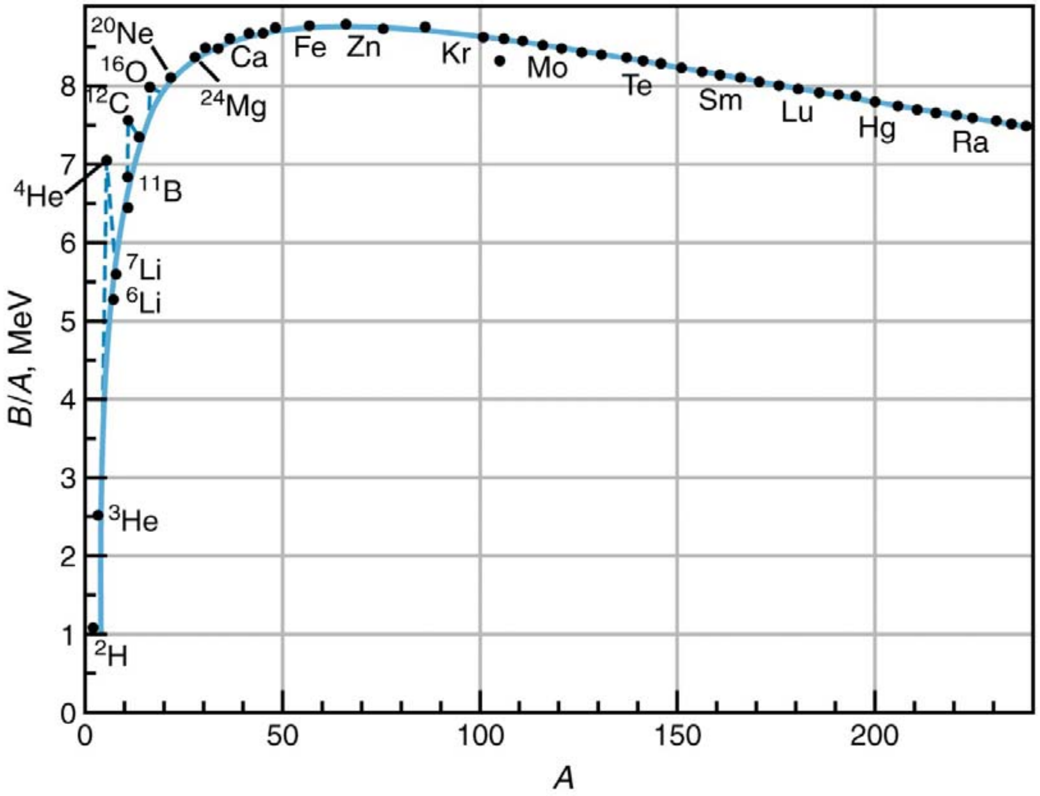
The difference is called the **Binding Energy E_B**

E_B is a measure of the energy gained in forming the nucleus from the individual nucleons

$$\boxed{E_B = (Z\, M_H + N\, m_N - {}^{A}_{Z}M)\, c^2}$$

Note that ${}^{A}_{Z}M$ is the mass of the neutral atom containing the nucleus, and M_H refers to the mass of hydrogen (to balance the Z electrons contained in ${}^{A}_{Z}M$)

Binding Energy per Nucleon



The binding energy per nucleon E_B/A is nearly constant as a function of A, suggesting that the nuclear force is saturated (a nucleon interacts only with its nearest neighbors).

The Nuclear Force

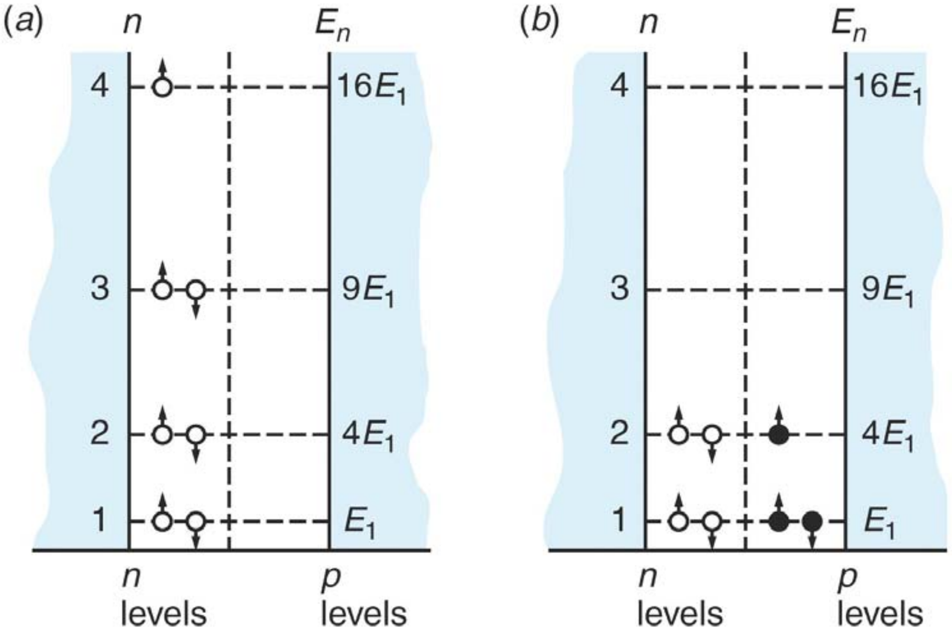
The force that binds together protons and neutrons inside the nucleus is called the **Nuclear Force**

Some characteristics of the nuclear force are:

- It does not depend on charge
- It is very short range ≈ 10^{-15} m
- It is much stronger than the electric force
- It is saturated (nucleons interact only with near neighbors)
- It favors formation of pairs of nucleons with opposite spins

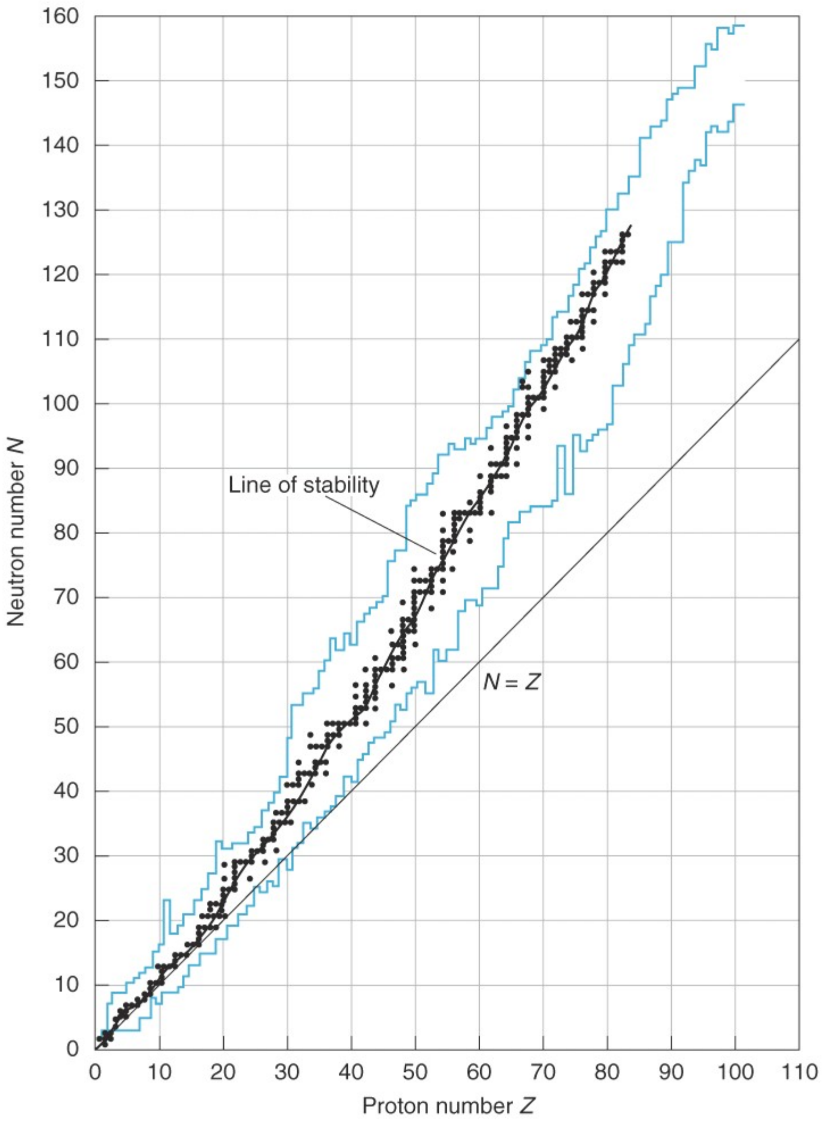
We do not have a simple equation to describe the nuclear force

Nuclear Stability



The energy of a group of nucleons in a square well (a reasonable first approximation to a nucleus) is smaller if $Z \cong N$. For large values of A we need $N \geq Z$ to compensate for the electric force

Nuclear Stability



Plot of N vs. Z for known nuclides.

The stable nuclides are indicated by the black dots.

Non-stable nuclides decay by emission of particles, or electromagnetic radiation, in a process called **radioactivity**

Radioactivity

Alpha Decay: nuclei that are too large to be stable tend to decay by alpha decay, the emission of an alpha particle.

[An alpha particle is the ^{4}He nucleus, two protons and two neutrons]

$$^{238}{}_{92}\mathrm{U} \rightarrow {}^{234}{}_{90}\mathrm{Th} + \alpha$$

Gamma Decay: the energy of internal motion (protons and neutrons in a nucleus is quantized. A nucleus has a set of allowed energy states (ground state and excited states) much like in an atom. Transitions between states lead to the emission of very energetic electromagnetic radiation called γ (gamma) rays

$$^{238}{}_{92}\mathrm{U}^* \rightarrow {}^{238}{}_{92}\mathrm{U} + \gamma$$

Radioactivity

Beta Decay: consist in a) the emission of an electron β^- , b) the emission of a positron β^+, or c) electron capture.

a) Nuclides with neutron to proton ratio too large for stability tend to decay by conversion of a neutron into a proton, an electron and an antineutrino: $n \rightarrow p + \beta^- + \underline{\nu}$

b) Nuclides with proton to neutron ratio too large for stability tend to decay by conversion of a proton into a neutron, a positron, and a neutrino: $p \rightarrow n + \beta^+ + \nu$

c) In certain cases an orbital electron can combine with a proton in the nucleus to form a neutron and a neutrino:

$$p + \beta^- \rightarrow n + \nu$$

Radioactivity

Radioactive decay is a statistical process. There is now way to predict when an individual nucleus will decay. However, it is possible to predict the decay rate of a group of nuclei.

If the initial number of radioactive nuclei at time $t = 0$ is N_0, then the number of remaining nuclei at time t is given by:

$$\boxed{N(t) = N_0 \exp(-\lambda t)}$$

The constant λ is called the decay constant and can be interpreted as the probability per unit time that a nucleus will decay

Radioactivity

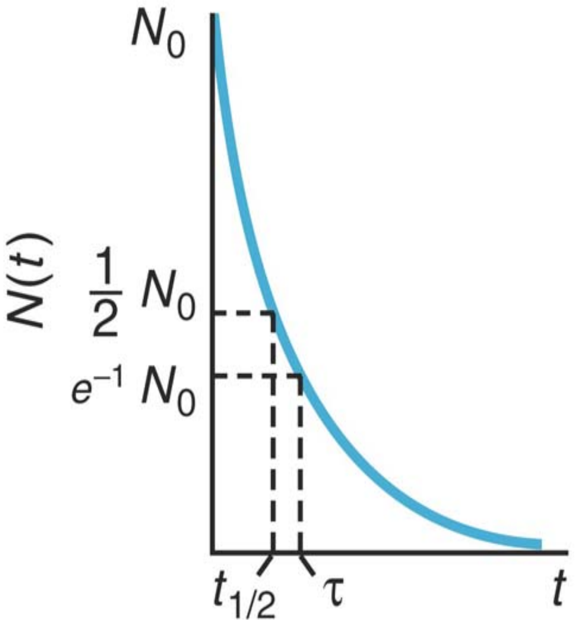
The Half-Life $T_{1/2}$ is the time required for the number of radioactive nuclei to decrease to half the initial value N_0

$$N_0/2 = N_0 \exp(-\lambda T_{1/2}) \Rightarrow T_{1/2} = \ln 2 / \lambda$$

The mean lifetime T_{mean}, or lifetime, is the time required for the number of radioactive nuclei to decrease to 1/e of the initial value N_0

$$\lambda T_{mean} = 1 \Rightarrow T_{mean} = 1 / \lambda$$

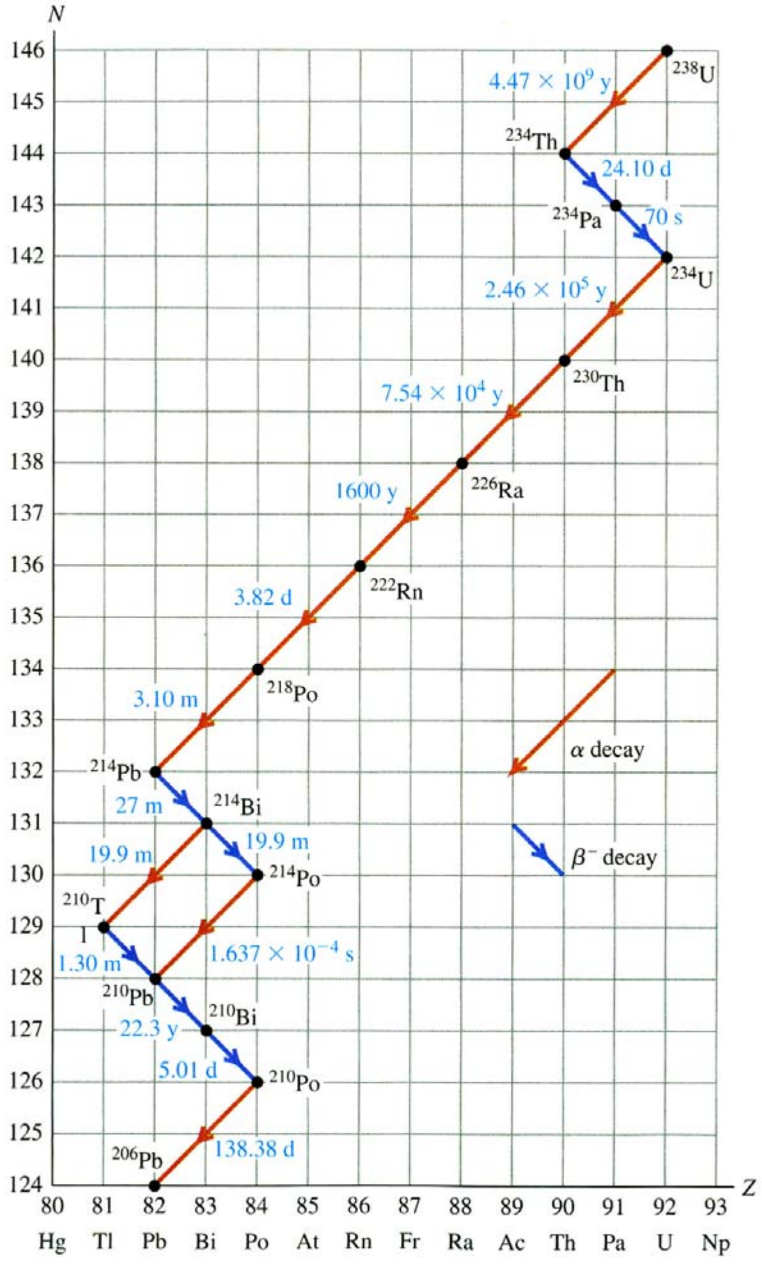
The number of decays per unit time dN/dt is the activity of a sample, and is measured in Curie (Ci) ⇒ 1 Ci = 3.7×10^{10} decays/second



$$t_{1/2} \equiv T_{1/2}$$

$$\tau \equiv T_{mean}$$

^{238}U decay series



^{14}C Dating

Radioactive ^{14}C is continuously produced in the atmosphere [$^{14}N(n,p)^{14}C$, the neutrons being produced by cosmic rays].

^{14}C decays by β^- emission with half life $T_{1/2} = 5730$ y

$$^{14}C \rightarrow {}^{14}N + \beta^- + \underline{\nu}$$

The chemical activity of ^{14}C is similar to that of ^{12}C, so living organisms have the same $^{14}C/^{12}C$ ratio as in the atmosphere, which is about 1.35×10^{-12}.

When an organism dies it stops absorbing ^{14}C, and the ratio $^{14}C/^{12}C$ decreases. Measurement of this ratio allows the calculation of the time of death of the organism.

Nuclear Reactions

A nuclear reaction is a rearrangement of nuclear components induced by particle bombardment

$$^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$$

$$^{14}_{7}\mathrm{N}(\alpha,\mathrm{p})^{17}_{8}\mathrm{O}$$

Nuclear reactions are subject to the following conservation laws:

Charge
Momentum and angular momentum
Energy
Total number of nucleons

Nuclear Reactions

Some nuclear reactions release energy, while other reactions require input energy to proceed

The amount of energy released or absorbed in a nuclear reaction (in the center of mass reference frame) is called the **Q value**, or **reaction energy**:

In a reaction: $M_A + M_B \rightarrow M_C + M_D$

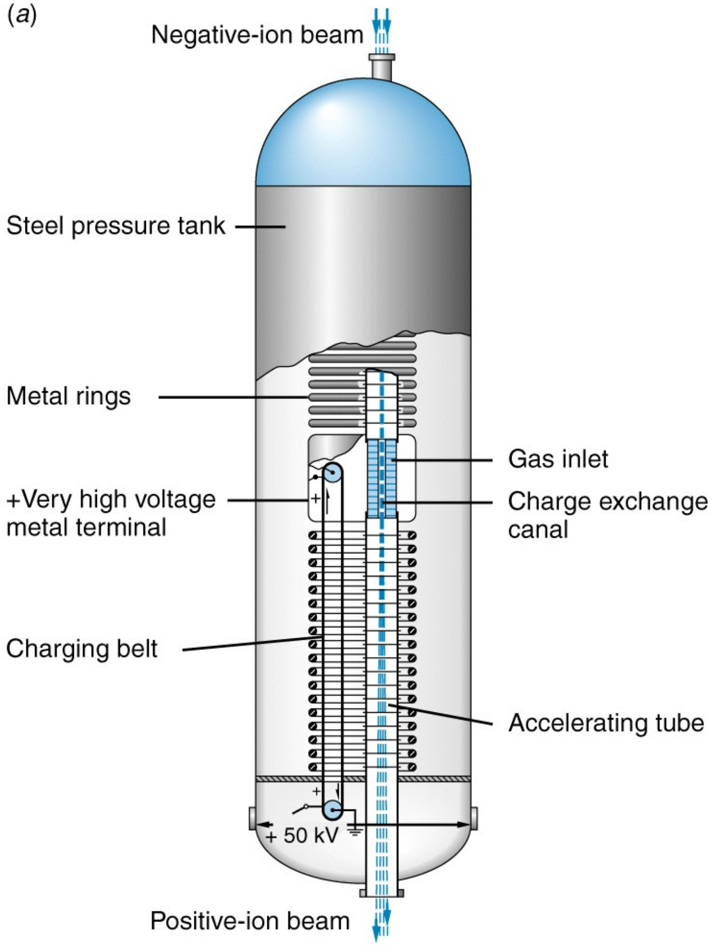
$$\boxed{Q = (M_A + M_B - M_C - M_D)\, c^2}$$

If $M_A + M_B > M_C + M_D \rightarrow Q > 0 \equiv$ exoergic reaction

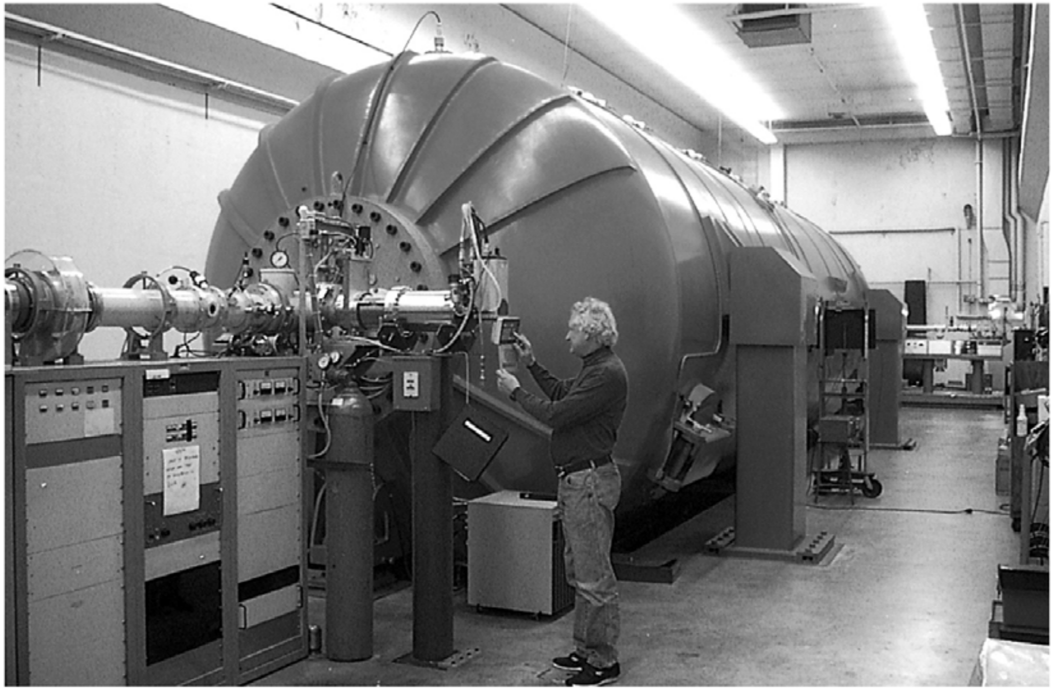
If $M_A + M_B < M_C + M_D \rightarrow Q < 0 \equiv$ endoergic reaction

An endoergic reaction will not proceed unless the incoming particle provides the reaction energy Q (in CM)

Particle Induced Nuclear Reactions: are used mostly for nuclear physics research, and for analytical purposes



The reaction $^7Li(p,\alpha)^4He$ can be used to detect Li in solids [1-2 MeV protons]



Neutron Induced Nuclear Reactions

Nuclear reactions induced by neutron bombardment are used:

a) In analytical techniques such as **neutron activation analysis**
b) In the generation of energy by **Fission** or **Fusion**

It is convenient to distinguish between fast and slow neutrons

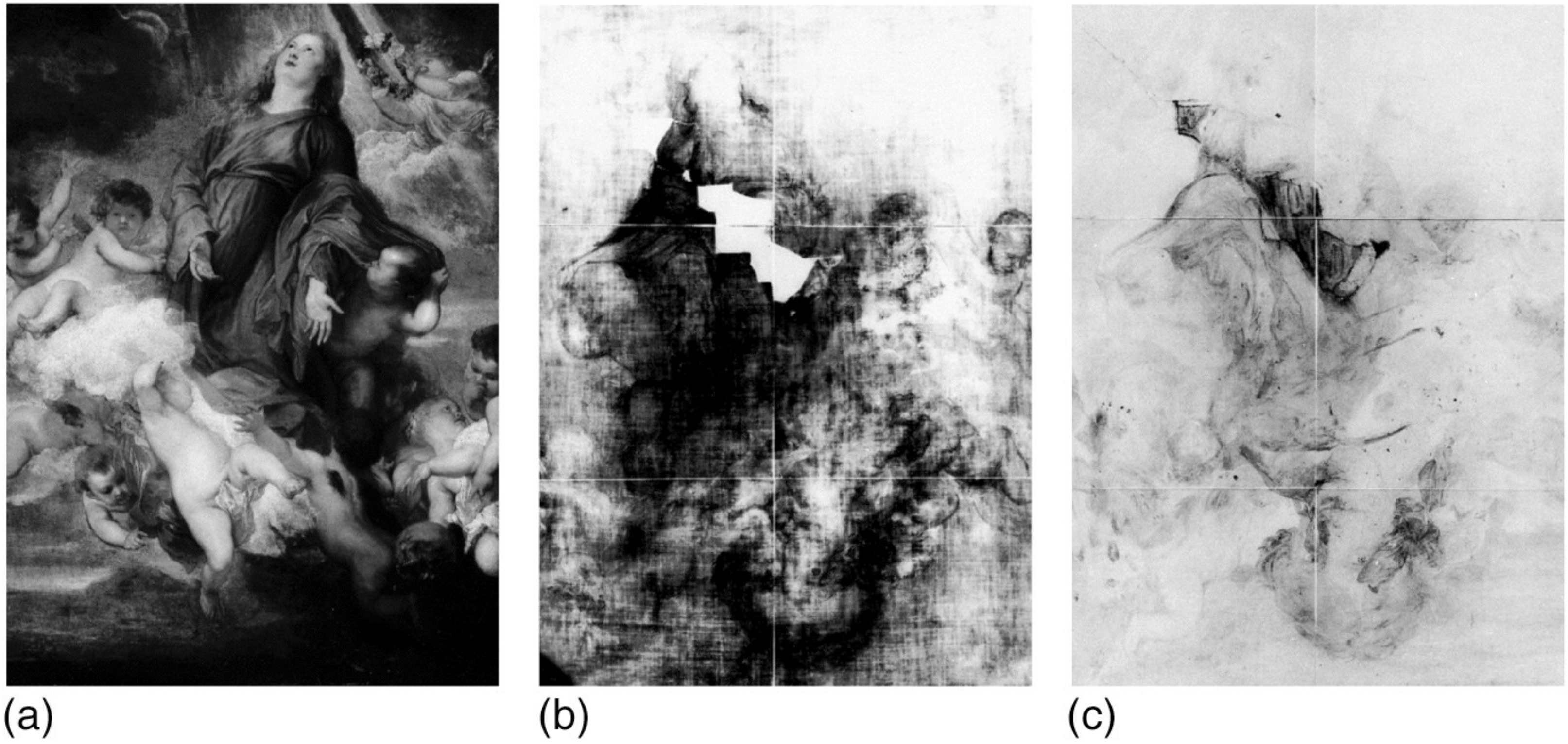
Fast neutron → kinetic energy ≥ 1 MeV
Slow neutron or thermal neutron → kinetic energy ~ 0.025 eV

The probability for a reaction to proceed or **Cross Section** depends strongly on the energy of the neutrons

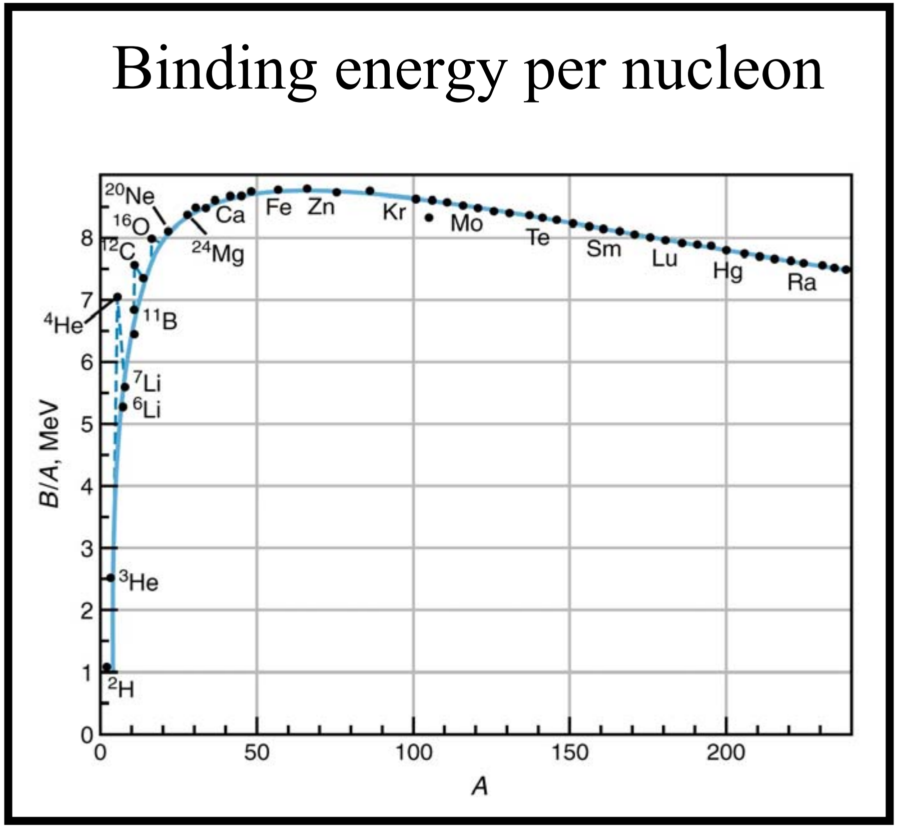
Neutron Activation Analysis

Low energy neutrons are likely to be captured by nuclei, with emission of radiation from the excited nucleus, as in X(n,γ)Y. The emitted radiation is a signature for the presence of element X

Various layers of a painting are revealed using NAA



Fission and Fusion



Binding energy per nucleon

The binding energy per nucleon peaks for A ~ 70, then:

a) splitting a large mass nucleus into two medium mass nuclei (fission), or

b) fusing two low mass nuclei into a larger mass nucleus (fusion)

result in the release of energy.

Fission

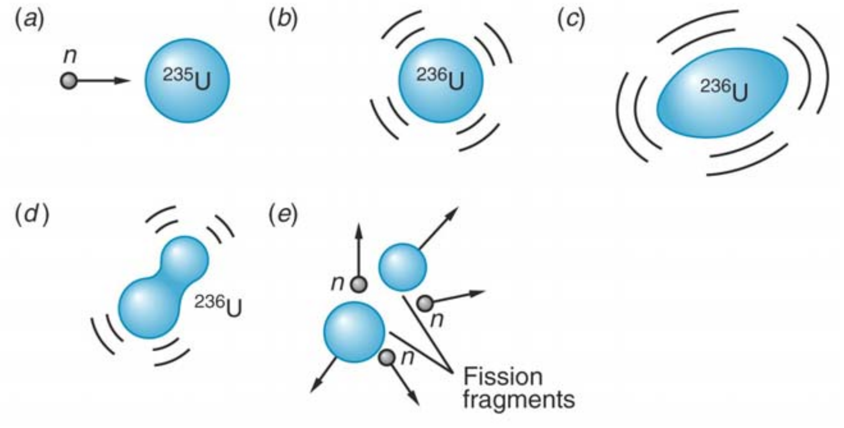
Uranium has two main isotopes:

^{238}U with an abundance of 99.3%

^{235}U with an abundance of 0.7%

When ^{235}U captures a thermal, or low energy, neutron it forms ^{236}U that decays by undergoing fission (85% of the time)

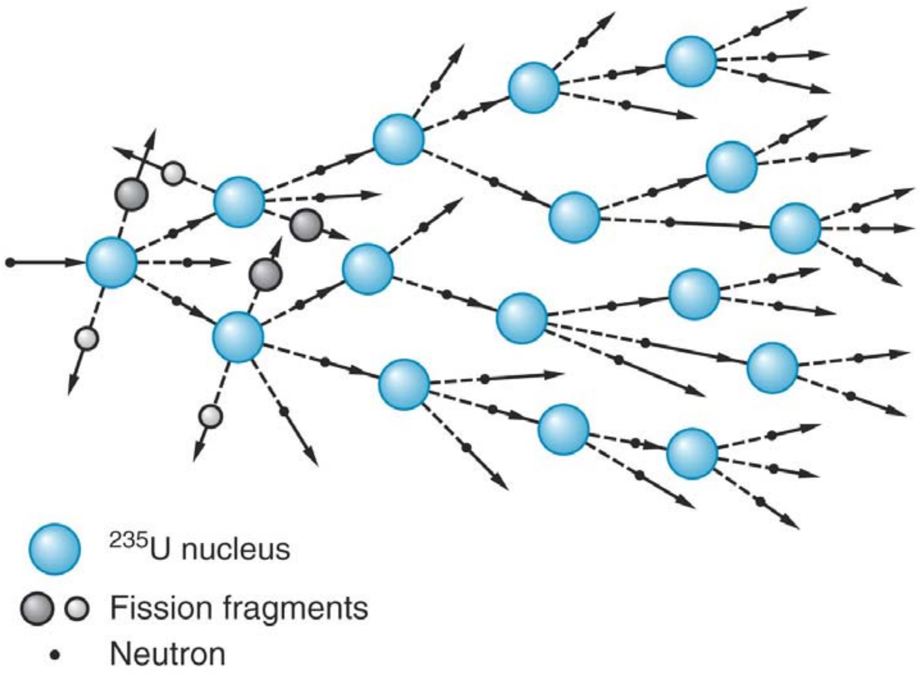
$$n + {}^{235}\mathrm{U} \rightarrow {}^{141}\mathrm{Ba} + {}^{92}\mathrm{Kr} + 3n$$



There is about 1 MeV per nucleon higher binding energy in the products of the reaction than in the Uranium. As a consequence, more that 200 MeV of energy are liberated in this reaction.

Furthermore, the emitted neutrons can induce additional fission

Chain Fission Reaction

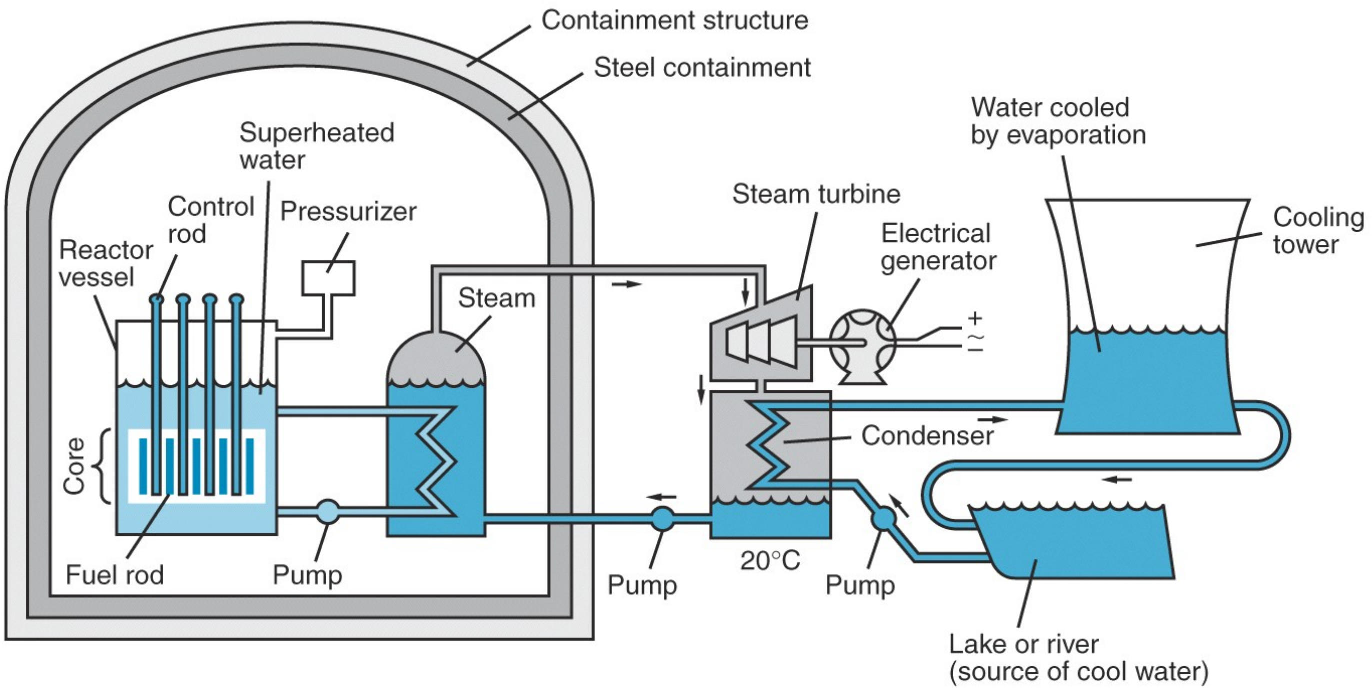


To sustain a chain reaction one of the emitted neutrons must be captured by another ^{235}U nucleus

The **reproduction constant k** is the average number of neutrons from each fission that cause subsequent fission

$k < 1 \rightarrow$ the reaction will die out
$k \approx 1 \rightarrow$ the reaction will be sustained (nuclear reactor)
$k > 1 \rightarrow$ the reaction will run away (nuclear bomb)

Nuclear Fission Reactor



Fission of ^{235}U is most likely for low energy neutrons. The neutrons emitted in fission are more energetic so they need to be slowed down by means of a moderator (water, graphite) placed in between the fuel rods. Control rods, of Cadmium or other materials, are further used to regulate the number of fission inducing neutrons

Fusion

In fusion, two light nuclei such as deuterium ^{2}H and tritium ^{3}H fuse together to form a heavier nucleus:

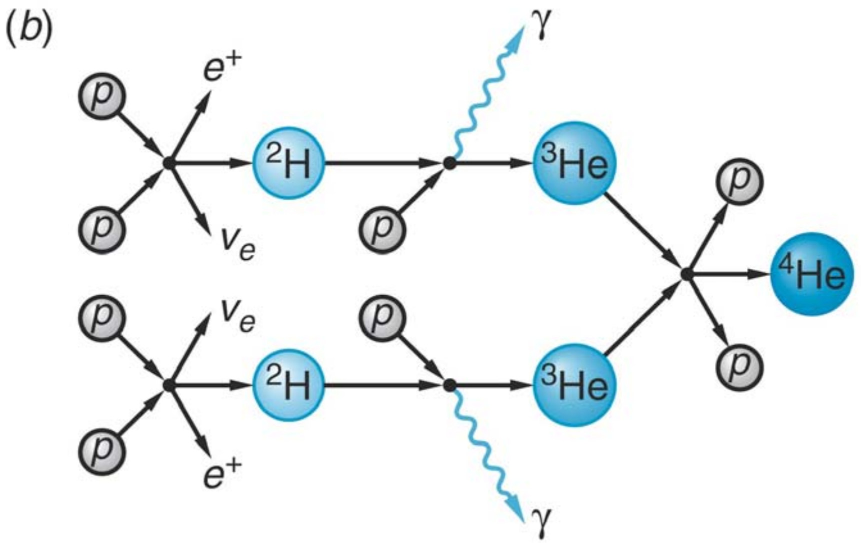
$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV}$$

The energy released per nucleon is larger than that released in fission

The production of power from fusion of light nuclei holds great promise because of the relative abundance of fuel, and the absence of some of the dangers inherent in fission.

However, the technology necessary to make fusion practical, has not been developed yet.

Fusion



The proton – proton cycle, resulting in the formation of ^{4}He, and the release of considerable energy, is the primary source of the sun's energy

In practice it is very difficult to generate the necessary density of super-hot gas (T > 10^7 K - plasma), and keep it confined, to facilitate the fusion process.