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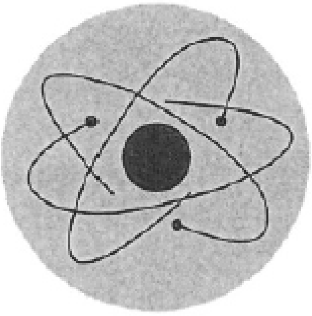
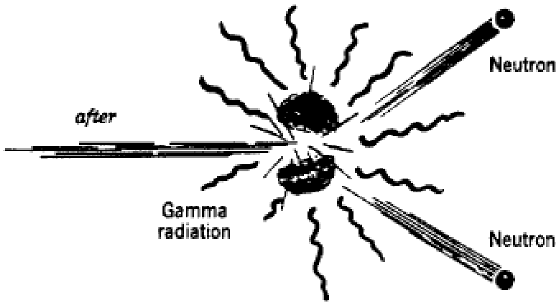


Fuel and Energy

Nuclear Energy

Dr.-Eng. Zayed Al-Hamamre



Content

The Equivalence of Matter and Energy

- The connection between energy and matter is provided by Einstein's theory of special relativity. It predicts that the mass of any object increases with its speed.
- Letting the mass when the object is at rest be m_0, the "rest mass," and letting m be the mass when it is at speed v

$$m = \frac{m_0}{\sqrt{1-(\upsilon / c)^2}}$$

Where the speed of light in a vacuum is $c = 3 \times 10^8$ m/s,

And the particle speed is very high, i.e., when several percent of *c.*

- The kinetic energy imparted to a particle by the application of force according to Einstein is

$$E_k = (m - m_0)\, c^2$$

The Equivalence of Matter and Energy

(For low speeds, $\upsilon \ll c$, this is approximately $\frac{1}{2} m\, \upsilon_0^2$, the classical relation.)

- For an electron,

mass 9.1×10^{-31} kg, the rest energy is

$$E_0 = m_0 c^2 = (9.1 \times 10^{-31})(3.0 \times 10^8)^2 = 8.2 \times 10^{-14} \text{ J}$$

$$E_0 = \frac{8.2 \times 10^{-14} \text{ J}}{1.60 \times 10^{-13} \text{ J / MeV}} = 0.51 \text{ MeV}$$

For one unit of atomic mass, 1.66×10^{-27} kg, (close to the mass of a hydrogen atom)

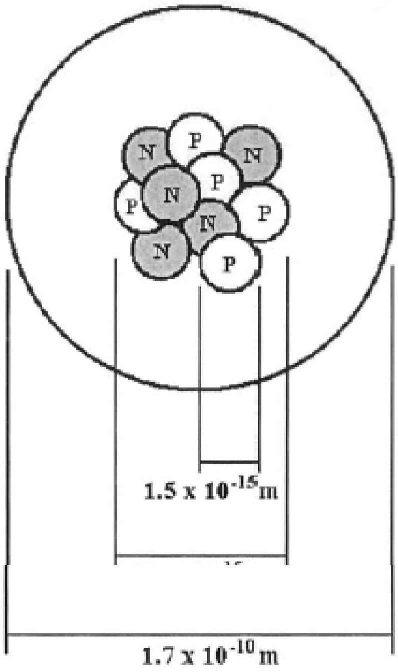
$$E_0 = 931 \text{ MeV}$$

The Equivalence of Matter and Energy

- The equation, is general, but it is especially important in calculating the release of energy by nuclear means.
- The energy yield from a kilogram of nuclear fuel is more than a million times that from chemical fuel.
- A small amount of mass corresponds to a large amount of energy (because the speed of light is large).

Atomic Theory

- Matter is composed of individual particles–atoms–that retai their identity as elements in ordinary physical and chemical interactions.
- Thus a collection of helium atoms that forms a gas has a total weight that is the sum of the weights of the individual atoms.
- The nucleus of an atom is composed of two types of particles, protons and neutrons, collectively called nucleons.
- A nucleus is characterized by its atomic number and atomic mass number, size, shape, binding energy, angular momentum, and stability
- Most of the mass and positive charge of an atom were concentrated in a *nucleus.*



Sizes and Masses of Nuclei

- The radius of any nucleus can be approximated using the *Fermi model:*

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

where A represents the atomic mass number, and $R_0 = 1.07$ fm.

And the nuclear volume is

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi R_0^3 A = V_0 A$$

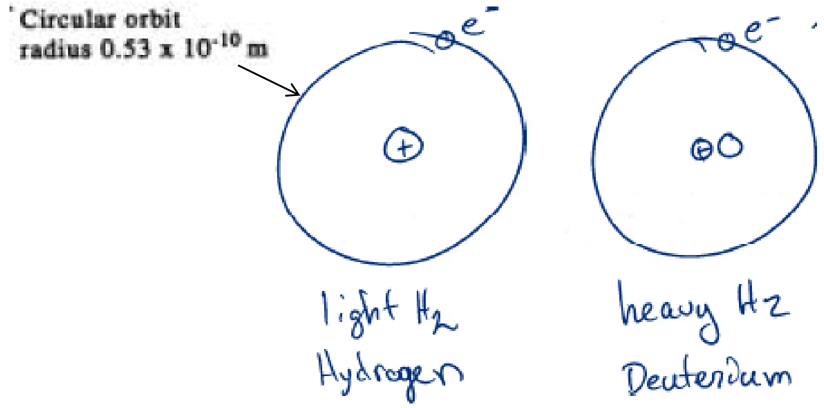
Volume per nucleon, V_0 is approximately the same for all nuclei.

Sizes and Masses of Nuclei

$\oplus$ proton

○ neutron

$\ominus$ electron, e^-



neutron mass : 1.008665 amu ← atomic mass units

proton mass . 1.007825 amu

electron mass : 0.0005486 amu

$$amu \equiv 1.66 \cdot 10^{-27}\,kg = 3.66 \cdot 10^{-27}\,lbm = \frac{1}{12}\text{ mass C-12 atom}$$

$$1\,amu = 931.5\,MeV\ (mc^2) \simeq \frac{1}{AV\#}$$

Nuclear Structure

nuclear symbol : $^{A}_{Z}X$

A ≡ Mass Number ≡ # of nucleons = protons + neutrons

Z ≡ Atomic Number ≡ # of protons

Hydrogen : $^{1}_{1}H$

Deuterium : $^{2}_{1}H$

Helium : $^{4}_{2}He$

helium - 4

He - 4

$_{2}He^{4}$

Chemical & Physical Properties dictated by # of protons

Nuclear Properties dictated by # of neutrons

Isotopes

- Most elements are composed of particles of different weight, called isotopes.

Natural Uranium

99.282 mass % $^{238}_{92}U$

0.712 mass % $^{235}_{92}U$

0.006 mass % $^{234}_{92}U$

Atomic # 92

- many isotopes do not occur naturally
- created in labs & nuclear reactors

14 known isotopes of Uranium

ranging from 227–240

$^{A}_{Z}X$

Radioactivity (Radioactive Decay)

- Radioactivity is the spontaneous emission of particles or energy from an atomic nucleus as it disintegrates.
- Radioactive decay is the spontaneous disintegration of decomposition of a nucleus.
  - We can predict the stability of a nucleus by using some simple rules
    - All isotopes heavier than atomic number 83 have an unstable nucleus
    - Isotopes with 2, 8, 20, 28, 50, 82, or 126 protons or neutrons in their nucleus occur in the most stable isotopes.
    - Nuclei are the most stable with pairs of protons and neutrons, so those with all protons and all neutrons paired up are the most stable.
    - Isotopes with an atomic number less that 83 are most stable when the ratio of protons to neutrons is 1:1.

Radioactivity (Radioactive Decay)

- unstable isotopes are radioactive – radioisotopes
- most naturally occuring isotopes are stable
- radioactivity → spontaneous disintigration
  - ↳ emission of one or more small particles from the "parent" nucleus which changes into the "daughter" nucleus
- radioactivity results in a net mass decrease → exothermic

- energy released is in the form of
  - (1) kinetic energy
  - (2) γ radiation
  - (3) both (1) & (2)

Radioactivity (Radioactive Decay)

naturally-occurring radioisotopes will emit
α-, β-, or γ particle & radiation

artificially-generated radioisotopes emit
α-, β-, γ-
as well as positrons, orbital electron
absorption, K-capture, neutrons, & neutrinos

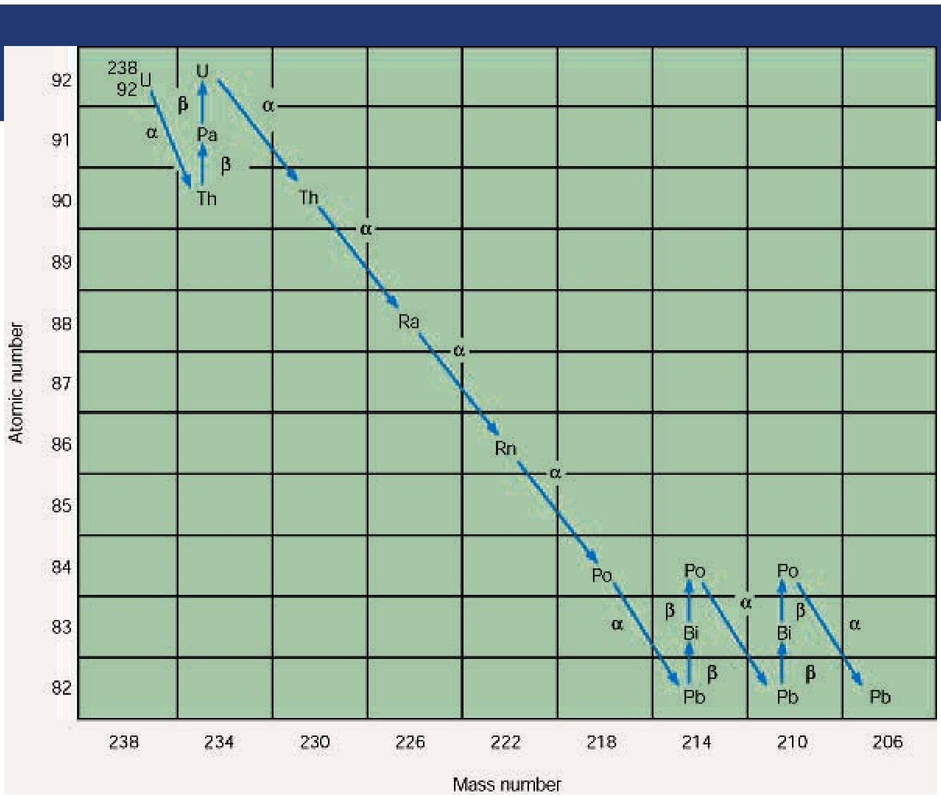
Radioactivity (Radioactive Decay)

- Type of Radioactive Decay
  - **Alpha emission**
    - This is the expulsion of an alpha particle
  - **Beta Emission**
    - Emission of a beta particle
    - a beta particle is an electron that is ejected form the nucleus
  - **Gamma emission**
    - This is a high energy burst of electromagnetic radiation
  - Emission occurs as nuclei try to obtain a balance between nuclear attractions, electromagnetic repulsions, and a low quantum of nuclear shell energy.

$^{4}_{2}He$

Radioactivity (Radioactive Decay)

- **Radioactive Decay Series**
  - Radioactive decay produces a simpler and more stable nucleus.
  - A radioactive decay series occurs as a nucleus disintegrates and achieves a more stable nuclei
  - There are 3 naturally occurring radioactive decay series.
    - Thorium 232 ending in lead 208
    - Uranium 235 ending in lead 207
    - Uranium 238 ending in lead 206



- The radioactive decay series for uranium-238. This is one of three naturally occurring series.

Radioactivity (Radioactive Decay)

- alpha decay, α

α-particle → $^{4}_{2}\alpha$ → Helium-4 nucleus

- 150 isotopes which emit α-particles
- important with respect to power production

$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}\alpha + \gamma_d$ $t_{1/2} = 4.51 \cdot 10^{9}$ years

γ-radiation

- daughter nucleus has a mass number 4 less than parent nucleus
- half-life, $t_{1/2}$, is time required for half or radioactive atoms to decay
- resulting nucleus may be stable or unstable (radioactive)

Radioactivity (Radioactive Decay)

- α-particles are monoenergetic, 4-6 MeV ← very high kinetic energy
- low penetration power & not a biological hazard unless injested

Having a narrow range of energies

- beta decay, β (negatron) $^{0}_{-1}\beta$, $^{-}\beta$, β^{-}

β-particle → $^{0}_{-1}\beta$ → electron

- 450 isotopes which emit β-particles
  - commonly used in medicine

$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}\beta + \gamma_d + \nu$ $t_{1/2}$ = 5.3 years

neutrino

Radioactivity (Radioactive Decay)

- neutrino is a very small mass, neutral particle that shares with the beta particle the reaction's energy release

$$\text{Total Energy} \sim \frac{1}{3} Ek_{\beta} + \frac{2}{3} Ek_{\nu}$$

- neutron in nucleus changes into a proton and an electron & neutrino are emitted

- gamma decay, γ_d

  electromagnetic radiation (photon)
  - very short wavelength ⟷ high frequency
  - high energy

Radioactivity (Radioactive Decay)

- similar to X-rays,

  X-rays ⟶ orbital change of electrons

  γ-rays ⟶ from nucleus

- usually accompanies α- and β-decay

- positron decay, β^+ ${}^{0}_{+1}\beta$, ${}^{+}\beta$

  - antielectron

$${}^{55}_{27}Co \rightarrow {}^{55}_{26}Fe + {}^{0}_{+1}\beta + \gamma_d + \nu \qquad t_{1/2} = 18 \text{ days}$$

Radioactivity (Radioactive Decay)

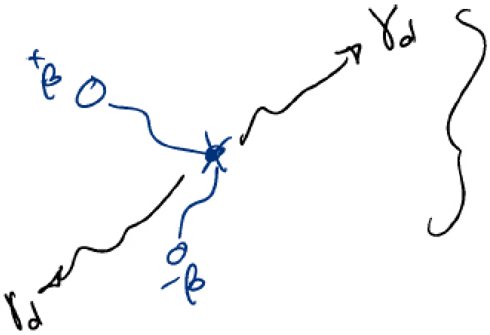
- proton changes into a neutron and emits a positron and neutrino

- annihilation with β^- results in 2 γ_a, each having a rest mass of an electron
  - γ_a travel in opposite direction to conserve momentum

↑ annihilation γ-rays

↑ 0.51 MeV

Radioactive energy results from the collision of β^+ and β^-



mass is completely converted into energy

Radioactivity (Radioactive Decay)

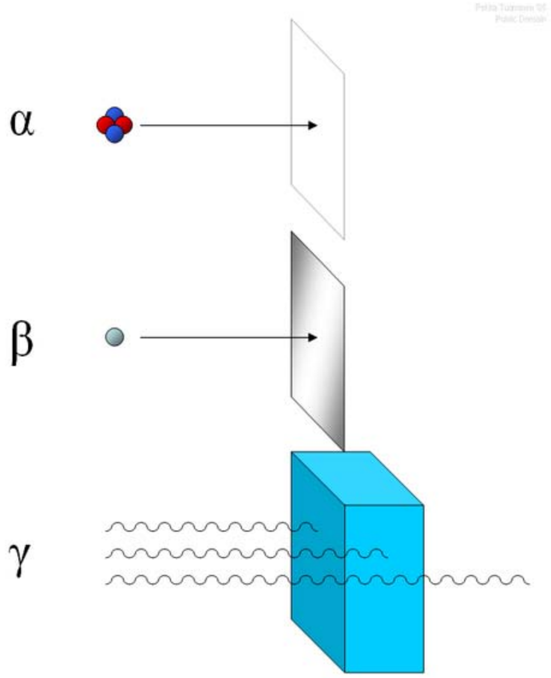
- reaction is reversible;
  - If a high energy γ-ray ($E_\gamma > 1.02$ MeV) passes near a nucleus, it can be converted into an electron and positron in a γ-ray reaction known as <u>pair production</u>

- k-capture (electron capture)
  - nucleus absorbs one of two nearest orbiting electrons (k-shell) and a proton is converted into a neutron
  - nucleus generally left in an unstable (excited) state

$$^{57}_{27}Co + ^{0}_{-1}e \longrightarrow ^{57}_{26}Fe + \gamma_d + \text{x-rays} \qquad t_{1/2} = 270 \text{ days}$$

↑ produced from orbital electrons falling into lower energy shells

Radioactivity (Radioactive Decay)



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Radioactivity (Radioactive Decay)

Units of Radioactivity

becquerel (Bq) ≡ 1 disintigration per second

curie (Ci) ≡ decay rate of 1 g of pure radium-266

$= 3,7 \cdot 10^{+10}$ Bq

rutherford ≡ 10^6 Bq

The Decay Law

Decay Rate, $\frac{dN}{dt} \sim N$

$N \equiv$ # of radioactive nuclei

$\lambda \equiv$ constant of proportionality
– decay constant

$$-\frac{dN}{dt} = \lambda N$$

-or-

$$\lambda t = \ln\left(\frac{N_0}{N}\right)$$

the probability that a radionuclide will decay in a unit time

- is the same for all nuclei of a given atom and
- does not depend on the age of nuclides, i.e., it does not change with time.

where N_0 is the starting number (amount) of nuclei, and N represents the amount of nuclei that did not decay after time t.

The Decay Law

Half-Life, $t_{1/2}$

- time required for half of radioactive nuclei to decay

$$N = \frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \longleftrightarrow \lambda t_{1/2} = \ln(2)$$

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

➢ Activity, A, is the number of nuclei decaying per unit time.

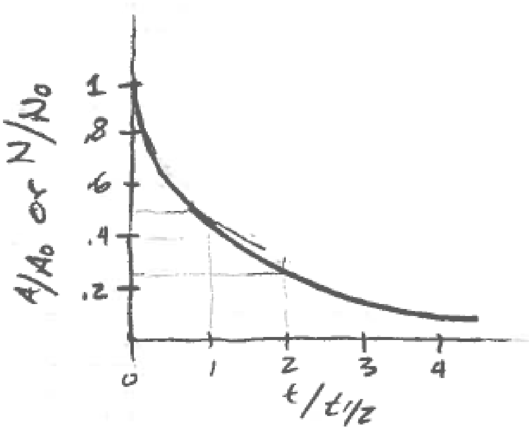
Activity $\equiv$ Decay Rate $= -\frac{dN}{dt}$

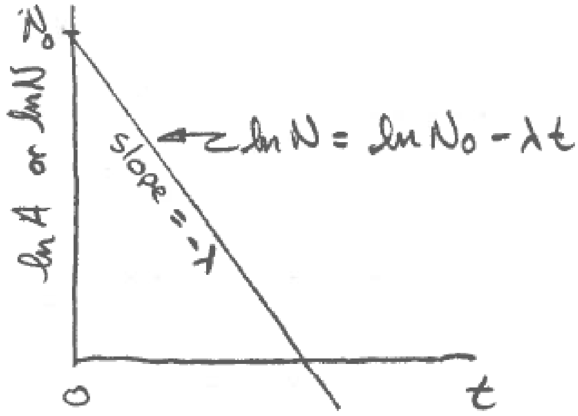
$$A = N\lambda = N_0 \lambda e^{\lambda t}$$

Activity $\propto$ N $\longrightarrow$ $A = A_0 e^{-\lambda t}$

$$\frac{N}{N_0} = \frac{A}{A_0}$$

The Decay Law





Example

Determine activity of theree natural uranium isotopes found 100 kg of Uranium Nidride (U_3N_4).

Example Cont.

Example Cont.

Example Cont.

Example

Aluminum bombarded with α-particles   α = nucleus of He-4

- result in silicon-30 isotope
- emit some small particle

Example Cont.

Radioactive Decay

During radioactive decay, the sum of mass and energy must be conserved.

$$E_{TOTAL} = 931.5\,\frac{MeV}{amu}\left\{\left[\begin{matrix}\text{parent}\\ \text{nuclear}\\ \text{mass}\end{matrix}\right] - \left[\begin{matrix}\text{particle}\\ \text{mass}\end{matrix}\right] - \left[\begin{matrix}\text{daughter}\\ \text{nuclear}\\ \text{mass}\end{matrix}\right]\right\}$$

Total kinetic Energy, $E_{KE,\,TOTAL} = E_{TOTAL} - E_{\gamma_d} = \frac{1}{2} m u^2 + \frac{1}{2} M v^2$

light nucleus

heavy nucleus

$\underbrace{\text{total emitted } \gamma\text{-ray energy}}_{\text{experimentally determined}}$

- neglecting E_{γ_d}

conservation of momentum requires $mu = Mv$

Radioactive Decay

therefore, $E_{KE} = \frac{1}{2} m U^2 + \frac{1}{2}\left(\frac{m^2 u^2}{M}\right) = \frac{1}{2} m u^2 \left(1+\frac{m}{M}\right)$

- similarly,

$$E_{KE} = \frac{1}{2} M U^2 \left(1+\frac{M}{m}\right)$$

$$\left.\begin{aligned} E_{KE,\,heavy} &= \frac{1}{2} M U^2 = \frac{E_{KE}}{1+\frac{M}{m}} \\ E_{KE,\,light} &= \frac{1}{2} m u^2 = \frac{E_{KE}}{1+\frac{m}{M}} \end{aligned}\right\}$$

$m << M$; thus, the light nucleus carries most of the momentum!

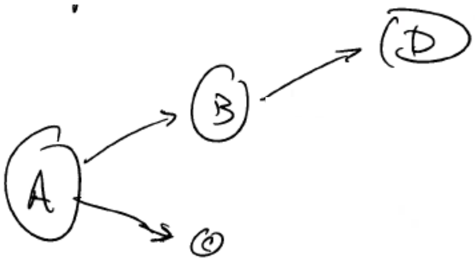
Example

U-235 undergoes α-decay with emission of a 0.17 MeV gamma ray. Find the kinetic energy of the product nucleus and the α-particle.

Example Cont.

Power from Radioisotopes

$$\text{Power} = \text{Activity} \times \left(\begin{matrix}\text{Energy Released}\\ \text{per disintigration}\end{matrix}\right) \Rightarrow P_A = P_{oA}e^{-\lambda_A t}$$



$$\left.\begin{matrix}\boxed{P_A = P_{oA}e^{-\lambda_A t}} \\ + P_B \\ + P_C \quad + P_D\end{matrix}\right\} \text{Total}$$

Energy released in a radioactive decay process is in form of decay-gamma (γ_d) energy and kinetic energy of particles.
γ_d are very penetrating & may pass through without capture.

Source of Radioisotopes

2 → naturally occurring
↳ manufactured ; in a nuclear reactor

- long-lived isotopes have been around since the formation of the earth

K-40 , U-235 , . . .

Th-232 ⟶ eventually ⟶ Pb-208
U-235 ⟶ " ⟶ Pb-207 } stable
U-238 ⟶ " ⟶ Pb-206

↳ included in decay chain

radium -266 ($t_{1/2}$ = 1690 yrs)

Source of Radioisotopes

$$^{232}_{90}Th \rightarrow {}^{208}_{82}Pb + 6\,{}^{4}_{2}\alpha + 4\,{}^{0}_{-1}\beta$$

$$^{235}_{92}U \rightarrow {}^{207}_{82}Pb + 7\,{}^{4}_{2}\alpha + 4\,{}^{0}_{-1}\beta$$

$$^{238}_{92}U \rightarrow {}^{206}_{82}Pb + 8\,{}^{4}_{2}\alpha + 6\,{}^{0}_{-1}\beta$$

⊕ U^{236} goes through 14 stages of radioactive decay to reach stable nuclei

– included in the decay chain are radium -266 ($t_{1/2}$=1690 yrs)

↳ isolated by M.Curie in 1902

Source of Radioisotopes

radon-222 ($t_{1/2}$ = 3.82 days) ← noble gas

- Cosmic radiation = high energy neutrons, protons, nuclei
  - produces isotopes from atoms in atmosphere
  - C-14 (radiocarbon)
  - H-3 (tritium)

manufacture in particle accelerators & nuclear fission reactors

Cobalt-60

$${}^{59}_{27}Co + {}^{1}_{0}n \longrightarrow {}^{60*}_{27}Co \longrightarrow {}^{60}_{27}Co + \gamma_c$$

↑ capture γ

↑ excited state because of BE of absorbed neutron

Nuclear Energy

- **Albert Einstein** showed us that energy and matter are the same thing, both are inter-convertible.
  - $E=mc^2$
- Using mass losses during nuclear reactions, one can calculate the energy change of a system.
  - $\Delta E=\Delta mc^2$
- There is a difference between the mass of the individual nucleons that make up a nucleus and the actual mass of the nucleus.
  - This is called the mass defect of the nucleus.
  - The mass defect occurs as energy is released when nucleons join to form a nucleus.

Binding Energy

- The energy that is released is called the **binding energy**.
  - This is also the energy that is required to break the nucleus into its individual protons and neutrons.
  - The ratio of the binding energy to the nucleon number is a measure of a nucleus' stability
  - **Massive nuclei** can gain stability by breaking into smaller nuclei with a release of energy.
  - **Smaller nuclei** can gain stability by joining together with the release of energy.

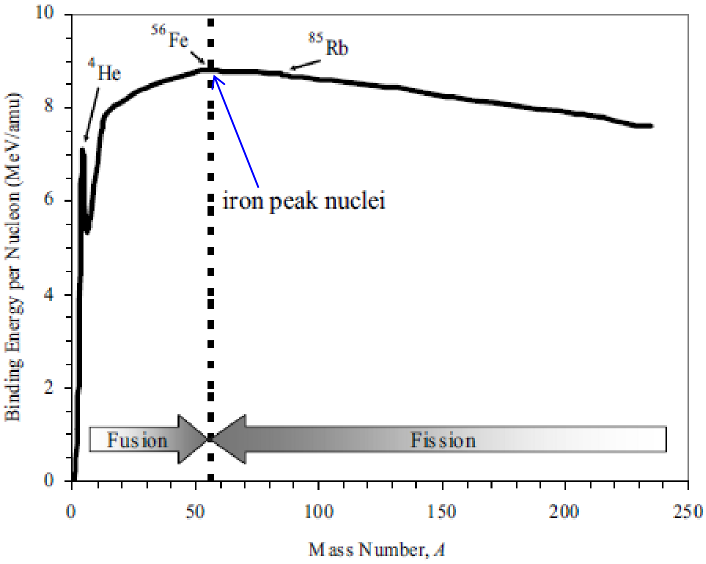
- The maximum binding energy per nucleon occurs around mass number 56, then decreases in both directions. As one result, fission of massive nuclei and fusion of less massive nuclei both release energy.

Binding Energy

The curve indicates three characteristic regions

$^{A}_{Z}X$

- Region of stability : A flat region between A equal to approximately 35 and 70.
- Region of fission reactions : the heaviest nuclei are less stable than the nuclei near A = 60, energy can be released if heavy nuclei split apart into smaller nuclei having masses nearer the iron peak.
- Region of fusion reactions: The lightest elements (like hydrogen and helium) have nuclei that are less stable than heavier elements up to the iron peak.
- If two light nuclei can form a heavier nucleus a significant energy could be released



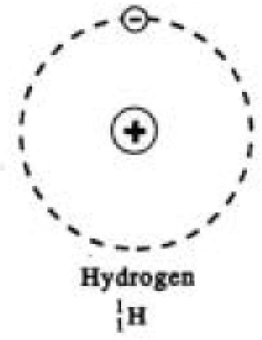
Binding Energy

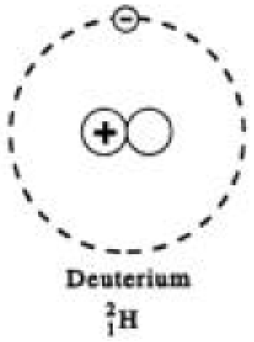
- Splitting massive nuclei apart with the release of energy is called **nuclear fission**.
- The joining together of less massive nuclei with the release of energy is called **nuclear fusion**

Mass Defect

Mass of $_1H^1$ - not quite equal to the sum of particle masses

isotope	mass (amu)
$_{-1}e^0$	0.000549
$_1p^1$	1.007277
$_0n^1$	1.008665





hydrogen, $_1^1H$ 1.007825 ← $m_e + m_p = 1.007826$

deuterium, $_1^2H$ 2.01410 ← $m_e + m_p + m_n = 2.016491$

difference in mass is known as mass defect

Mass Defect

- An atom contains *Z* positively charged particles (protons) and *N* (= *A* - *Z*) neutral particles (neutrons),
- The total charge of a nucleus is +*Ze,* where *e* represents the charge of one electron.
- Thus, the mass of a neutral atom, M_{atom}, can be expressed in terms of the mass of its nucleus, M_{nuc}, and its electrons, m_e

$$M_{atom} = M_{nuc} + Zm_e \qquad M_{nuc} = Zm_p + (A-Z)m_n$$

$^{A}_{Z}X$

where m_p is the proton mass, m_e the mass of an electron and m_n the mass of a neutron.

- The atomic mass, indicated on most tables of the elements, is the sum of the nuclear mass and the total mass of the electrons present in a neutral atom.
- For rubidium nucleus, ^{87}Rb, contains 37, protons and 50 neutrons,

$$M_{nuc}(^{87}Rb) = 37 \times 1.007277 + 50 \times 1.008665 = 87.7025 amu$$

Mass Defect

$$M_{atom}(^{87}\text{Rb}) = M_{nuc}(^{87}\text{Rb}) + Zm_e = 87.7025 + 37 \times 0.00055 = 87.7228 amu$$

From the periodic table,

$$M_{atom}^{measured}(^{87}Rb) = 86.909187\ amu.$$

$^{A}_{Z}X$

$$\Delta m = M_{atom}(^{87}Rb) - M_{atom}^{measured}(^{87}Rb) = 0.813613 amu$$

- The difference in mass corresponds to a difference in the mass of the nucleus

$$\begin{aligned}\Delta m &= M_{atom} - M_{atom}^{measured}\\ &= Zm_p + Zm_e + (A-Z)m_n - \left[M_{nuc}^{measured} + Zm_e\right]\\ &= Zm_p + (A-Z)m_n - M_{nuc}^{measured} = M_{nuc} - M_{nuc}^{measured}\end{aligned}$$

when using atomic mass values given by the periodic table,

$$\Delta m = M_{nuc} - M_{nuc}^{measured} = Zm_p + Zm_e + (A-Z)m_n - M_{atom}^{measured}$$

Mass Defect

and $$Zm_p + Zm_e = Zm_H$$

where m_H is a mass of the hydrogen atom.

$^{A}_{Z}X$

The mass defect

$$MD = Z \cdot m_p + (A-Z)\, m_n - \text{nucleus mass}$$

neutron mass

proton mass

nuclear symbol : $^{A}_{Z}X$

A = Mass Number = # of nucleons = protons + neutrons

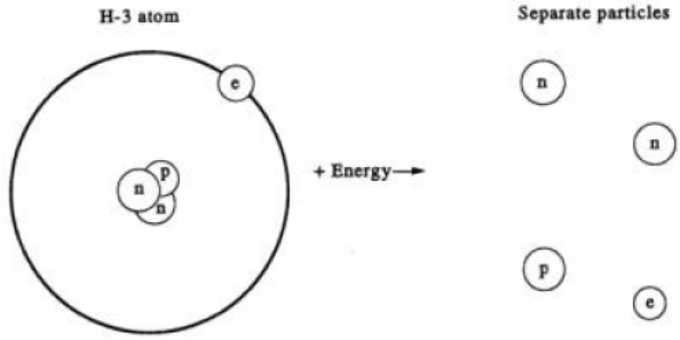
Z = Atomic Number = # of protons

Binding Energy

- The actual mass of an atomic nucleus is *always* smaller than the sum of the rest masses of all its nucleons (protons and neutrons).
- This is because some of the mass of the nucleons is converted into the energy that is needed to form that nucleus and hold it together.
- This converted mass, Δm, is called the "*mass defect*"
- The corresponding energy is called the "*binding energy*" and is related to the stability of the nucleus; the greater the binding energy, the more stable the nucleus.
- The nuclear force acts only when the nucleons are very close to each other, and binds them into a compact structure.
- To disrupt a nucleus and separate it into its component nucleons, energy must be supplied from the outside.

Binding Energy

$^{A}_{Z}X$



Energy Equivalent (mc^2) of MD is the total Binding Energy

- The mass defect and binding energy can be directly related

$$BE = Z \cdot M_{H\text{-}1} + (A-Z)\,m_n - \text{Atomic Mass}$$

$\uparrow$ Mass of H_1 (H^1)

$$BE = \Delta m \times 931.5\,MeV/amu \quad \text{or}$$

Binding Energy

$$BE = \left(Zm_p + Zm_e + (A-Z)m_n - M^{measured}_{atom}\right)c^2$$

$^{A}_{Z}X$

BE ≡ absolute minimum energy required to break a nucleus into Z-protons & (A-Z) neutrons, or A nucleons.

- For tritium, the heaviest hydrogen atom $^{3}_{1}H$

$m_n = 1.008665$, $m_H = 1.007825$, $M = 3.016049$.

$$B = 2(1.008665) + 1(1.007825) - 3.016049$$

$$B = 0.009106 \text{ amu.} = 8.48 \text{ MeV.}$$

the *binding energy per nucleon*, E_b

$$E_b = \frac{BE}{A} = \frac{\Delta m(amu) \times 931.5(MeV/amu)}{A(\text{nucleons})}[MeV/\text{nucleon}]$$

Example

Calculate the Binding Energy per nucleon for

(a) heavy hydrogen, ^2_1H

atomic mass = 2.0141 amu

$Z \equiv$ # of protons = 1

$A \equiv$ # of nucleons = 2

$$\text{Mass Defect} = (1)\underbrace{1.007825\ \text{amu}}_{\substack{\text{mass of } ^1_1H \\ \text{(proton + neutron)}}} + (2-1)\underbrace{1.0086625\ \text{amu}}_{\text{mass of neutron}} - \underbrace{2.0141\ \text{amu}}_{\text{mass of } ^2_1H}$$

MD = 0.00239 amu

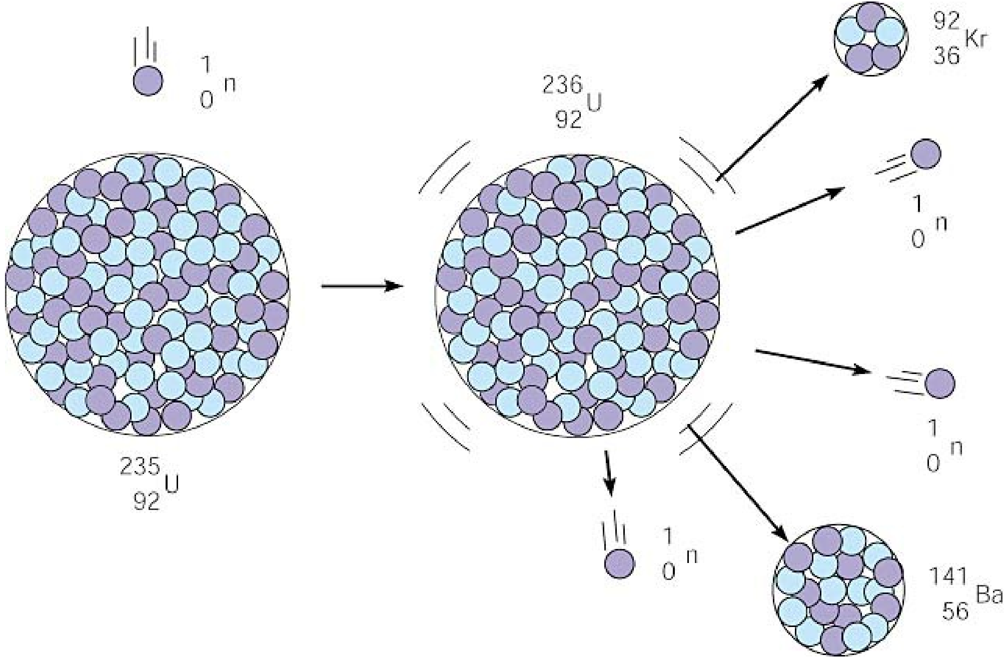
Binding Energy = 0.00239 amu · 931.5 MeV/amu = 2.226 MeV

BE/nucleon = 1.113 MeV/nucleon

Nuclear Fission

- As a nuclear reaction occurs, it has the ability to produce a chain reaction
  - A **chain reaction** is a reaction where the products are able to produce more products in a self-sustaining reaction series.
- In order to achieve a chain reaction there must be:
  - A sufficient mass.
  - A large concentration of fissionable nuclei
- The **critical mass** is when the mass and concentration are high enough to sustain a chain reaction.
- A **sub-critical mass** is one that is too small to achieve a chain reaction.

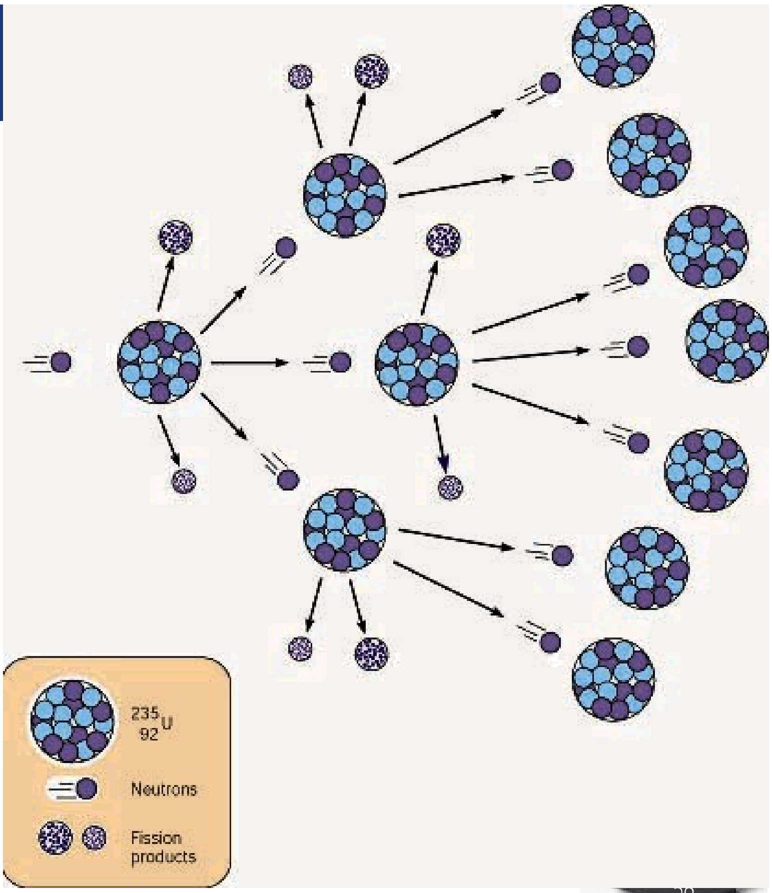
Nuclear Fission



- The fission reaction occurring when a neutron is absorbed by a uranium-235 nucleus. The deformed nucleus splits any number of ways into lighter nuclei, releasing neutrons in the process.

Nuclear Fission

- A schematic representation of a chain reaction. Each fissioned nucleus releases neutrons, which move out to fission other nuclei. The number of neutrons can increase quickly with each series.



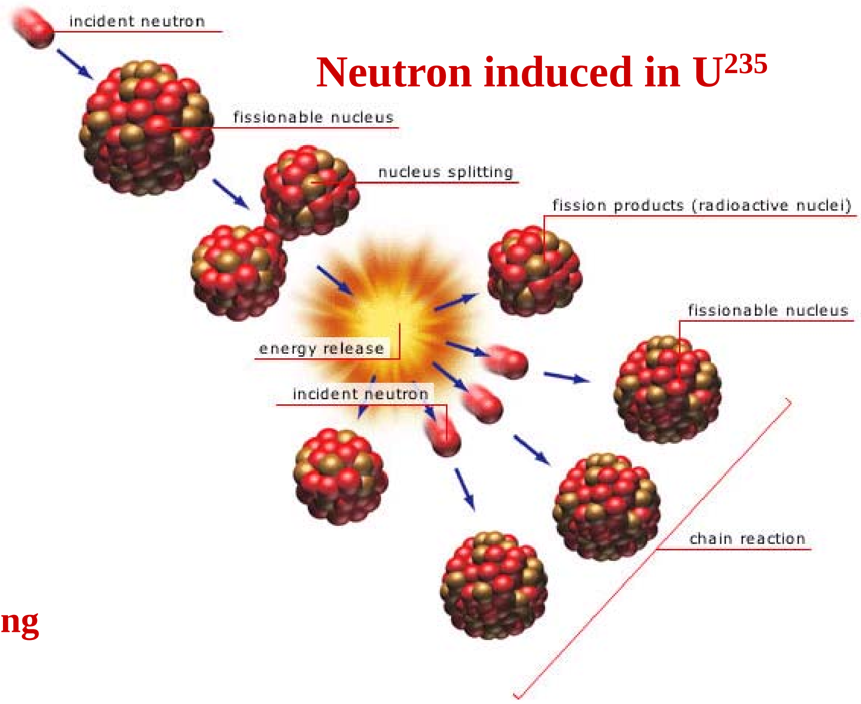
Nuclear Fission

Fission is Exothermic

The sum of the masses of the resulting nuclei is less than the original mass (about 0.1% less)

The "missing mass" is converted to energy according to $E=mc^2$

Neutron induced in U^{235}

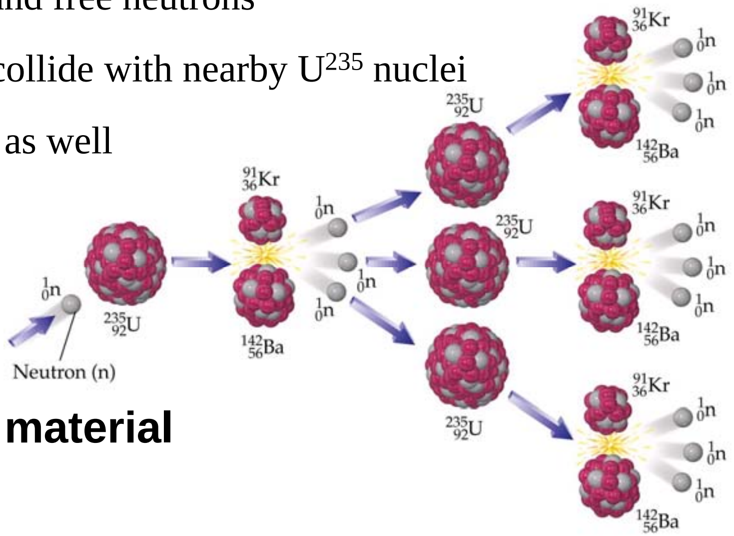


Neutrons may:

1 - Cause another fission by colliding with a U^{235} nucleus

- Creates two smaller nuclides and free neutrons
- The free neutrons potentially collide with nearby U^{235} nuclei
- May cause the nuclide to split as well

Each split (fission) is accompanied by a large quantity of **E-N-E-R-G-Y**



2 - Be absorbed in other material

3 - Lost in the system

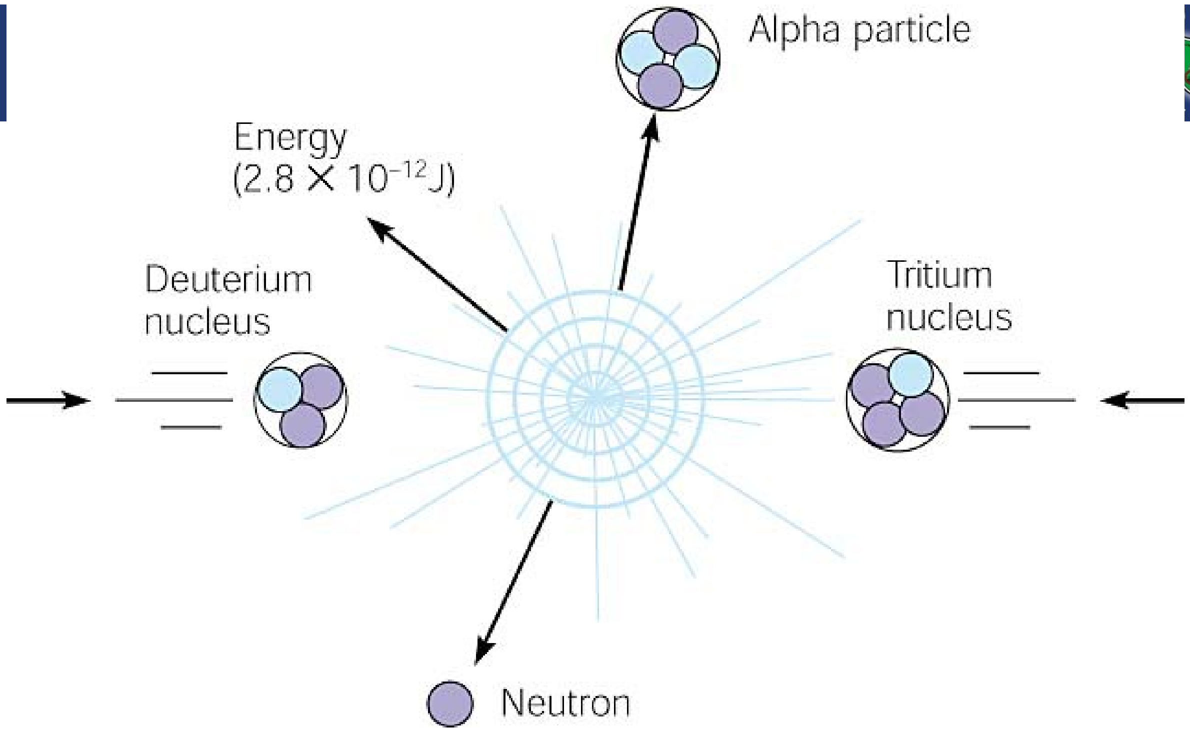
If sufficient neutrons are present, we may achieve a **chain reaction**

Nuclear Fusion

- Nuclear fusion is the source of the energy from the Sun and other stars.
- Fusion is a very desirable energy source as:
  - Two isotopes of hydrogen (deuterium and tritium) undergo fusion at a relatively low temperature.
  - The supply of deuterium is unlimited with seawater being a very large source
  - Enormous amounts of energy are released with no radioactive byproducts.

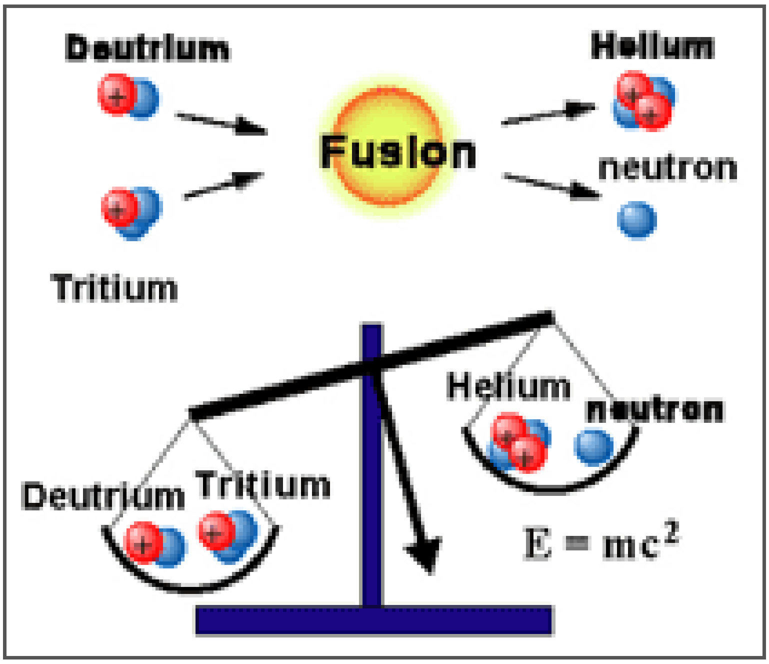
Nuclear Fusion

- The problems with utilizing fusion as an energy source are:
  - **Temperature**.
    - The amount of energy required to bring two nuclei together is enormous.
  - **Density**
    - The density of the reacting hydrogen nuclei must be significantly high so that there are enough reactions occurring in a short period of time.
  - **time**
    - These nuclei need to be confined to up to a second or more at 10 atmospheres of pressure in order for enough reactions to take place.

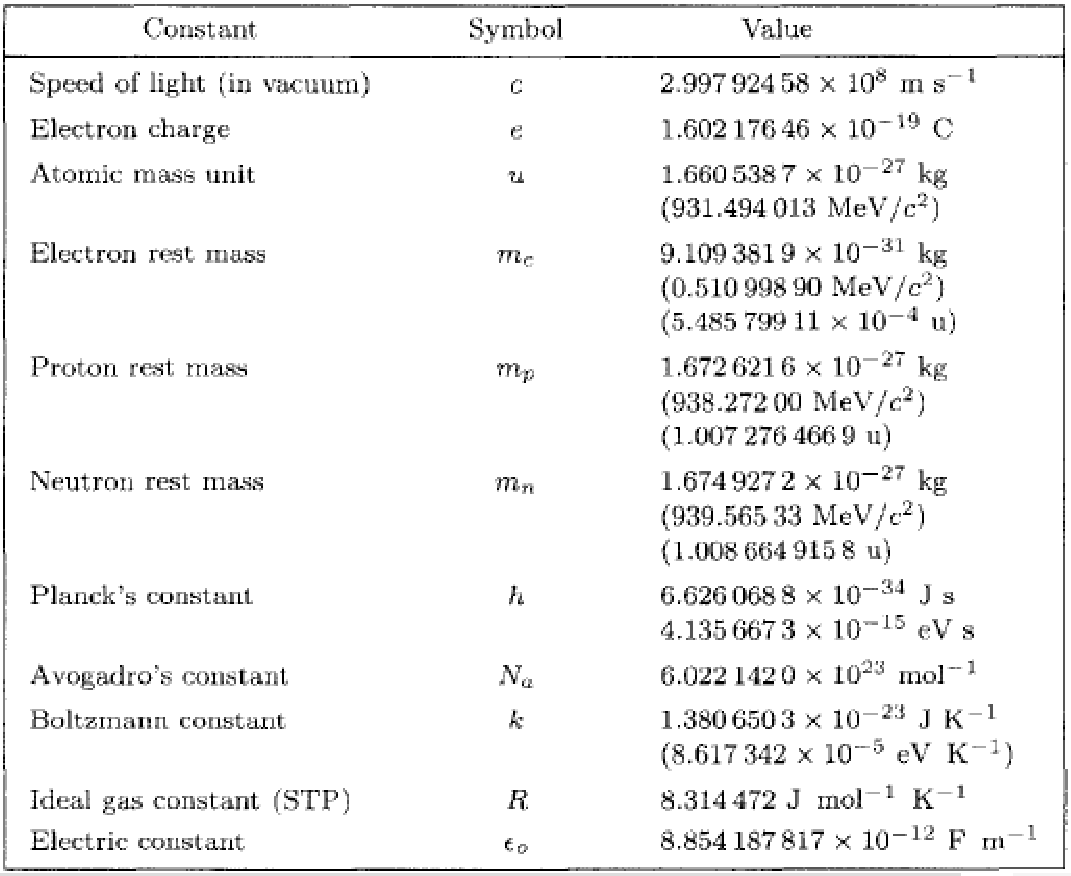


- A fusion reaction between a tritium nucleus and a deuterium nucleus requires a certain temperature, density, and time of containment to take place.

Nuclear Fusion



Values of some physical constants



Constant	Symbol	Value
Speed of light (in vacuum)	c	$2.997\,924\,58 \times 10^{8}$ m s^{-1}
Electron charge	e	$1.602\,176\,46 \times 10^{-19}$ C
Atomic mass unit	u	$1.660\,538\,7 \times 10^{-27}$ kg ($931.494\,013$ MeV/c^2)
Electron rest mass	m_e	$9.109\,381\,9 \times 10^{-31}$ kg ($0.510\,998\,90$ MeV/c^2) ($5.485\,799\,11 \times 10^{-4}$ u)
Proton rest mass	m_p	$1.672\,621\,6 \times 10^{-27}$ kg ($938.272\,00$ MeV/c^2) ($1.007\,276\,466\,9$ u)
Neutron rest mass	m_n	$1.674\,927\,2 \times 10^{-27}$ kg ($939.565\,33$ MeV/c^2) ($1.008\,664\,915\,8$ u)
Planck's constant	h	$6.626\,068\,8 \times 10^{-34}$ J s $4.135\,667\,3 \times 10^{-15}$ eV s
Avogadro's constant	N_a	$6.022\,142\,0 \times 10^{23}$ mol^{-1}
Boltzmann constant	k	$1.380\,650\,3 \times 10^{-23}$ J K^{-1} ($8.617\,342 \times 10^{-5}$ eV K^{-1})
Ideal gas constant (STP)	R	$8.314\,472$ J mol^{-1} K^{-1}
Electric constant	ϵ_o	$8.854\,187\,817 \times 10^{-12}$ F m^{-1}