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Topic:

Elements of Modern Physics (4): Size and structure of atomic nucleus and its relation with atomic weight; Impossibility of an electron being in the nucleus as a consequence of the uncertainty principle. Nature of nuclear force, NZ graph.

Elements of Modern Physics (4):

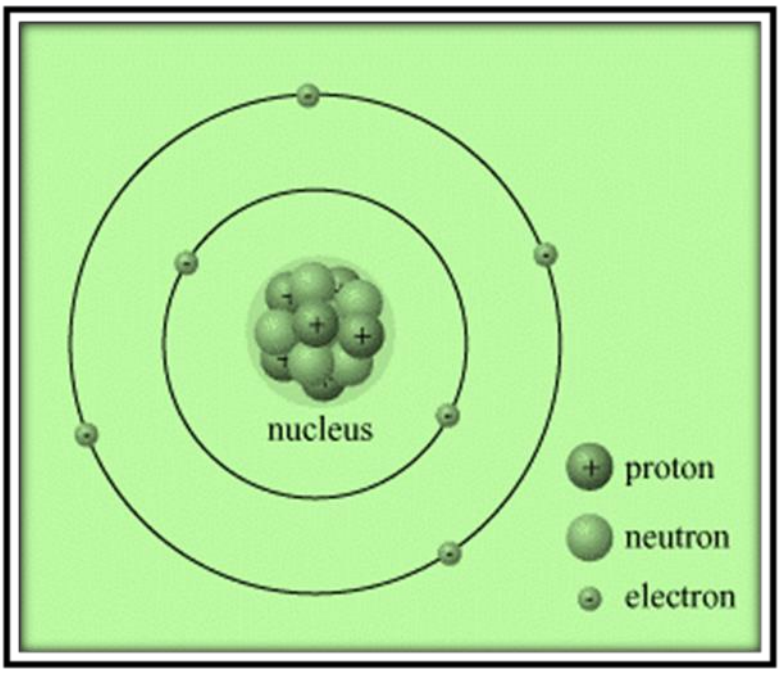
Size and Structure of Atomic Nucleus:

Nuclear Size:

Assuming the nucleus to be a sphere of radius 'R' and its volume (V) is proportional to the total number of nucleons in it or its mass number A.

Therefore, $V = \frac{4}{3}\pi R^3 \propto A$ $\quad or,\ R \propto A^{\frac{1}{3}}$

Therefore, $R = R_0 A^{\frac{1}{3}}$, where R is the radius of the nucleus and R_0, a constant called the nuclear radius parameter. The value of R_0 ranges from (1.1 x 10^{-15} to 1.5 x 10^{-15} m or 1.1 to 1.5 fm).



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Nuclear Mass & Binding Energy:

$M_{nuc} = M\ (A,Z) - Zm_e$

Here, M_{nuc} = Nuclear Mass, $M\ (A,Z)$ = Atomic mass and m_e = mass of electron, A= Mass number and Z= atomic Number. Binding Energy (B.E.) $= E_B = \Delta M c^2$, where ΔM= amount of mass disappeared.

$\Delta M = ZM_H + NM_n - M(A,Z)$

$E_B = [ZM_H + NM_n - M(A,Z)]c^2$

$E_B = [ZM_p + NM_n + Zm_e - M_{nuc} - Zm_e]c^2$

$E_B = [ZM_p + NM_n - M_{nuc}]c^2$

$\Delta M = [ZM_p + NM_n - M_{nuc}]$

Impossibility of an electron being in the nucleus as a consequence of the uncertainty principle

The uncertainty in position of the electron will be the same as the diameter of the nucleus $\Delta x = 2 \times 10^{-14}\ m$.

From the uncertainty principle $\Delta x\ .\Delta p_x \geq \hbar$

The uncertainty in momentum $\Delta p_x \geq \frac{\hbar}{\Delta x}$

The minimum uncertainty in momentum

$$\Delta p_x = \frac{\hbar}{\Delta x} = \frac{6.62 \times 10^{-34}}{2 \times 3.14 \times (2 \times 10^{-14})} = 5.278 \times 10^{-21}\ kg - m/sec$$

If, electron exist in nucleus, the minimum momentum

$$p_{min} = 5.278 \times 10^{-21}\ kg - m/sec$$

Now, for the electron,

$E_{min}^2 = p_{min}^2 c^2 + m_0^2 c^4$

$E_{min}^2 = (5.278 \times 10^{-21})^2 (3 \times 10^8)^2 + (9.1 \times 10^{-31})^2 (3 \times 10^8)^4$

$E_{min} = 9.875\ MeV$

If, for the electron to be present in nucleus its minimum energy should be $\sim 10\ MeV$. However, experiments shows that the maximum energy of the β-particles emitted from the radioactive nuclei is $\sim 4\ MeV$. Therefore, the electron cannot exist within the nucleus.

Nature of nuclear force

Nuclear force is the force that binds the neutrons and protons in a nucleus together. The forces inside the nucleus binds neutrons to neutrons, protons to protons and protons to neutrons are classified as strong interactions and represented by $n-n$, $n-p$, and $p-p$ forces, respectively.

The following are the few characteristics of nuclear forces: -

1. It is attractive in nature and short range force.

2. Nuclear force is identical for all nucleons and is charge independent.

3. They are strongest known force in nature.

4. They get readily saturated by the surrounding nucleons.

5. They are spin dependent.

The distances larger than 0.7 fm the force becomes attractive between spin-aligned nucleons, becoming maximal at a centre–centre distance of about 0.9 fm.Apart from this distance the force drops exponentially, until beyond about 2.0 fm separation, the force is negligible. Nucleons have a radius of about 0.8 fm.

Mass Defect and Packing Fraction

The difference between the measured atomic mass $M\ (A,Z)$ and the mass number A of a nuclide is called the mass defect, $\Delta M'$

$$\Delta M' = M\ (A,Z) - A$$

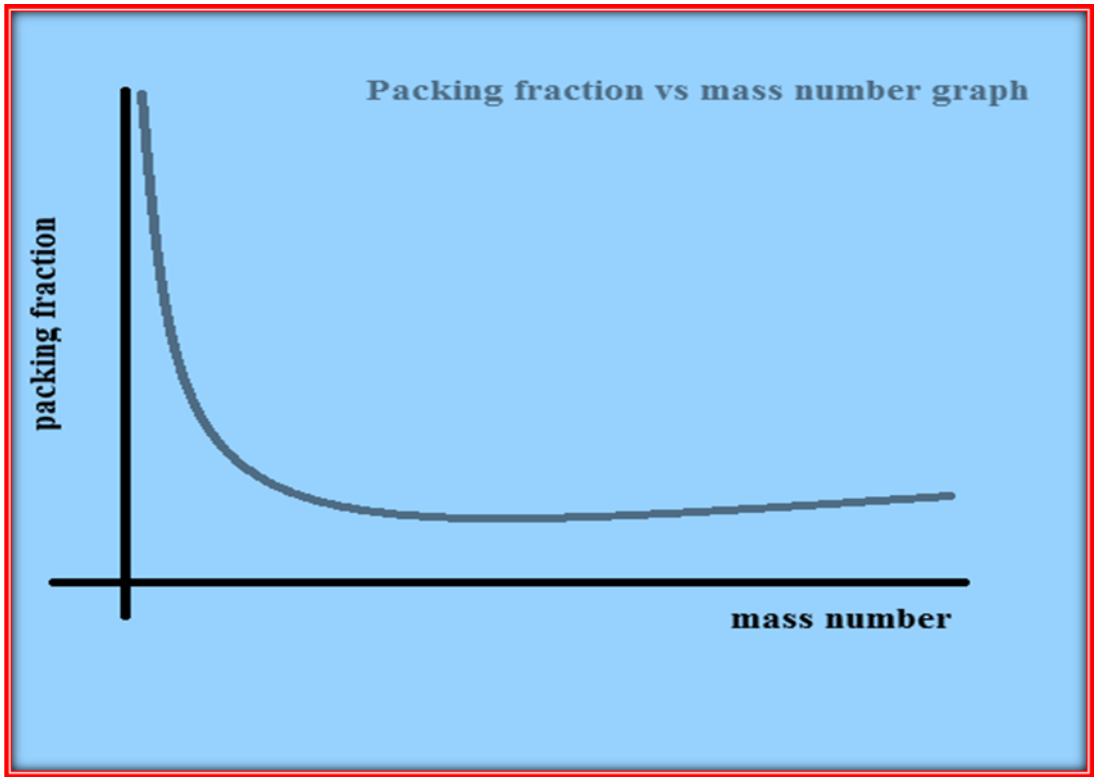
The packing fraction f is defined as the mass defect per nucleon in the nucleus,

$$f = \frac{\Delta M'}{A} = \frac{M\ (A,Z) - A}{A}$$

$$f = \frac{M\ (A,Z)}{A} - 1$$

Or, $M\ (A,Z) = A(1+f)$

And the packing fraction curve with mass number (A) becomes-



The binding fraction, $f_B = \frac{E_B}{A} = \frac{ZM_p + NM_n - M(A,Z)}{A}$ in energy unit

The $\frac{E_B}{A}\ vs\ A\ curve$ becomes-

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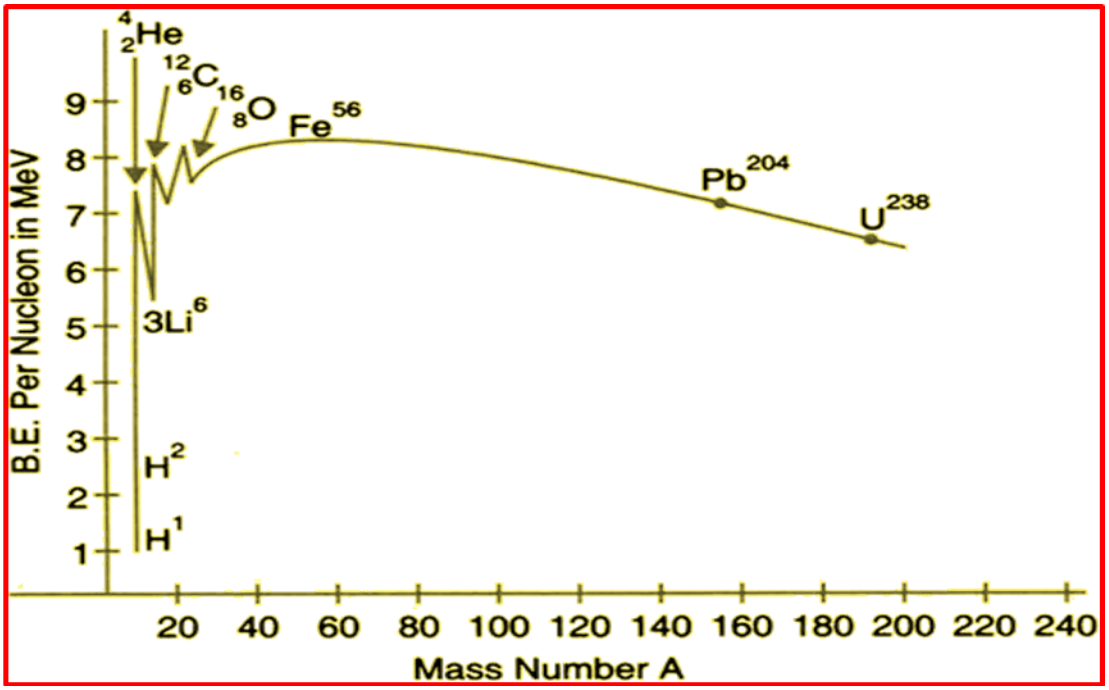

The critical survey of the curves-

1. f_B is very small for light nuclei and goes rapidly with increasing with A. For, $A = 20$ it reaches to $\sim 8\ MeV$. Then curve rises much slower and reaching at maximum value $\sim 8.7\ MeV\ for\ A = 56$. Thereafter, with increase of A, the f_B slowly decreases.
2. $Between\ 20 < A < 180$,the variation of f_B is very small.
3. When $A > 180$, f_B decreases with increasing A and is $\sim 7.5\ MeV$ for the heaviest nuclei.
4. A rapid fluctuations $in\ f_B$ is observed for $A = 4n, where, n = 1,2,3,4$ and also for magic numbers (peaks are less prominent for $A/Z = 2,8,20,50,82,126$

Frequently Asked Questions/Numerical:

For theoretical questions and problems in this section, students can solve the problems of Modern Atomic and Nuclear Physics, Author-A.B.Gupta, published byBooks & Allied Pvt. Ltd. (2017 Ed.).

References:

(i) *Modern Atomic and Nuclear Physics, Author-A.B.Gupta, published by Books & Allied Pvt. Ltd. (2017 Ed.).*
(ii) *https://en.wikipedia.org/wiki/Nuclear_binding_energy (Pictures are taken only for class note.)*

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Link to Audio visual Lectures (e-Lectures) on this topic given by Distinguish Professors of Indian &Foreign Universities:

(1)https://nptel.ac.in/courses/115104043/
(2)https://nptel.ac.in/courses/112/103/112103243/
(3)https://nptel.ac.in/courses/104106096/
(4)https://www.youtube.com/watch?v=6LoWEs8z1A4