Salahaddin University-Erbil
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Physics Department

Nuclear Physics Lectures

4th Year Physics

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Chapter One

Basic Nuclear Concepts

Basic Nuclear Properties

Nomenclature

As in any specialized field, a certain nomenclature has developed based on convenience and tradition. The important terms are given bellow

$\boldsymbol{Nuclide}$: A specific nuclear species, with a given proton number Z and neutron number N.

Example 1.1: $^{7}_{4}\boldsymbol{Be}$ this can be written in symbol form $^{A}_{Z}\boldsymbol{X}_{\boldsymbol{N}}$ where;

Z=atomic number (number of proton) $=\ 4$

A=mass number (number of protons plus number of neutrons) $=\ Z+N=7$

N=neutron number (number of neutron) $=\ A-Z\ =7-4\ =\ 3$

$\boldsymbol{Isotopes}$: Nuclides of same Z and different N

Example 1.2: $^{7}_{4}\boldsymbol{Be}$, $^{8}_{4}\boldsymbol{Be}$, $^{9}_{4}\boldsymbol{Be}$, $^{10}_{4}\boldsymbol{Be}$

$^{7}_{4}\boldsymbol{Be}$: (7-4=3 neutrons)

$^{8}_{4}\boldsymbol{Be}$: (8-4=4 neutrons)

$^{9}_{4}\boldsymbol{Be}$: (9-4=5 neutrons)

$^{10}_{4}\boldsymbol{Be}$: (10-4=6 neutrons)

all of them in the same Z , while they are in the different N

$\boldsymbol{sotones}$: Nuclides of same N and different Z

Example 1.3: $^{5}_{2}\boldsymbol{He}$, $^{6}_{3}\boldsymbol{Li}$, $^{7}_{4}\boldsymbol{Be}$

$^{5}_{2}\boldsymbol{He}$: (5-2=3 neutrons)

$^{6}_{3}\boldsymbol{Li}$: (6-3=3 neutrons)

$^{7}_{4}\boldsymbol{Be}$: (7-4=3 neutrons) all of them in the same N , while they are in the different Z

$\boldsymbol{Isobars}$**:** Nuclides of same mass number A $(A = Z + N)$

Example 1.4: $^{7}_{3}\boldsymbol{Li}$, $^{7}_{4}\boldsymbol{Be}$, $^{7}_{5}\boldsymbol{B}$ all of them in the same A

The isotopes, isotones, isobars and their symbols can be shown in the table (1.1)

$\boldsymbol{Isomer}$: Nuclides in an excited state with a measurable half-life

Example 1.5: $^{210}_{84}\boldsymbol{Po}$ (polonium)

Half-life = 138.38 days, $\alpha - emitting$ and $\gamma - radiation$.

Table 1.1: Light elements and their possible atoms.

Element	Atomic (Proton) number Z	Electron number Z	Neutron number N	Mass number A	Symbol
Hydrogen	1	1	0	1	${}^{1}_{1}H$ (proton
	1	1	1	2	${}^{2}_{1}H$ (deuteron
	1	1	2	3	${}^{3}_{1}H$ (tritium)
	1	1	3	4	${}^{4}_{1}H$
Helium	2	2	1	3	${}^{3}_{2}He$
	2	2	2	4	${}^{4}_{2}He$ (α-particle)
		2	3	5	${}^{5}_{2}He$
	2	2	4	6	${}^{6}_{2}He$
Lithium	3	3	3	6	${}^{6}_{3}Li$
	3	3	4	7	${}^{7}_{3}Li$
	3	3	5	8	${}^{8}_{3}Li$
Beryllium	4	4	3	7	${}^{7}_{4}Be$
	4	4	4	8	${}^{8}_{4}Be$
	4	4	5	9	${}^{9}_{4}Be$
	4	4	6	10	${}^{10}_{4}Be$

Nucleon: Neutron or proton

Mesons: Particles of mass between the electron mass (m_0) and the proton mass (M_H). The best known mesons ate the π-mesons ($\approx 270\ m_0$) which play an important role in nuclear force, μ-mesons ($207\ m_0$) which are important in cosmic-ray phenomena.

Electron: Negative charged particle of mass (m_0)

Positron: Positive charged electron of mass (m_0)

Photon: Quantum of electromagnetic radiation like (γ-ray, x-ray, light…)

Nuclear Mass

Early chemical methods of mass comparison and already brought out the following approximate relation):

$$M \approx Integer \times M_H \tag{1.1}$$

where M = mass of a specific atom

M_H = mass of a hydrogen atom

Note:
1-Nucleons: Neutrons or protons
2-Nucleus: Neutrons and protons

The integer is now called $mass\ number\ A$

Example 1.6: $M({}^{9}_{4}Be) \approx 9 \times M_H$

$M({}^{11}_{5}B) \approx 11 \times M_H$

It was shown by x-ray scattering (Barkla, 1911) that the number (Z) of atomic electrons, and hence the number of positive nuclear charges, was not equal to the mass number A with the (neutron-proton hypothesis) we expect the mass of an atom to be:

$$M \approx ZM_H + NM_n \qquad (1.2)$$

$where\ \ Z = atomic\ number$ (number of protons in the nucleus)

$N = neutron\ number$ (number of neutrons in the nucleus)

$M_n = mass\ of\ neutron$

Exact Atomic Mass and Mass Excess

Any exact atomic mass (M) can be written in terms of the atomic mass unit (M_u) or (u), or (amu):

$$M = A \pm \Delta M \tag{1.3}$$

where M = atomic mass or exact atomic mass

A = mass number (is an integer = total number of nucleons in the nucleus)

ΔM = Mass excess or mass defect or mass difference

Therefore the mass excess can be written :

$$\Delta M = Mass\ Excess = M - A \tag{1.4}$$

The sign of ΔM is not always positive because of the choice of (^{12}C) as our standard of atomic mass , i.e., the unified atomic mass unit, (M_u), is ($\frac{1}{12}$) of the mass of an atom of the (^{12}C) nuclide. Some examples are given in table (1.2), where in all cases, (M) is the mass of neutral atom, that is includes all the electrons, and ΔM is the mass excess ($M - A$) the units of the table are the atomic mass unit M_u, this unit is:

$1M_u or\ 1u = 1.67 \times 10^{-27} kg$, or more correctly it is ($\frac{1}{12} \times M$ ^{12}C kg),

where M ^{12}C = 12.0 M_u.

Table 1.2: Some isotopic masses in $M_u\ or\ amu$

Nuclide	M	A	$\Delta M (Mass\ Excess)$
^{1}H	1.007825	1	$+ 0.007825$
^{4}He	4.002603	4	$+ 0.002603$
^{16}O	15.994915	16	$- 0.005085$
^{35}Cl	34.96885	35	$- 0.031149$

Nuclear Size

When an alpha particle is very distance from a given nucleus , it has only kinetic energy T_α .It comes closest to the nucleus in ahead-on collision. At that point ,the alpha particle has only potential energy V_p , if the recoil of the nucleus is neglected.

Hence, by conservation of energy, $T_\alpha = V_p$

where $T_\alpha = 1/2 M_\alpha {v_\alpha}^2$, and $V_p = k\frac{Ze2e}{D}$

where M_α, v_α *are the mass and the velocity of the alpha particle*

$2e = charge\ of\ the\ alpha\ particle\ (e = 4.80 \times 10^{-10} esu)$

$Ze = charge\ of\ the\ scattering\ nucleus$

$D = distance\ of\ closest\ approach$

and $k = 1\ \ in\ esu\ (electrostatic\ unit)$

therefore

$$D = \frac{2Ze^2}{T_\alpha} \qquad (1.5)$$

Example 1.7: Alpha particles show deviations from pure Coulomb scattering on uranium beyond 25 MeV ($1\text{MeV} = 1.60 \times 10^{-6}$ergs). In that case

$$D = \frac{2 \times 92 \times (4.80 \times 10^{-10})^2}{25 \times 1.60 \times 10^{-6}} \approx 10^{-12}\ \text{cm} = 10\ \text{F}$$

where $1\ \text{F} = 1\ \text{Fermi} = 10^{-13}\ \text{cm} = 10^{-15}\ meter$

If we assume that a nucleus is spherical, we may express its size in terms of its radius (R). The nuclear radius (R) may then be defined as the distance from the center of the nucleus; we can obtain this radius (R), for example, by analyzing difference types of nuclear processes, such as the scattering of fast neutron by nuclei. The experimental result is that the nuclear radius is proportional to ($A^{1/3}$), where (A) is the mass number of the nucleus, that is:

$$R = R_0 A^{1/3} \tag{1.6}$$

where R_0 is called the $radius\ constant$ and the same for all nuclei, and has the values

$$R_0 \approx \begin{cases} 1.4\ F \text{ for nuclear particle scattering on nuclei} \\ \\ 1.2\ F \text{ for electron scattering on nuclei} \end{cases} \tag{1.7}$$

The simple form of Eq. (1.6) would be obtained if the nucleus were a spherical assembly of A hard particles. In that case, the volume of the nucleus would be proportional A and the radius proportional to $A^{1/3}$.

Since the volume of a sphere is ($\frac{4}{3}\pi R^3$), we conclude from Eq. (1.6), that the nuclear volume is:

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi(R_0 A^{\frac{1}{3}})^3 \qquad with\ R_0 = 1.2\ F$$

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

$$\approx 7.238 \times 10^{-45} A.m^3$$

That is, the volume of nucleus is proportional to the mass number A of nucleus. This suggests that the nucleus is maintained at fixed average distances, independent of the number of particles. So that the volume per nuclear is a constant quantity the same for all nuclei.

Example 1.8: Determine the radius of a ^{208}Pb (assume that $R_0 = 1.4F$).

Solution: $R = R_0 A^{1/3} = 1.4(208)^{1/3} \approx 8.3\ F$

Another conclusion is that nuclear matter has a constant density; this may be seen as follows: The mass of a nucleus of mass number A is approximately,

$$M = 1.67 \times 10^{-27} A\ .\ kg$$

therefore the average density ρ of nuclear matter is:

$$\rho = \frac{M}{V}$$

$$= \frac{1.67\times10^{-27} A\ .kg}{7.238\times10^{-45} A.m^3} \approx 2.307 \times 10^{17}\ kg/m^3$$

which means that the density of nuclear matter is nearly constant for all nuclei and it has a large value and is independent of mass number A.

Nuclear Charge Distributions

Refined electron scattering experiments show that the nuclear density distribution does not have a sharp cutoff at the radius R, but has roughly the shape given in Fig (1.1). Nevertheless the concept of *nuclear radius* is often useful. Equation (1.6) applied to ^{238}U gives ($R = 9\ F$).

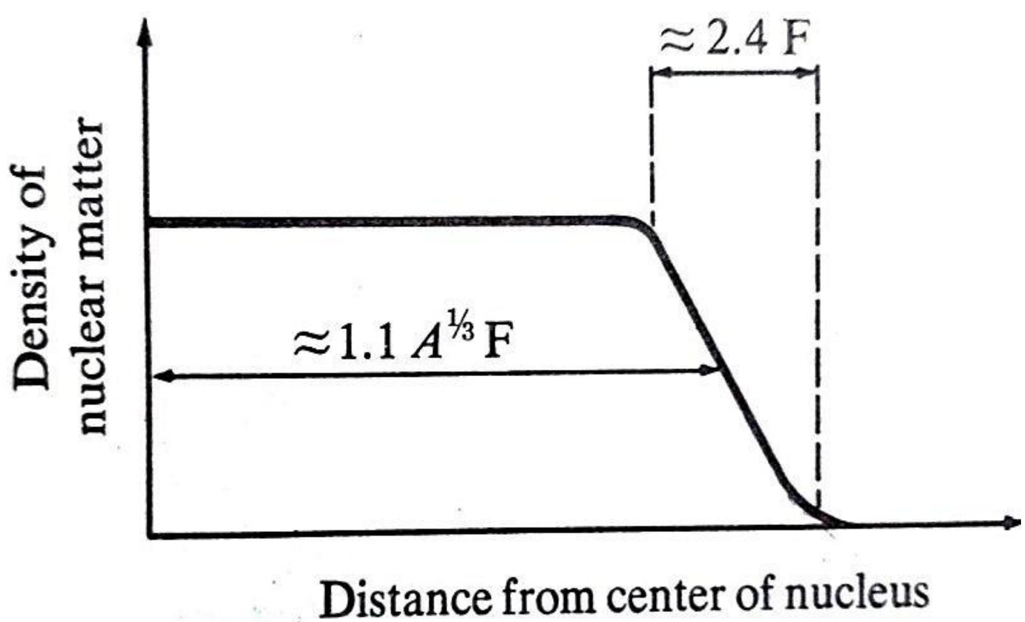

Fig 1.1: Density distribution of nuclear matter in a nucleus.

The best information we have about nuclear charge distributions comes from electron scattering, where one uses short-wavelength electrons to explore the structure. In the work of Hofstadter and colleagues at Stanford a phaseshift analysis was made of elastic electron scattering from an arbitrary charge distribution through the Coulomb interaction. The best fit to the data, on the average, was found with the following shape, illustrated in Fig. 1.2 .

$$\rho(r) = \frac{\rho_0}{1+e^{(r-R)/a}} \tag{1.8}$$

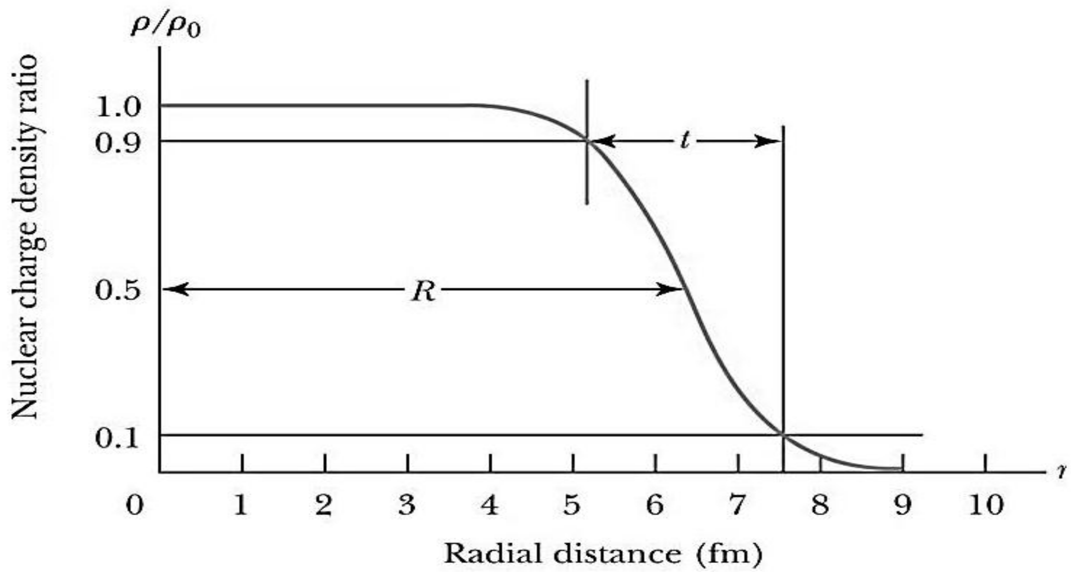

Fig. 1.2: Charge Distribution of Nuclei

ρ_0 is nucleus density near the center of the nucleus;

R is the radius at which the density has decreased by a factor of 2 below its central value.

Skin thickness t ; is the measured of the surface thickness such that the distance over which the density falls from 90 % of ρ_0 to 10% of ρ_0

Example 1.9: Show from Eq. (1.8) and Fig. (1.2) that the skin thickness is $4.4a$.

Solution: $\rho(r) = \frac{\rho_0}{1+e^{(r-R)/a}}$

$$0.9\rho_0 = \frac{\rho_0}{1+e^{(r_1-R)/a}}$$

$$\frac{10}{9} = 1 + e^{(r_1-R)/a} \Longrightarrow \frac{10}{9} = \frac{9}{9} + e^{(r_1-R)/a}$$

$\frac{1}{9} = e^{(r_1-R)/a}$ by taking the natural logarithm of each side we get,

$ln1 - ln9 = (r_1 - R)/a$;

$$(0 - ln9)a = r_1 - R \Longrightarrow -aln9 = r_1 - R \Longrightarrow$$

$r_1 = R - aln9$; and

$$0.1\rho_0 = \frac{\rho_0}{1+e^{(r_2-R)/a}}$$

by the same way of the steps of finding the r_1; r_2 becomes

$r_2 = R + aln9$

Then $r_2 - r_1 = t = R + aln9 - (R - aln9) = aln9 + aln9 = 2aln9 = 4.4a$

therefore Fig. (1.2) which is plot of Eq. (1.8) becomes

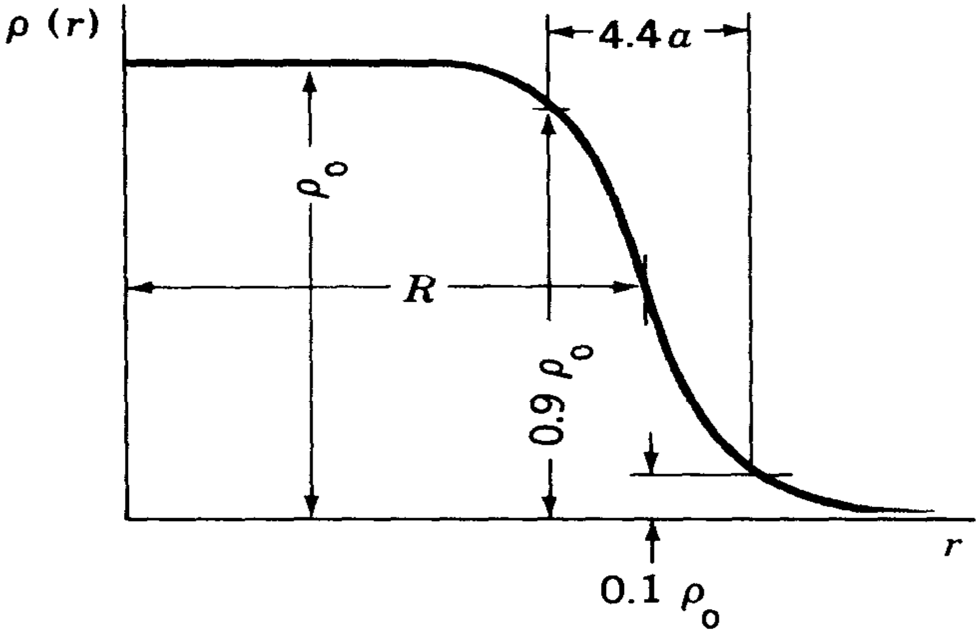

Fig. 1.3: Plot of Eq. (1.8) for $\rho(r)$ vs. r. the meaning of ρ_0, R, and a are illustrated

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Note: $a \cong 0.55\ F \Longrightarrow t \cong 2.4\ F$, $\rho_0 = 0.17\ F^{-3}$

PROBLEMS

1.1 Find the stable nucleus that has a radius 1/3 that ^{189}Os is

a. ^{7}Li b. ^{4}He c. ^{10}B d. ^{12}C

1.2 If the radius of a nucleus is given by $R = R_0 A^{\frac{1}{3}}$ with $R_0 = 1.2$ F , what is the density of nuclear matter (a) in g/cm^3, (b) in nucleons/F^3?

1.3 Determine the approximate density of a nucleus? If the nucleus is treated as a uniform sphere. If you know that the mass of a nucleon is $(1.67 \times 10^{-27} Kg)$

1.4 An 0.2 MeV proton makes a head-on collision with an alpha particle at rest. What is distance of closest approach in Fermi?