FUTURE OF PHYSICS

FORUM FOR IIT JAM,GATE,JEST,TIFR,NET,DU,JNU

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Nuclear and Particle Physics

Contribution

NET

3 Questions in Part C (5 mark each) = 3×5 = 15 marks

GATE

3 Questions (1 mark)
2-3 Questions (2 marks) } 7-9 marks (equal contribution) for all books

TIFR

1-2 Questions

JEST

1 Question

Books

(1) Introductory Nuclear Physics – Kenneth S. Krane (John Wiley & Sons 1988)

(2) Introduction to High Energy Physics – Donald H. Perkins (1972)

(3) Introduction to Elementary Particles – David Griffith

(4) Introductory Nuclear Physics – David Halliday (John Wiley & Sons 1955)

(5) Nuclear Physics – S. N. Ghoshal (S. Chand)

(6) Nuclear Physics – D. C. Tayal (Himalaya Publishing House)

(7) Elements of Nuclear Physics (M. L. Pandaya & R. P. S. Yadav) (Kedar Nath Ram Nath)

Syllabus

① Basic Nuclear (Static) Properties

Mass, Size, Shape, Density (charge distribution)

Spin & Parity (covered in Shell Model)

Binding Energy

② Nuclear Models → Liquid Drop Model, Shell Model, Fermi Gas Model, Collective Model

③ Radioactivity

④ α, β and γ decay

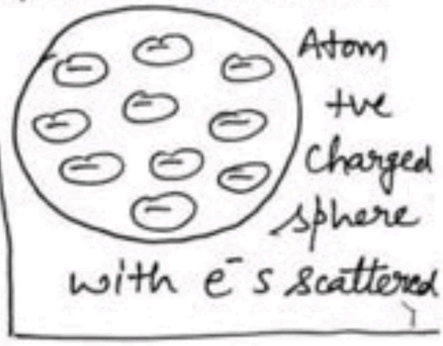
⑤ Q value of a Nuclear reaction (Including Q value in α and β decay)

6. Nuclear Fusion and Fission
7. Elementary Particles –
   Classification, Types of Fundamental Forces, Quantum numbers, Conservation Laws, Quark Model, SU(2) and SU(3) Symmetry.
8. Relativistic Kinematics
9. Particle Accelerator (cyclotron)
10. Deuteron Problem

Plum Pudding Atomic Model of J.J. Thomson

Atom is a sphere of +ve charge & e^- distributed.

If α particle incident towards a matter (atoms), it would just fly straight, its path being deflected at most a fraction of a degree.



Thomson model predicted that electric fields in an atom are too weak to affect a passing α particle (highly energetic).

✓ According to Coulomb's law, the less concentrated a sphere of electric charge is, the weaker its electric field at its surface will be.

1906 → Hans Geiger developed Geiger-Muller tube to count the hitting alpha particles.

1909 → Rutherford & Roybls (α particle shown to be He nucleus)

1908-1911

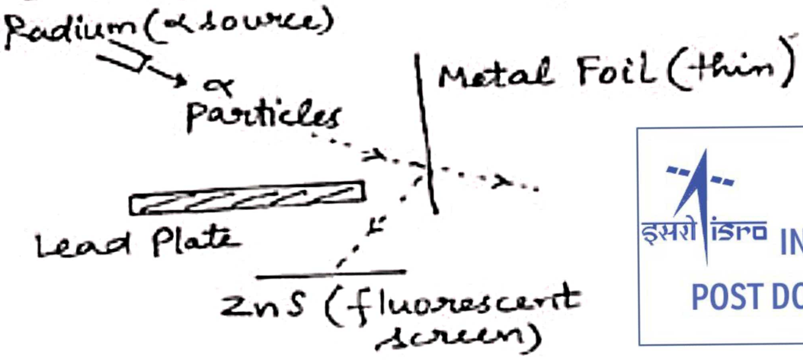
Geiger-Marsden experiments - also called Rutherford gold foil experiment

Hans Geiger from Germany visited Rutherford (Ernest Marsden is Geiger's student) in University of Manchester, England.

Rutherford → New Zealand born British scientist

Although Rutherford was awarded Nobel Prize in 1908 but these experiments were landmark for him.

1911 (1908–1911) → Geiger Marsden experiments
Rutherford Scattering



- Counting scintillations, they observed that metals with higher atomic mass such as gold, reflected more α particles (some even more than 90°) than lighter ones such as aluminium.
- Rutherford gave mathematical expression of Rutherford scattering (will be covered in α decay)
- Very few α particles were reflected at large angles & most of them passes undeviated or at a very small angles.

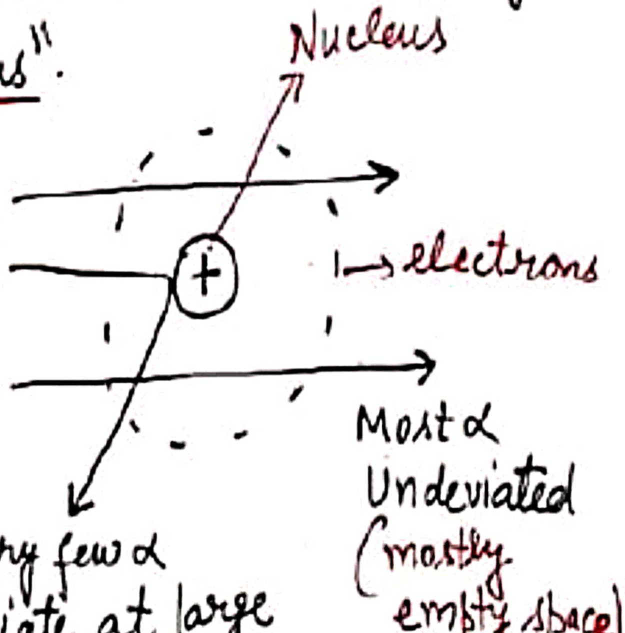
Conclusion

→ Large deflections are possible only if all the charge is concentrated at a small region which is called "Nucleus".

Rutherford ⇒ Father of "Nuclear Physics" α

1911 → Nuclear physics started

Nucleus differentiated from Atom



Isotopes (isos = same, topos = place)

1912 → First evidence of stable isotopes by J. J. Thomson on Neon

1913 → Frederick Soddy suggested and indicated 40 species although periodic table allowed for 11 elements.

1913 → Rutherford – Bohr Atomic Model or just Bohr Model.
(Bohr was his Ph.D Student)

1914 → H. G. J. Moseley
Used X ray diffraction and explained that Periodic table is based upon Atomic number Z instead of Atomic mass A. $[{}_{Z}X^{A}]$

[Died in battle of Gallipoli (Peninsula) in Turkey.
1916 – no nobel prize in Physics given. Moseley would have won but cannot be given posthumously.

1914 – 1918 → No major discoveries due to World War I.

1919 → Aston development of Mass Spectrometer (measures Atomic mass)

Whole number rule → Atomic masses are nearly equal to mass numbers.

Deviations in Atomic masses due to the fact that element is a mixture of isotopes.

He calculated Atomic weight of chlorine as weighted average of all isotopes Cl^{35} and Cl^{37}.

1919 → Discovery of proton

Background

1815 – William Prout proposed all atoms are composed of hydrogen atoms (which he called protyles) which is based on early values of Atomic weights which was disapproved when more accurate values were measured.

1886 – Eugen Goldstein discovered canal rays (anode rays) and showed that they were +ve charged particles (ions) produced from gases. However since particles from different gases had different e/m ratio, they could not be identified with single particle, unlike -ve electrons discovered by J. J. Thomson in 1897.

1919 - Discovery of Proton (by Rutherford)

$\alpha + N \rightarrow {}_6C + \underbrace{H \text{ nucleus}}_{\text{Proton}} + \alpha$

α: incident from radioactive nuclei

N: Nitrogen gas

Proposed that α particle knocked H nucleus out of Nitrogen ${}_7N$ nucleus turning into ${}_6C$

1920 → Proton name given by Rutherford. Appeared first time in scientific literature.

Greek word - first

Prout's word - protyle

1925 → First reported nuclear reaction

Rutherford realised after observing Blackett's Cloud chamber images that Z is increased & not decreased i.e.

$$\alpha + {}^{14}_{7}N \rightarrow {}^{17}_{8}O + P$$

→ H' nucleus is fundamental particle building block of all Atomic nuclei

Z increased from 7→8

and $\alpha + {}^{14}_{7}N \not\rightarrow {}^{12}_{6}C + P + \alpha$ Z not decreased & from 7 to 6

This proposal was wrong

Use → Protons are used for accelerators, particle physics experiments, Large Hadron Collidor (LHC) etc.

Electron - Proton Hypothesis (As neutron was discovered in 1932)

Nucleus consist of e^- and proton p.

Why this was proposed

- e^- inside nucleus → as β particles are emitted from inside nucleus (radioactive nucleus) (β particles are nothing but energetic electrons).
- Proton inside nucleus → The mass of nucleus is about mass number times the mass of proton. So all mass concentrated inside nucleus.
- Atom is electrically neutral

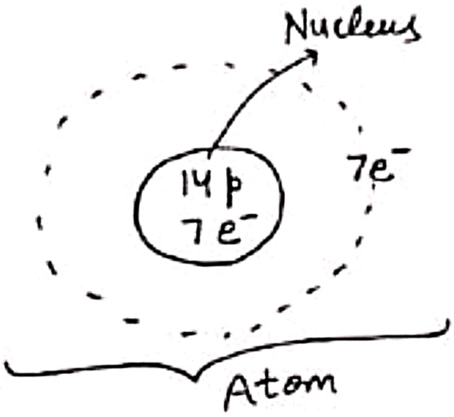
e.g. $_7N^{14}$ Atom and $_7N^{14}$ nucleus

$_7N^{14}$ **Atom** → contains 14 p (to explain mass of Nitrogen atom which is 14 times the mass of hydrogen Atom)

Also $_7N^{14}$ Atom contains 14 e^- (to explain Atom is electrically neutral).

$_7N^{14}$ **Nucleus** → 14 p + 7 e^- → So charge = +7 equal to Atomic number

→ mass ≃ 14 times H nucleus.



Limitations of Electron – Proton Hypothesis

① By Heisenberg Uncertainty Principle → Electrons cannot reside inside nucleus. (Discuss later)

② Magnetic dipole moment → M.D.M. of e^- is about 2000 times larger than proton

$|\mu_L| = \frac{e}{2m_e}\sqrt{l(l+1)}\,\hbar$ $\qquad \frac{eh}{4\pi m_e}$ Bohr Magneton 9.27×10^{-24} J/T

But $\frac{eh}{4\pi m_p}$ is Nuclear Magneton 5.05×10^{-27} J/T

Calculations of M.D. Moment of nucleus cannot be satisfied by electrons & protons inside nucleus.

③ Statistics for Nuclear Spin

First what is Nuclear Spin.

Nuclear Spin - in Nuclear Physics is the resultant of orbital angular momentum and spin angular momentum of all the particles inside nucleus i.e. Nuclear spin is total angular momentum (and not spin angular momentum) denoted by $\bar{I}$ or $\bar{J}$.

In Atomic - Spin is spin $\bar{S}$

In Nuclear - Spin is used for total ang. momentum denoted by $\bar{I}$ (or $\bar{J}$). Just terminology e.g. $_7N^{14}$ nucleus → has 14 p and 7 e^- inside nucleus

Total 21 fermions of spin $\frac{1}{2}$ (both p & e^- are fermions)

$s_1 = \frac{1}{2}$, $s_2 = \frac{1}{2}$ - - - - - $s_{21} = \frac{1}{2}$

Resultant spin quantum no of odd (21) fermions

$= \frac{1}{2}$ odd integer $= \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$ - - -

Resultant orbital angular momentum quantum no. L = Always integer irrespective of even or odd no. of fermions ($l_1, l_2 --- l_{21}$ gives L)

Now Nuclear spin

$\bar{I}$ (or $\bar{J}$) $= |\bar{L} - \bar{S}|$ to $|\bar{L} + \bar{S}|$ with difference of one

Since $S = \frac{1}{2}$ odd integer & $\bar{L}$ = integer

Thus $\bar{I} = \frac{1}{2}$ odd integer

but Experimental value of Nuclear spin of $_7N^{14}$ = Integer

Neutron

Although Neutron was discovered in 1932 by Chadwick but

1920 → Rutherford proposed neutron inside nucleus. He proposed proton and an electron in some way to form neutral particles.

NOTE → Word neutron in connection with atom is found in literature as early as 1899.

$n \rightarrow$ (p, e) spin of $p = \frac{1}{2}$ & spin of $e^- = \frac{1}{2}$

Thus spin of $n = |\frac{1}{2} - \frac{1}{2}|$ to $|\frac{1}{2} + \frac{1}{2}| = 0, 1$ (integer)

which was later proved to be wrong as spin of n is also equal to $\frac{1}{2}$.

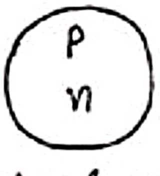
1932 - Discovery of neutron by James Chadwick

Chadwick performed series of experiments that showed the new radiation of uncharged particles with about the same mass as the proton. These particles were neutrons

$$ {}_2He^4 (\alpha) + {}_4Be^9 \rightarrow {}_6C^{12} + {}_0n^1 $$

Chadwick won the 1935 Nobel Prize in Physics

Thus Proton – Neutron Model replaced Electron - Proton Model



Nucleus

Proton- Neutron hypothesis

- Atomic nucleus consist of P and n.
- e^- cannot reside inside nucleus by calculations.

So why & how β particles emitted in β decay

- β particles emitted in radioactivity from unstable radioactive nucleus to makes themselves stable.
- β particles are fromed by change of Protons into neutrons and vice versa.

$n \rightarrow p$ emitting β^- } both inside nucleus ⇒ will be discussed in β decay
$p \rightarrow n$ emitting β^+ }

- Both P and n are together called nucleons and are responsible for strong nuclear forces and stability of nucleus.

1934 → Enrico Fermi explained the process of β decay.

Nuclear Nomenclature

$_ZX^A$ or ^A_ZX or $^A_ZX_N$

X is any nucleus and can be replaced by symbol of an element

where

A is Mass Number → Total number of Protons plus neutrons

Z is Atomic Number → Total number of protons.

$N = A - Z$ = Total number of neutrons

X → symbol of an element

e.g. $_1H^1$, $_2He^4$, $_6C^{12}$ etc

Classification of Nuclei

(1) Isotopes → Nuclei having same Atomic (Proton) number Z but different Mass number A

e.g. ${}_1H^1$, ${}_1H^2$ and ${}_1H^3$; ${}_8O^{16}$, ${}_8O^{17}$; ${}_{17}Cl^{35}$, ${}_{17}Cl^{37}$ etc

All isotopes of an element have identical chemical properties and differ physically only in mass.

i.e. Same chemical property ⇒ Same Z ⇒ Same element

Thus ${}_1X^1$ and ${}_1Y^2$ is wrong

as if $Z=1$ is same then element should be same i.e. ${}_1X^1$ and ${}_1X^2$ OR ${}_1Y^1$ and ${}_1Y^2$

(2) Isobars → Nuclei having same mass number A but different Atomic number Z

e.g. ${}_6C^{14}$ and ${}_7N^{14}$

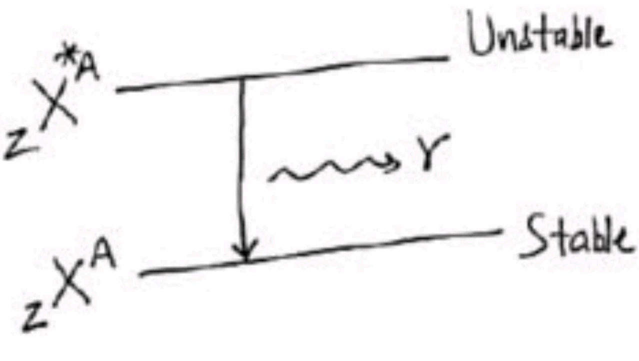
Since Z is different ⇒ Element is different

(3) <u>Isotones</u> → Nuclei having same number of neutrons ($N = A - Z$)

e.g. $_6C^{13}$ and $_7N^{14}$

$N = 13 - 6 = 7$ $N = 14 - 7 = 7$

(4) <u>Isomers</u> → Nuclei having same A and same Z but differ from one another in their nuclear energy states. They also exibit different life times.



$$_Z X^{*A} \longrightarrow {}_Z X^{A} + \gamma$$

(5) <u>Mirror Nuclei</u> → Nuclei with same mass number A but with proton and neutron number interchanged (i.e. different Atomic number Z)

e.g. $_{4}Be^{7}$ $(Z=4, N=3)$ and $_{3}Li^{7}$ $(Z=3, N=4)$

NOTE → Since Same A and different Z, so they are also <u>isobars</u>

. Thus all mirror nuclei are isobars, but all isobars need not be mirror nuclei.

<u>Also</u> For a <u>pair of</u> mirror nuclei $\boxed{A = 2Z \pm 1}$ ↓ Thus always odd

& $\boxed{A = Z_1^2 - Z_2^2}$ if $Z_1 > Z_2$

e.g. $_{4}Be^{7}$ and $_{3}Li^{7}$

$A = 2Z - 1 = 2\times4 - 1 = 7$ $A = 2Z+1 = 2\times3+1 = 7$

Also $A = Z_1^2 - Z_2^2 \Rightarrow A = 4^2 - 3^2 = 16 - 9 = 7$

Also Z_1 and Z_2 differ always by one i.e. $\boxed{|Z_1 - Z_2| = 1}$