Chapter 30

Nuclear Physics and Radioactivity

Lecture 1
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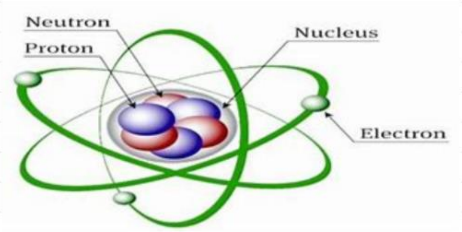
30-1] Structure and Properties of the Nucleus.

The atom is made up of electrons orbiting the nucleus.



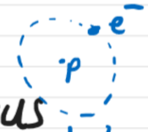
The nucleus is made up of protons and neutrons.

Particle	mass(kg)	Electric charge (coulomb)
Proton	1.67262×10^{-27}	$+1.6 \times 10^{-19}$
Neutron	1.67493×10^{-27}	0
Electron	9.110×10^{-31}	-1.6×10^{-19}

NOTE: $m_p \sim 2000\, m_{e^-}$

\# Neutrons and protons are called nucleons.

\# The simplest atom is the Hydrogen atom and it has one electron orbiting the nucleus which is made of one proton.



hydrogen atom.

\# Different nuclei are referred to as nuclides.

\# We refer to a given nuclide (nucleus) as:

Atomic number (Z):
number of protons in the nucleus.

mass number $\rightarrow$ A

$$^{A}_{Z}X_{N}$$

atomic number $\rightarrow$ Z

N $\leftarrow$ neutron number

Neutron number (N)
number of neutrons in the nucleus.

Mass number: the sum of proton and neutron numbers in the nucleus

$$A = Z + N.$$

Examples: $^{12}_{6}C$ (this implicitly means $^{12}_{6}C_6$) $^{A}_{Z}X_{N=A-Z}$

$^{14}_{7}N$, $^{16}_{8}O$, $^{40}_{20}Ca$, $^{208}_{82}Pb$, $^{235}_{92}U$, ... Nuclides

A neutral atom has the same number of protons and electrons $\Rightarrow$ it has a net charge of zero (neutral atom).

no net charge

Some definitions:

Isotopes: nuclides that have the same number of protons, but different number of neutrons. $^{11}_{6}C_{5}$, $^{12}_{6}C_{6}$, $^{13}_{6}C_{7}$, $^{14}_{6}C_{8}$, $^{15}_{6}C_{9}$

(same Z different N) have the same chemical properties but different phys. prop.

Isotones: nuclides that have the same number of neutrons, but different number of protons. $^{12}_{5}B_{7}$, $^{13}_{6}C_{7}$

(same N different Z)

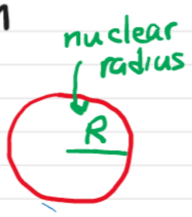
Isobars: nuclides that have the same mass number A. $^{40}_{18}Ar_{22}$; $^{40}_{19}K_{21}$; $^{40}_{20}Ca_{20}$

(same A)

Nuclei (nuclides) have roughly spherical shapes. The radius of a nucleus is given by:

$$R = 1.2 \times 10^{-15} \, A^{1/3} \text{ meters}$$

↑mass number $A = Z + N$



$1 \text{ fermi} = 10^{-15} \text{ m}$

$$R = 1.2 \, A^{1/3} \text{ fermi}$$

Example: Determine the radius of ^{16}O.

$$R = 1.2 \times 10^{-15} (16)^{1/3} \simeq 3.02 \times 10^{-15} \text{ m}$$

$R \sim 3.02 \text{ fm}$ ($\text{fm} \equiv \text{fermi}$).

Example 30-2]

Nuclear and atomic densities. Compare the density of nuclear matter to the density of normal solids.

$\rho_w = 1\,\text{gram}/\text{cm}^3$
$= 1000\,\text{kg}/\text{m}^3$

typical atomic radius $\sim 10^{-10}$ m.

typical nuclear radius $\sim 10^{-15}$ m

$\frac{r_{atom}}{r_{nuc}} = \frac{10^{-10}}{10^{-15}} = 10^{5}$

$r_{atom} = 10^{5}$ cm
$= 10^{3}$ m
$= 1$ km.

rho density

$$\frac{\rho_{nucl}}{\rho_{atom}} = \frac{m_{nuc}/V_{nuc}}{m_{atom}/V_{atom}} = \frac{m_{nuc}}{m_{atom}} \; \frac{V_{atom}}{V_{nuc}}$$

Remember: $m_p \sim m_n \sim 2000 \; m_{e^-}$

$\Rightarrow m_{atom} \sim m_{nuc}$.

In fact more than 99.9% of the mass of the atom is due to the nucleus.

$$\Rightarrow \frac{m_{nuc}}{m_{atom}} \sim 1 \quad \Rightarrow$$

volume of a sphere $= \frac{4}{3}\pi R^3$ R: radius

$$\therefore \frac{\rho_{nuc}}{\rho_{atom}} = (1)\,\frac{\cancel{\frac{4}{3}}\pi(10^{-10})^3}{\cancel{\frac{4}{3}}\pi(10^{-15})^3} = 10^{15} \;!!!$$

$\rho_{nuc} = 10^{15}\,\rho_{atom}$

Nuclear density is 10^{15} times larger than the density of normal matter.

Density of normal matter is in the range of $10^3 - 10^4\ \text{kg}/\text{m}^3$ (e.g $\rho_{water} = 10^3\ \text{kg}/\text{m}^3$) -

$\therefore$ Nuclear density $\sim 10^{18} - 10^{19}$ kg/m^3 .

Nuclear masses are measured in atomic mass unit (u).

On this scale ^{12}C has a mass of exactly 12.000000 u

On this scale :

$m_p = 1.007276$ u
$m_n = 1.008665$ u
$m(^1_1H) = 1.007825$ u
$m_{e^-} = 0.00054858$ u

[Note ^1_1H is the hydrogen atom made up of one proton and one electron] .

1u is equivalent to how much in kg?

amu

$m_n = 1.67262 \times 10^{-27}$ kg , $m_n = 1.008665$ u

$$\therefore 1u = 1\cancel{u} \left(\frac{1.67262 \times 10^{-27} \text{ kg}}{1.008665 \cancel{u}} \right) = 1.6605 \times 10^{-27} \text{ kg} .$$

Mass can also be measured in units of energy. Remember Einstein's equation :

$$\underset{\text{Joule}}{\overset{\text{in}}{}} \rightarrow E = mc^2 \Rightarrow m = \frac{E}{c^2}$$

$$\underset{\text{electron volt}}{1\ \text{eV}} = 1.6022 \times 10^{-19}\ \text{J} \qquad (\Delta U = q\,\Delta V)$$

[1 eV is the energy gained by an e^- when accelerated through an electric potential difference of 1 volt]

$$1\ \text{MeV} = 10^6\ \text{eV}.$$

How much is 1u in units of eV ?

$$E = mc^2 = \underbrace{(1.66054 \times 10^{-27}\ \text{kg})}_{1u \text{ in kg}}(2.9979 \times 10^8\ \text{m/s})^2$$

$$E = (1.66054 \times 10^{-27})(2.9979 \times 10^8)^2\ \text{kg}\ \frac{\text{m}^2}{\text{s}^2}$$

Note: $\underset{\text{force}}{\left(\text{kg}\,\frac{\text{m}}{\text{s}^2}\right)}\underset{\text{distance}}{(\text{m})} \equiv$ Joule

$$\therefore \quad E = (1.66054 \times 10^{-27})(2.9979 \times 10^8)^2\ \text{J}$$

but $1\text{eV} = 1.6022 \times 10^{-19}\ \text{J} \Rightarrow$

$$E = \frac{(1.66054 \times 10^{-27})(2.9979 \times 10^8)^2\ \cancel{\text{J}}}{1.6022 \times 10^{-19}\ \frac{\cancel{\text{J}}}{\text{eV}}}$$

$$= 931.5 \times 10^6\ \text{eV} = 931.5\ \text{MeV}$$

$$\overset{1u}{m}c^2 = 931.5 \text{ MeV}$$

$$\therefore\ 1u = 931.5\ \frac{\text{MeV}}{c^2}$$

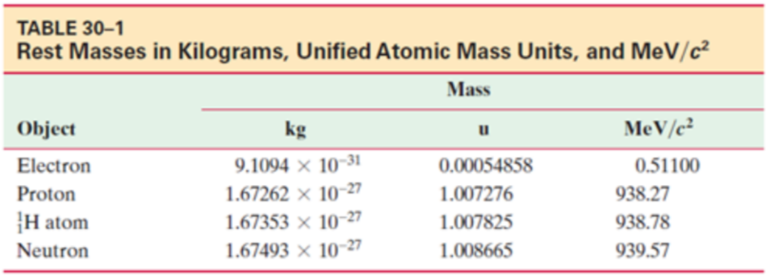


TABLE 30–1
Rest Masses in Kilograms, Unified Atomic Mass Units, and MeV/c^2

	Mass		
Object	**kg**	**u**	**MeV/c^2**
Electron	9.1094×10^{-31}	0.00054858	0.51100
Proton	1.67262×10^{-27}	1.007276	938.27
$^1_1$H atom	1.67353×10^{-27}	1.007825	938.78
Neutron	1.67493×10^{-27}	1.008665	939.57

$$0.511 \times \overbrace{10^{6}}^{M} \times \frac{\overbrace{1.6\times10^{-19}}^{J}\ J}{(3\times10^{8})^2}$$

30-3] Radioactivity

Some nuclei (particularly heavy ones) are unstable and emit neutrons, protons, alpha particles, γ-radiation, X-rays, etc. to become more stable.

The isotopes of uranium $^{235}_{92}U$ and $^{238}_{92}U$ are radioactive. Both are naturally occuring nuclides

⇒ natural radioactivity.

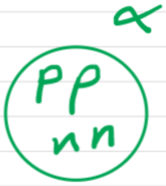
Manufactured radioactive nuclides lead to artificial radioactivity. (Californium)
↑ artificially radiactive manufactured element

Unstable nuclei emit three main types of nuclear radiation, classified according to their penetrating power:

i) Alpha (α) particles [also can say α-radiation]

An α-particle is made up of 2 protons and 2 neutrons. So it is the nucleus of helium atom ⇒ it is a doubly ionized helium atom

$\alpha \equiv {}^{4}_{2}He^{++}$ ← doubly ionized (two e^- are removed).



ii) $\beta^{\pm}$ particles [$\beta^{\pm}$ radiation]

β^- is an electron e^- -1.6×10^{-19} J

β^+ is a positron e^+ $+1.6\times10^{-19}$ J

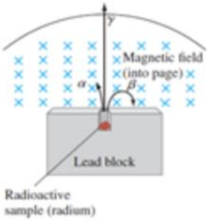
e^+ is the antiparticle of the e^-.

$m_{e^+} = m_{e^-}$ but $e^+ = +1.6022\times10^{-19}$ Coulomb.

iii) γ-radiation

Very high frequency electromagnetic radiation.

FIGURE 30–4 Alpha and beta rays are bent in opposite directions by a magnetic field, whereas gamma rays are not bent at all.



magnetic field only deflects charged particles.
It does not act with a force on neutral particles.

Radiation	Penetrating Power
α	can be stopped using a piece of paper.
$\beta^{\pm}$	can be stopped using few mm of aluminum.
γ	has high penetrating power. can pass through several cm of lead.