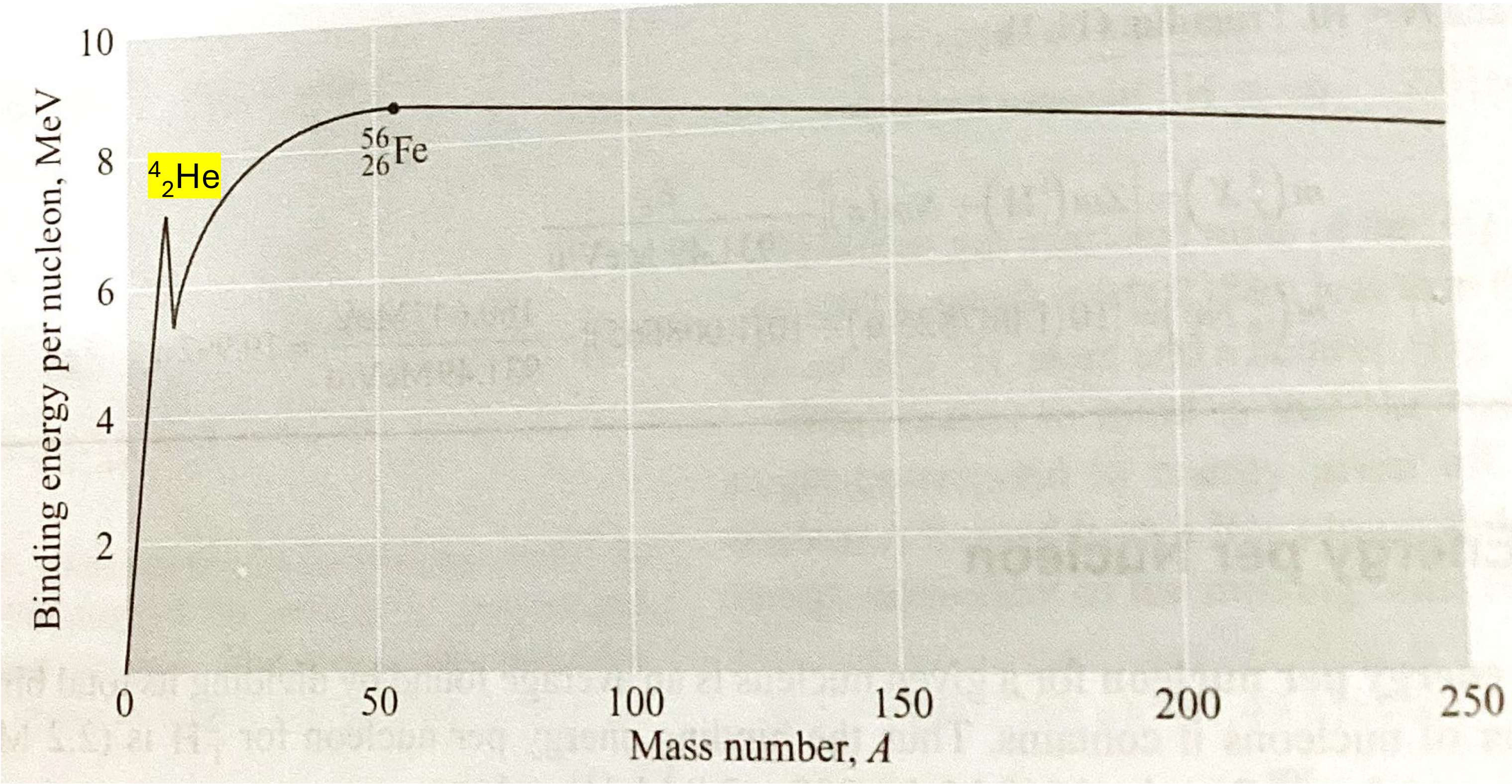
Nuclear Physics: Learning Objectives

- Liquid drop model
- Shell model
- Radioactive decay

Nuclear Physics: Binding energy per nucleon

- **Strong interaction in nucleus**
- Electromagnetic interaction between charge particles
- Gravitational interaction everywhere



- While attractive forces that nucleons exert upon one another are very strong, their range is short.
- Up to a separation of about 3fm, the nuclear attraction between two protons is about 100 times stronger than electric repulsion between them.
- Nuclear interaction between proton and proton, between proton and neutron and between neutron and neutron appear to be identical.

Nuclear Physics: Liquid drop model

- At a first approximation, we can think of each nucleon in a nucleus as interacting solely with its nearest neighbors.
- Analogy with liquid was proposed by George Gamow in 1929 and developed in detail by C.F. von Weizsacker in 1935.
- Assume energy associated with each nucleon-nucleon bond has some value U.
- This value is actually negative since attractive forces are involved, but usually written as positive for convenience.

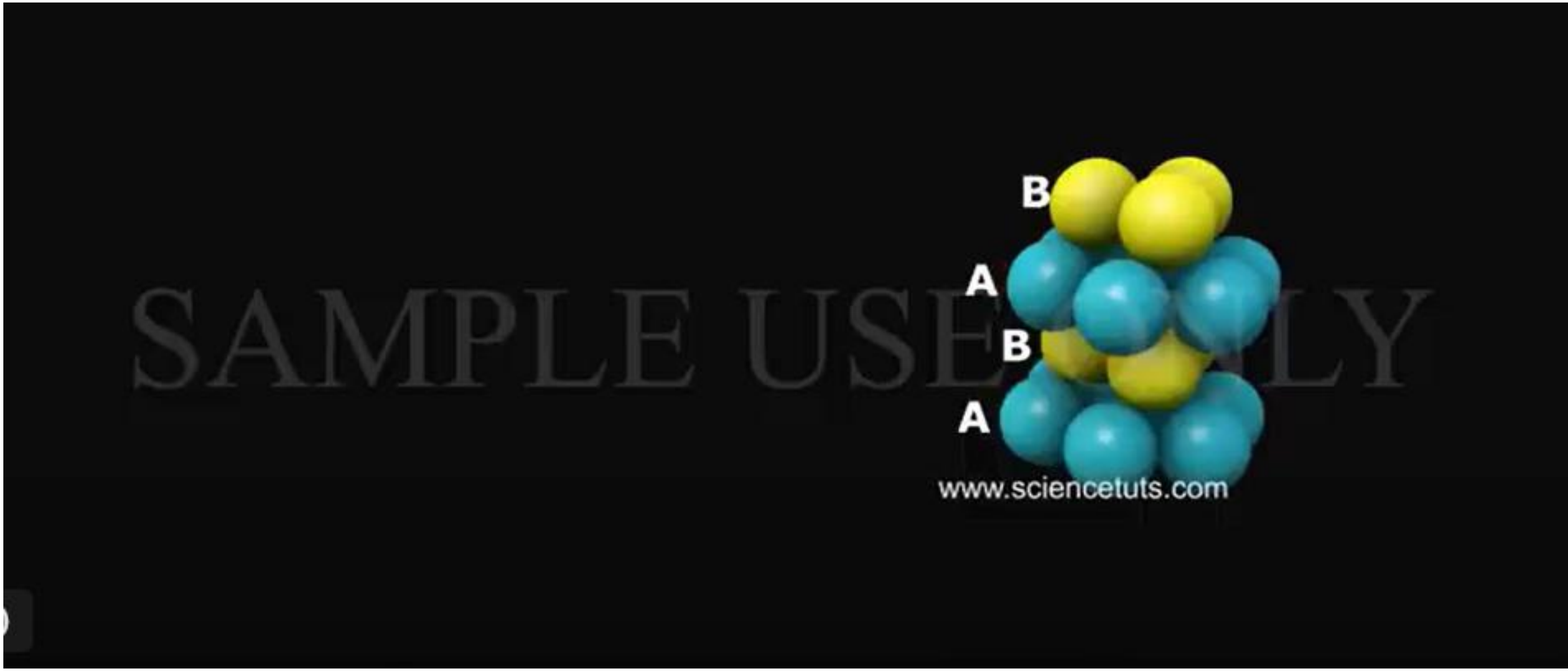
each bond is shared by two nucleons, each has a binding energy of $\frac{1}{2}U$.

assembly of nucleons packed together into smallest volume each sphere is surrounded by 12 other spheres.

(volume energy) $E_V = 12 \times \frac{1}{2} U(A) = 6U(A) = 6UA$

if all "A" nucleons in a nucleus were in its interior

(volume energy) $E_V = a_1 A$ —— (1)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Some nucleons are on the surface, no. of such nucleons depend on the surface area of the nucleus.

nucleus of radius R has an area of $4\pi R^2 = 4\pi R_0^2 A^{2/3}$

surface energy $E_s = -a_2 A^{2/3}$ —— (2)

potential energy of a pair of protons "r" apart is

$$V = -\frac{e^2}{4\pi\epsilon_0 r}$$

$\frac{Z(Z-1)}{2!}$ pair of protons

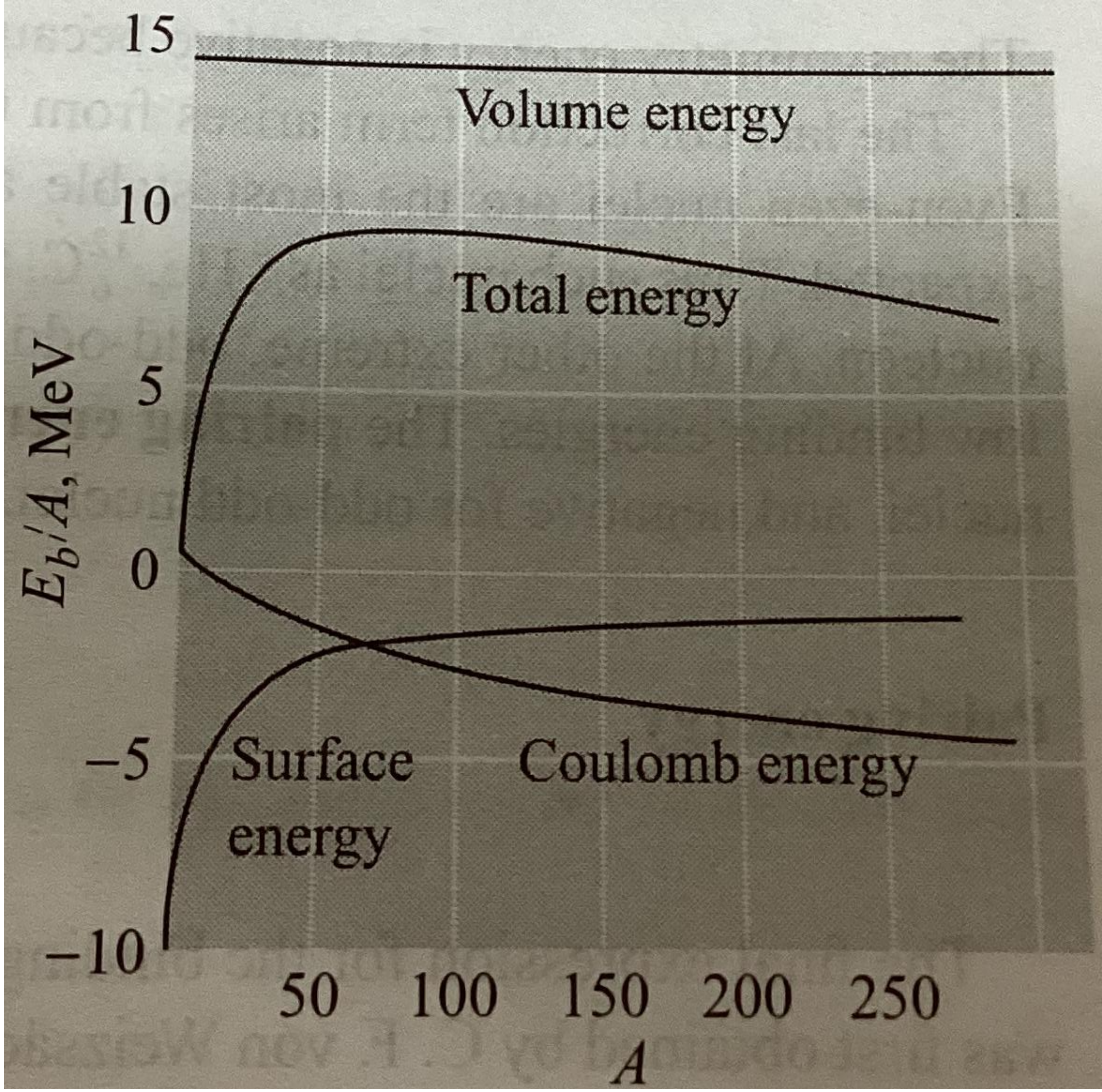
Coulomb energy $E_c = \frac{Z(Z-1)}{2} V = -\frac{Z(Z-1)e^2}{8\pi\epsilon_0}\left(\frac{1}{r}\right)_{avg.}$

$$E_c = -a_3 \frac{Z(Z-1)}{A^{1/3}} \quad \text{—— (3)}$$

Binding energy (BE) $E_b = E_v + E_s + E_c$

$$= a_1 A - a_2 A^{2/3} - a_3 \frac{Z(Z-1)}{A^{1/3}}$$

BE/nucleon $\frac{E_b}{A} = a_1 - \frac{a_2}{A^{1/3}} - a_3 \frac{Z(Z-1)}{A^{4/3}}$



BE/nucleon $\frac{E_b}{A} = a_1 - \frac{a_2}{A^{1/3}} - a_3 \frac{Z(Z-1)}{A^{4/3}}$

Corrections to the Formula

Asymmetry energy

$$E_a = -\Delta E = -a_4 \frac{(A-2Z)^2}{A}$$

Pairing energy

$$E_p = (\pm, 0) \frac{a_5}{A^{3/4}}$$

+ positive for even-even nuclei
0 odd-even and even-odd
− odd-odd nuclei

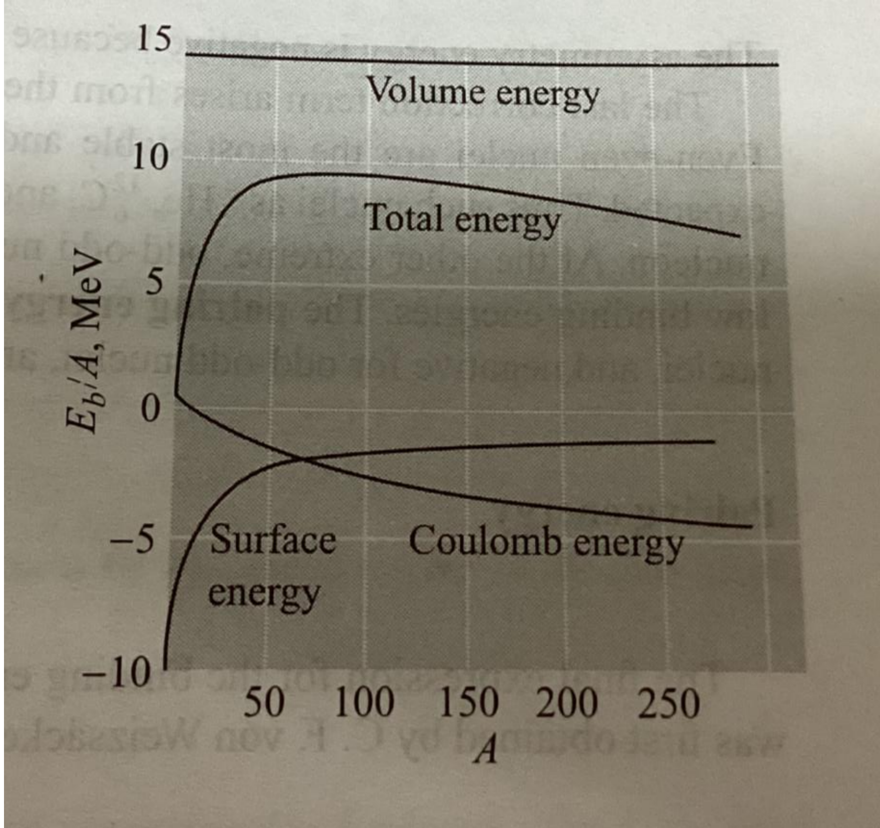
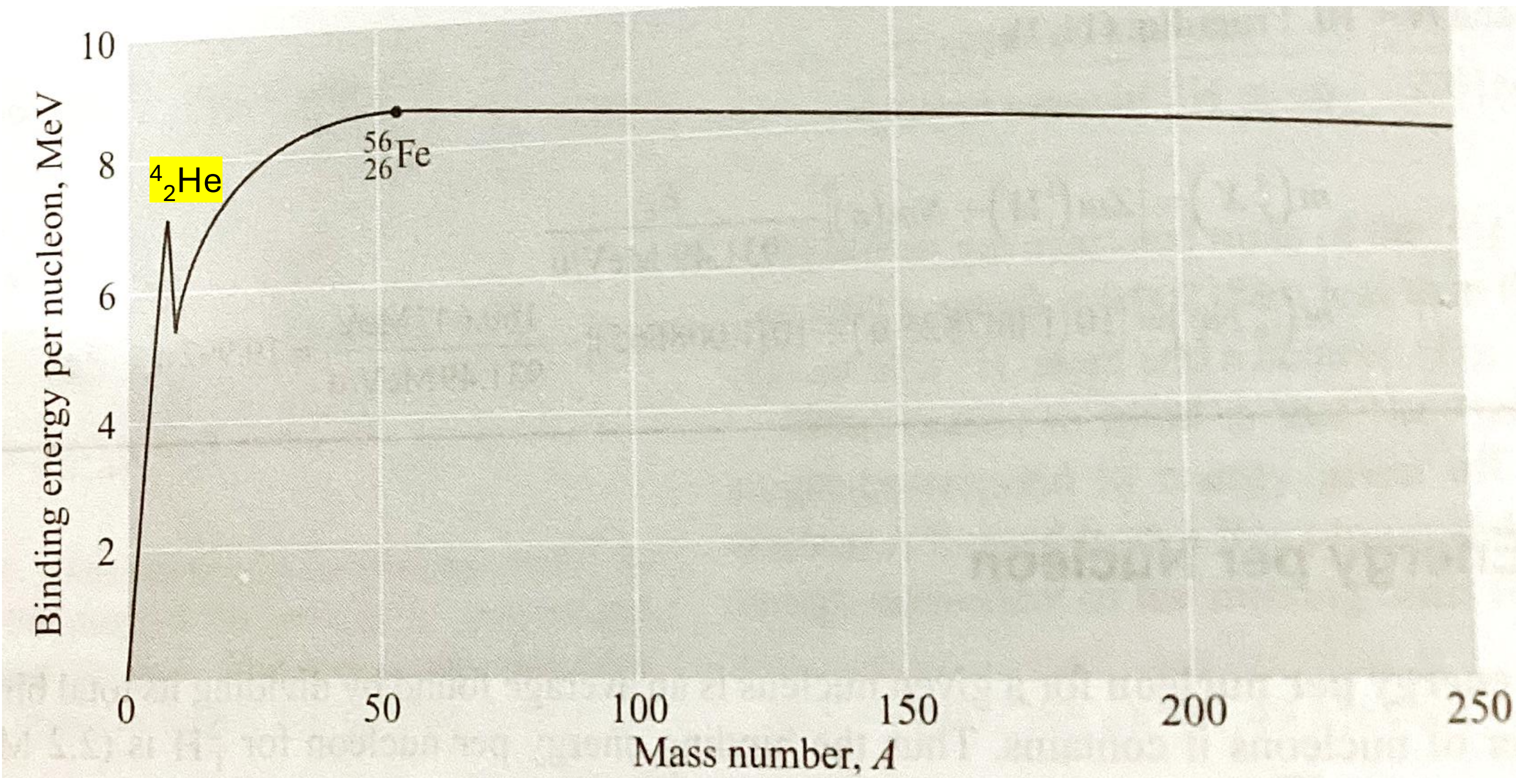


Fig. 11.15 *The binding energy per nucleon is the sum of the volume, surface, and coulomb energies.*

$$E_b = a_1 A - a_2 A^{2/3} - a_3 \frac{Z(Z-1)}{A^{1/3}} - a_4 \frac{(A-2Z)^2}{A} (\pm, 0) \frac{a_5}{A^{3/4}}$$

Liquid drop model- explain binding energy/nucleon curve

BUT why some nucleons are more favourable?



SHELL MODEL

Basic assumption of liquid-drop model is that each nucleon in a nucleus interacts only with its nearest neighbors, like a molecule in a liquid.

The hypothesis that each nucleon interacts with a general force field produced by all other nucleon has a lot of support.

Fermions : spin $\frac{1}{2}$ particle. e^-, proton and neutron

Similar to e^-, nucleons are also filled in shells

atoms with 2, 10, 18, 36, 54 and 86 electrons have all their e^- shells completely filled. Such atomic structure are more stable.

Same effect is observed w.r.t. nuclei

Nuclei that have 2, 8, 20, 28, 50, 82 and 126 neutrons or protons are more abundant than other nuclei of same mass no.

magic numbers

SHELL MODEL → explain existence of magic no.s based on a common

How magic numbers arise?

solved by Maria Goeppert Mayer and Jensen in 1949.

They realised importance of including spin-orbit interaction.

Total spin momentum (S): intrinsic spin angular momenta (S_i) of each nucleon coupled together into total spin mom. (S)

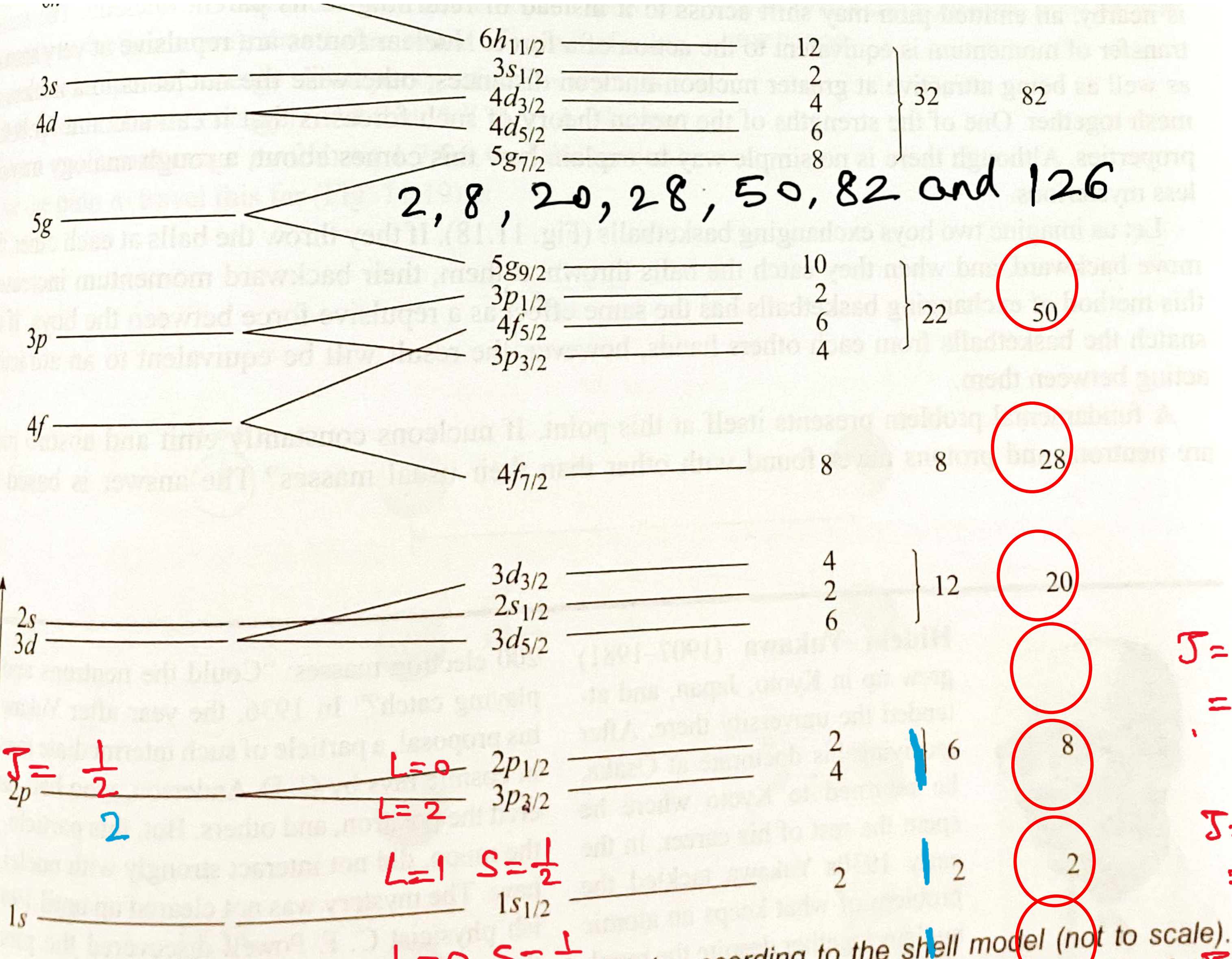
Similarly total orbital angular momenta is L.

S and L are coupled together to form total angular mom. (J)

$|J| = \sqrt{J(J+1)}\,\hbar$ no. of states = $2J+1$

J can vary from $|L-S|$ to $|L+S|$ in integer steps

L values	0	1	2	3	4	S values	$+\frac{1}{2}$
	s	p	d	f	g		



Sequence of neutron and proton energy levels according to the shell model (not to scale). ...s in the right-hand column correspond to the magic numbers expected on the basis of this...

$J = |2-\frac{1}{2}|$ to $|2+\frac{1}{2}|$

$= \frac{3}{2}$ to $\frac{5}{2} = \frac{3}{2}, \frac{5}{2}$

4 6

$J = |1-\frac{1}{2}|$ to $|1+\frac{1}{2}|$

$= \frac{1}{2}$ to $\frac{3}{2} = \frac{1}{2}, \frac{3}{2}$

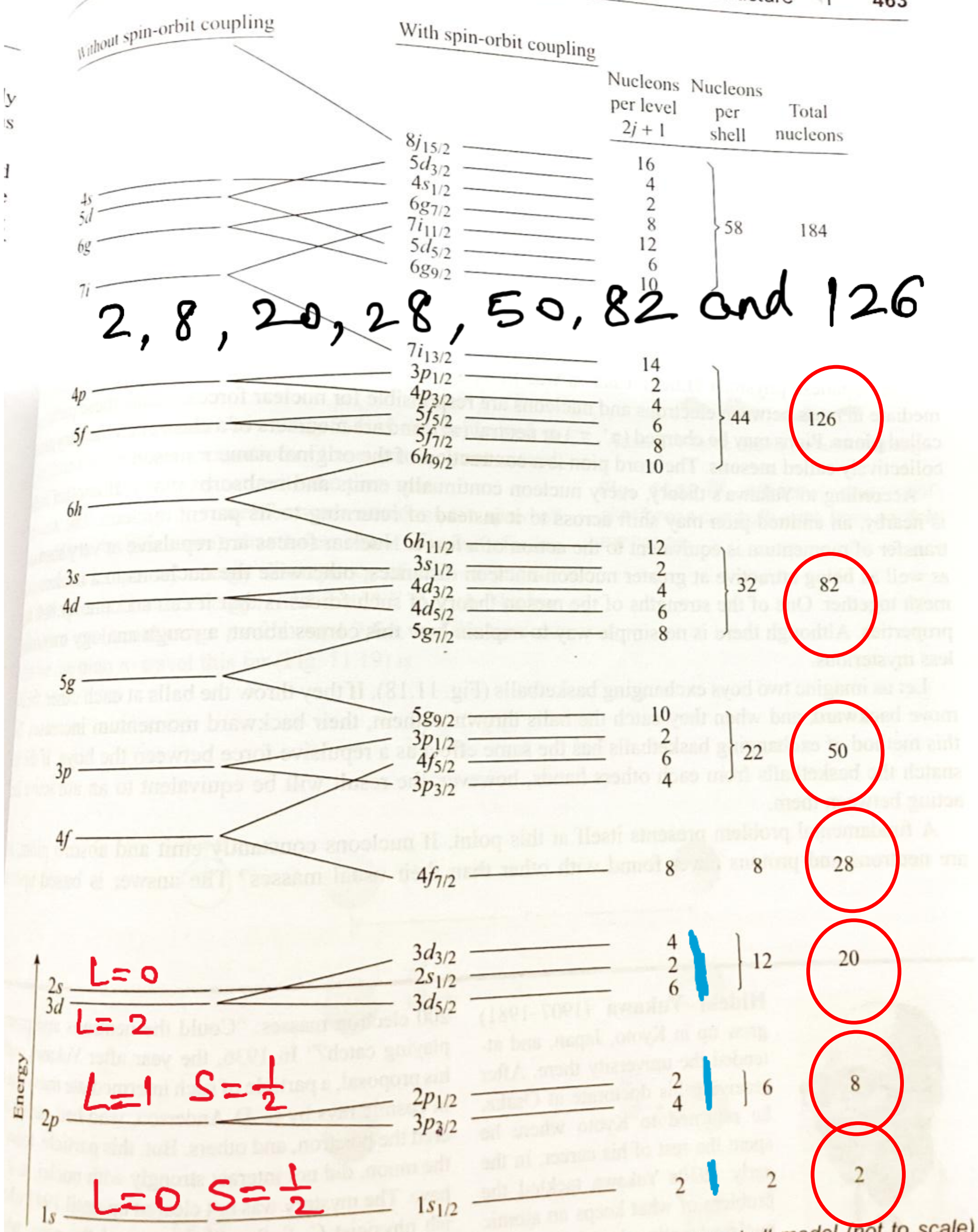
2 4

$J = \frac{1}{2}$ 2

$J = \frac{1}{2}$

2

2J+1 states



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Nuclear Physics: Nuclear Decay

Nuclear (or Radioactive) decay: It is the process in which an unstable nucleus spontaneously loses energy by emitting ionizing particles and radiation. This decay, or loss of energy, results in an atom of one type, called the parent nucleon, transforming to an atom of a different type, named the daughter nucleon.

<u>WHY IT OCCUR?</u>

Coulomb repulsion is appreciable throughout the entire nucleus, there is a limit to the ability of neutrons to prevent disruption of large nucleus. This limit is represented by Bismuth. All nucleus with $Z>83$ and $A>209$ spontaneously decay to become stable.

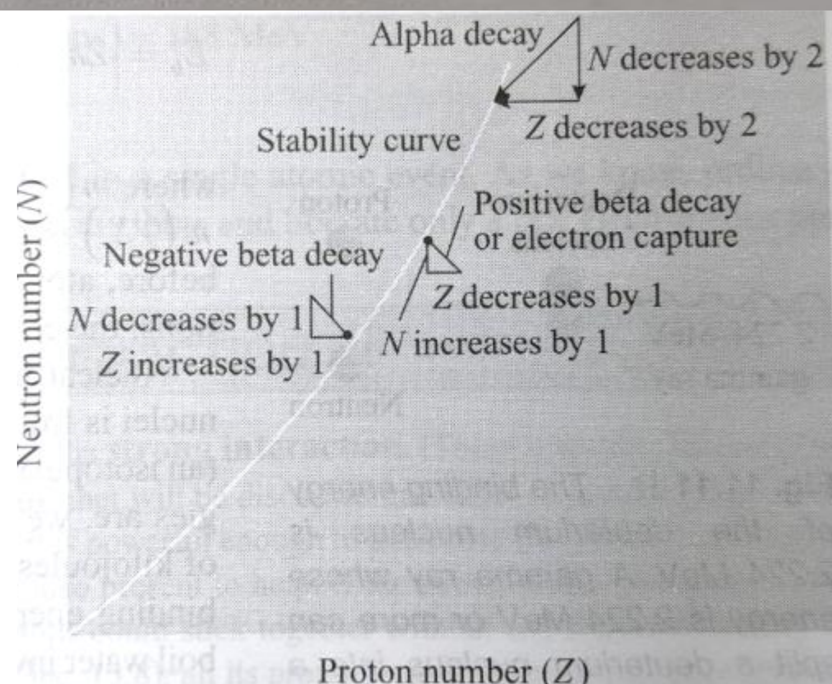
Nuclear Physics: Nuclear Decay

Types of decay

Table 12.1 *Radioactive Decay*[†]

Decay	Transformation	Example
Alpha decay	$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$	$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$
Beta decay	$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e$	$^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-}$
Positron emission	$^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + e^{+}$	$^{64}_{29}CU \rightarrow {}^{64}_{28}Ni + e^{+}$
Electron capture	$^{A}_{Z}X + e^{-} \rightarrow {}_{Z-1}^{A}Y$	$^{64}_{29}CU + e^{-} \rightarrow {}^{64}_{28}Ni$
Gamma decay	$^{A}_{Z}X^{*} + \rightarrow {}^{A}_{Z}X + \gamma$	$^{87}_{38}Sr^{*} \rightarrow {}^{87}_{38}Sr + \gamma$

† The * denotes an excited nuclear state and γ denotes a gamma-ray photon.



Radioactive Decay

No single phenomenon has played so significant role in development of nuclear physics as radioactivity, which was discovered in 1896 by Antoine Becquerel.

Three features

1. When nucleus undergoes alpha or beta decay , its atomic number Z changes and it becomes the nucleus of different element.
2. The energy liberated during radioactive decay comes from within individual nuclei. From Einstein's relation $E = mc^2$.
3. Radioactive decay obeys the law of chance.

Radioactive Decay: Discovery

Accidental discovery in 1896

- Henri Becquerel was trying to investigate x-rays (discovered in 1895 by Roentgen).
- Exposed uranium compound to sunlight, then placed it on photographic plates
- Believed uranium absorbed sun's energy and then emitted it as x-rays.
- On the 26th-27th February, experiment "failed" because it was overcast in Paris.
- Becquerel developed plates anyway, finding strong images,
- Proved uranium emitted radiation without an external source of energy.

French physicist Henri Becquerel (1852-1908) won the 1903 Nobel Prize in Physics for discovering spontaneous radioactivity. The Royal Academy of Sciences awarded him half of the prize, and the other half was given to Pierre and Marie Curie for their research on the radiation.

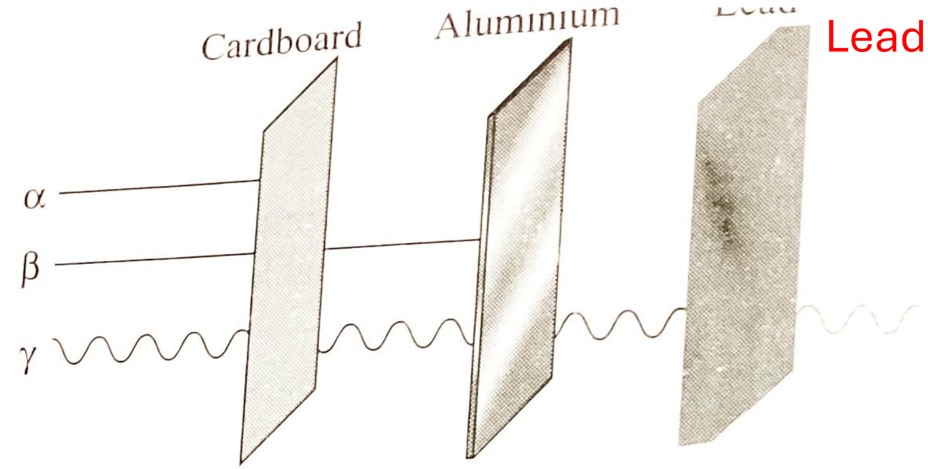


Fig. 12.2 *Alpha particals from radioactive materials are stopped by a piece of cardboard. Beta particl penetrate the cardboard but are stopped by a sheet of aluminum. Even a thick slab of lead may not stop the gamma rays.*

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^6_2He is unstable. What kind of decay would you expect it undergo?

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${}^{6}_{2}He$ is unstable. What kind of decay would you expect it undergo?

Excess neutrons (4) while protons (2)
Negative beta decay

$${}^{6}_{2}He \rightarrow {}^{6}_{3}Li + e^{-}$$