NUCLEAR SCIENCE

Dr. Dipika Patel
Assistant Professor
Department of Physics
SVNIT, Surat, Gujarat

PH – 113 B. Tech. (Division H – O)
S2: Physics of Materials and Nuclei (PMN)

- CRYSTALLOGRAPHY : Crystalline and amorphous solids, Lattice and unit cell, Seven crystal system and Bravais lattices, Symmetry operation, Miller indices, Atomic radius, Coordination number, Packing factor calculation for SC, BCC, FCC, Bragg’s law of X-ray diffraction, Laue Method, Powder crystal method.

- SEMICONDUCTOR PHYSICS : Introduction, Direct and indirect band gap semiconductors, Intrinsic and extrinsic semiconductors, Law of Mass action, Charge neutrality, Hall effect.

- NANOMATERIALS : Introduction and properties, Synthesis: Chemical vapour deposition, Ball milling and relevant applications, Carbon nanotubes: structure and properties and Synthesis: Arc method and Pulsed laser deposition, Applications.

- MAGNETIC MATERIALS, CONDUCTORS AND SUPERCONDUCTORS : Magnetic materials: Definition of terms, Classification of magnetic materials and properties, Domain theory of ferromagnetism, Hard and soft magnetic materials, Conductors: Classical free electron theory (Lorentz–Drude theory), Electrical conductivity, Superconductors: Definition, Meissner effect, Type I & II superconductors.

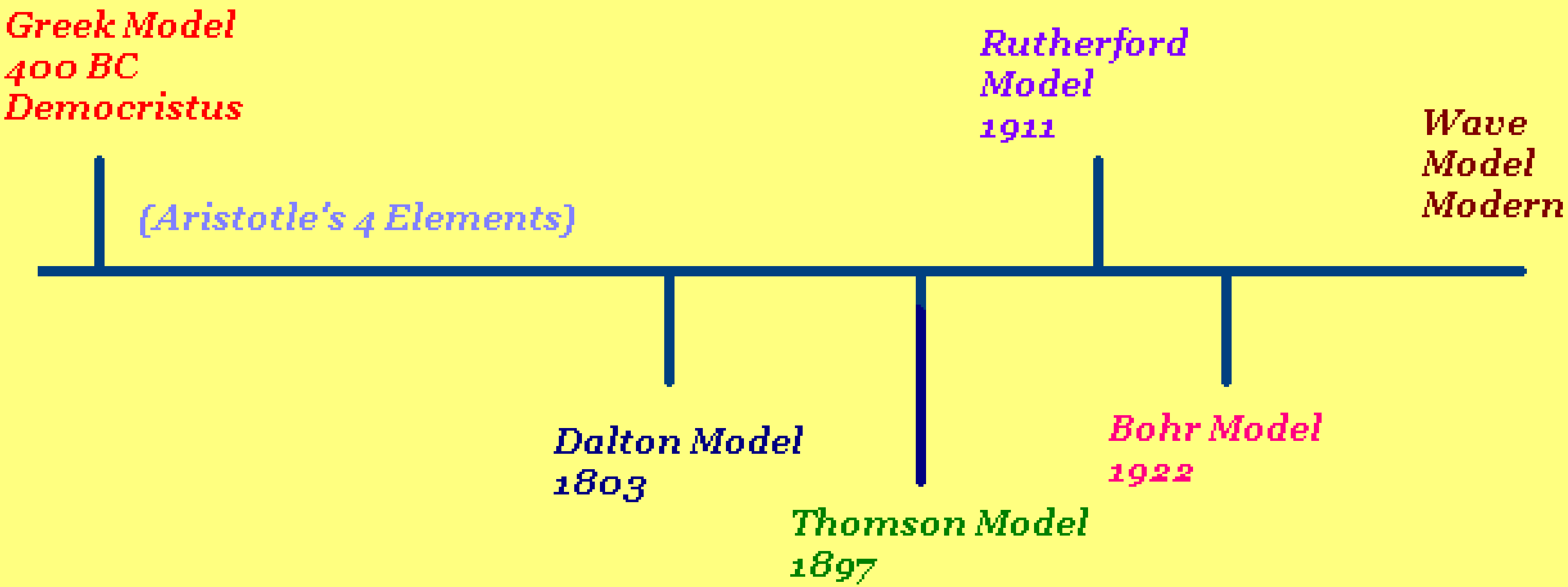
- STATISTICAL MECHANICS : Macroscopic and microscopic states, Phase space, Condition for statistical equilibrium, Micro-canonical ensemble, canonical ensemble, Grand-canonical ensemble, Partition function, Bose-Einstein and Fermi-Dirac distribution.

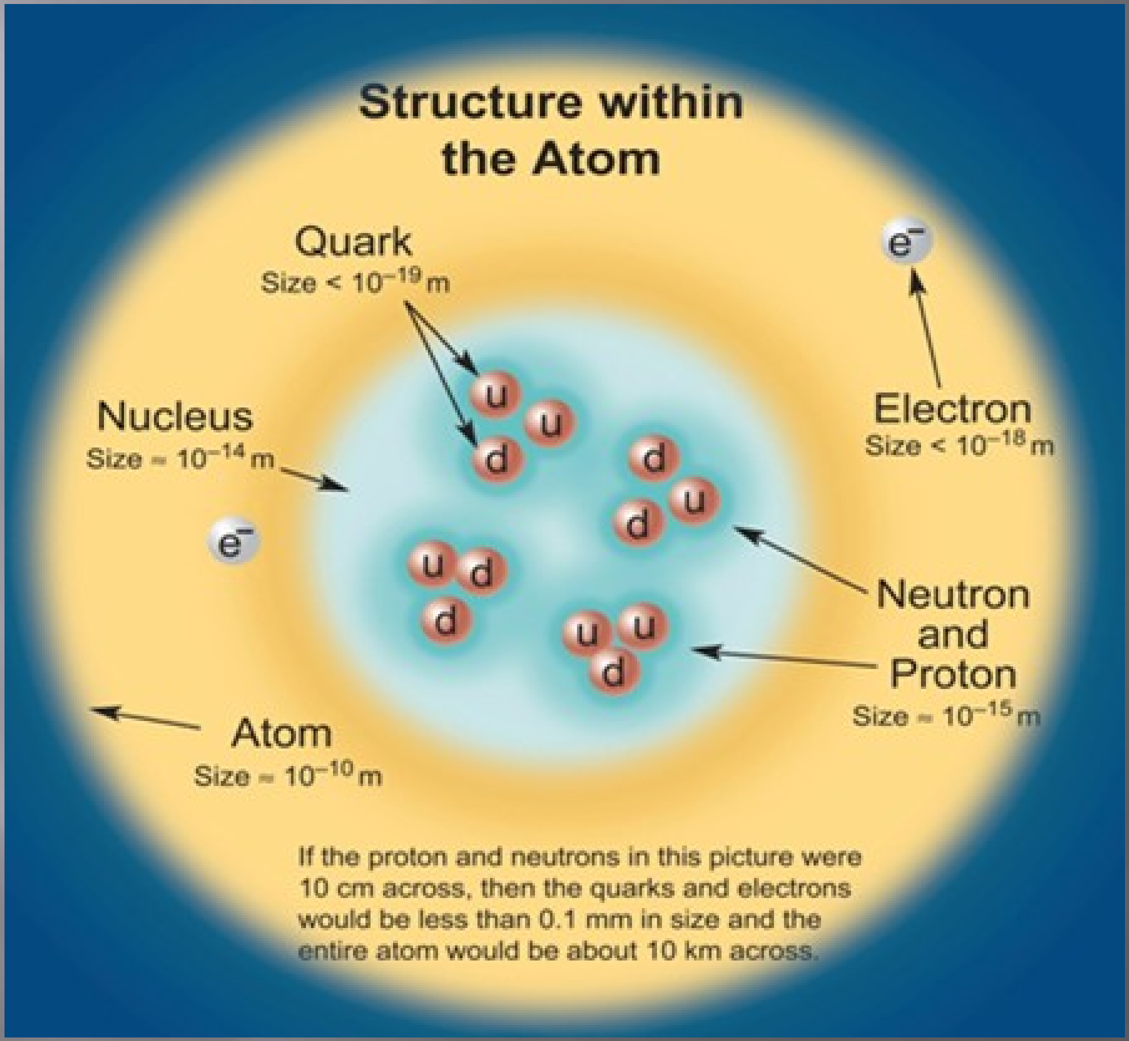
- NUCLEAR AND PARTICLE PHYSICS : Nuclear properties and forces, Nuclear models, Shell model, Nuclear reaction, Radioactivity, Types and half-lives, Application in determining the age of rock and fossils, Stellar nucleosynthesis, Fundamental forces, Particle physics, Classification of matter, Quark model, Neutrino properties and their detection.

Reference book : Concept of modern physics by Arthur Beiser (6^{th} Adition, Tata McGraw-Hill)
(Chapter -11, 12 and 13)

Atomic Theory

Timeline of Atomic Theory




Structure within the Atom
Quark
Size < 10^{-19} m
Nucleus
Size ≈ 10^{-14} m
Electron
Size < 10^{-18} m
e⁻
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

What is Nuclear Science?

Nuclear science: study of structure, properties, and interactions of atomic nuclei at fundamental level.

nucleus – contains almost all mass of ordinary matter in a tiny volume

understanding behavior of nuclear matter under normal conditions

and conditions far from normal a major challenge extreme conditions existed in the early universe, exist now in the core of stars, and can be created in the laboratory during collisions between nuclei

Nuclear scientists investigate by measuring the properties, shapes, and decays of nuclei at rest and in collisions.

=> properties of the nucleus

Interactions

- Electromagnetic

e^- (lepton) bound in the atoms by the electromagnetic force

- Weak interaction

Neutrino observed in beta decay.

- Strong interaction

Quarks are bound in together by the strong force in nucleons. Nuclear forces bind nucleons into nuclei.

- Gravitation

Gravitational interaction between the elementary particles is in practice very small compared to the other three.

Fundamental forces

1. Strong force (also known as strong nuclear force:)

The strong interaction is very strong, but very short-ranged (order is 10^{-15} m). It is responsible for holding the nuclei of atoms together. It is basically attractive, but can be effectively repulsive in some circumstances. Mesons are the force carrier for it in case of nucleon (ie protons and neutrons) and Gluons are the force carrier in the case of quarks.

2. Electro-magnetic force:

The electromagnetic force causes electric and magnetic effects such as the repulsion between like electrical charges or the interaction of bar magnets. It is long-ranged, but much weaker than the strong force. It can be attractive or repulsive, and acts only between pieces of matter carrying electrical charge. Electricity, magnetism, and light are all produced by this force. Relative strength is in the order of 0.01. Time frame for this is 10^{-16} to 10^{-21} sec. All conservation rule are obeyed except the isospin. Charge is responsible for this force. Photons are the force carriers.

3. Weak force:

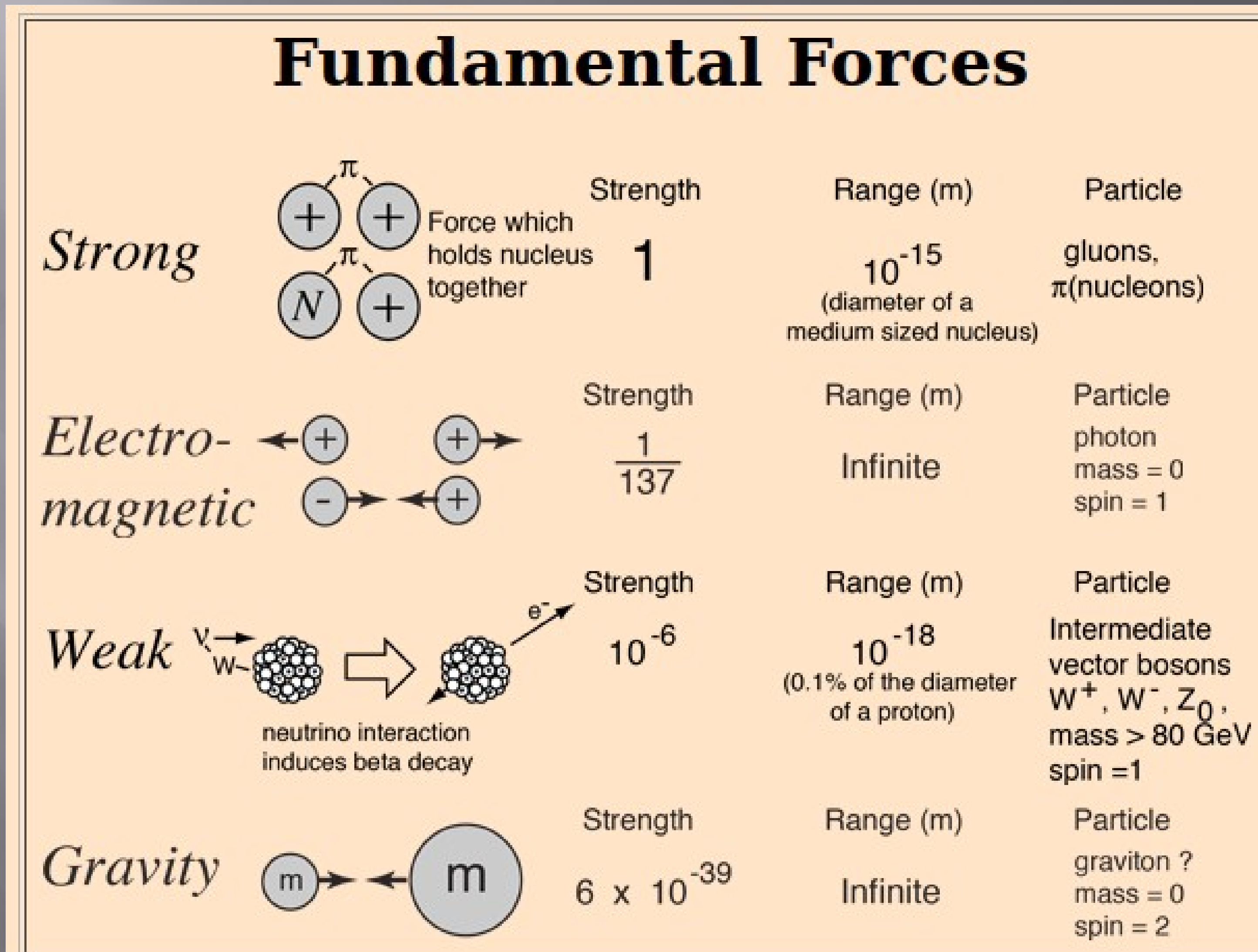
The weak force is responsible for radioactive decay and neutrino interactions. It has a very short range and. As its name indicates, it is very weak. The weak force causes Beta decay ie. the conversion of a neutron into a proton, an electron and an antineutrino. Relative strength is in the order of 10^{-10}. Time frame for interaction is 10^{-7} to 10^{-10} sec. Many conservation rule is violated. Spin is responsible for this force. Vector bosons (Z^0,W^+,W^-) are the force carriers.

4. Gravitational force:

The gravitational force is weak, but very long ranged. Furthermore, it is always attractive. It acts between any two pieces of matter in the Universe since mass is is responsible for this force. Relative strength is 10^{-40}. Force is mediated by a hypothetical graviton (a spin 2 particle).

Interactions

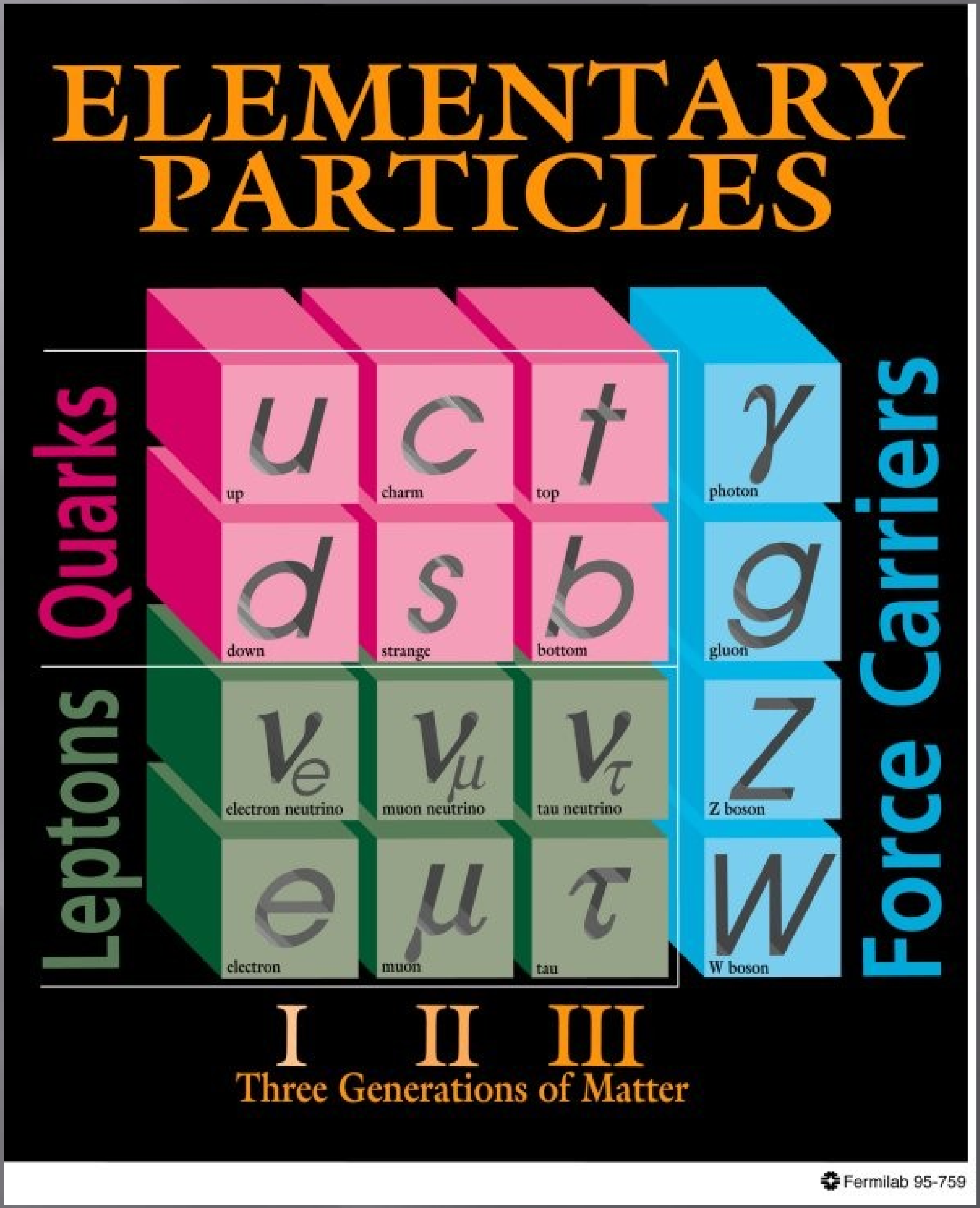
The forces of elementary particle physics are associated with the exchange of particles. An interaction between particles is characterized by both its strength and its range.



Standard Model

- Attempts to explain all phenomena of particle physics in terms of properties and interactions of a small number of three distinct types.
- Leptons: spin-1/2
- Quarks: spin-1/2
- Bosons: spin-1; force carriers

These are assumed to be elementary.



ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I II III
Three Generations of Matter
Fermilab 95-759

Hadrons

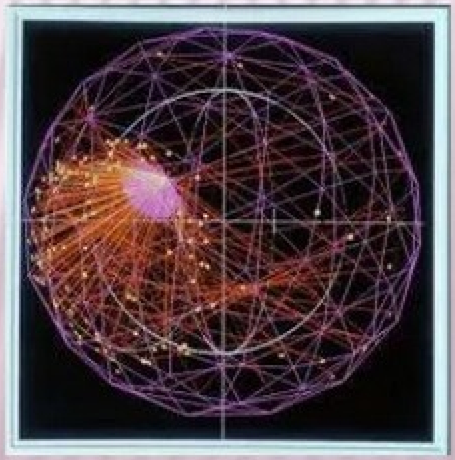
Hadrons: any strongly interacting subatomic particle; composed of quarks.

There are 2 categories:

- Baryons: fermions, make of 3 quarks
- Mesons: bosons, made of quark, antiquark

WHAT IS NEUTRINO?

- Neutrinos are a kind of elementary particle
- It has no electric charge , so they are not affected by electromagnetic forces.
- They are much lighter than the electrons
- They are represented by (ν)

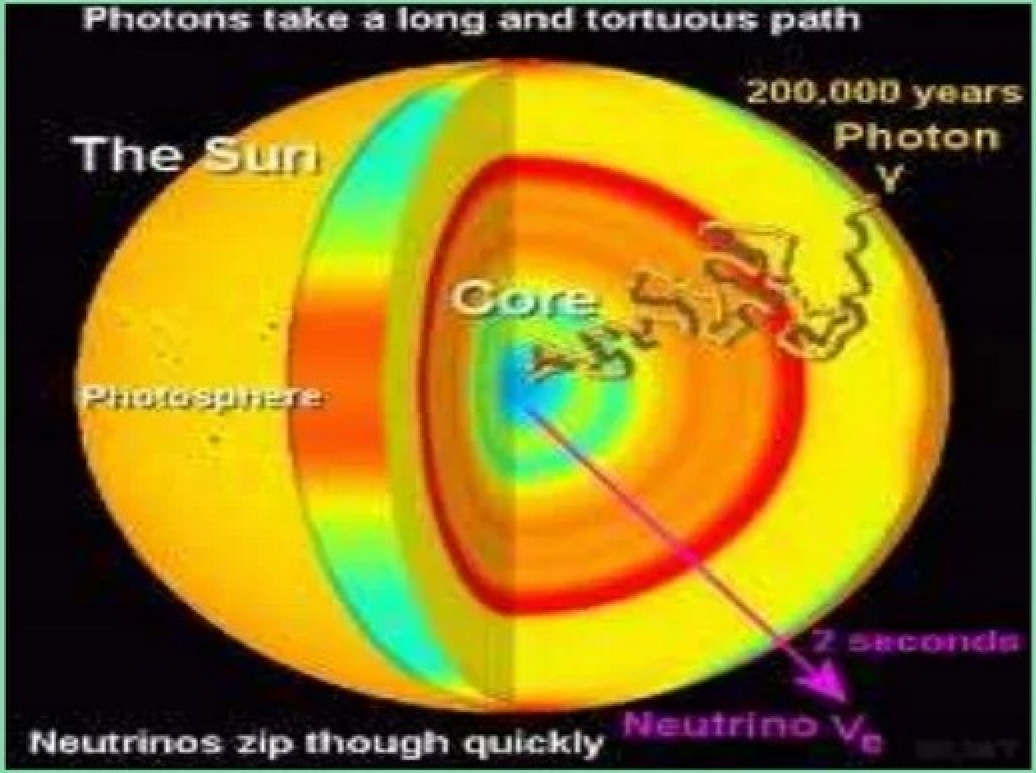


Kinds of neutrinos

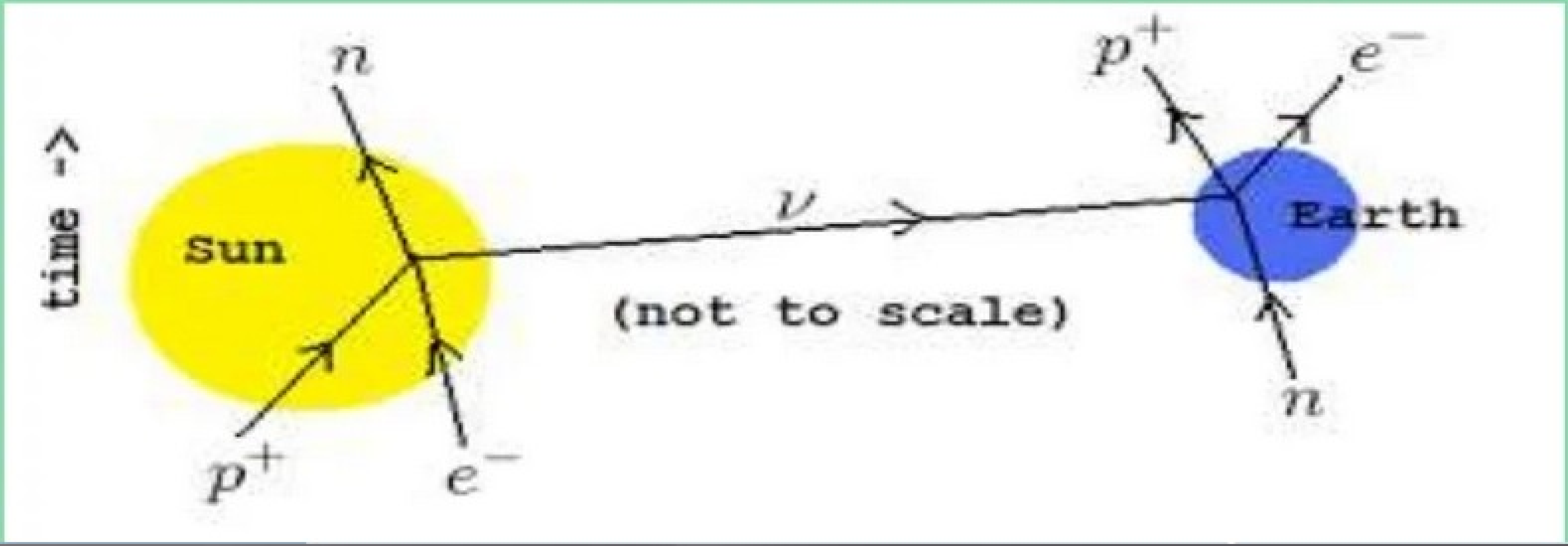
- Currently there are 3 types of neutrinos
- One type is related to the electron ,and one related to Muon , another one related to Tau.
- Neutrinos are electrically neutral while the electrons , muon and tau are electrically charged.

WHERE NEUTRINOS ARE PRODUCED?

- Neutrinos are abundantly found in nature
- The sun , the stars and the atmosphere produce millions of neutrinos every second.
- They can also be produced artificially.
- They are produced in radioactive decays (Beta decay) and in nuclear reactors.

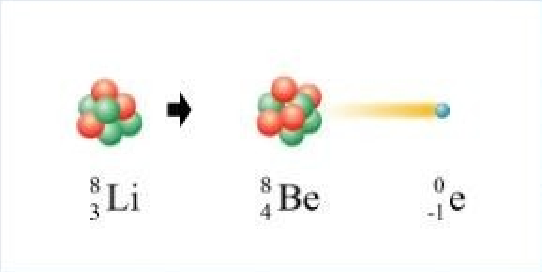


Photons take a long and tortuous path
200,000 years
Photon
γ
The Sun
Core
Photosphere
7 seconds
Neutrinos zip though quickly
Neutrino ν_e

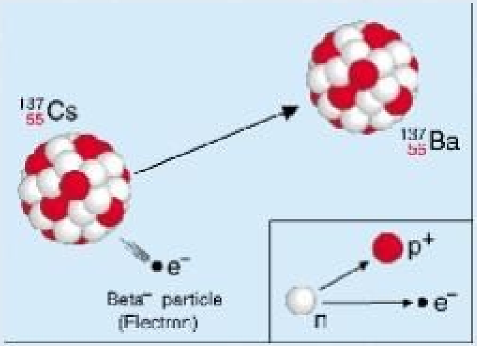


time ->
n
p^+
e^-
Sun
ν
(not to scale)
Earth
p^+
e^-
n

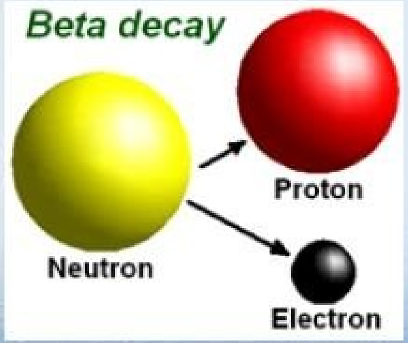
1. Beta decay – experimental results



- radioactive decay
- nucleus emits electron or positron (β^- or β^+ particle)

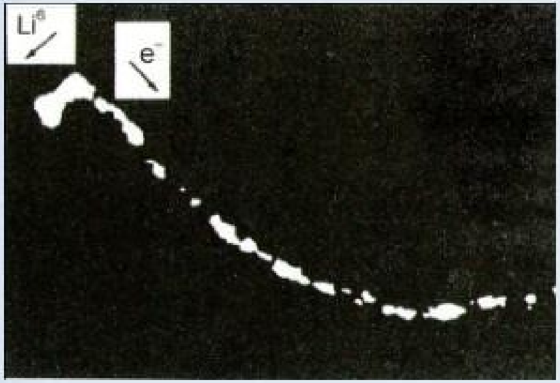


- mass of nucleus nearly constant → nucleon reaction:
- β^- decay: $^1_0n \rightarrow ^1_1p + ^0_{-1}e$
- (β^+ decay: $^1_1p \rightarrow ^1_0n + ^0_1e$)



1. Beta decay – experimental results

- beta decay was observed closer
- cloud chambers showed curious results



- $^{6}_{2}He \rightarrow {}^{6}_{3}Li + {}^{0}_{-1}\beta$
- anticipated: $\vec{p}_{Li} = -\vec{p}_{e^-}$
- but both objects in the **<u>same half room</u>**

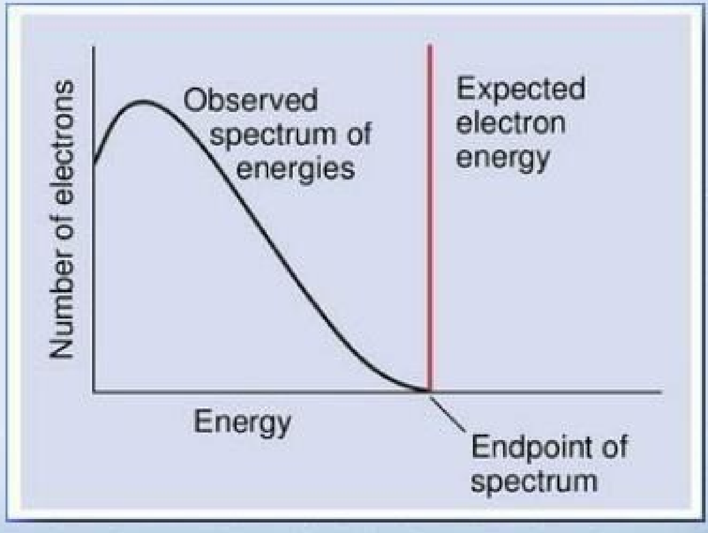
→**<u>disagreement with conservation of momentum</u>**

1. Beta decay – experimental results

- measurement of electron/positron energy provided next unexpected result

$$E_{kin} = \frac{p^2}{2m} \qquad E_{kin1} + E_{kin2} = (M - m_1 - m_2)c^2 = E_0$$

$$\rightarrow \qquad E_{kin1} = \frac{m_2}{m_1 + m_2} E_0$$



- instead of discrete → **continuous spectrum**

1. Beta decay – experimental results

- investigation of spin → example:

$n \rightarrow p + e^-$

nucleus$_{\text{half-integer spin}}$ → nucleus$_{\text{half-integer spin}}$ + electron$_{\text{half-integer spin}}$

$1/2 \quad 1/2 \quad 1/2$

→ **disagreement with conservation of angular momentum**

2. Neutrino hypothesis

- instead of giving up the conservations of energy, momentum and angular momentum,

Wolfgang Pauli theorized a new particle, called neutrino (1930)

Wolfgang Pauli (1900-1958)

2. Neutrino hypothesis

- according to the exp. results, the neutrino has:
  - half-integer spin
  - no electric charge
  - very small mass
- new equation: β⁻ decay: $${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \bar{\nu}$$

  β⁺ decay: $${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}e + \nu$$

$n \rightarrow p + \bar{e} + \bar{\nu}$

- determination of ν and $\bar{\nu}$ necessary, because of **conservation of lepton number** (lepton L=1, antilepton L=-1)

DO YOU KNOW??..........

- Most of the neutrinos pass through our body and we do not realize it.
- Because they interact very less with anything that come in their path.
- For example , light rays from a torch can't penetrate a wall, because particles of light interact with the wall and get scattered.
- But the neutrinos can penetrate through the wall and even through the mountain.

INTERACTION OF NEUTRINOS

- They simply bounce off whatever they hit (a
  electron or the nucleus) so the neutrino
  remains a neutrino.
- But they transfer momentum and energy to
  the object which it collides with
- They may convert into a charged lepton(an
  electron or tau or their anti-particles
  depending on the type of neutrinos.

NEUTRINO DETECTION

- It is impossible to detect the neutrino by placing the detector in the open space.
- Because there are particles other than the neutrinos that are produced in the atmosphere and it is difficult to identify and separate signals produced from the neutrinos from the signals produced by the other particles.
- So to avoid the other particles from reaching the detector ,it is kept inside the mountain.

NEUTRINO DETECTOR

- Neutrino detector is called as Iron calorimeter (ICAL).
- This consist of detectors called Resistive Plate Chamber (RPC) arranged in a stack of about 150 layers.
- Iron plates are placed in between these layers.
- Current carrying coils through the detector will produce a magnetic field , thus magnetizing the entire detector.

Iron calorimeter to detect Neutrino

- The ICAl consists of 150 layers of alternating iron slabs and glass detectors called Resistive plate chambers(RPC).

- The muon neutrino interacts with the iron to produce a muon which is electrically charged. This charge is picked up by sensors in the glass RPCs which set off an electrical pulse, to be measured by the electronics.

- By piecing together the pulses set off in successive glass plates, the path followed by the muon is tracked. This is used to infer the properties of the neutrino which caused the pulses.

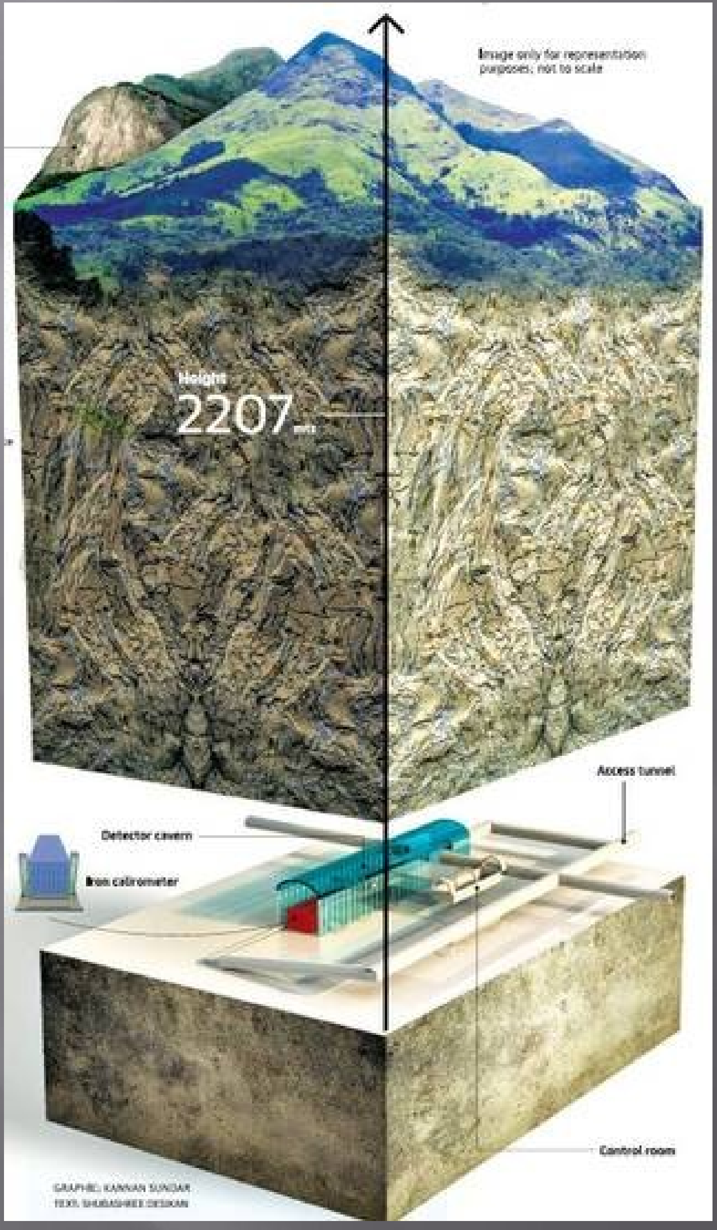


Image only for representation purposes; not to scale
Height
2207 mts
Access tunnel
Detector cavern
Iron calorimeter
Control room
GRAPHIC: KANNAN SUNDAR
TEXT: SHUBASHREE DESIKAN

3.Detection

β^- decay: ${}_0^1n \rightarrow {}_1^1p + {}_{-1}^{0}e + \bar{\nu}$

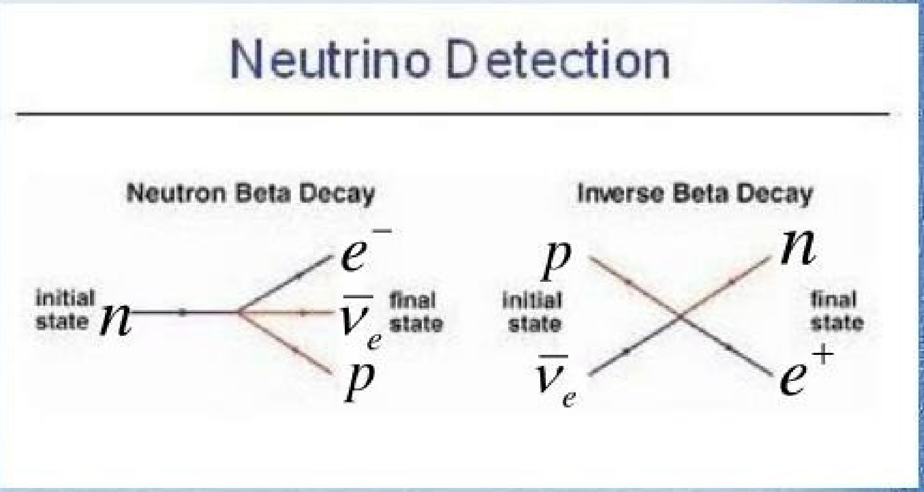
β^+ decay: ${}_1^1p \rightarrow {}_0^1n + {}_1^0e + \nu$

inverse β^- decay: ${}_0^1n + \nu \rightarrow {}_1^1p + {}_{-1}^{0}e$

inverse β^+ decay: ${}_1^1p + \bar{\nu} \rightarrow {}_0^1n + {}_1^0e$

- $\bar{\nu}_e$ used in the inverse β^+ decay to create neutron and positron

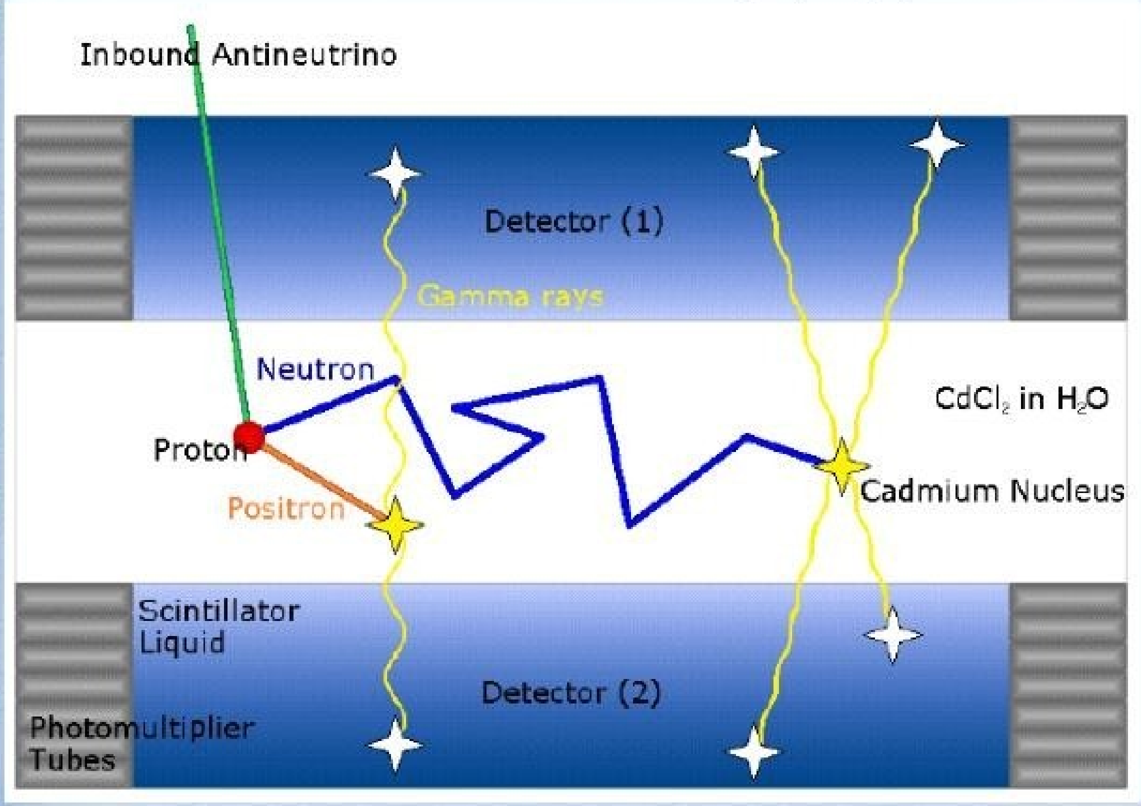
→ $\bar{\nu}_e$ "trigger“ for reaction



3.Detection

-measurement: ○ first E(e+e)=1,02MeV,

○ later E(n)=9,1MeV



$${}^{1}_{1}p+\overline{\nu}_{e}\rightarrow{}^{1}_{0}n+{}^{0}_{1}e$$

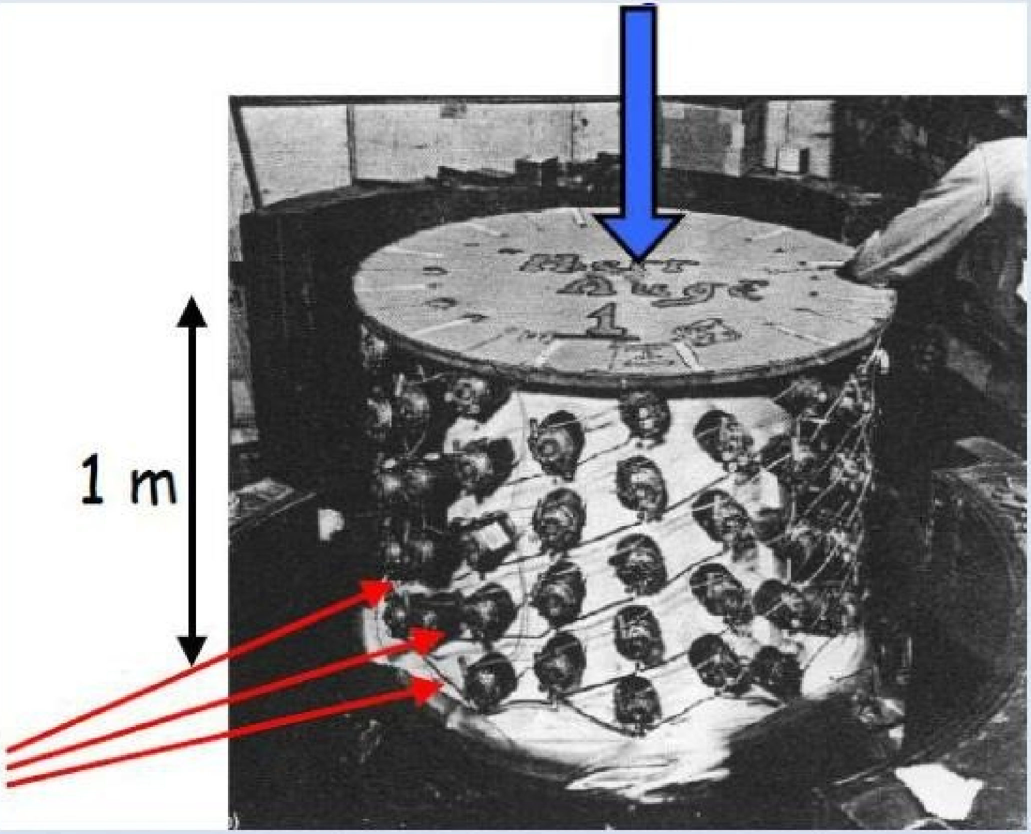
$$e^{+}+e^{-}\rightarrow\gamma+\gamma$$

$${}^{113}Cd+{}^{1}n\rightarrow{}^{114}Cd^{*}\rightarrow{}^{114}Cd+\gamma$$

3.Detection

200l reservoir

-The neutrino detector „Herr Auge“:



90 photomultiplier

PRODUCTION OF NEUTRINOS IN THE SUN (ELECTRON NEUTRINO)

- The Electron neutrinos are produced in the sun as a product of nuclear fusion reaction.
- Because they are produced in the sun these electron neutrinos are also known as Solar Neutrinos.
- The main and the initial reaction in the sun is the proton-proton reaction.

$$p + p \rightarrow \mathrm{d} + e^{+} + \nu_{\mathrm{e}}$$

- In the previous reaction 86% of all solar neutrinos are produced.
- The electron neutrinos produced in this reaction have low energy(about 400 keV)
- Then deuterium will fuse with another proton to create a ^3He atom and a gamma ray.

$$d + p \rightarrow {}^3He + \gamma$$

- The isotope ^4He can be produced by using the ^3He in the previous reaction which is seen below.

$${}^3He + {}^3He \rightarrow {}^4He + 2p$$

- Now the helium-3 and helium-4 fuse to give beryllium

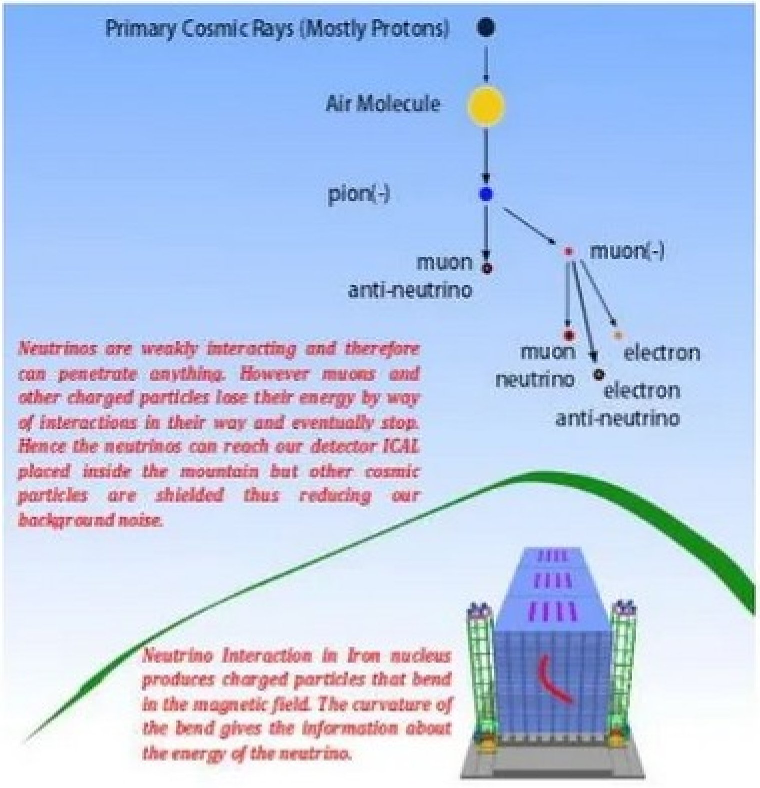
$$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$

- Then the beryllium captures an electron and produce a lithium-7 atom and an electron neutrino

$$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$$

- The electron produced in this reaction produces 14% of solar neutrons.
- The electron neutrinos produced in this reaction have larger energies.

- Neutrino interaction in the nucleus of iro
plates produces charged particles that be
in the magnetic field.
- The curvature of the bend gives the information about the energy of the neutrino.



INDIA-BASED NEUTRINO OBSERVATORY (INO)

- INO is the world class laboratory constructed in India for studying Neutrinos.
- INO project will benefit the country by enhancing its scientific manner.
- INO will also find use in fields such as Medical imaging.

Building Blocks

- Molecules consists of atoms.
- An atom consists of a nucleus, which carries almost all the mass of the atom and a positive charge *Ze*, surrounded by a cloud of *Z* electrons.
- Nuclei consist of two types of fermions: protons and neutrons, called also nucleons.
- Nucleons consists of three quarks.

$e = 1.6022 \times 10^{-19}$ C

Some Nuclear Properties

Nuclear sizes are usually measured by “scattering.”

Experimentally, using neutrons of energy 20 MeV or more, or electrons of 1 GeV (10^9 eV) or greater, it is found that the volume of a nucleus is proportional to the number of nucleons (neutrons and protons) it contains.

Since the mass number A is proportional to volume and volume is proportional to the R^3, where R is the nuclear radius, it follows that R is proportional to $A^{1/3}$. We usually write

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

where R_0 is a constant and $R_0 \approx 1.2\text{x}10^{-15}$ m.

The nucleus does not have a sharp boundary, so the "constant" R_0 is only approximate; also, nuclear matter and nuclear charge do not seem to be identically distributed.

The unit of length 10^{-15} m is called a femtometer, abbreviated fm, and also often called a fermi, so $R=1.2A^{1/3}$ in units of fm.

Example: the radius of the $^{107}_{47}Ag$ nucleus is $R = 1.2x(107)^{1/3} \approx 5.7$ fm.

If a nucleus is not spherically symmetric, it will produce an electric field that will perturb atomic electronic energy levels.

Such an effect is, in fact, observed, but it is small -- "hyperfine." The departures from spherical symmetry are small.

Skip the subsection on nuclear spin and magnetic moment.

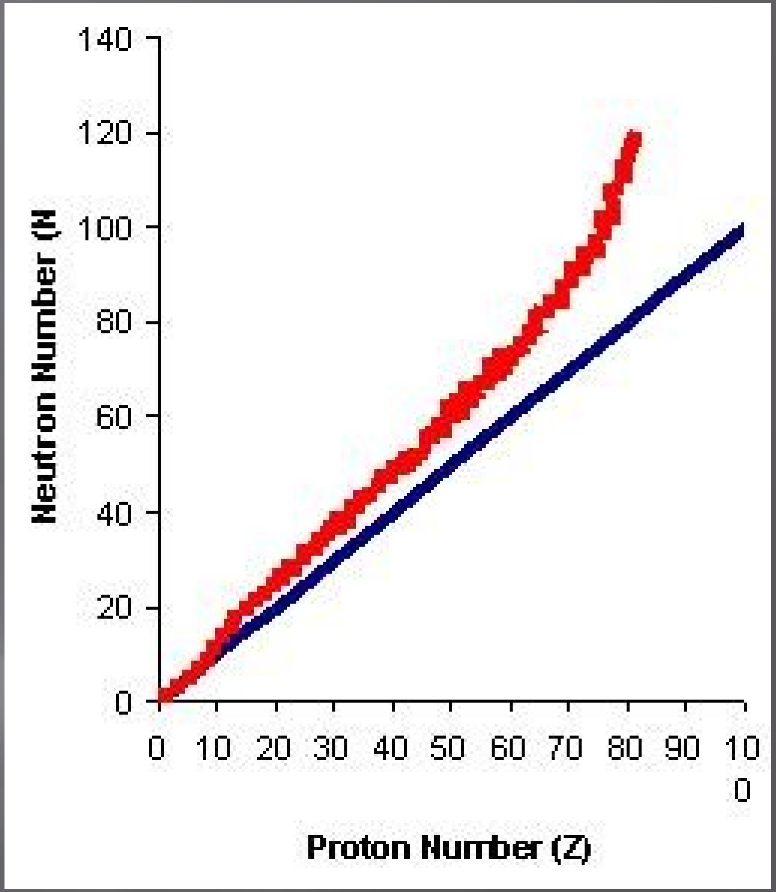
Stable Nuclei

We can begin to understand why certain nuclei are stable and others unstable by realizing that nucleons have spins of 1/2 and obey the Pauli exclusion principle.

Nucleons, like electrons and their electronic energy levels, occupy discrete nuclear energy levels.

Minimum energy configurations (i.e., nucleons in the lowest possible energy levels) give the most stable nuclei.

A plot of N versus Z for the stable nuclides looks like this:



Neutrons produce attractive forces within nuclei, and help hold the protons together.

For small numbers of protons, about an equal number of neutrons is enough to provide stability, hence N≈Z for small Z.

As the number of protons gets larger, an excess of neutrons is needed to overcome the proton-proton repulsion.

The stability of nuclei follows a definite pattern.

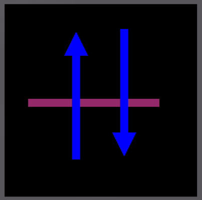
- The majority of stable nuclei have both even Z and even N ("even-even" nuclides).

- Most of the rest have either even Z and odd N ("even-odd") or odd Z and even N ("odd-even").

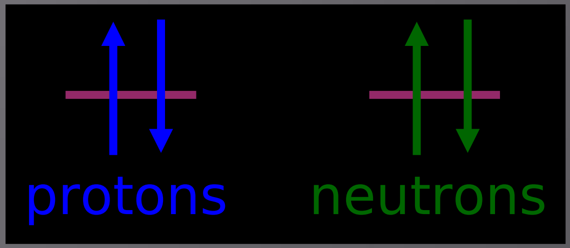
- Very few stable nuclei have both Z and N odd.

The reasons for this pattern are the Pauli exclusion principle and the existence of nuclear energy levels.

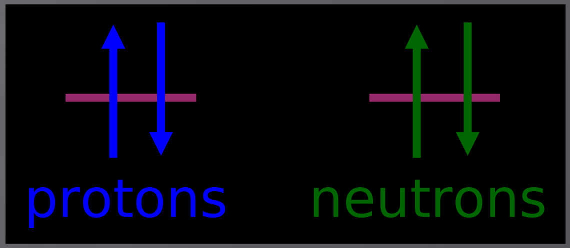
Each nuclear energy level can contain two nucleons of opposite spin.



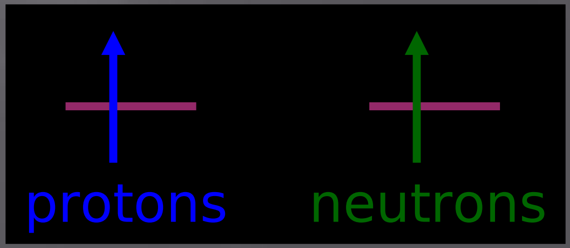
The neutrons and protons occupy separate sets of energy levels.



When both Z and N are even, the energy levels can be filled. The nucleus doesn't "want" to gain or lose nucleons by participating in nuclear reactions. The nucleus is stable.



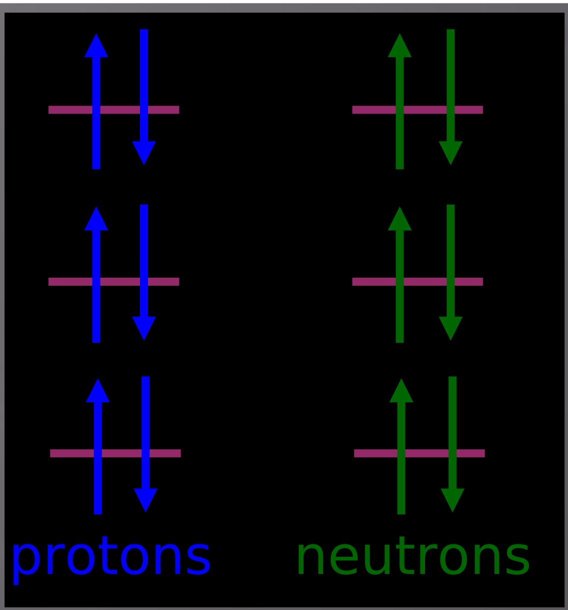
When both Z and N are odd, the nucleus is much more likely to "want" to participate in nuclear reactions or nuclear decay, because it has unfilled nuclear energy levels.



Example: $^{12}_{6}C$

All of its neutrons and protons in filled energy levels—very stable.

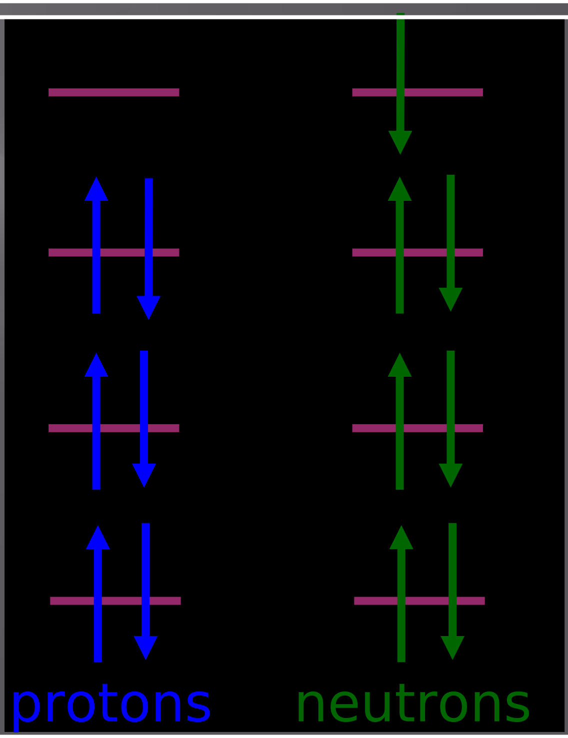
Energy level diagrams illustrative only; not quantitatively accurate!



Example: $^{12}_{5}B$

“Extra” neutron in higher energy level; therefore unstable.

Decays via β decay into $^{12}_{6}C$.



Attractive nuclear forces are limited in range and primarily operate between nearest neighbors ("saturation"), so there is a nuclear size beyond which neutrons are unable to overcome the proton-proton repulsion.

The heaviest stable nuclide is $^{209}_{83}Bi$. Heavier ones decay into lighter nuclides through alpha decay (the emission of a $^{4}_{2}He$ nucleus):

$$^{A}_{Z}X \rightarrow \; ^{A-4}_{Z-2}Y + \; ^{4}_{2}He \; .$$

X is called the ***parent*** nucleus and Y is called the ***daughter*** nucleus.

It may be that a nucleus produced by alpha decay has too many neutrons to be stable. In this case, it may decay via beta decay:

$$n^0 \rightarrow \; p^+ + e^- \; .$$

If the nucleus has too few neutrons, it may decay via positron emission

$$p^+ \rightarrow \; n^0 + e^+$$

or by electron capture

$$p^+ + e^- \rightarrow \; n^0 \, .$$

Note that Z decreases by 1 as a result of positron emission or electron capture, but ***increases*** by 1 as a result of beta decay.

Binding Energy

The binding energy that holds nuclei together "shows up" as "missing" mass.

Deuterium is an isotope of hydrogen which contains a neutron, a proton, and an "orbiting" electron.

mass of hydrogen	1.0078 u
mass of neutron	1.0087 u
sum	2.0165 u
mass of deuterium	2.0141 u
difference	0.0024 u

Since 1 u of mass has an energy equivalent of 931 MeV, the missing mass is equal to 931x0.0024 MeV = 2.2 MeV.

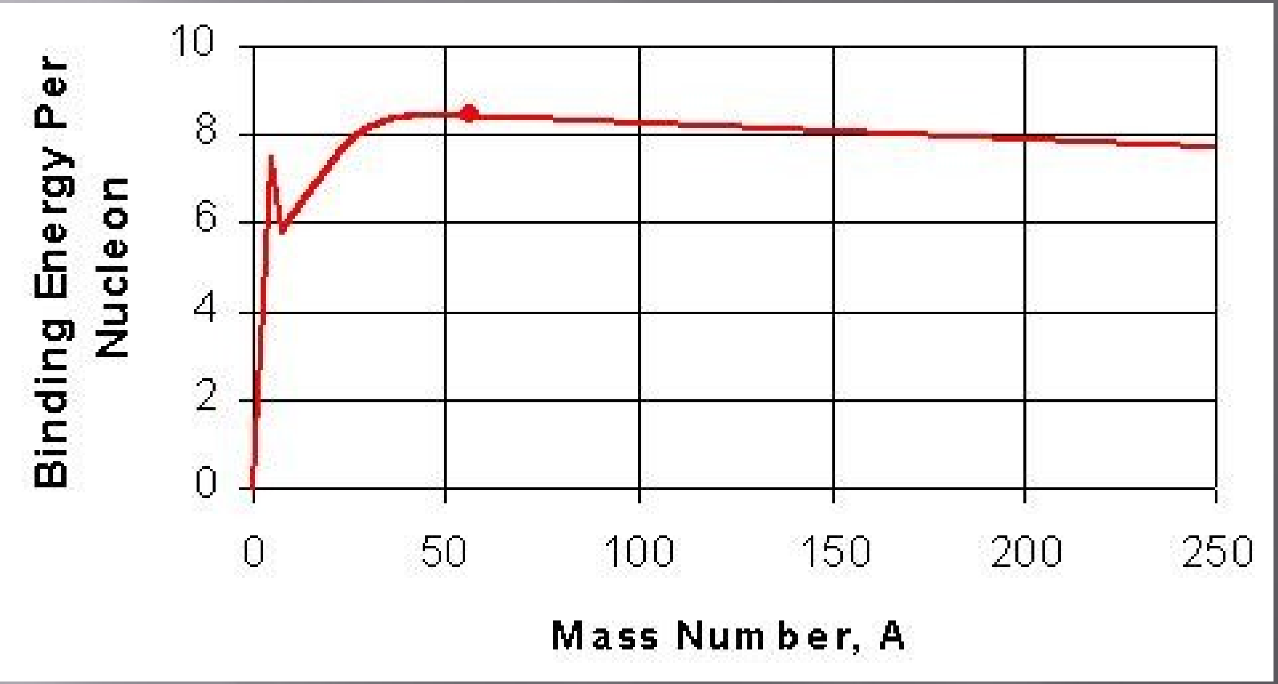
The fact that this mass deficit is the binding energy is demonstrated by experiments which show that it takes 2.2 MeV of energy to split a deuterium into a neutron and a proton.

Nuclear binding energies range from 2.2 MeV for deuterium to 1640 MeV for bismuth-209.

These binding energies are enormous; millions of times greater than even the energies given off in highly energetic chemical reactions.

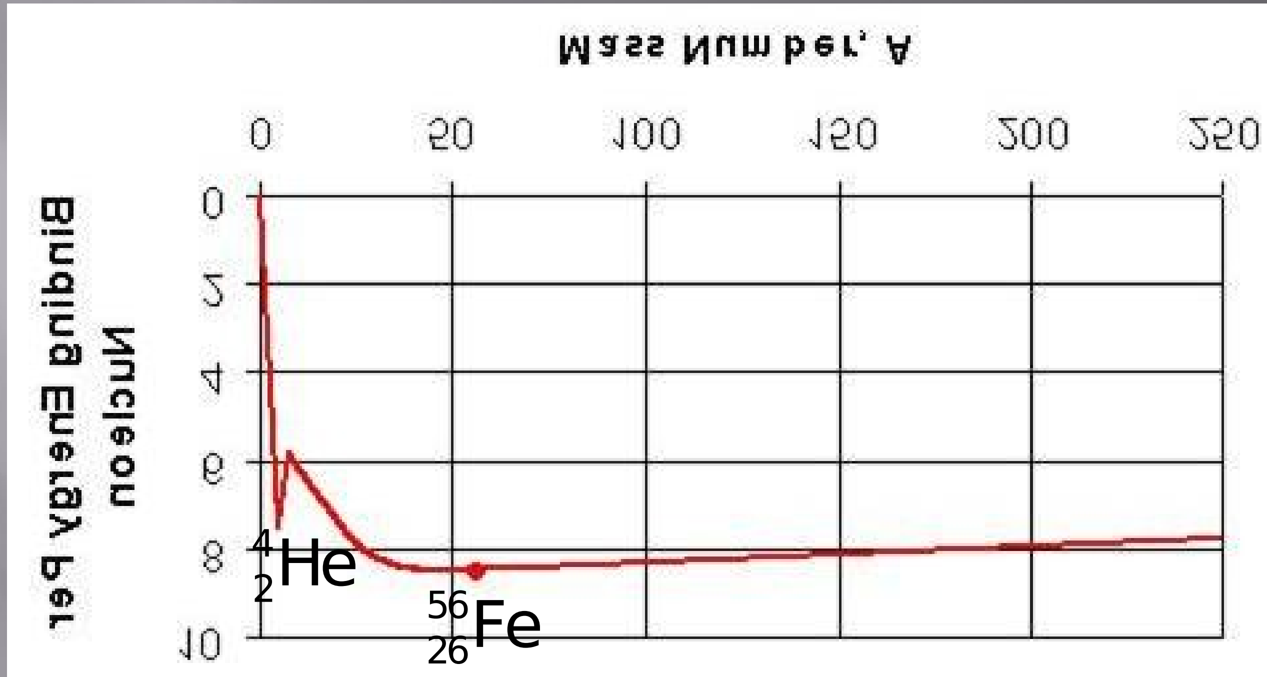
We usually talk in terms of binding energy per nucleon, which is 2.2/2=1.1 MeV per nucleon for deuterium, or 1640/209=7.8 MeV per nucleon for bismuth-209.

The figure below shows a plot of binding energy per nucleon as a function of nucleon number.



Keep in mind that energies are reduced on binding. The binding energy is negative, but when we say the words “binding energy” we associate them with the magnitude of the binding energy.

In other words, this plot is upside down. Let’s fix it.



More difficult to read the lettering, but makes more physical sense!

Notice the local minimum at $^{4}_{2}He$, which is a very stable nucleus.

Notice the absolute minimum at $^{56}_{26}Fe$, which is the most stable nucleus of all.

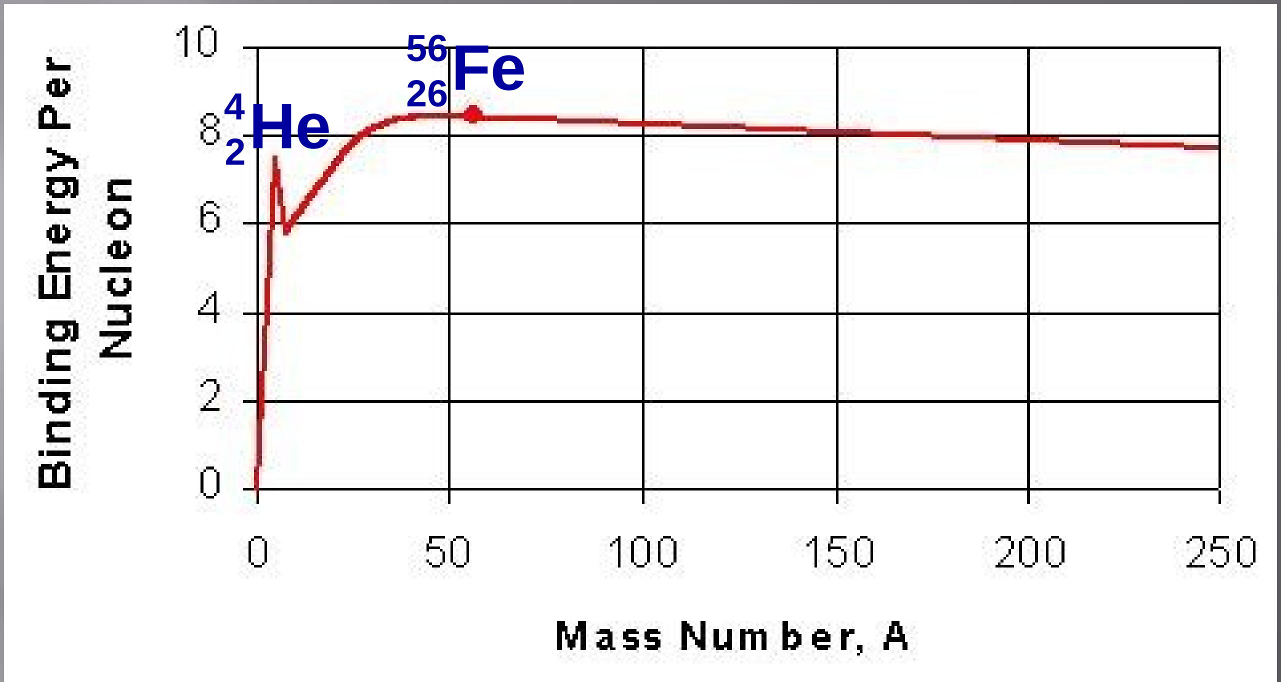
If ${}^{56}_{26}Fe$ is so stable, how come heavier elements exist?

Heavier elements are less stable, but stable enough to exist. It takes enormous energies to make elements heavier than iron-56. The only place in the universe where those energies are available are supernovae.

Do you have gold in a ring (or silver in the fillings in your teeth)? If you do, you are carrying with you debris from a supernova.

Let’s go back and consider some implications of the binding energy per nucleon plot.

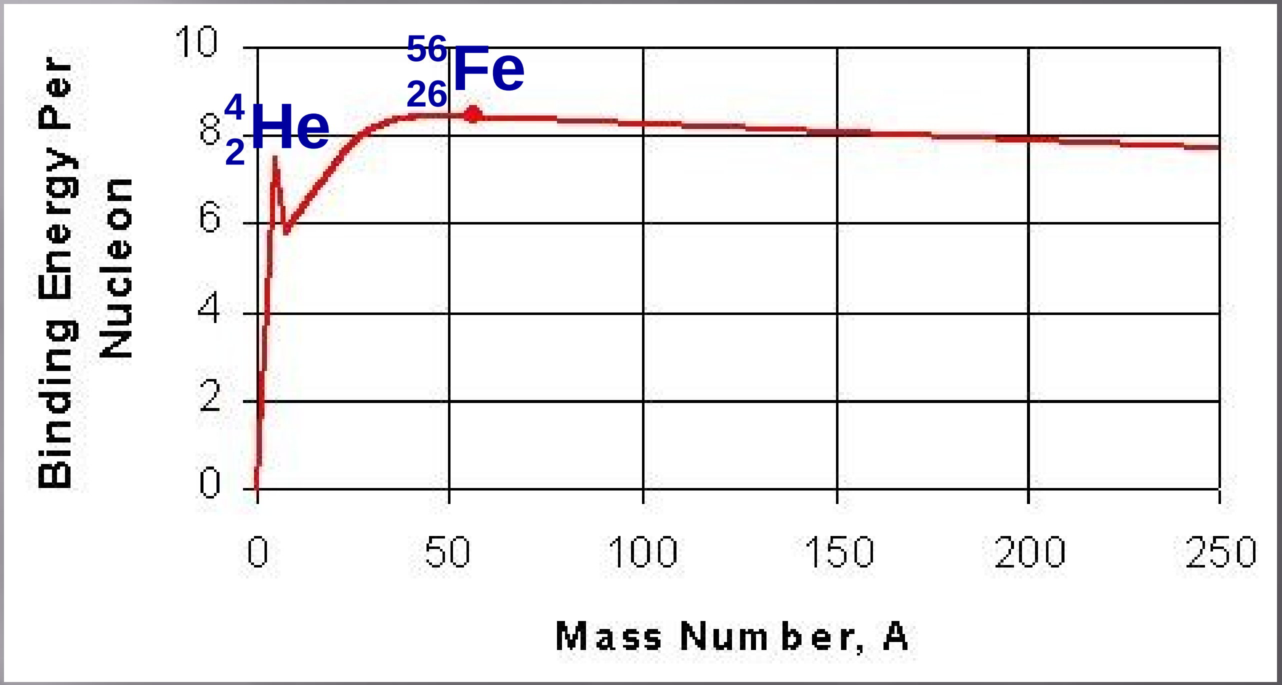
I’ll display the plot “right (??)” side up again, because that’s they way you’ll usually see it. Remember, higher on the plot means lower in energy and more stable.



Consider a nucleus with a large A. If we could split it into two smaller nuclei, with A's closer to iron, the two nuclei would have ***more*** binding energy per nucleon.

But remember, binding energies are negative. If the resulting nuclei have more negative energy than the starting element, some ***positive*** energy must have been released in splitting the starting element.

The positive energy is the energy released in the fission reaction.



If we begin with two nuclei significantly lighter than iron-56, and somehow make them fuse, the resulting nucleus will have more binding energy per nucleon.

sample binding energy problem

Homework problem 11.16 Find the binding energy per nucleon in $^{197}_{79}Au$.

There is no equation in your text, so I'll make one up.

$$E_b(M,A,Z) = \left[M - Zm_H - (A-Z)m_n\right] 931.5$$

mass of atom

mass of hydrogen

mass of neutron

converts to MeV

Note that all masses must be in units of u, and all electrons are automatically counted in this calculation.

$$E_b(M,A,Z) = \left[M - Zm_H - (A-Z)m_n\right] 931.5$$

This gives the total nuclear binding energy for the atom. We usually want the binding energy per nucleon, so I'll make another OSE:

$$E_{b\_per\_nucleon}(M,A,Z) = \frac{E_b(M,A,Z)}{A}.$$

Because $E_b(M,A,Z)$ is in units of MeV, the binding energy per nucleon is in units of MeV/nucleon.

Now, back to our problem.

The mass of gold-197 is 196.966560 u. You could look that up, or I would give it to you on an exam or quiz (unless it were the quantity I wanted you to calculate).

The mass of hydrogen is 1.007825 u and the mass of a neutron is 1.008665 u. Yes, you do need to keep all the decimal places. Note the hydrogen mass includes the mass of one electron—enough to make a difference!

For gold-197, A=197 and Z=79.

$$E_b(M,A,Z) = \left[M - Zm_H - (A-Z)m_n\right] 931.5$$

$$E_b = \left[(196.966560) - (79)(1.007825) - ((197)-(79))(1.008665)\right] 931.5$$

$$E_b = -1559\,\mathrm{MeV}$$

$$E_{b\_per\_nucleon} = \frac{E_b(M,A,Z)}{197} = -7.916\,\mathrm{MeV}.$$

The binding energy is negative, as it must be.

NUCLEAR MODELS

Liquid Drop Model

- we can think of each nucleon in a nucleus as interacting solely with its nearest neighbors. This situation is the same as that of atoms in a solid, which ideally vibrate about fixed positions in a crystal lattice, or that of molecules in a liquid, which ideally are free to move about while maintaining a fixed intermolecular distance.

- The analogy with a solid cannot be pursued because a calculation shows that the vibrations of the nucleons about their average positions would be too great for the nucleus to be stable.

- The analogy with a liquid, on the other hand, turns out to be extremely useful in understanding certain aspects of nuclear behavior.

- This analogy was proposed by George Gamow in 1929 and developed in detail by C. F. von Weizsäcker in 1935.

ANALOGY BETWEEN A SMALL LIQUID DROP AND A NUCLEUS

- LIQUID DROP IS SPHERICAL IN SHAPE DUE TO SURFACE TENSION FORCE ACTING TOWARDS THE CENTRE. THE NUCLEUS IS ALSO ASSUMED TO BE SPHERICAL IN SHAPE.

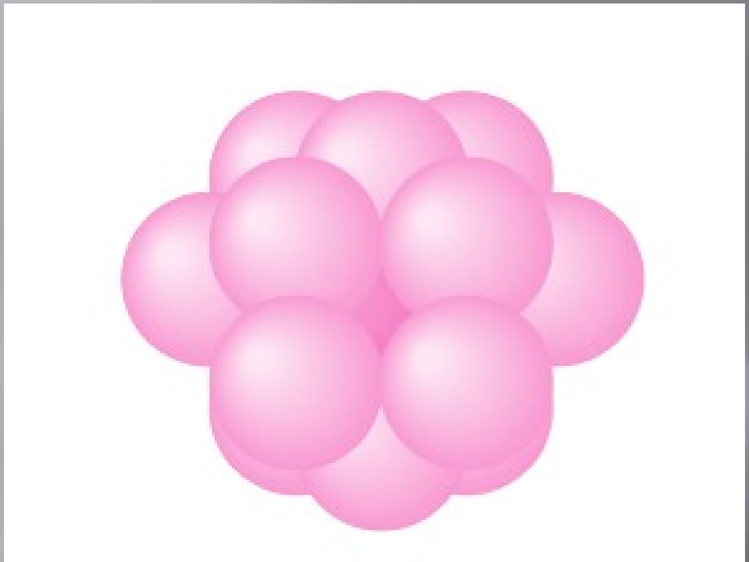
- DENSITY OF SPHERICAL DROP IS KNOWN TO BE INDEPENDENT OF ITS VOLUME. NUCLEAR DENSITY IS ALSO FOUND TO BE INDEPENDENT OF NUCLEAR VOLUME

- Let us see how the picture of a nucleus as a drop of liquid accounts for the observed variation of binding energy per nucleon with mass number.

- Assume that the energy associated with each nucleon-nucleon bond has some value U. This energy is actually negative since attractive forces are involved, but is usually written as positive because binding energy is considered a positive quantity for convenience.

- Each bond energy U is shared by two nucleons, each pair has a binding energy of 1/2 U.

1)Volume energy



In a tightly packed assembly of identical spheres, each interior sphere is in contact with 12 others.

- Each interior nucleon in a nucleus has a binding energy of (12)(1/2 U) or 6 U.
- If all A nucleons in a nucleus were in its interior, the total binding energy of the nucleus would be

$$E_v = 6\ AU$$

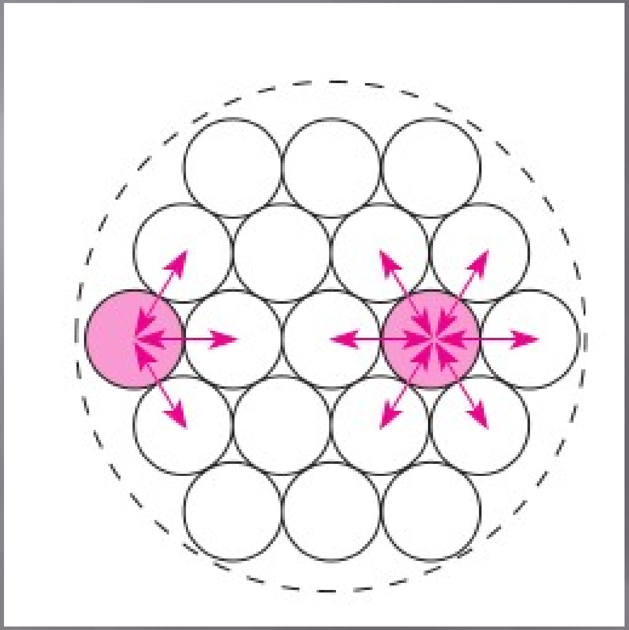
$$E_v = a_v A$$

The energy E_v is called the volume energy of a nucleus and is directly proportional to A

$$E_v = a_v A$$

BINDING ENERGY PER NUCLRON IS PROPORTIONAL TO MASS NUMBER A JUST AS ENERGY REQUIRED TO EVAPORATE LIQUID IS PROPORTIONAL TO ITS MASS.

2) Surface energy



- A nucleon at the surface of a nucleus interacts with fewer other nucleons than one in the interior of the nucleus and hence its binding energy is less. The larger the nucleus, the smaller the proportion of nucleons at the surface.

- some nucleons are on the surface of every nucleus and therefore have fewer than 12 neighbors. The number of such nucleons depends on the surface area of the nucleus in question.

A nucleus of radius R has an area of

$$4\pi R^2 = 4\pi R_0^2 A^{2/3} .$$

Hence the number of nucleons with fewer than the maximum number of bonds is proportional to $A^{2/3}$

Which, reduces the total binding energy by Surface energy,

$$E_s = -a_s A^{2/3}$$

The negative energy E_s is called the surface energy of a nucleus. It is most significant for the lighter nuclei since a greater fraction of their nucleons are on the surface.

3)COULOMB ENERGY

- The electric repulsion between each pair of protons in a nucleus also contributes toward decreasing its binding energy.
- The coulomb energy E_c of a nucleus is the work that must be done to bring together Z protons from infinity into a spherical aggregate the size of the nucleus.
- The potential energy of a pair of protons *r* apart is equal to

$$V = -e^2/4\pi\epsilon_0 r$$

In a nucleus, total Z(Z - 1)/2 pairs of protons can be formed.

$$E_c = \frac{Z(Z-1)}{2} V = -\frac{Z(Z-1)e^2}{8\pi\epsilon_0}\left(\frac{1}{r}\right)_{av}$$

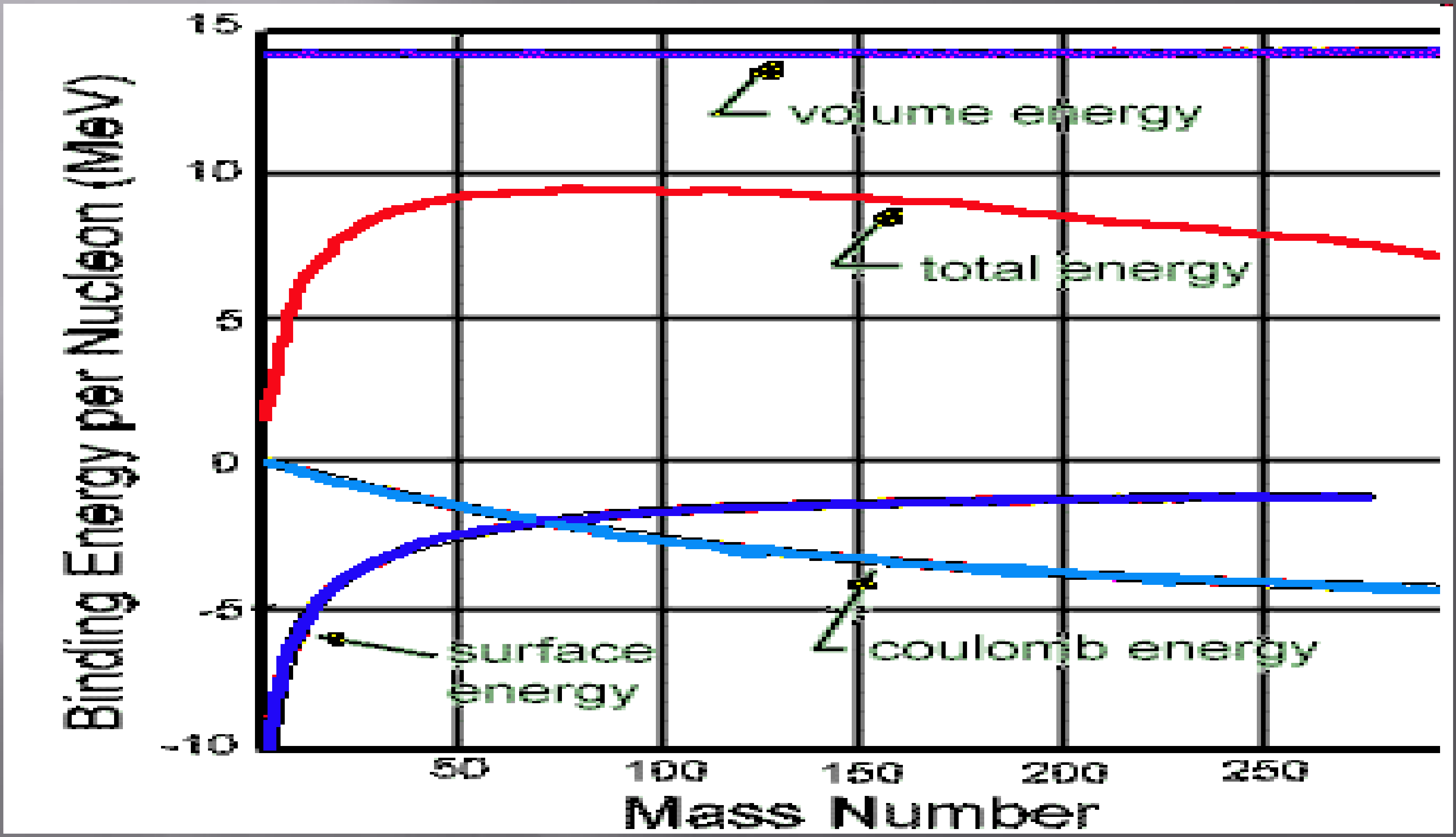
where $(1/r)_{av}$ is the value of 1/r averaged over all proton pairs. If the protons are uniformly distributed throughout a nucleus of radius R, $(1/r)_{av}$ is proportional to 1/R and hence to $1A^{1/3}$, so that

$$E_C = -a_c Z(Z-1)A^{-1/3}$$

OR

$$E_c = -a_3 \frac{Z(Z-1)}{A^{1/3}}$$

The coefficients were chosen to make the E_b / A curve resemble as closely as possible the empirical binding energy per nucleon curve



- NUCLEAR MASS IS GIVEN BY

$M_{NUCLEUS} = [ZM_P + (A-Z) M_N] - B/C^2$

THIS IS CALLED SEMI-EMPIRICAL MASS FORMULA.

TOTAL BINDING ENERGY $E_B = E_V + E_S + E_C + E_A + E_P$

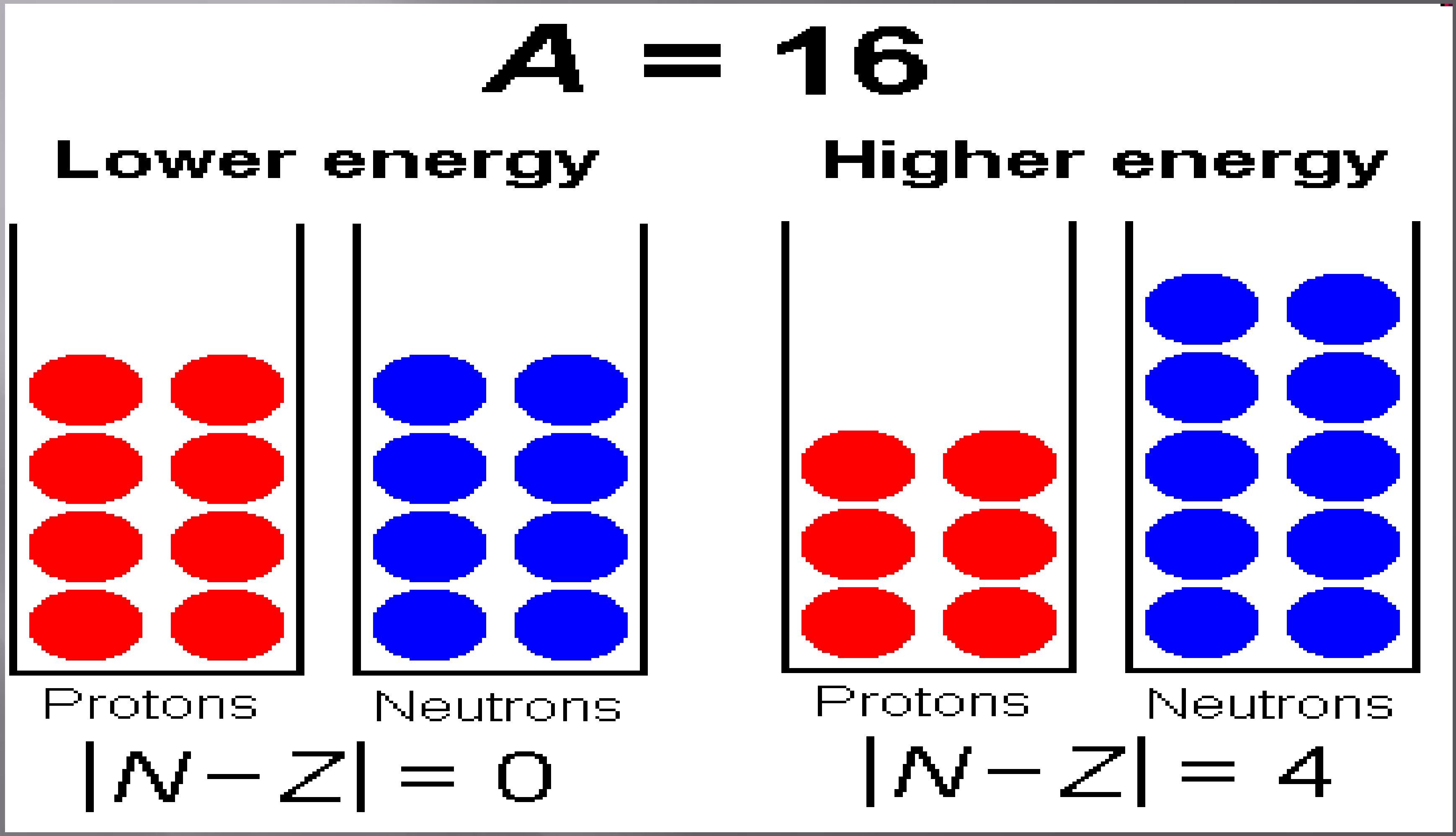
The binding-energy formula can be improved by taking into account two effects as follows:

1. Assymetry energy
2. Pairing energy

4)ASYMMETRY ENERGY

- FOR HEAVY NUCLEI, AS NO. OF NEUTRONS INCREASES, NUCLEUS ACQUIRES AN ASYMMETRICAL CHARACTER, DUE TO WHICH A FORCE COMES INTO PLAY WHICH REDUCES THE ASYMMETRY ENERGY

HOW?.....let’s see...


A = 16
Lower energy
Higher energy
Protons
Neutrons
|N − Z| = 0
Protons
Neutrons
|N − Z| = 4

$E_a = -a_a (N-Z)^2/A$

$= -a_a (A-2Z)^2/A$;$(A=N+Z)$

Where, a_a IS A CONSTANT

5) PAIRING ENERGY

- NUCLEI WITH EVEN **Z** AND EVEN **N** ARE HIGHLY STABLE,
  -->EVEN Z- ODD N, OR ODD Z-EVEN N ARE LESS STABLE.

SO THIS EFFECT CONTRIBUTES TOWARDS VOLUME ENERGY BY

- $E_P = a_p A^{-3/4}$

WHERE a_p IS CONSTANT

- COMBINING ALL THESE TERMS WE GET TOTAL BINDING ENERGY

$E_B = E_V + E_S + E_C + E_A + E_P$

- SO BINDING ENERGY IS GIVEN BY

$$E_B = a_V A - a_s A^{2/3} - a_c Z(Z-1)A^{-1/3} - a_a (A-2Z)^2/A + a_p A^{-3/4}$$

a_v=14.1MeV, a_s=13.0MeV, a_c=0.595 MeV, a_a=19.0, a_p=33.5 Mev

- **Example:**
- **$_{30}$Zn64 Compare its binding energy with the prediction from semi empirical formula**

M(Zn)=63.929 u, M(p)= 1.007825 u, M(n)= 1.008665 u

$$E_b = [(30)(1.007825 \text{ u}) + (34)(1.008665 \text{ u}) - 63.929 \text{ u}](931.49 \text{ MeV/u}) = 559.1 \text{ MeV}$$

$$E_b = (14.1 \text{ MeV})(64) - (13.0 \text{ MeV})(64)^{2/3} - \frac{(0.595 \text{ MeV})(30)(29)}{(64)^{1/3}} - \frac{(19.0 \text{ MeV})(16)}{64} + \frac{33.5 \text{ MeV}}{(64)^{3/4}} = 561.7 \text{ MeV}$$

Difference is less than 0.5%

ACHEIVEMENTS

- 1) **STABLE NUCLEUS**:-

STABILITY OF LIQUID DROP IS DUE TO FORCE OF COHESION BETWEEN THE MOLECULES, AND STABILITY OF NUCLEUS IS DUE TO THE BINDING ENERGY OF EACH NUCLEON.

2)RADIOACTIVE NUCLEUS:-

A LIQUID EVAPORATES BY GAINING ENERGY FROM ITS NEIGHBOURING MOLECULES DURING THE PROCESS OF COLLISIONS. SIMILARLY NUCLEON MAY LEAVE THE NUCLEUS BY GAINING ENERGY FROM NEIGHBOURING NUCLEONS,THUS EXHIBITING THE PROCESS OF RADIOACTIVITY

- ARTIFICIAL RADIOACTIVITY:-

LIQUID DROP MODEL ALSO EXPLAINS THE PHENOMENON OF ARTIFICIAL RADIOACTIVITY

FISSION:-

LIQUID DROP MODEL ALSO EXPLAINS THE PHENOMENON OF NUCLEAR FISSION

FAILURES:-

1)IT FAILS TO EXPLAIN THE HIGH STABILITY OF NUCLEI WITH MAGIC NO.

2)IT FAILS TO EXPLAIN THE MEASURED SPIN AND MAGNETIC MOMENTS OF THE NUCLEI

DIFFERENCE BETWEEN SHELL MODEL AND LIQUID DROP MODEL

- IN LIQUID DROP MODEL, IT IS ASSUMED THAT NUCLEONS INTERACT STRONGLY WITH IMMEDIATE NEIGHBOURS.

- BUT SHELL MODEL TREATS NUCLEONS INDIVIDUALLY AND IT IS ASSUMED THAT NUCLEONS DO NOT INTERACT WITH EACH OTHER

EVIDENCE IN FAVOUR OF SHELL MODEL

- NUCLEONS HAVE A TENDENCY TO FORM PAIR AND ITS DIFFICULT TO REMOVE A PAIRED NUCLEON THAN UNPAIRED.
- NUCLEI WITH EVEN Z AND EVEN N ARE MOST ABUNDANT,ODD Z AND ODD N ARE LEAST ABUNDANT,EVEN N AND ODD Z OR EVEN Z AND ODD N COME IN BETWEEN

- It has been found that the nuclei with proton number or neutron number equal to certain numbers 2,8,20,28,50,82 and 126 behave in a different manner when compared to other nuclei having neighboring values of Z or N.
- Hence these numbers are known as MAGIC NUMBERS
- Nuclei with magic numbers of neutrons or protons have their first excited states at higher energies than in cases of the neighboring nuclei

ASSUMPTIONS

- NUCLEONS FORM CLOSED SUB-SHELLS WITHIN THE NUCLEUS JUST AS ELECTRONS IN CASE OF ATOMS
- NUCLEONS IN NUCLEUS RE ARRANGED IN SHELL STRUCTURE .
- THE SHELLS GET CLOSED WITH SUITABLE NO. OF PROTONS AND NEUTRONS
- EACH NUCLEON MOVES INDEPENDENTLY INSIDE A NUCLEUS IN A FIXED ORBIT UNDER THE EFFECT OF CENTRAL POTENTIAL PRODUCED BY AVERAGE INTERACTION BETWEEN REMAINING (A-1) NUCLEONS IN IT.
- EACH NUCLEON IS ASSUMED TO POSSESS A SPIN ANGULAR MOMENTUM AND ORBITAL ANGULAR MOMENTUM

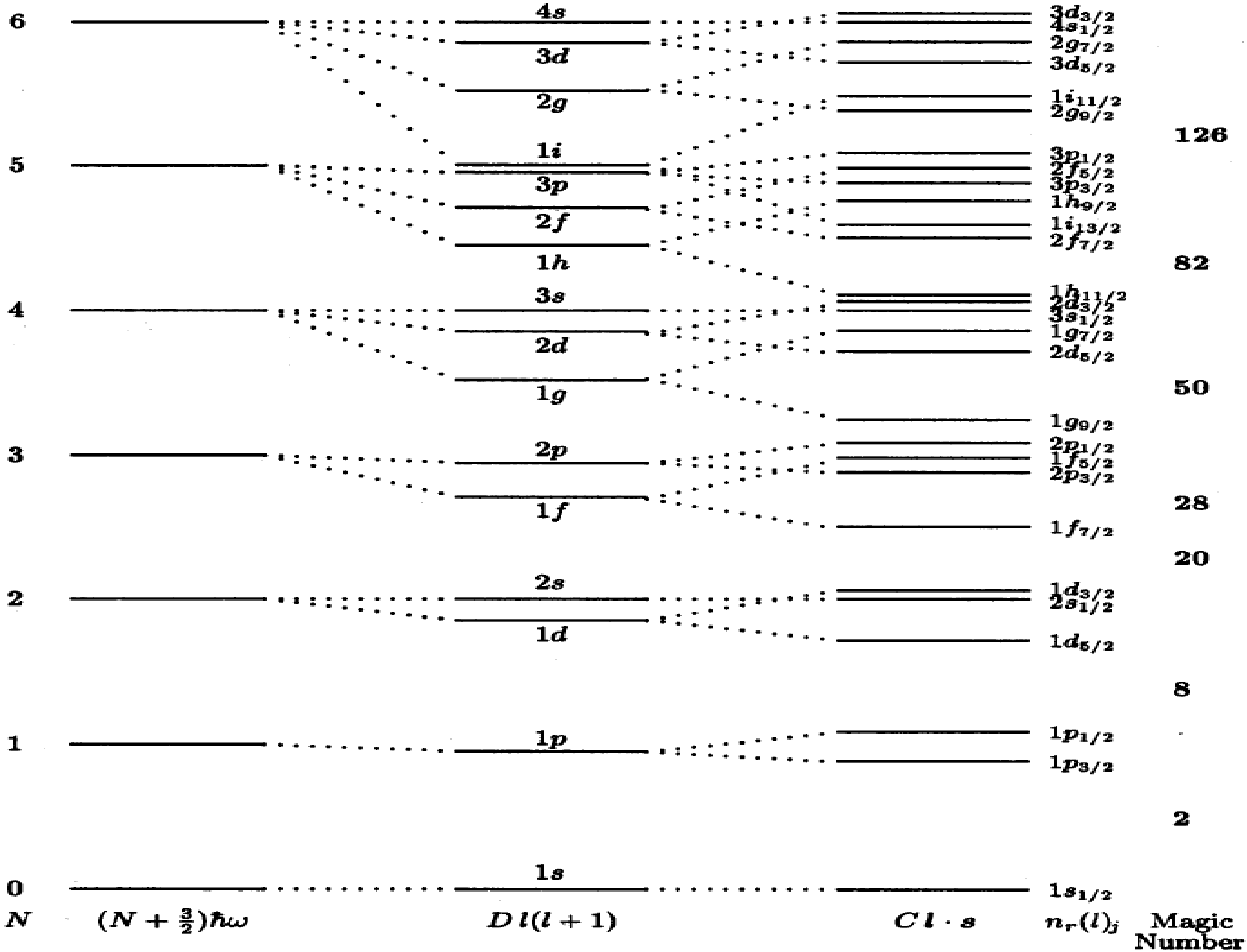
- Consider a nucleon moving independently in the harmonic oscillator potential which is spherically symmetric.
- The Schrodinger equation given below can be solved in the Cartesian coordinate system as well as in the spherical coordinate system.

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V(\boldsymbol{r})\right)\psi(\boldsymbol{r}) = E\psi(\boldsymbol{r}),$$

$$V(r) = \frac{1}{2}m\omega^2 r^2 = \frac{1}{2}m\omega^2(x^2 + y^2 + z^2).$$

$$E = \hbar\omega\left(n_x + n_y + n_z + \frac{3}{2}\right) = \hbar\omega\left(N + \frac{3}{2}\right),$$

N	E	Orbitals (n_r, l)	$\mathcal{N}_N = (N+1)(N+2) = \sum_l 2(2l+1)$	$\sum_N \mathcal{N}_N$
0	3/2	$1s$	2	2
1	5/2	$1p$	6	8
2	7/2	$1d, 2s$	12	20
3	9/2	$1f, 2p$	20	40
4	11/2	$1g, 2d, 3s$	30	70
5	13/2	$1h, 2f, 3p$	42	112
6	15/2	$1i, 2g, 3d, 4s$	56	168



6
5
4
3
2
1
0
4s
3d
2g
1i
3p
2f
1h
3s
2d
1g
2p
1f
2s
1d
1p
1s
$3d_{3/2}$
$4s_{1/2}$
$2g_{7/2}$
$3d_{5/2}$
$1i_{11/2}$
$2g_{9/2}$
$3p_{1/2}$
$2f_{5/2}$
$3p_{3/2}$
$1h_{9/2}$
$1i_{13/2}$
$2f_{7/2}$
$1h_{11/2}$
$2d_{3/2}$
$3s_{1/2}$
$1g_{7/2}$
$2d_{5/2}$
$1g_{9/2}$
$2p_{1/2}$
$1f_{5/2}$
$2p_{3/2}$
$1f_{7/2}$
$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
126
82
50
28
20
8
2
N
$(N+\frac{3}{2})\hbar\omega$
$D\,l(l+1)$
$C\,\boldsymbol{l}\cdot\boldsymbol{s}$
$n_r(l)_j$
Magic Number

Success of shell model

- MAGIC NUMBERS:-shell model explains the existence of magic no.s
- It has been found that the nuclei with proton number or neutron number equal to certain numbers 2,8,20,28,50,82 and 126 behave in a different manner when compared to other nuclei having neighboring values of Z or N. Hence these numbers are known as magic numbers.

- SPIN :-Shell model successfully explains the ground state spins and magnetic moments of the nuclei.

- Even-even nuclides (both Z and A even) have zero intrinsic spin and even parity.

- Odd A nuclei have one unpaired nucleon. The spin of the nucleus is equal to the j value of that unpaired nucleon

- MAGNETIC MOMENT:- Shell model successfully explains the magnetic moments of the nuclei.
- For even-even nuclei magnetic moment is zero
- For even-odd or odd-even magnetic moment depends upon the last unpaired nucleon whether its proton or a neutron.

- STABILITY:-VERY HIGH STABILTY AND HIGH BINDING ENERGY IS ALSO EXPLAINED ON THE BASIS OF CLOSED SHELLS.
- NUCLEAR ISOMERISM:-EXISTENCE OF ISOBARIC,ISOTOPIC NUCLEI IN DIFFERENT ENERGY STATE IS ALSO EXPLAINED ON THE BASIS OF SHELL MODEL

MAGIC NUMBERS

- It has been found that the nuclei with proton number or neutron number equal to certain numbers 2,8,20,28,50,82 and 126 behave in a different manner when compared to other nuclei having neighboring values of Z or N. Hence these numbers are known as magic numbers.

- **Experimental evidences for the existence of magic numbers;**

- 1. The binding energy of magic numbered nuclei is much larger than the neighboring nuclei. Thus larger energy is required to separate a single nucleon from such nuclei.

- 2. Number of stable nuclei with a given value of Z and N corresponding to the magic number are much larger than the number of stable nuclei with neighboring values of Z and N. For example, Sn with Z=50 has 10 stable isotopes, Ca with Z=20 has six stable isotopes.

- 3. Naturally occurring isotopes whose nuclei contain magic numbered Z or N have greater relative abundances. For example, Sr-88 with N=50, Ba-138 with N=82 and Ce-140 with N=82 have relative abundances of 82.56%, 71.66% and 88.48% respectively.

- 4. Three naturally occurring radioactive series decay to the stable end product Pb with Z=82 in three isotopic forms having N=126 for one of them.

- 5. Neutron absorbing cross section is very low for the nuclei having magic numbered neutron number.

6. Nuclei with the value of N just one more than the magic number spontaneously emit a neutron (when excited by preceding beta-decay) E.g., O-17, K-87 and Xe-137.

7. Nuclei with magic numbers of neutrons or protons have their first excited states at higher energies than in cases of the neighboring nuclei.

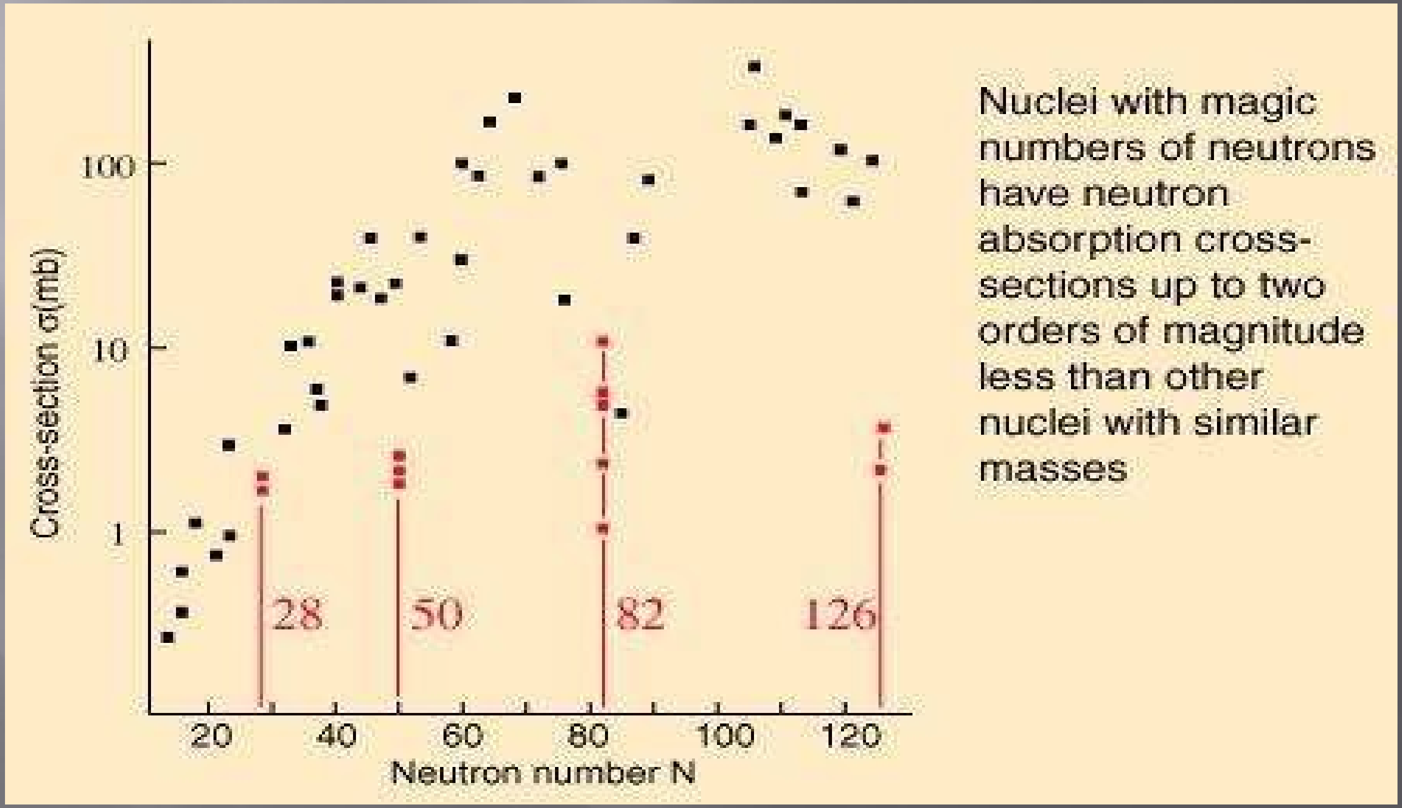
8. Electric quadrupole moment of magic numbered nuclei is zero indicating the spherical symmetry of nucleus for closed shells.

9. Energy of alpha or beta particles emitted by magic numbered radioactive nuclei is larger than that from other nuclei.

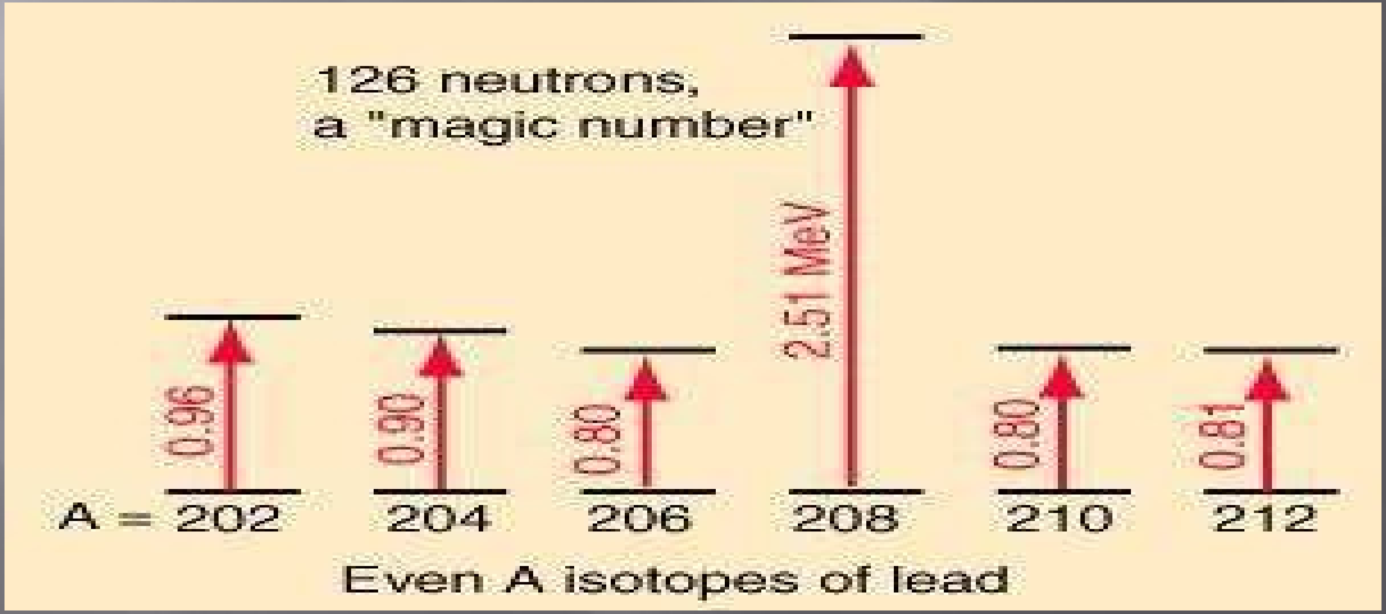
SPECIAL FEATURES OF MAGIC NUCLEI

- The neutron (proton) separation energies (the energy required to remove the last neutron(proton)) peaks if N (Z) is equal to a magic number.
- There are more stable isotopes if Z is a magic number, and more stable isotones if N is a magic number

- If N is magic number then the cross-section for neutron absorption is much lower than for other nuclides.

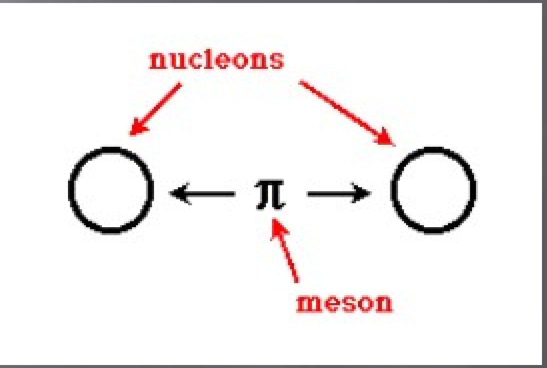


- The energies of the excited states are much higher than the ground state if either N or Z or both are magic numbers.



Meson Theory of Nuclear Forces

The forces between nucleons involves exchange of particles called pi mesons.



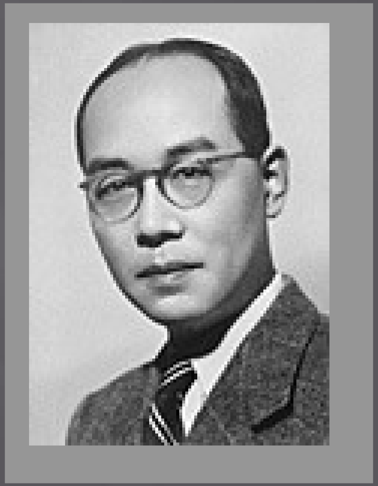
The word pion is a contraction of the original name meson.

Today these particles are called pions. Pions may be charged (π^+ , π^-)
or neutral (π^0),

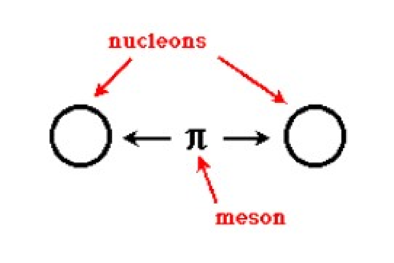
The pi meson is a short-lived, relatively heavy particle (about 250 times the mass of an electron). In fact, it is so short-lived that we never have time to “catch” a proton or neutron lacking a meson.

Mesons were predicted as the basis of nuclear forces by Yukawa in 1934. Experimental verification came in 1937.

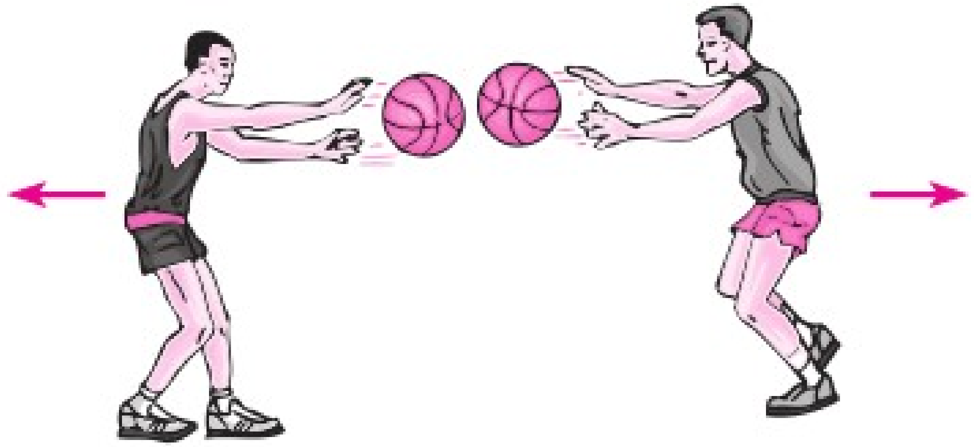
Yukawa was awarded the Nobel prize in 1949 for his theory.



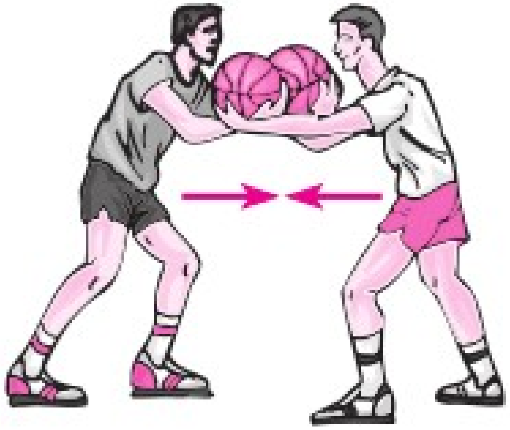
- Every nucleon continually emits and reabsorbs pions. If another nucleon is nearby, an emitted pion may shift across to it instead of returning to its parent nucleon.



- The associated transfer of momentum is equivalent to the action of a force.
- Nuclear forces are repulsive at very short range as well as being attractive at greater nucleon-nucleon distances; otherwise the nucleons in a nucleus would mesh together.
- The meson theory of such forces can account for both these properties..
- Let us understand this using some rough analogy..



Repulsive force due to particle exchange



Attractive force due to particle exchange

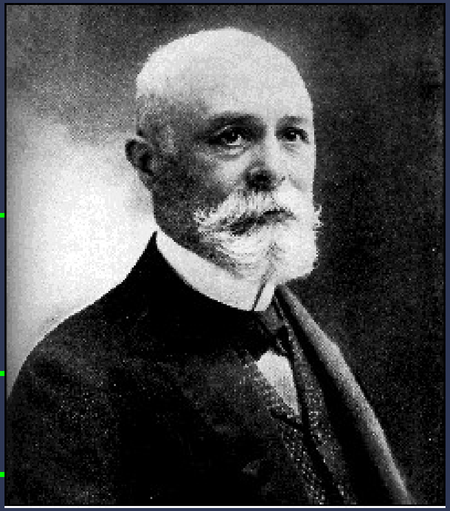
If nucleons are “held together” by the exchange of pi mesons, explain the other forces in nature. You can’t have one force due to particle exchange but not the others.

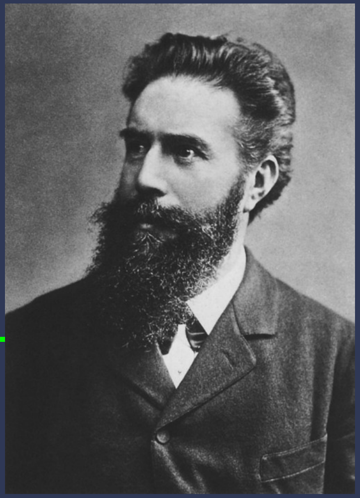
Sure! Gravity—the attractive force between any two masses—is due to exchange of gravitons.

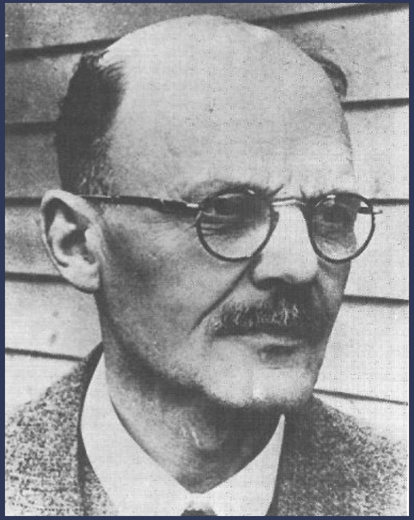
We haven’t found any gravitons yet (gravity is an incredibly weak force). That’s OK. I believe the theory.

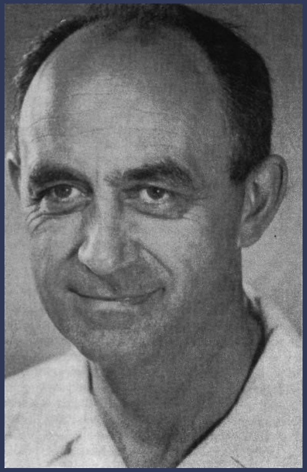
The weak force—another nuclear force—is due to the exchange of vector bosons.

Pioneers of Radioactivity



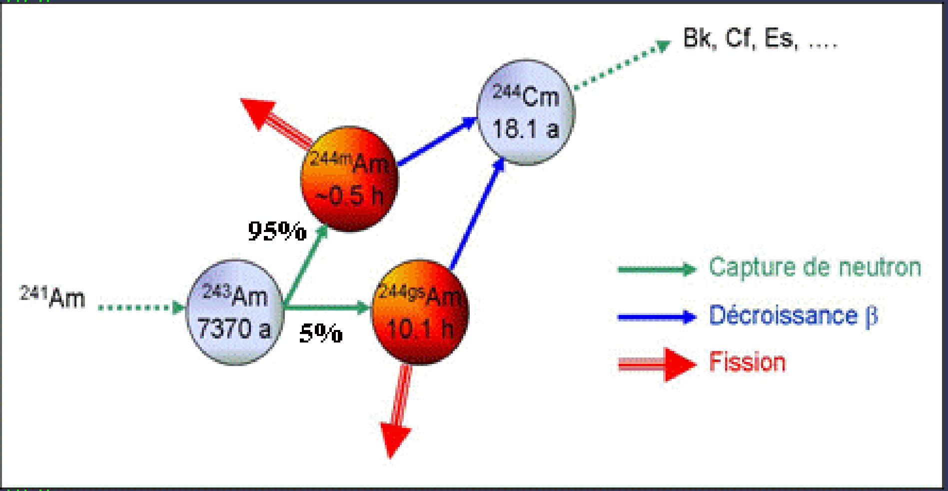






Clockwise from left: Wilhelm Roentgen, Henri Becquerel, Marie and Pierre Curie, Hans Geiger, and Enrico Fermi.

What happens to a radioactive nucleus?



- A nuclear reaction is a change in the nucleus.
- A transmutation is a type of change where the identity of the atoms changes.
- What would change the identity of an atom?

Nuclear Reaction Examples

$$^{9}_{4}Be + ^{4}_{2}He \longrightarrow ^{12}_{6}C + ^{1}_{0}n$$

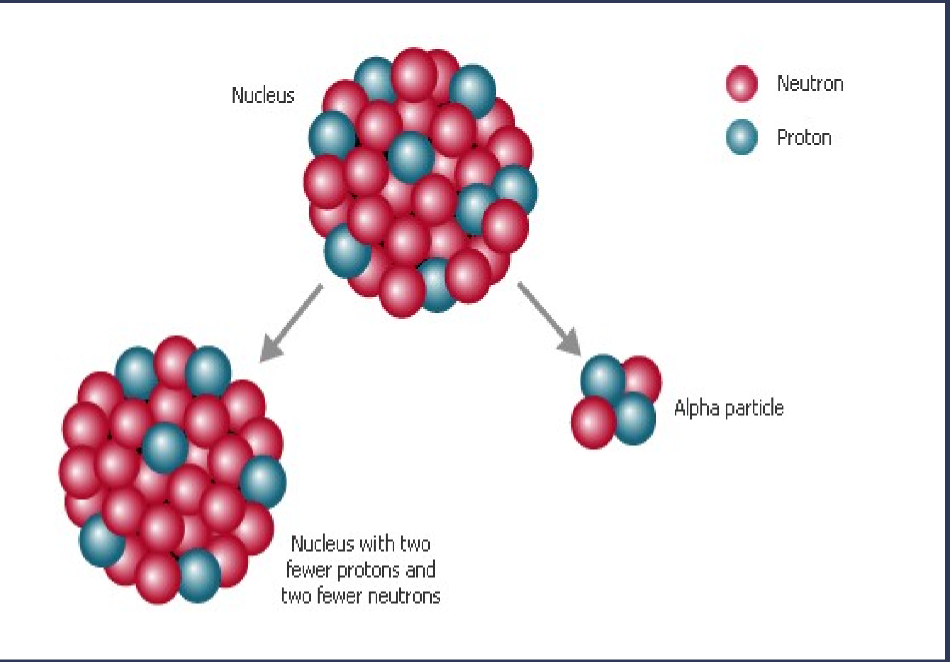
$$^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$$

$$^{14}_{6}C \longrightarrow ^{14}_{7}N + ^{0}_{-1}e$$

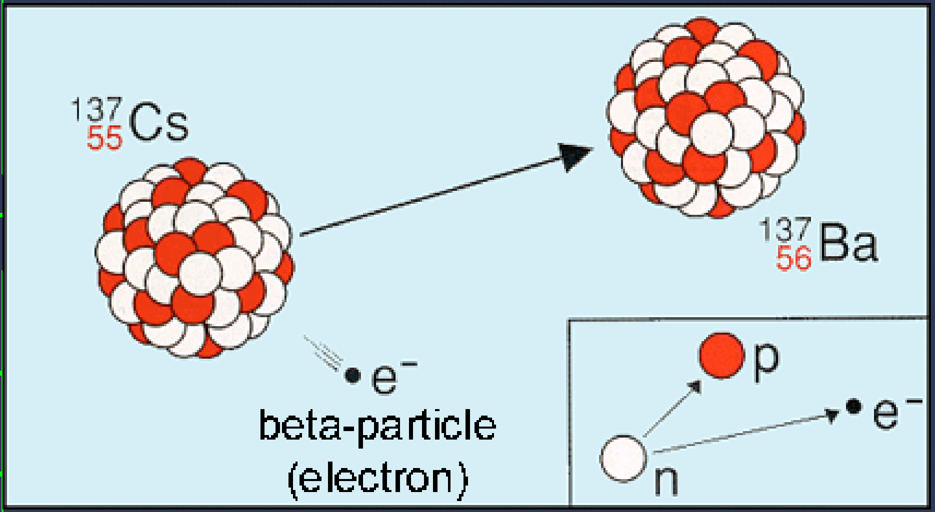
In each example the total mass number and atomic number is conserved!

Alpha Decay

- Alpha decay of a nucleus produces a lighter nucleus and an alpha particle.
- Mass # -4
- Atomic # -2
- An alpha particle (α) is made up of 2 protons and 2 neutrons.

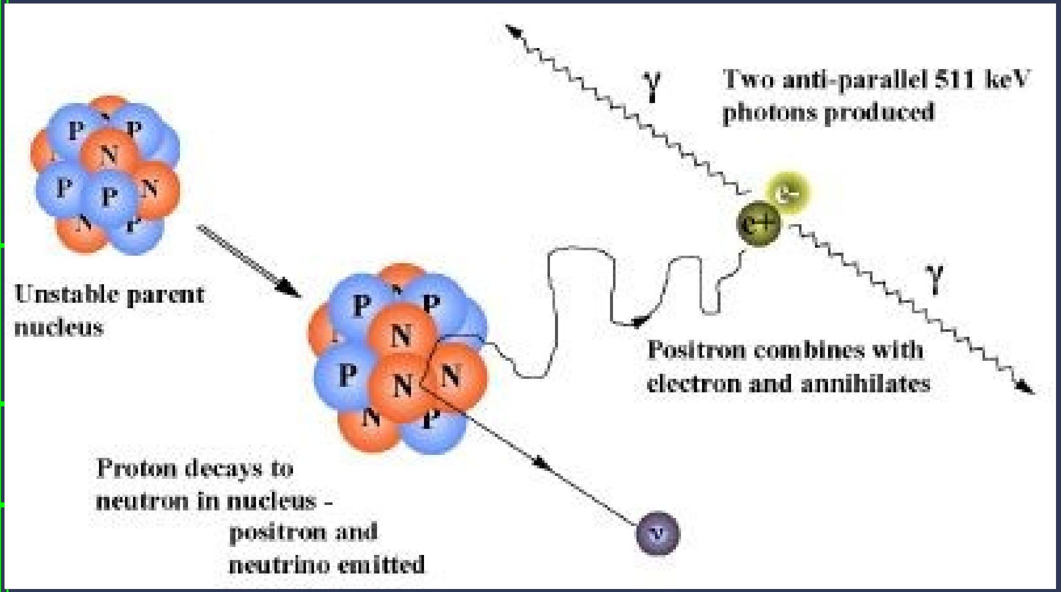


Beta Decay



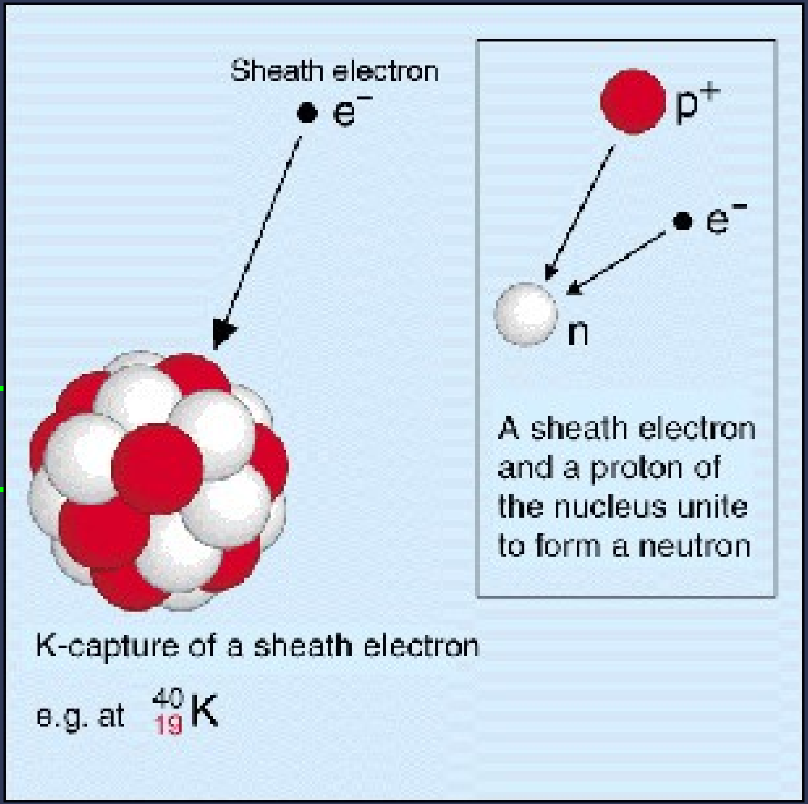
- Beta decay of a nucleus results in a new element (atomic number +1) with the same mass and a beta particle.
- A beta particle (β) is the same as an electron.

Positron emission



- A positron is an antimatter particle – a “positive electron”
- Mass unchanged
- Atomic number decreases by 1
- PET scans – Positron Emission Tomography

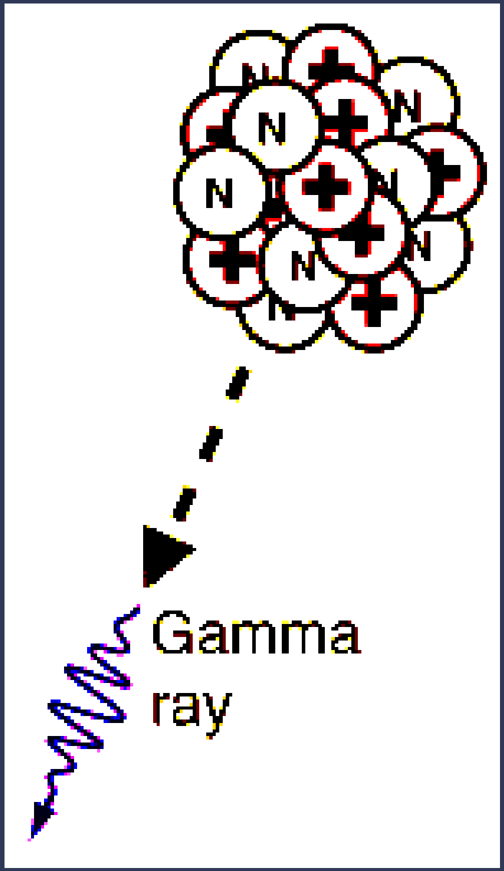
Electron Capture



- Electron captured by its own nucleus
- Mass unchanged
- Atomic number goes down by 1

Gamma Decay

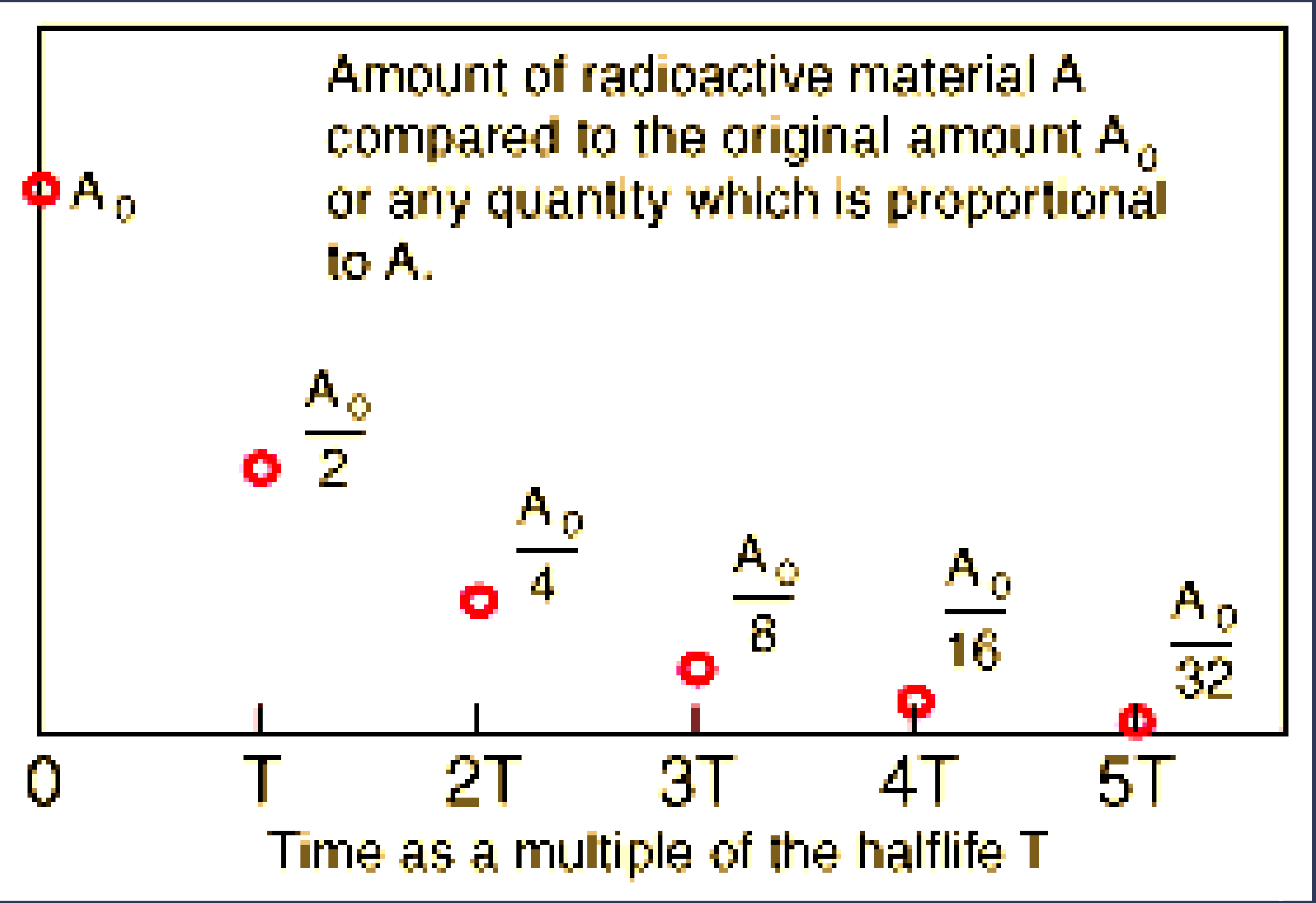
- During Gamma (γ) decay only energy is released from the nucleus.
- Gamma decay often follows other types of changes.



Rate of Decay

- Half-life is the term used to describe the time needed for half the atoms in a sample of radioactive material to change.
- Half-life times can vary greatly:
  - Cobalt – 60 10.5 minutes
  - Carbon – 14 5715 years
  - Uranium – 238 4.5 billion years

Half – life Diagram



Half life calculation

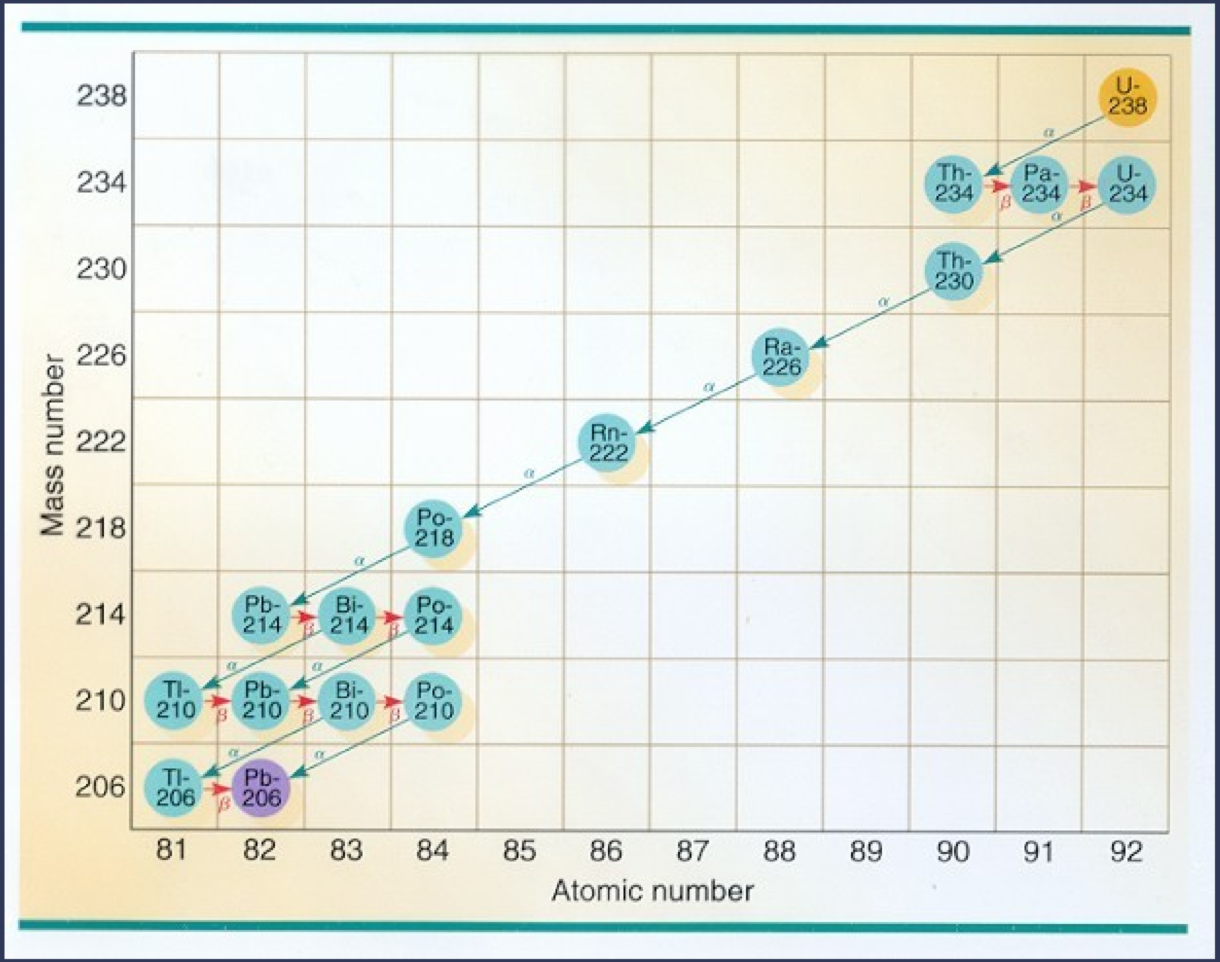
$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

Example:

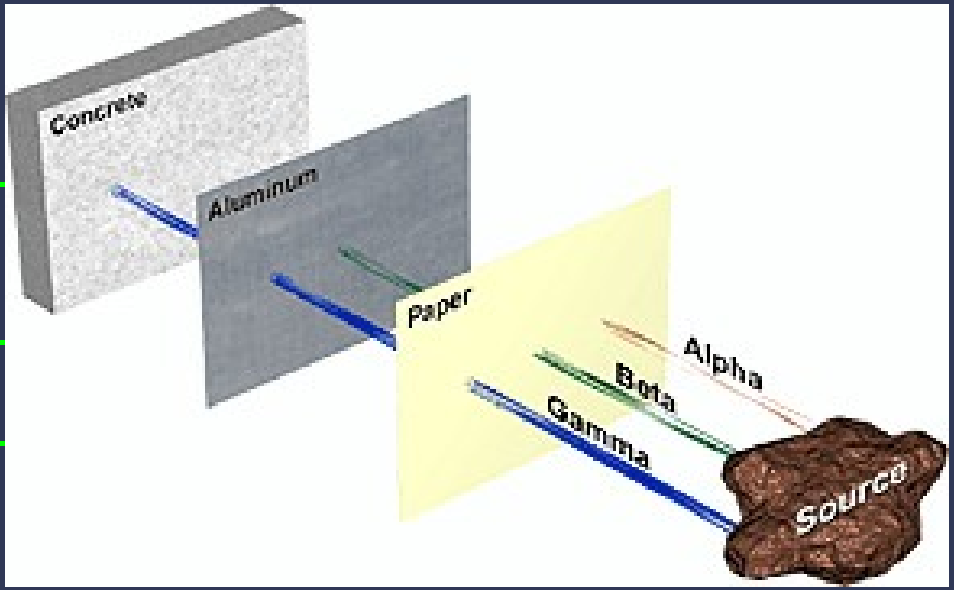
The decay constant of the radionuclide whose half-life is 5.00 h is therefore

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{(5.00\ \text{h})(3600\ \text{s/h})} = 3.85 \times 10^{-5}\ \text{s}^{-1}$$

Decay Series



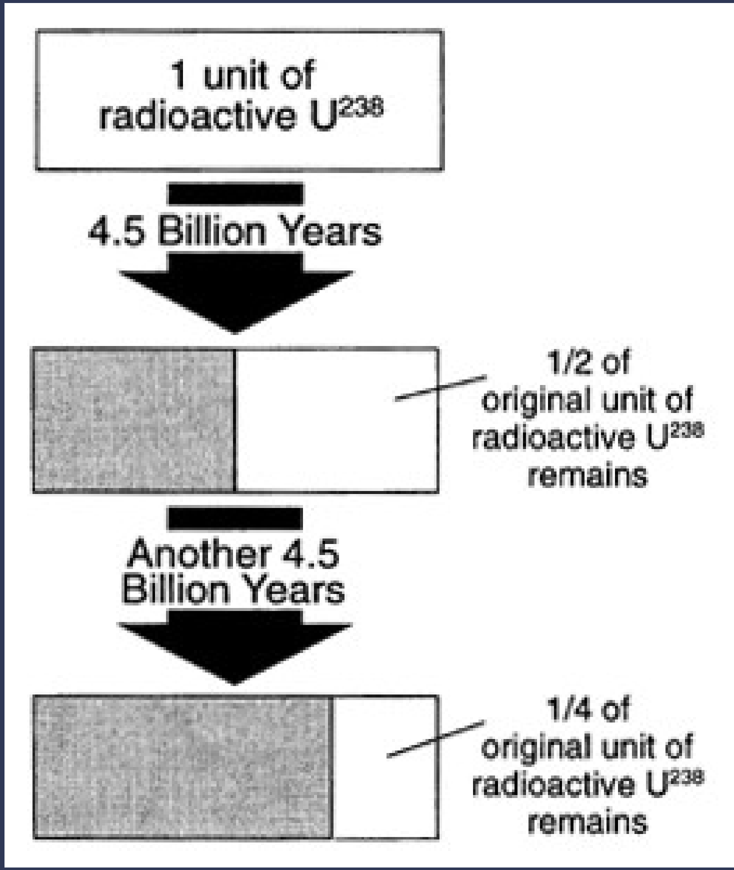
Radiation exposure



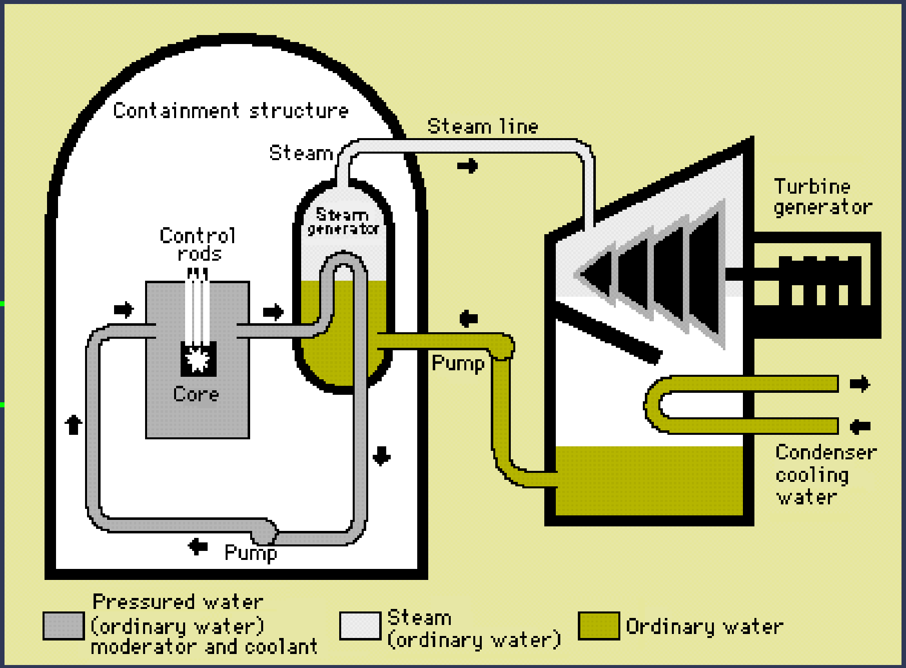
- Alpha – low energy, don’t penetrate
- Beta – higher energy, penetrate, short range
- Gamma – much higher energy, hard to stop.

Radioactive Dating

- Determining the approximate age of a material by measuring the amount of radioactive material left over and comparing it to the amount that has changed.
- This allows us to estimate the age of rocks, organic materials and the Earth!
- Because the decay of any particular radionuclide is independent of its environment, the ratio between the amounts of that nuclide and its stable daughter in a specimen depends on the latter's age.
- The greater the proportion of the daughter nuclide, the older the specimen.



Energy(Fusion and/or Fission)

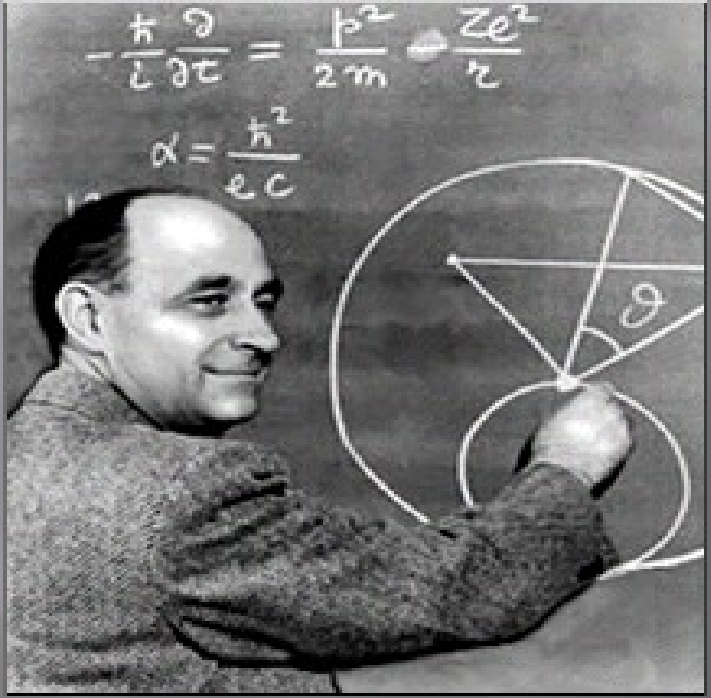


- Nuclear power plants use heat from nuclear reactions to generate electricity.
- Process uses
  - Fuel rods
  - Control rods
  - Moderators

History of Nuclear Power

- James Chadwick first identified free neutrons in 1932.
- These neutrons were relatively heavy and able to plough through electrons surrounding the nucleus of other atoms
- Neutrons are electrically neutral and are not deflected by positive nuclear charge

Enrico Fermi



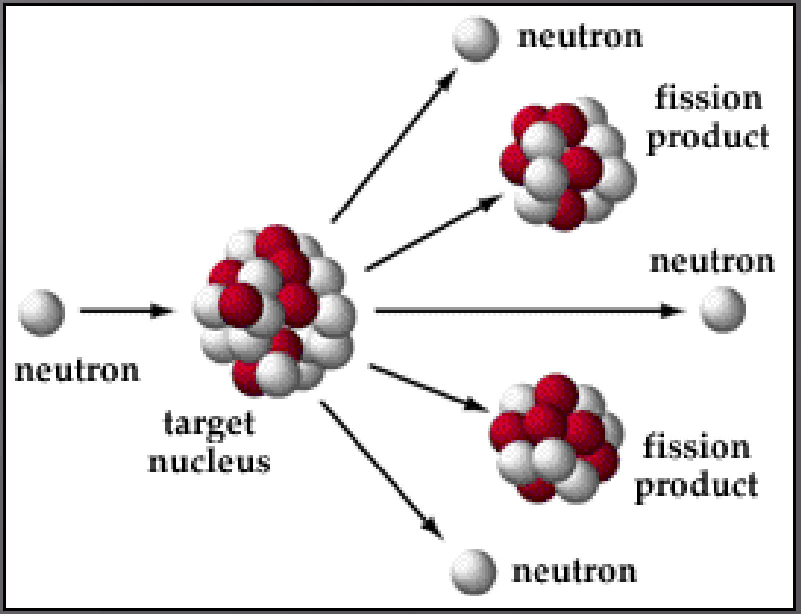
- Discovered that firing neutrons at elements caused them to become radioactive and emit β-particles.
- Nuclear Tranformation can take place in every elements.

Discovery of Nuclear Fission

- 1939 –Lise Meitner and Otto Frisch proposed that the splitting of a heavy nucleus by way of absorbing a neutron, caused the atom to become unstable and split into two lighter nuclei.
- This process was called Nuclear Fission and they observed that this reaction released a great deal of energy.

Nuclear Fission

- Fermi later discovered that the fission reaction might release free neutrons which could cause further fission reactions
- A chain reaction could occur releasing a great deal of energy in a short time, a nuclear explosion.



Enrichment

- Niels Bohr was the first to establish that the U-235 isotope readily underwent fission, but the U-235 isotope is “diluted” in natural uranium by 140 atoms of U-238
- Enrichment was a way to increase the proportion of U-235 and aid in the chain reaction.

NUCLEAR FISSION

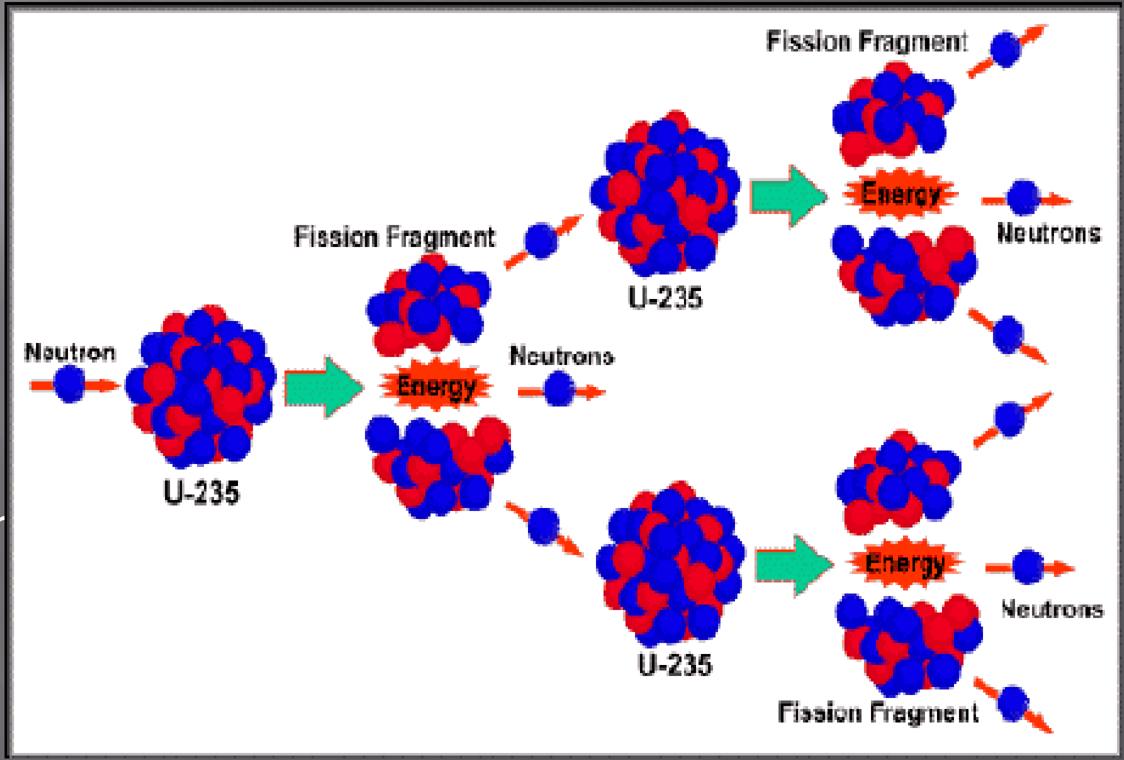
“A mechanism by which a heavy nucleus absorbing a neutron might become unstable and split into two lighter nuclei.”

Inducing Fission

- Absorption of a free Neutron
  - free protons / other nuclei can also induce fission
- Easiest in Heavy elements
  - fission in elements heavier than Fe → Output E
  - fission in elements lighter than Fe → Input E
- Abundance / Easy of Fission:
  - Uranium heaviest naturally occurring element
  - Plutonium undergoes spontaneous fission

Chain Reaction

- Initiation → 2 or more neutrons → neutrons escape/initiate more fission.
- High Concentration of U-235 required to maintain chain reaction



Source: ThinkQuest '98

Animation of Fission & Chain Reaction

- Critical Mass- *The amount of material of a given shape and volume to maintain a chain reaction*

Source: Energy systems & sustainability

Products of Fission

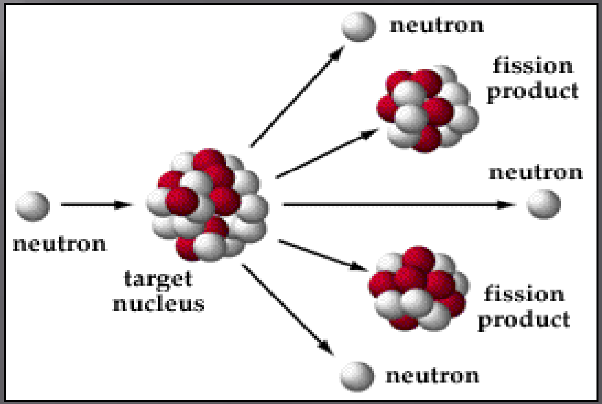
- 2 new radioactive nuclei
- 2 or 3 free neutrons
- Heat / Gamma Radiation
- ENERGY

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{139}_{56}Ba + {}^{94}_{36}Kr + 3\,{}^{1}_{0}n$$

Source: Nuclear Fission and Nuclear Fusion

Where does the Energy come from?

- Sum of Mass of products < Original Mass
- “Missing” Mass (~0.1% of Original Mass) has been converted to energy
- E=Δmc^2



- U235 + n → fission + 2 or 3 n + 200 MeV

Source: Think Quest

Nuclear Fusion

- *“the comming together of two lighter nuclei to form one heavier one*
- Process that powers the stars
- Original source of almost all of earths energy

Source: Joint European Torus (JET)

Nucleosynthesis

Nucleosynthesis is the process of element (nuclei) formation.

Three types: Big Bang nucleosynthesis
Stellar (star) nucleosynthesis
Supernova nucleosynthesis

Today, only stellar and supernova nucleosynthesis are occurring in our universe.

Element formation in our universe relies on **nuclear fusion** reactions.

(*fusion* = come together)

When nuclei collide, some of the mass of the nuclei is converted to energy by Einstein's famous equation, $E=mc^2$. Nuclear fusion releases a lot of energy per gram of material; much more energy than is released by burning a comparable amount of wood, coal, oil, or gasoline!

Origin of elements

- The Big Bang: H, D, ^{3,4}He, Li
- All other nuclei were synthesized in stars
- Stellar nucleosynthesis $\Leftrightarrow$ 3 key processes:
  - Nuclear fusion: PP cycles, CNO bi-cycle, He burning, C burning, O burning, Si burning $\Rightarrow$ till ^{40}Ca
  - Photodisintegration rearrangement: Intense gamma-ray radiation drives nuclear rearrangement $\Rightarrow$ ^{56}Fe
  - Most nuclei heavier than ^{56}Fe are due to neutron capture:
    - s-process, in which neutron addition is slow compared to β-decay
    - r-process, in which neutron addition is rapid compared to β-decay

Nuclear Reactions

$$^{A1}_{Z1}X + ^{A2}_{Z2}Y \Rightarrow ^{A3}_{Z3}A + ^{A4}_{Z4}B$$

$$\text{Conservation laws:} \begin{cases} A1 + A2 = A3 + A4 & \text{(mass numbers)} \\ Z1 + Z2 = Z3 + Z4 & \text{(atomic numbers)} \end{cases}$$

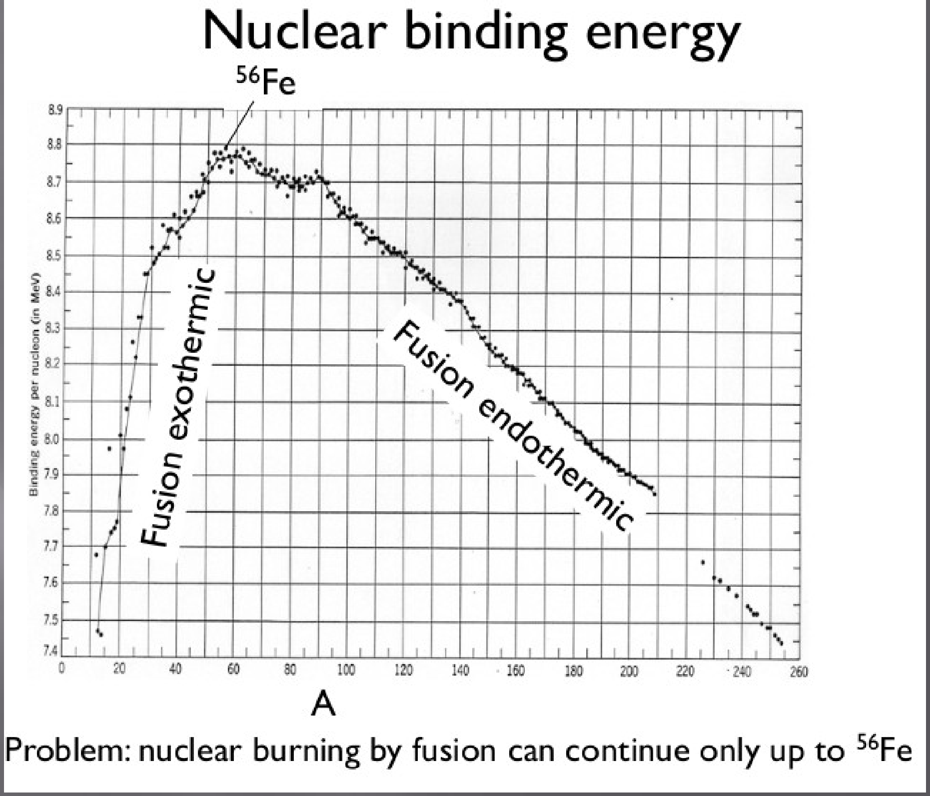
Amount of energy liberated in a nuclear reaction (Q-value):

$$Q = [\underbrace{(m_1 + m_2)}_{\text{initial}} - \underbrace{(m_3 + m_4)}_{\text{final}}]c^2$$

$Q > 0$: exothermic process (release of energy)

$Q < 0$: endothermic process (absorption of energy)

- Fusing light elements is enegitically advantageous.
- In 1920, an english Astronomer showed that fusing of 4 H atoms onto He would release 7MeV/nucleon, i.e. about 28MeV in all.
- This work started the understading of of energy given by stars particulary by SUN.
- By 1939, nucelar reactions were well understoodand Hense Bethe proposed a set of reactions by whihc H might be converted into He in the SUN



Hydrogen Burning

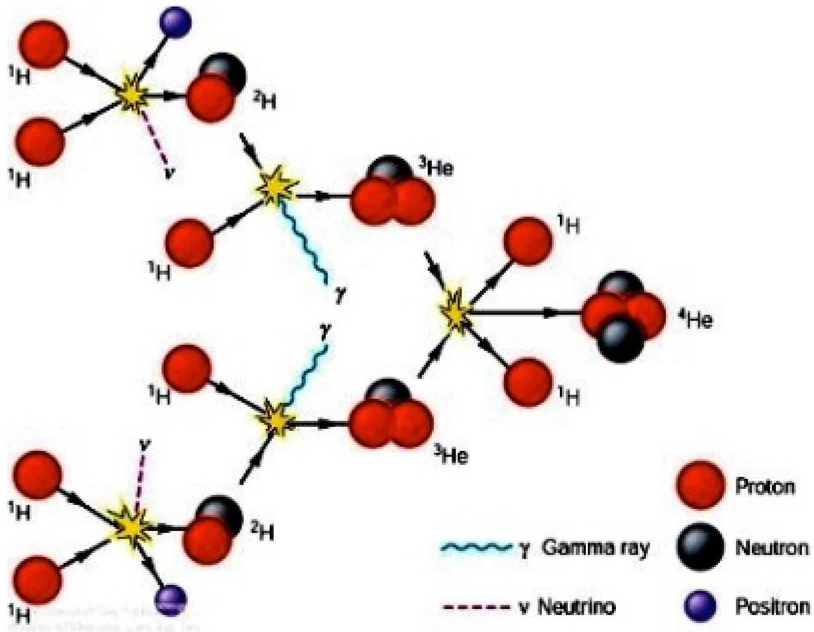
- PP-I cycle, $T > 4 \times 10^6$ K: $4\ ^1H \Rightarrow {}^4He$:

  $2\ (^1H + {}^1H = {}^2D + \beta^+ + \nu_e + 0.42\ \text{MeV})$

  $(\beta^+ + \beta^- = \gamma + 1.02\ \text{MeV})$

  $2\ (^1H + {}^2D = {}^3He + \gamma + 5.49\ \text{MeV})$

  ${}^3He + {}^3He = {}^4He + 2\ {}^1H + 12.86\ \text{MeV}$



- PP-II cycle, $T > 14 \times 10^6$ K:

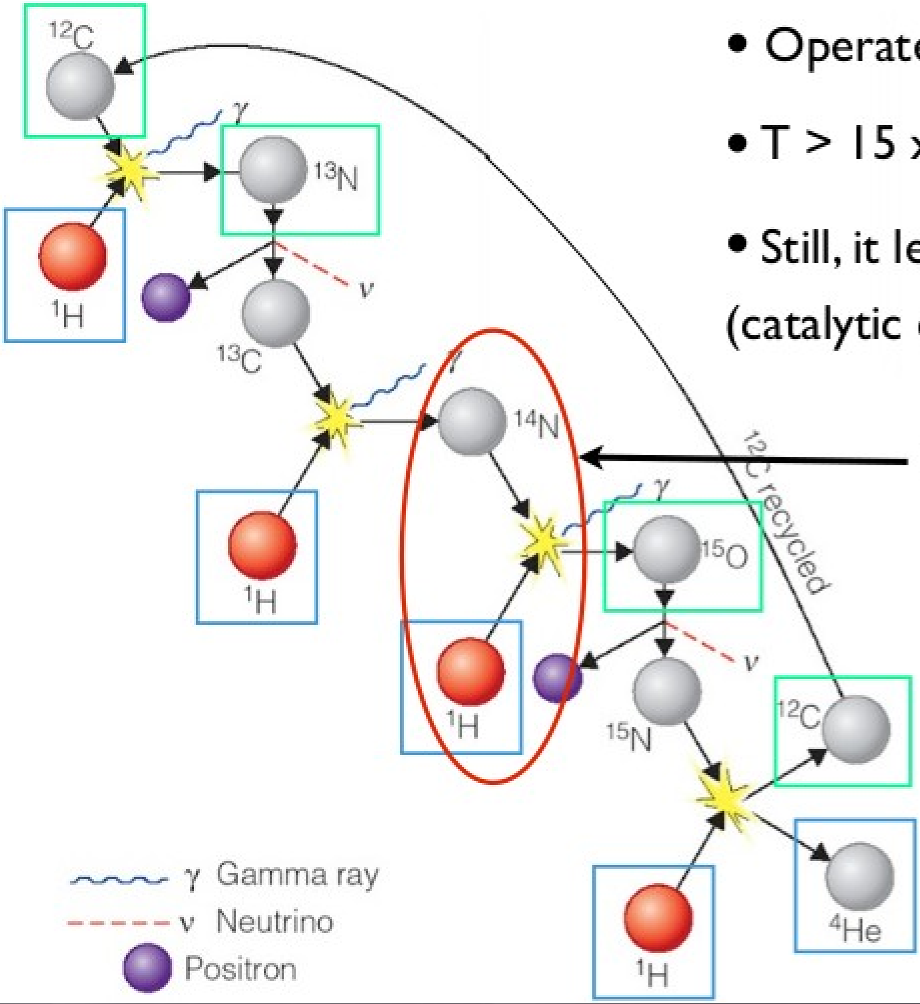
  ${}^3He + {}^4He = {}^7Be + \gamma$

  ${}^7Be + \beta^- = {}^7Li + \nu_e$

  ${}^7Li + {}^1H = 2\ {}^4He$

- In the Sun, PP-I = 86 %, PP-II = 14 %

The CNO Cycle



- Bethe–Weizsäcker cycle
- Operates in stars with $M > 1.3\ M_{sun}$
- $T > 15 \times 10^6$ K
- Still, it leads to: $4\,^1H \rightarrow {}^4He$ + energy (catalytic cycle)

limiting (slowest) step

Carbon cycle-CNO cycle

$$ {}^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{13}_{7}\mathrm{N} + Q $$

$$ {}^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{+1}e $$

$$ {}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{14}_{7}\mathrm{N} + Q $$

$$ {}^{14}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{15}_{8}\mathrm{O} + Q $$

$$ {}^{15}_{8}\mathrm{O} \rightarrow {}^{15}_{7}\mathrm{N} + {}^{0}_{+1}e $$

$$ {}^{15}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} $$

$$ 4\left({}^{1}_{1}\mathrm{H}\right) \rightarrow {}^{4}_{2}\mathrm{He} + 2\left({}^{0}_{+1}e\right) + 24.7\ \mathrm{MeV} $$

$$ Q\left(4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He}\right) = 26.7\ \mathrm{MeV} $$

Possibilities of Controlled Fusion

$$ {}^{2}_{1}\mathrm{H}\left({}^{2}_{1}\mathrm{H},\ {}^{1}_{1}\mathrm{H}\right){}^{3}_{1}\mathrm{H} \quad Q = 4.02\ \mathrm{MeV} $$

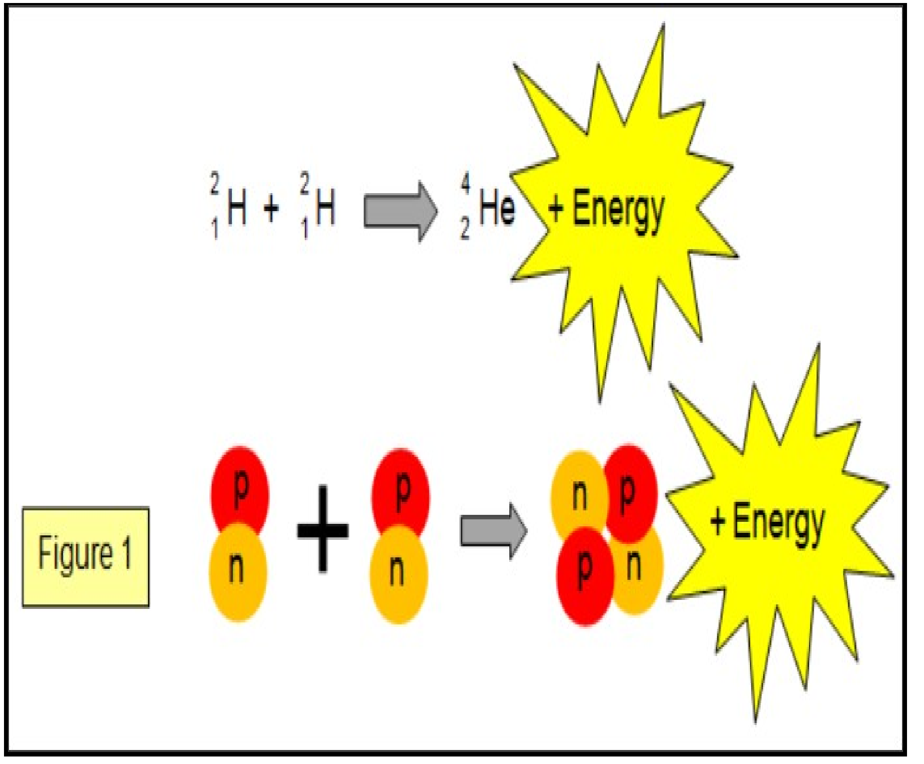
$$ {}^{3}_{1}\mathrm{H}\left({}^{1}_{1}\mathrm{H},\ \gamma\right){}^{4}_{2}\mathrm{He} \quad Q = 19.6\ \mathrm{MeV} $$

$$ {}^{6}_{3}\mathrm{Li}\left({}^{2}_{1}\mathrm{H},\ {}^{4}_{2}\mathrm{He}\right){}^{4}_{2}\mathrm{He} \quad Q = 22.4\ \mathrm{MeV} $$

$$ {}^{7}_{3}\mathrm{Li}\left({}^{1}_{1}\mathrm{H},\ {}^{4}_{2}\mathrm{He}\right){}^{4}_{2}\mathrm{He} \quad Q = 17.3\ \mathrm{MeV} $$

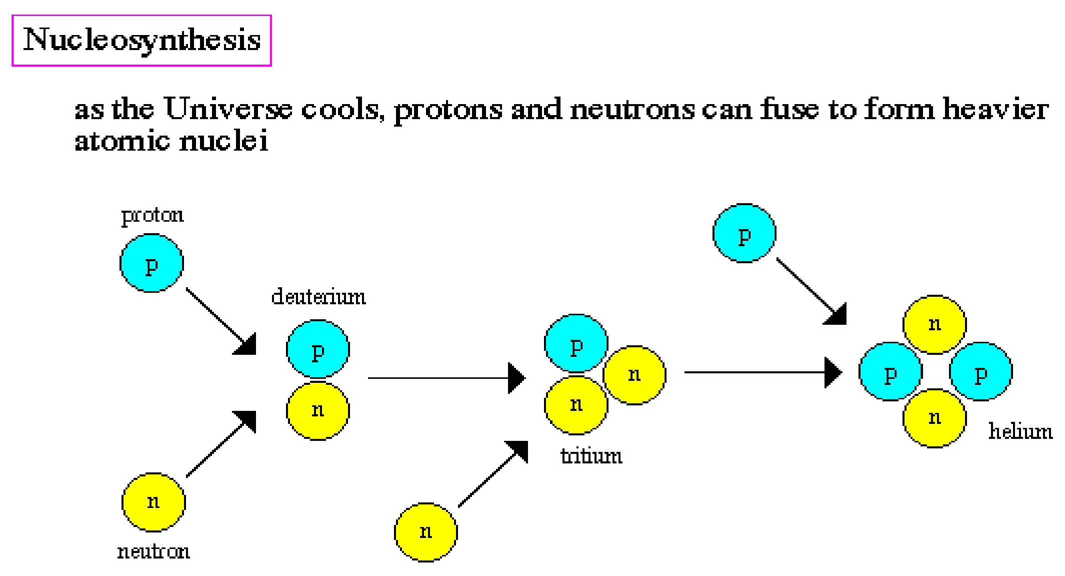
Nuclear Fusion

- In **nuclear fusion**, smaller nuclei collide together to make larger nuclei, and energy is released in the form of electromagnetic radiation.
- Requires extremely high temperatures and pressures beyond those found on or within Earth. However, these temperatures and pressures are found inside stars and did occur during the initial formation of our universe (during the **Big Bang** event).
- Fusion involves only the *nuclei* of atoms. At the temperatures at which fusion can occur, matter exists as a *plasma*. This is the state of matter where the electrons have been stripped off of the atoms. *Plasma* is basically a super high energy, electrically charged gas.
- When nuclei collide, some of the mass of the nuclei is converted to energy by Einstein's famous equation, $E=mc^2$. Nuclear fusion releases a lot of energy per gram of material; much more energy than is released by burning a comparable amount of wood, coal, oil, or gasoline!



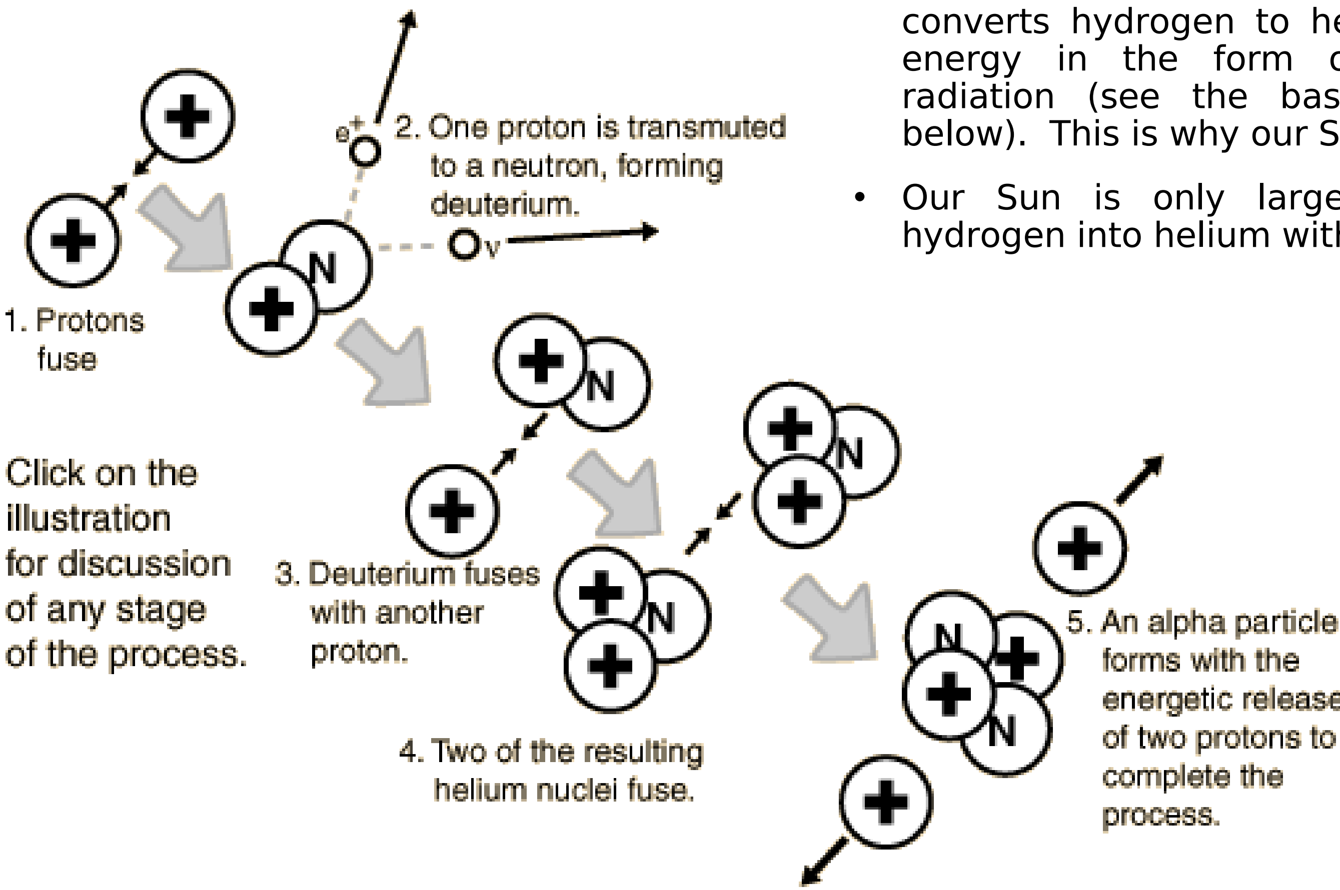
Big Bang Nucleosynthesis

- *All Hydrogen and most Helium* in the universe was produced during the Big Bang Event, starting ~100 seconds after the explosion. A small amount of Lithium was also produced.

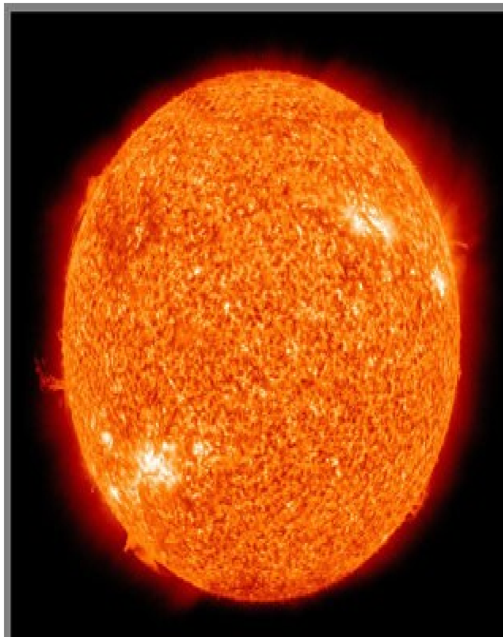


- Big Bang nucleosynthesis *ceased* within a few minutes after the Big Bang because the universe had expanded and cooled sufficiently by then such that the temperatures and pressures were too low to support additional nuclear fusion reactions.

Stellar Nucleosynthesis

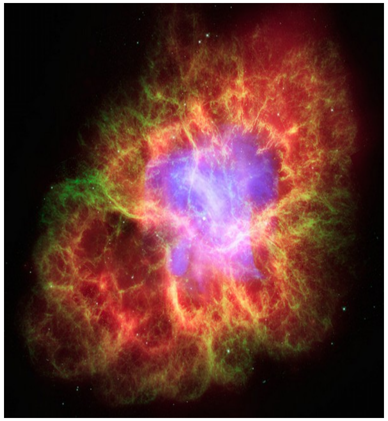


- A **star** is a very hot ball of gas (plasma). Stars create elements by combining lighter nuclei into heavier nuclei via nuclear fusion reactions in their cores and releasing energy in the process. They are natural nuclear reactors!
- Enormous temperatures (15,000,000 K), pressures, and densities of matter are needed to initiate the fusion (thermonuclear) reactions which squeeze nuclei together and release energy.
- The basic nuclear reaction in the Sun converts hydrogen to helium and releases energy in the form of electromagnetic radiation (see the basic fusion reaction below). This is why our Sun shines!
- Our Sun is only large enough to fuse hydrogen into helium within its core.

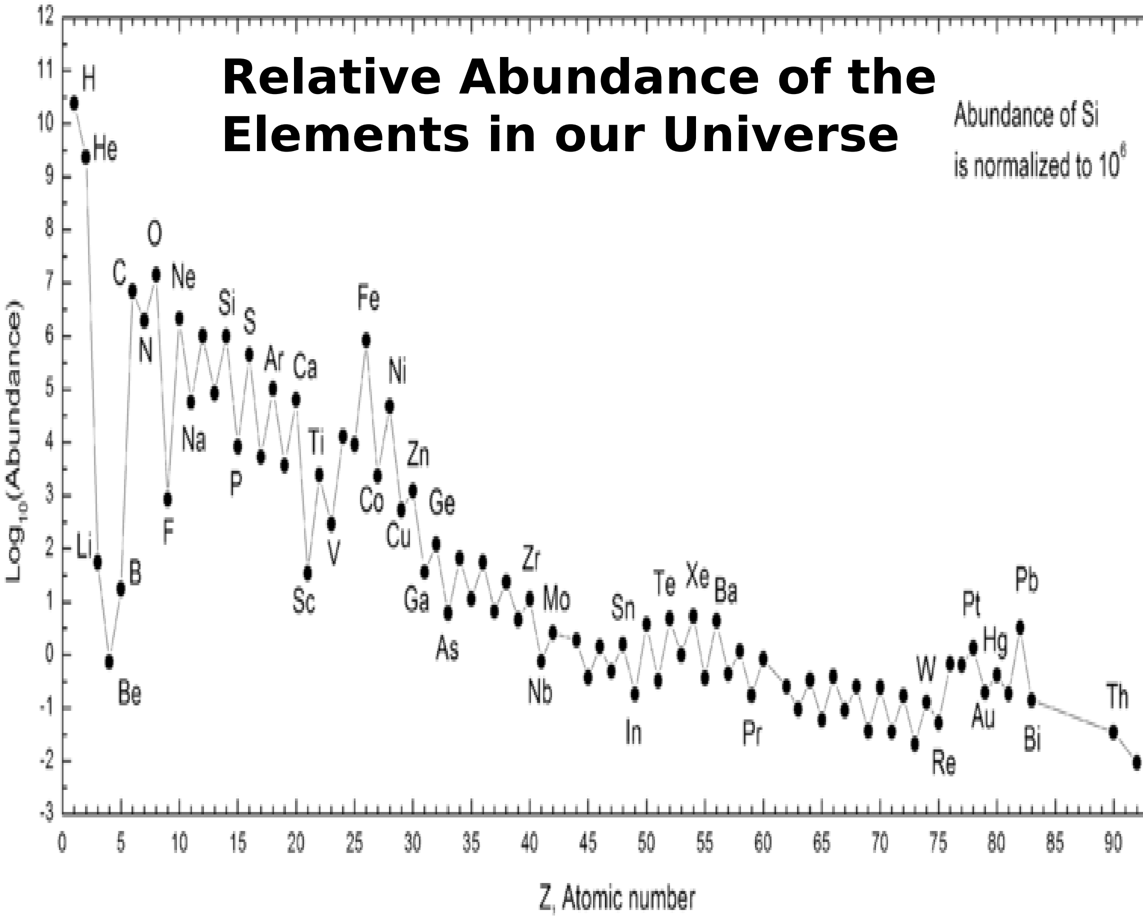


Supernova Nucleosynthesis

An exploded star (supernova)



- Elements heavier than Iron (Z = 26) are made primarily when giant stars explode in **supernovae**.
- Even the largest stars do not have core temperatures and pressures high enough to fuse iron into heavier elements. Therefore, when a star runs out of



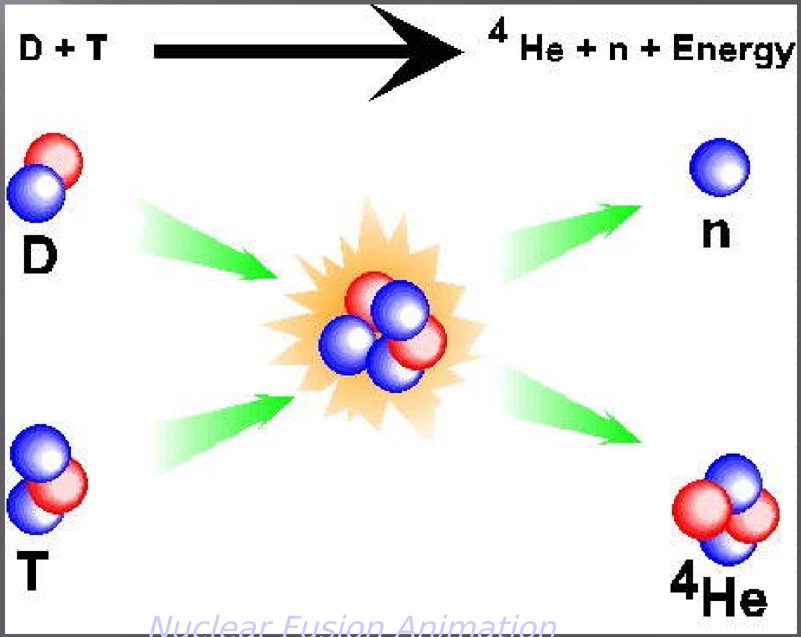
How Fusion works

- Most suitable reaction involves:
  - Deuterium (D)
  - Tritium (T)

    (Isotopes of Hydrogen)

- Temperatures of >10 million deg. C
- Plasma: State in which electrons have been removed from atomic nuclei

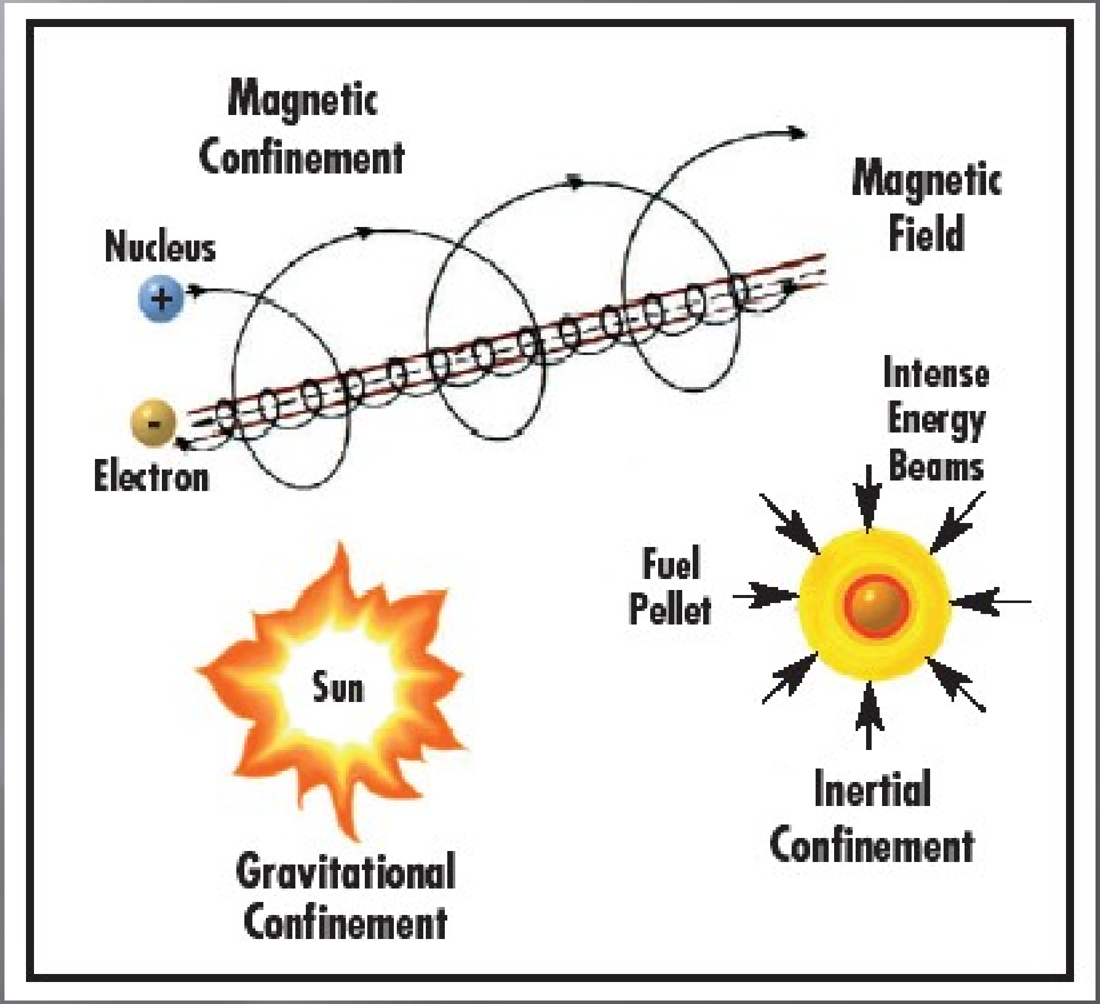
$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n $$



Nuclear Fusion Animation

Source: Joint European Torus (JET)

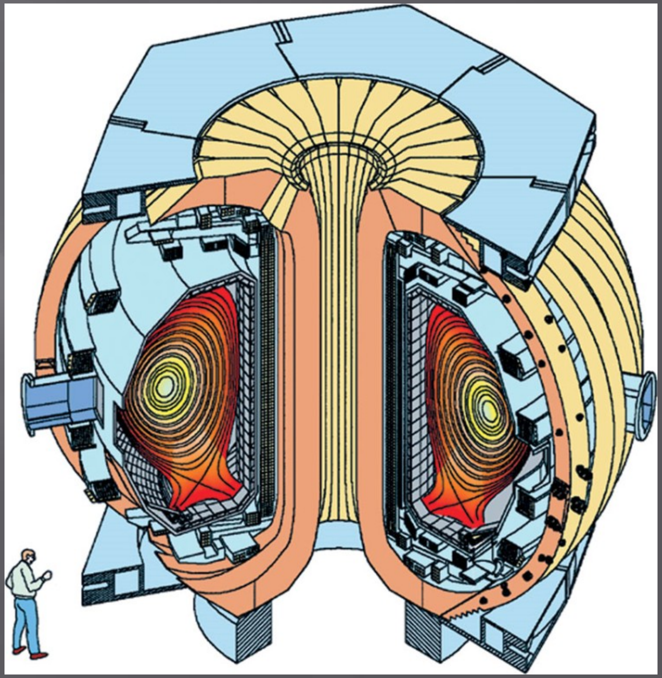
Means of Initiating Fusion:



Source: FusEdWeb: Fusion Energy Educational Web Site

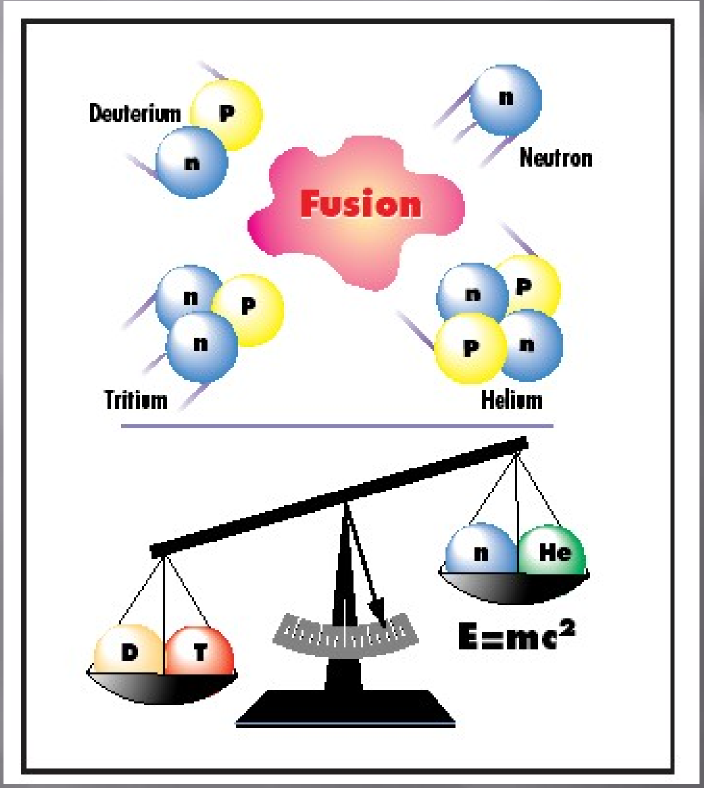
Fusion by Magnetic Confinement

- PLASMA is so high in energy it requires Magnetic Fields to contain it.
- Magnetic fields trap superheated fusion fuel in center of loop.
- Immense temperatures/pressures



Source: FusEdWeb: Fusion Energy Educational Web Site http://fusedweb.pppl.gov/

Why does Fusion yield Energy?



- Mass of Products is less than mass of reactants.
- E=mc^2
- mass converted to ***kinetic*** energy

Source: FusEdWeb: Fusion Energy Educational Web Site

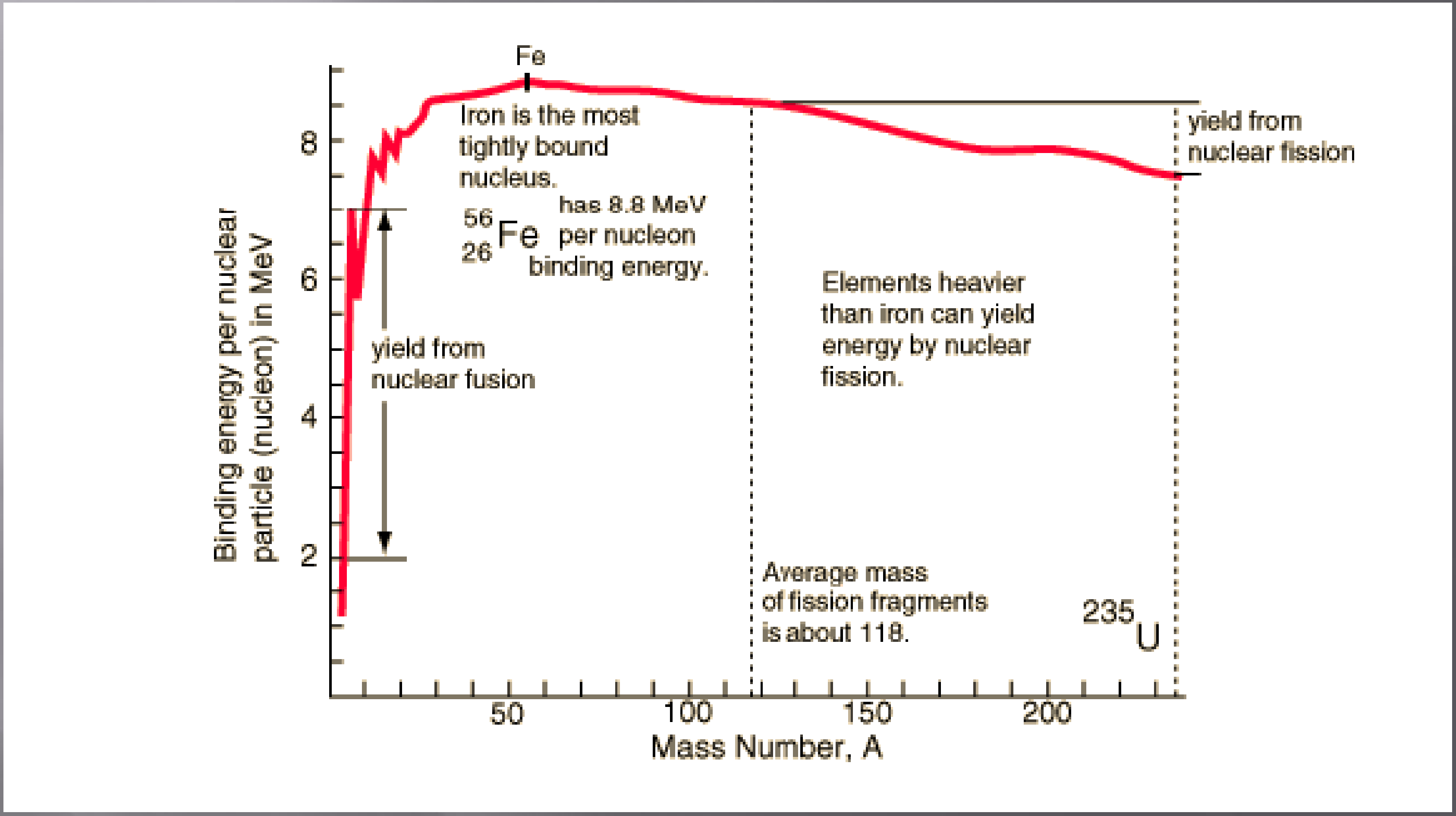
Where does Tritium & Deuterium Come from?

- Tritium:
  - Bombarding Lithium with a Neutron
- Deuterium:
  - Plentiful in ordinary water.
  - 1/6500 hydrogen atoms in water is Deuterium

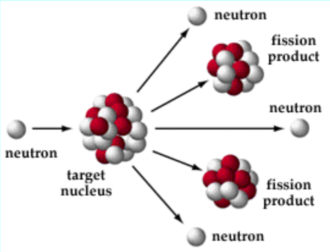
1 gallon of water conceivably has the energy content of 300 gallons of gasoline

Source: General Atomics
http://fusedweb.pppl.gov/

Yield of Fission vs. Fusion



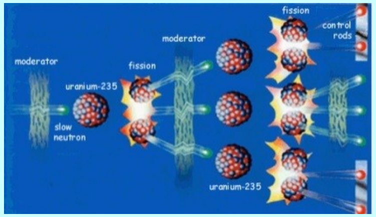
Source: General Atomics



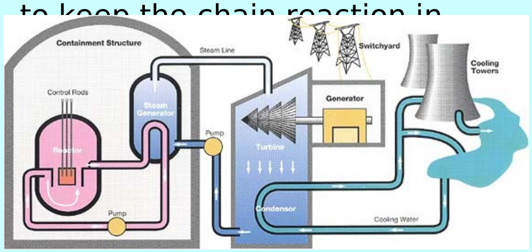
Fission is the release of energy by **splitting** heavy nuclei such as Uranium-235 and Plutonium-239

How does a nuclear plant work?

- Each fission releases 2 or 3 neutrons
- These neutrons are slowed down with a moderator to initiate more fission events
- Control rods absorb neutrons to keep the chain reaction in



Controlled Fission Chain Reaction



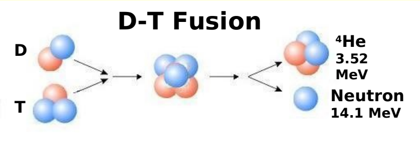
Nuclear Power Plant

The energy from the reaction drives a steam cycle to produce electricity

Nuclear Power produces **no greenhouse gas emissions**; each year U.S. nuclear plants **prevent** atmospheric emissions totaling:

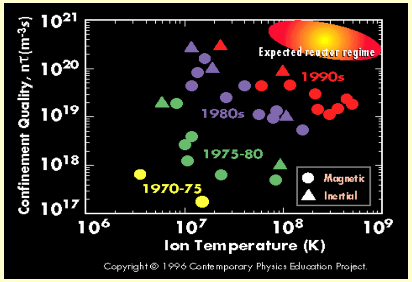
- 5.1 million tons of sulfur dioxide
- 2.4 million tons of nitrogen oxide
- 164 million tons of carbon

Nuclear power in 1999 was the ch
source of electricity costing 1.83 c/kWh
compared to 2.04 c/kWh from coal



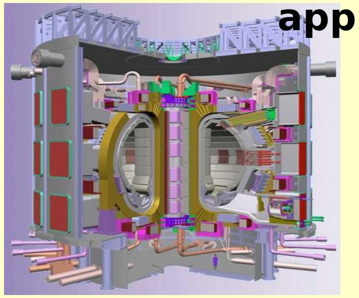
Fusion is the release of energy by **combining** two light nuclei such as deuterium and tritium

- The goal of fusion research is to confine fusion ions at high enough temperatures and pressures, and for a long enough time to fuse
- This graph shows the exponential rate of progress over the decades



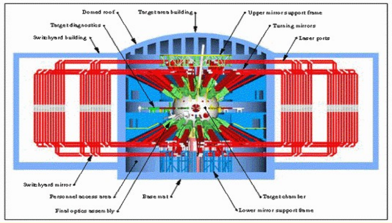
Confinement Progress

There are two main confinement approaches:

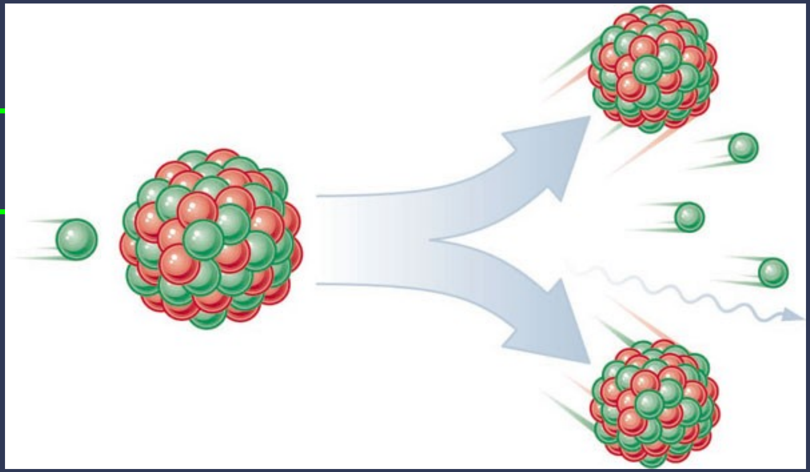


- Magnetic Confinement uses strong magnetic fields to confine the plasma
- This is a cross-section of the proposed International Thermo-nuclear Experimental Reactor (ITER)

- Inertial Confinement uses powerful lasers or ion beams to compress a pellet of fusion fuel to the right temperatures and pressures
- This is a schematic of the National Ignition Facility (NIF) being built at Lawrence Livermore National Lab



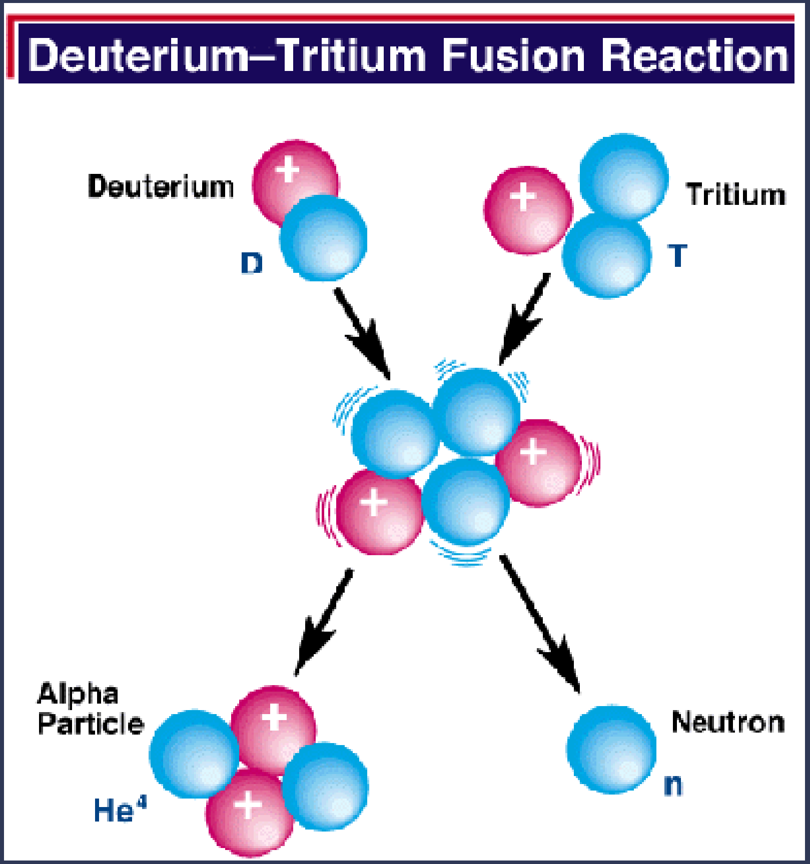
Fission



- In fission a heavy nucleus splits to form lighter nuclei with the release of energy.
- Fission may start a chain reaction where one split starts more.
- Fission is used in nuclear power plants.

Fusion

- In fusion lighter nuclei combine to form a heavier nucleus with the release of energy.
- Uncontrolled fusion is the process in more advanced nuclear weapons.
- Stars uses fusion to combine hydrogen atoms into helium. Energy is released.



Manhattan Project

- 1941- President Roosevelt put resources into the development of the “atomic bomb”
- This lead to further studies of nuclear fission and the discovery of the first controlled chain reaction. achieved by Fermi and a group of scientists at the University of Chicago

Small Steps Toward Power Production

- December 20, 1951 – experimental reactor produced enough power to light four 150 watt light bulbs
- July 17, 1955 - Argonne Lab designed first reactor to provide power for an entire town (Arco, Idaho).
- 1957 - The Atomic Energy Commission sponsored a 60 megawatt breeder reactor plant in Shippingport, PA.

First Commercial Power Plant

- 1959 – Dresden Unit One was built at a cost of $18 million in Morris, Illinois.
- 200 MW Duel Cycle Boiling Water Reactor
- Designed and operated by General Electric until 1979 when it was shut down.