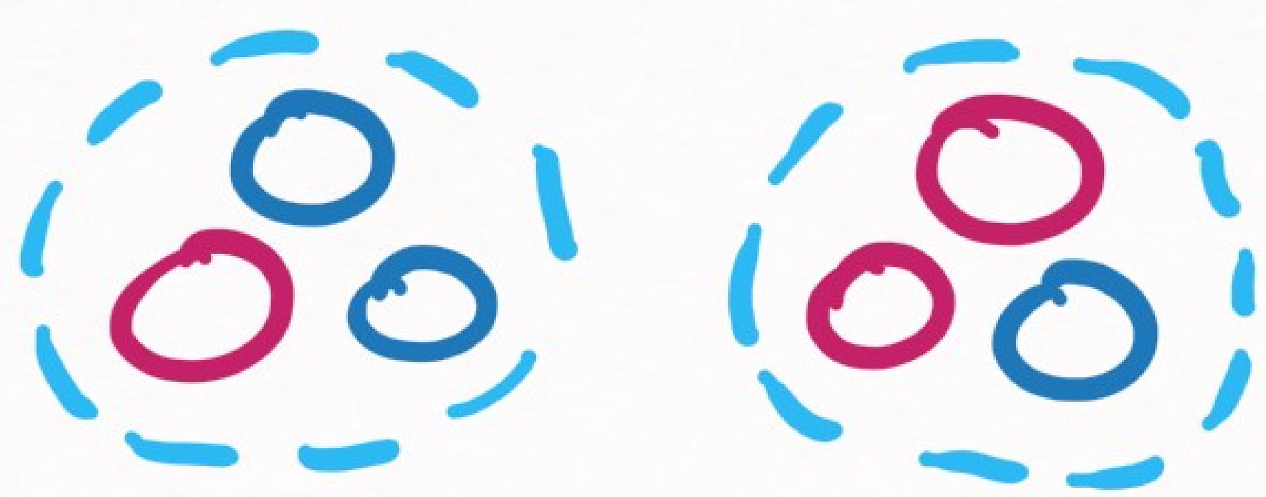
NUCLEAR PHYSICS 18

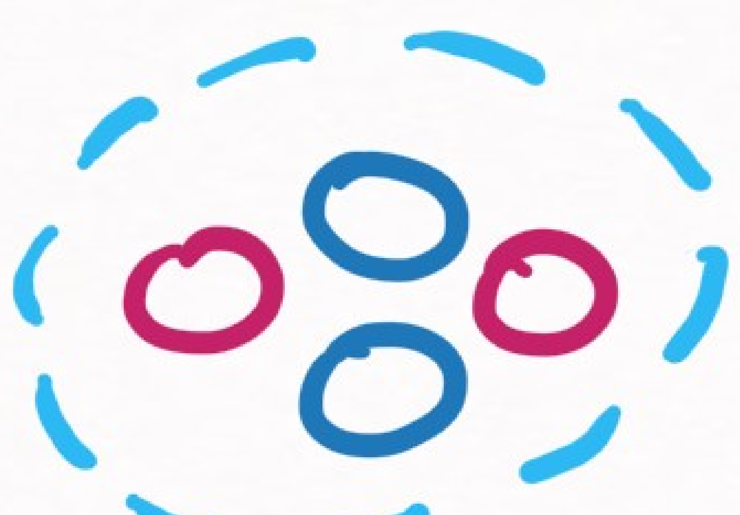
NUCLEAR STRUCTURE

[NUCLEAR STRUCTURE: WHY?]

A = 2) Deuteron → [NN force] + Schrödinger or Lippmann-Schwinger equation (easy)



A = 3) Triton & ^{3}He → Schrödinger / Faddeev equations (moderately difficult)



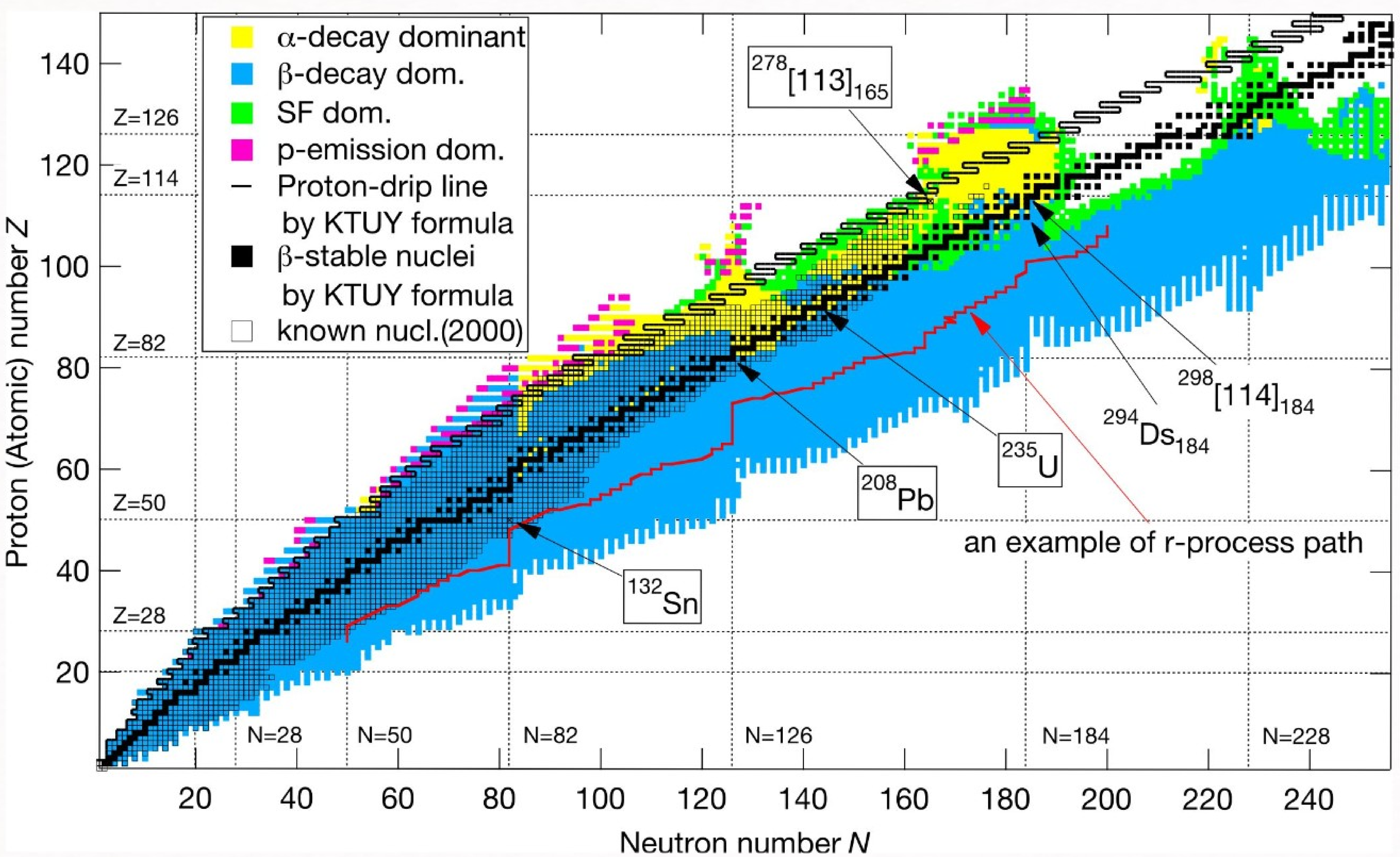
A = 4) ^{4}He (α-particle) → Schrödinger / Faddeev-Yakubowsky equations (hard)

[NUCLEAR STRUCTURE: WHY?]

$A \to$ # of nucleons

a) A small ($A \leq 10-12$) $\Rightarrow$ Exact (ab-initio) methods

b) A big ($A \geq 10-12$) $\Rightarrow$ We have to find a different way to understand these nuclei



$\Downarrow$

[Nuclear models]

[NUCLEAR STRUCTURE : SHOPPING LIST]

⇒ [What do we want to describe?]

1) Binding energies ✓
2) Nuclear size ✓
3) Angular momentum & parity ✓
4) Magnetic dipole & Electric quadrupole moments ✓
5) Stability & decays of nuclei ✓

BINDING ENERGIES

1

⇒ Sort of an obvious property (yet there is a lot to learn about it)

a) Deuteron:

$$B_d = (m_p + m_n) - m_d \simeq 2.2 \text{ MeV}$$

b) Triton:

$$B_t = (m_p + 2m_n) - m_t \simeq 8.5 \text{ MeV}$$

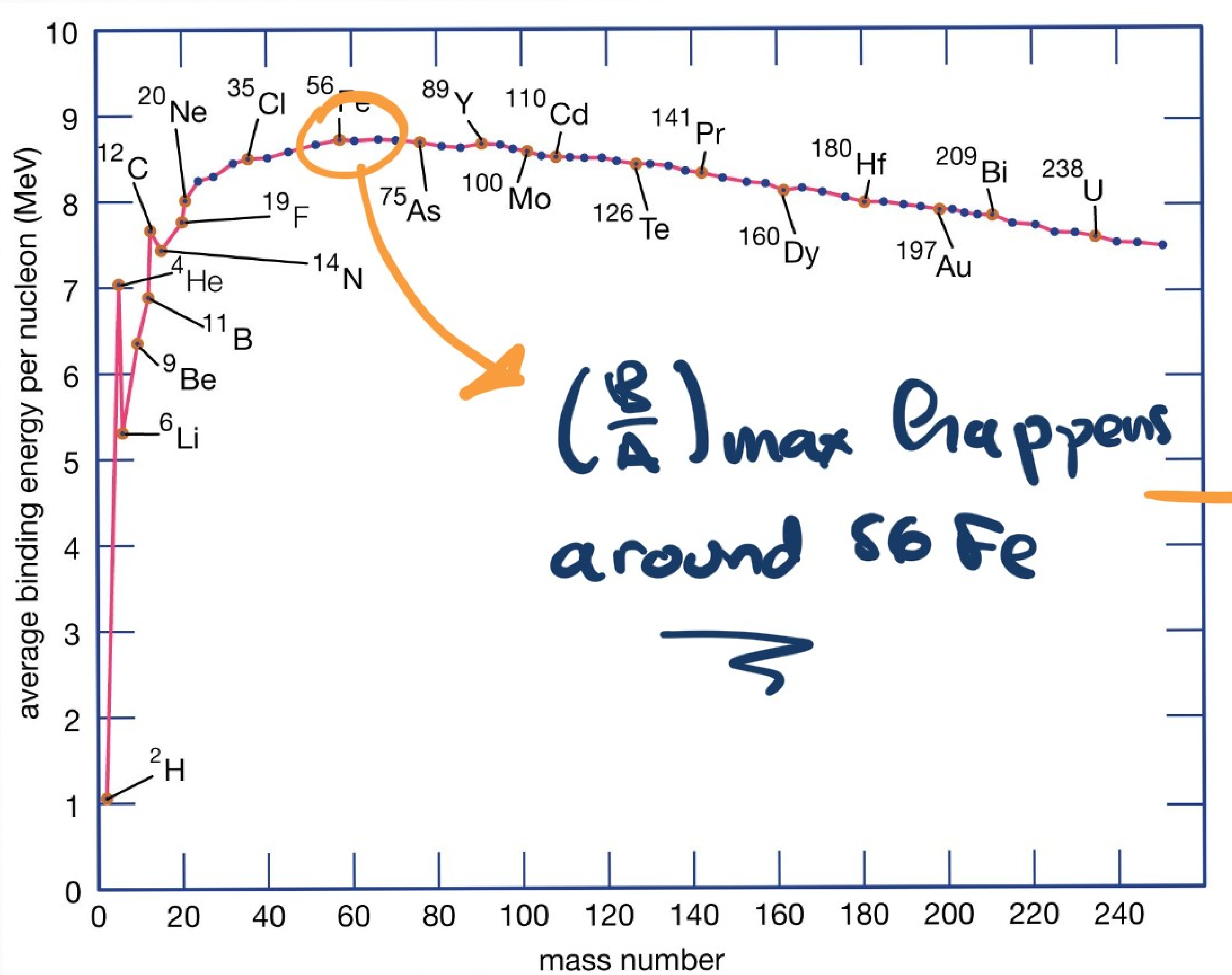
c) Or, more generally:

$$B(Z,N) = (Z m_p + N m_n) - m(Z,N)$$

- $Z \rightarrow$ # of protons
- $N \rightarrow$ # of neutrons
- $A = Z + N$

BINDING ENERGIES (2)

$\Rightarrow$ Binding energies show [SATURATION]



$\frac{B}{A} \sim$ constant

$\sim (8-9)\,\text{MeV}/\text{nucleon}$

$A \gtrsim (20\text{-}30)$

$\left(\frac{B}{A}\right)_{max}$ happens around 56 Fe

$\Rightarrow$ Observation:

$A < 56 \to$ nuclear fusion is energetically possible

$A > 56 \to$ nuclear fission is energetically possible

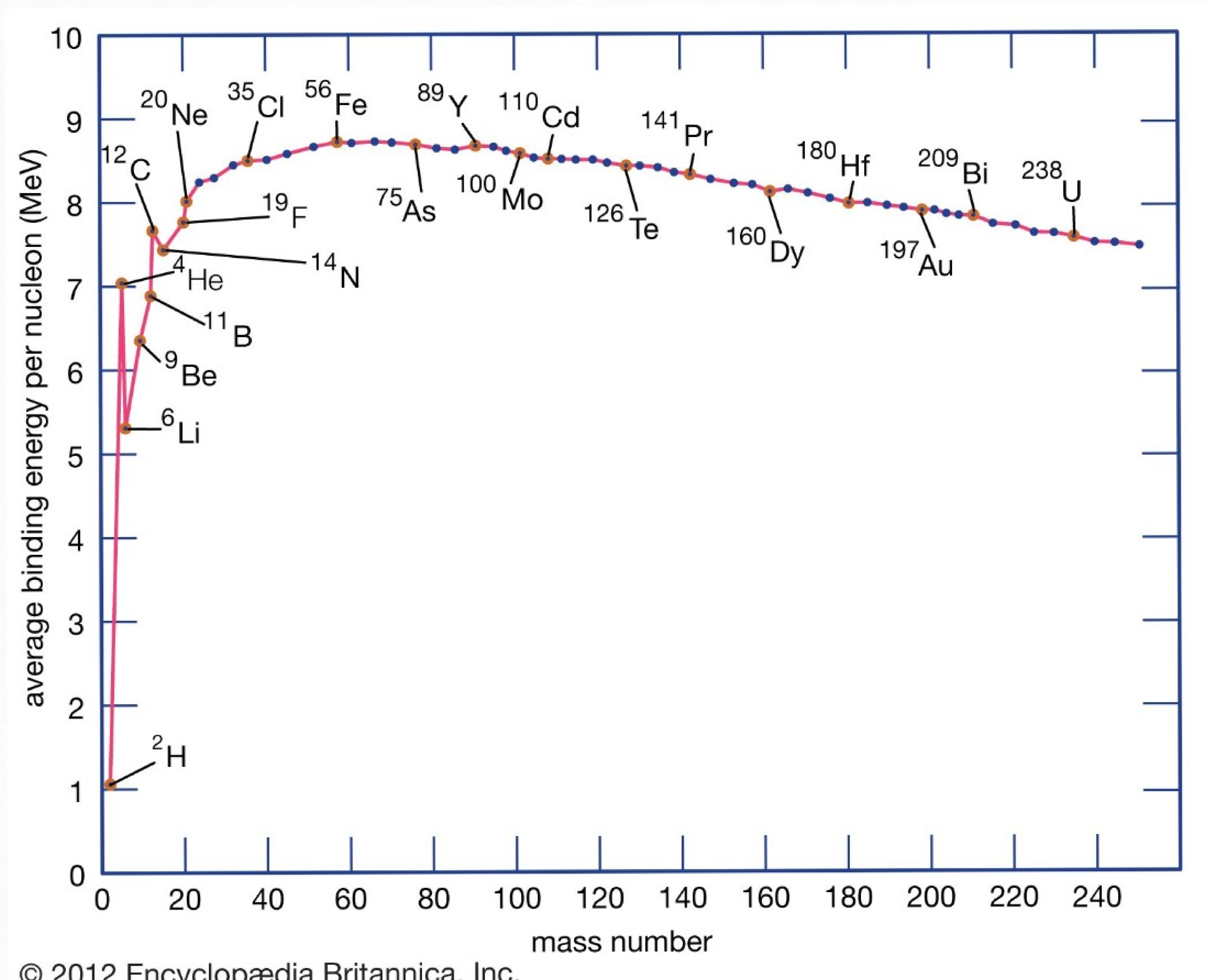
$\underline{\underline{\frac{B}{A}}}$

$\underline{\underline{A}}$

BINDING ENERGIES 3

⇒ Observation: Fusion/Fission and B/A

$\frac{B}{A}$



A

→ Check the previous slide

BINDING ENERGIES (4)

=> Separation energy (another useful quantity):

a) Proton separation energy:

$$S_p(Z,N) = B(Z,N) - B(Z-1,N)$$

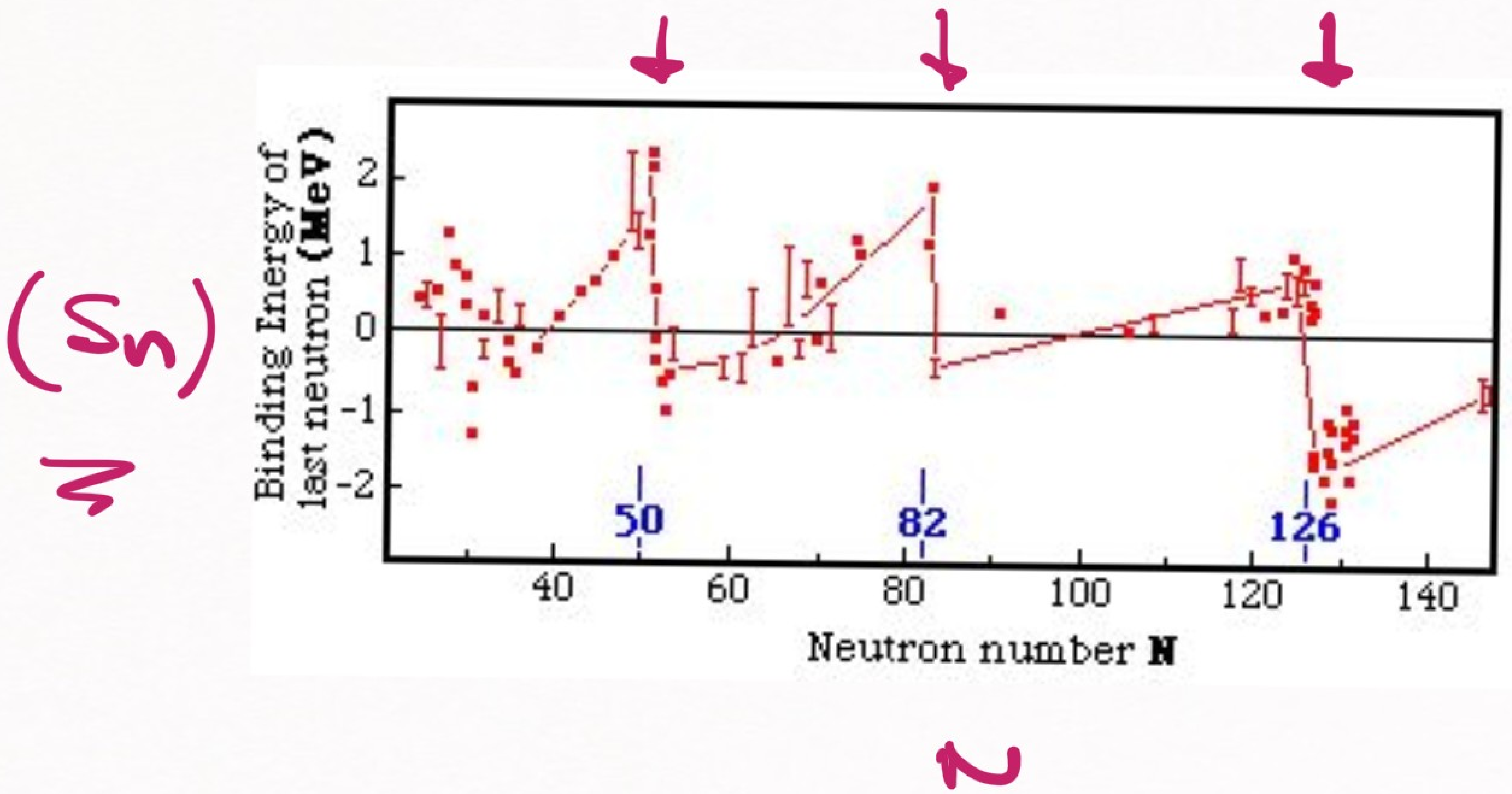
b) Neutron separation energy:

$$S_n(Z,N) = B(Z,N) - B(Z,N-1)$$

BINDING ENERGIES (5)

⇒ Separation energy (another useful quantity):

∃ a pattern in $S_p(Z,N)$ / $S_n(Z,N)$:



⇒ For some (Z,N) the separation energy reaches a local maximum

Magic numbers:

$N = 2, 8, 20, 28, 50, 82, 126$

BINDING ENERGIES (6)

⇒ It's possible to define other types of separation energies

For instance:

$$S_\alpha(Z,N) = B(Z,N) - B(Z-2,N-2) - B(2,2)$$

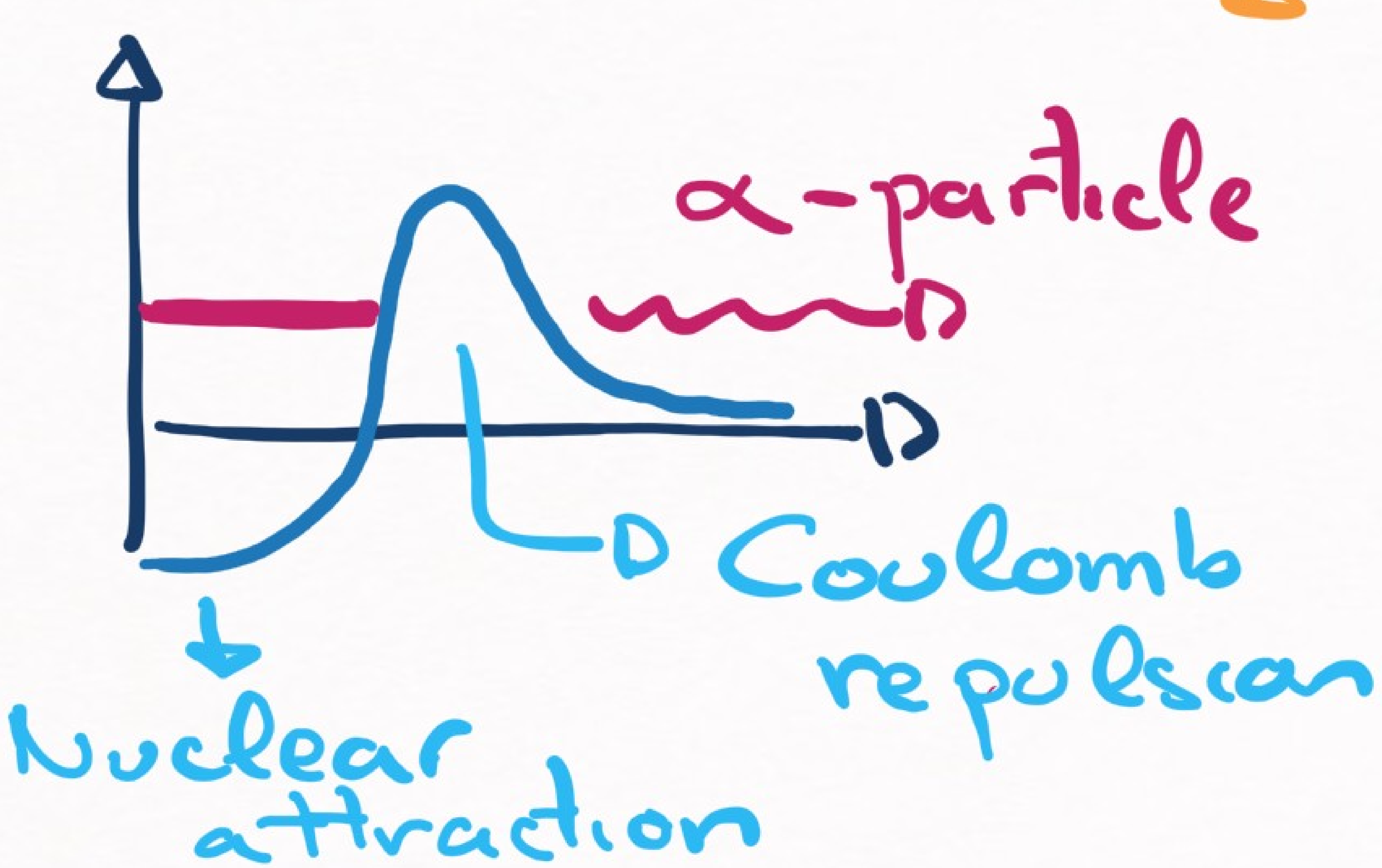
$\boxed{S_\alpha < 0}$ ⇒ A nuclei can decay via emission of an α-particle

^4He nucleus

↓

For most $A > 150$ nuclei

&



BINDING ENERGIES (7)

⇒ There is also a separation energy related to "pairs"

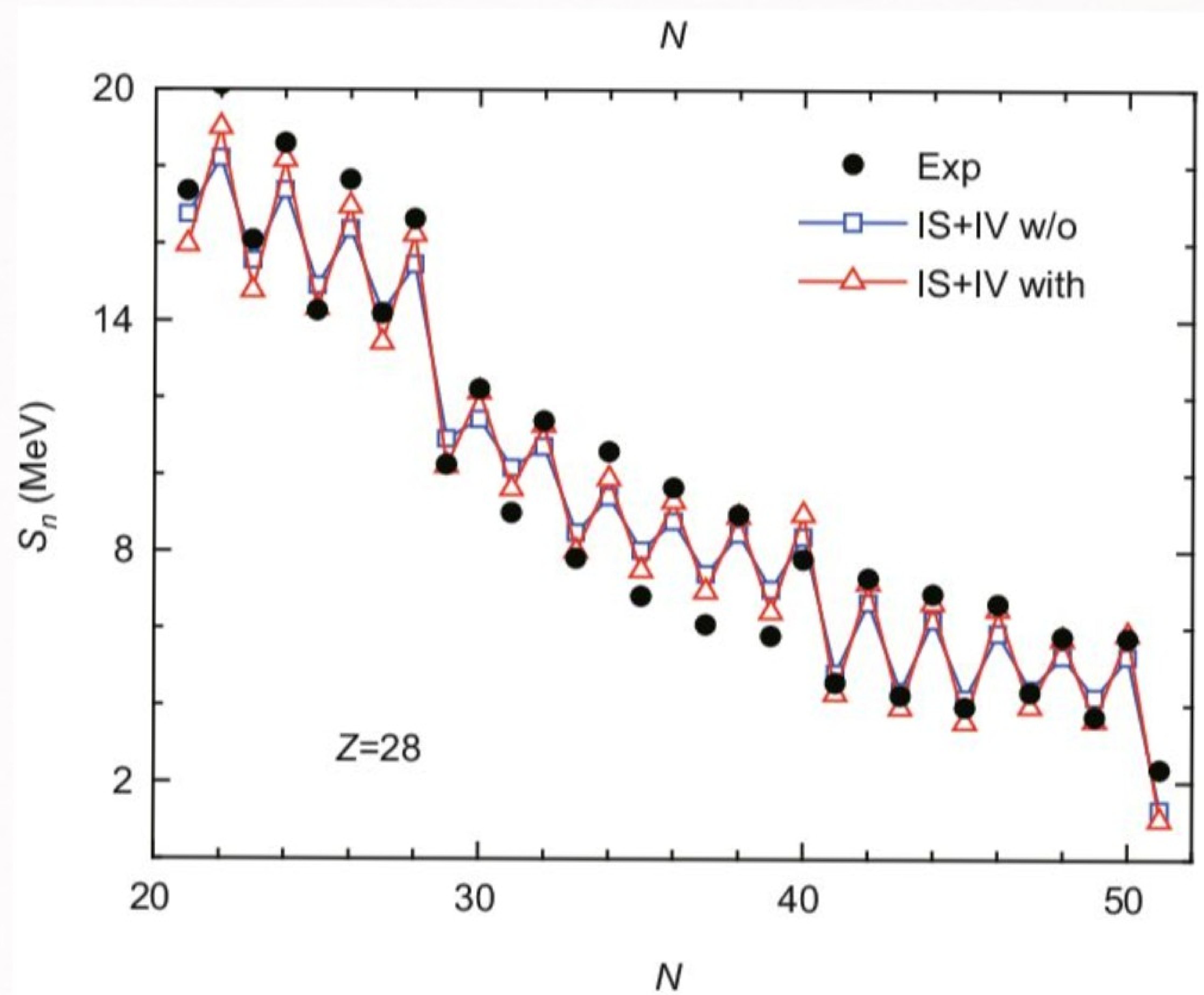
$\delta_n = S_n(Z,N) - S_n(Z,N-1)$

with N even, N−1 odd

$\delta_n \sim 2\,\text{MeV}$ usually

(∃ equivalent for protons)

What is the interpretation of this?



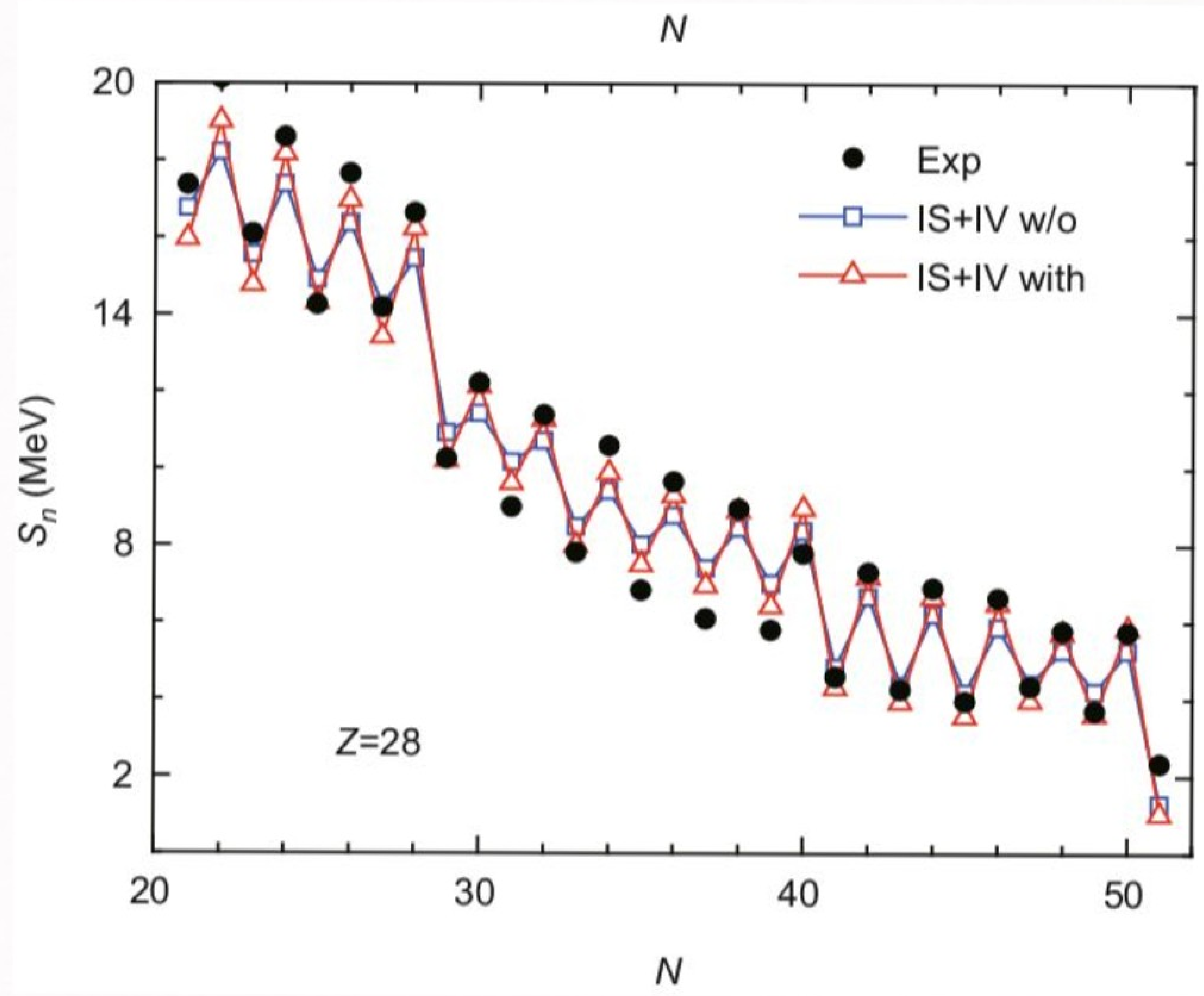
BINDING ENERGIES (B)

=> There is also a separation energy related to "pairs"

The bottom-line here:

nuclei with an even number of neutrons or protons are <u>more</u> stable

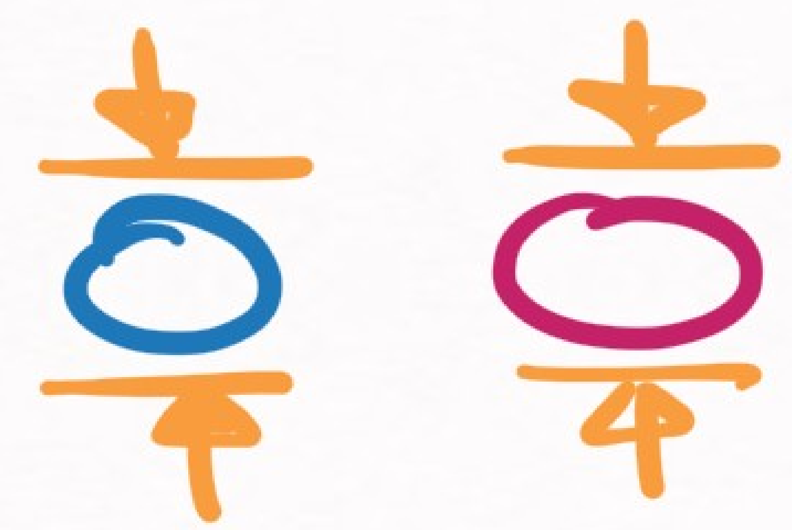
<u>even-even</u>



NUCLEAR SIZE (1)

⇒ Next nuclear property on our list

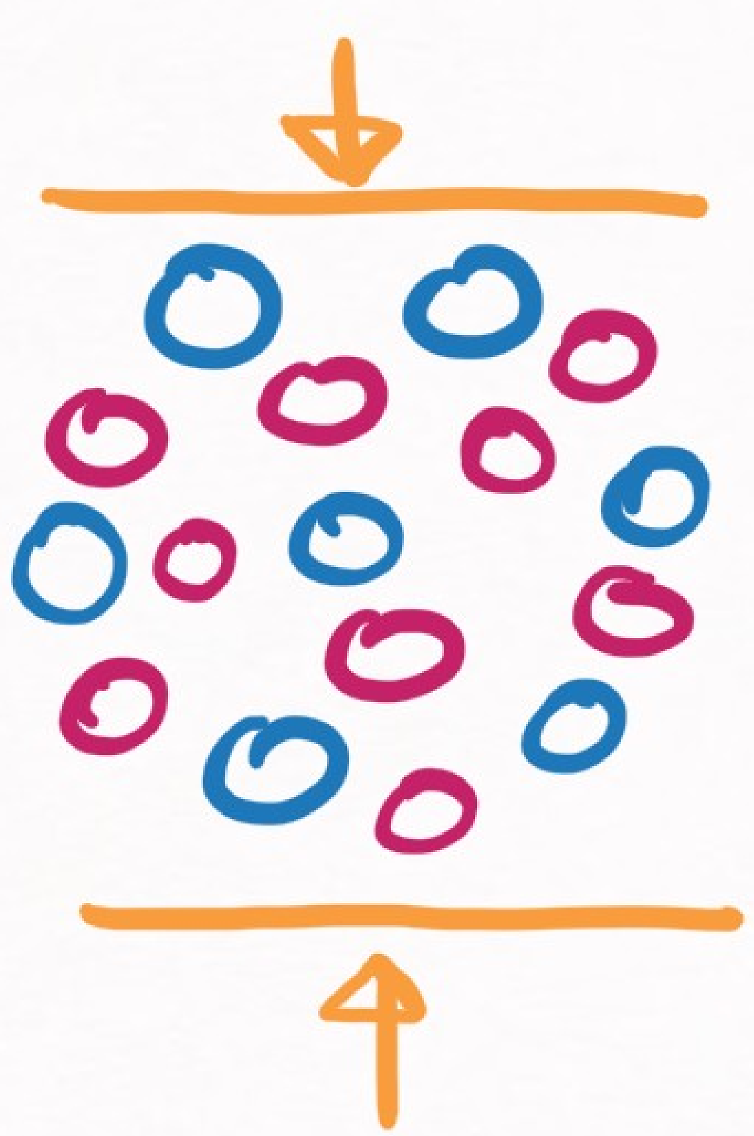
0) Nucleon size:



$\sqrt{\langle r^2 \rangle_N} \sim (0.5-1.0)\,\mathrm{fm}$

(nucleons are composite)

1) Nuclear size:



$$\underbrace{R^3 \sim A r_0^3}_{r_0 \sim (1.2-1.3)\,\mathrm{fm}} \quad \text{with } r_0 \gtrsim \sqrt{\langle r^2 \rangle_N}$$

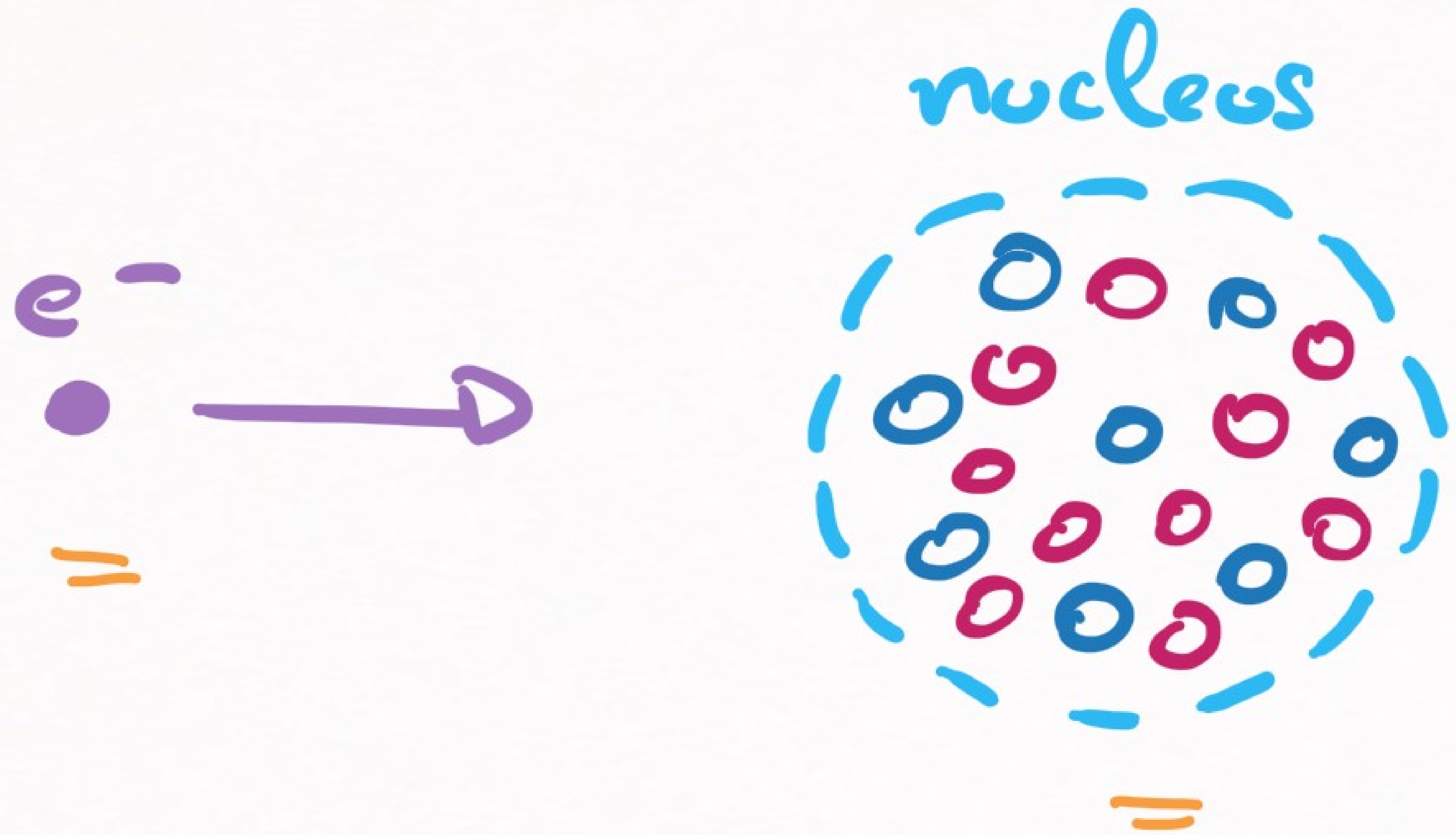
$$\boxed{R \sim A^{1/3} r_0} \Leftarrow$$

NUCLEAR SIZE ②

⇒ But there is more than just $\sqrt{\langle r^2 \rangle}$:

[THE HOFSTADTER EXPERIMENT]

Form factors



$$\frac{d\sigma}{d\Omega} = \underbrace{\left(\frac{d\sigma}{d\Omega}\right)_{\text{point-like}}}_{\text{Cross section if the nucleus was point-like}} \times \underbrace{|F(\vec{q})|^2}_{\text{Form factor}}$$

Internal structure of the nucleus

NUCLEAR SIZE ③

⇒ Form factors and density:

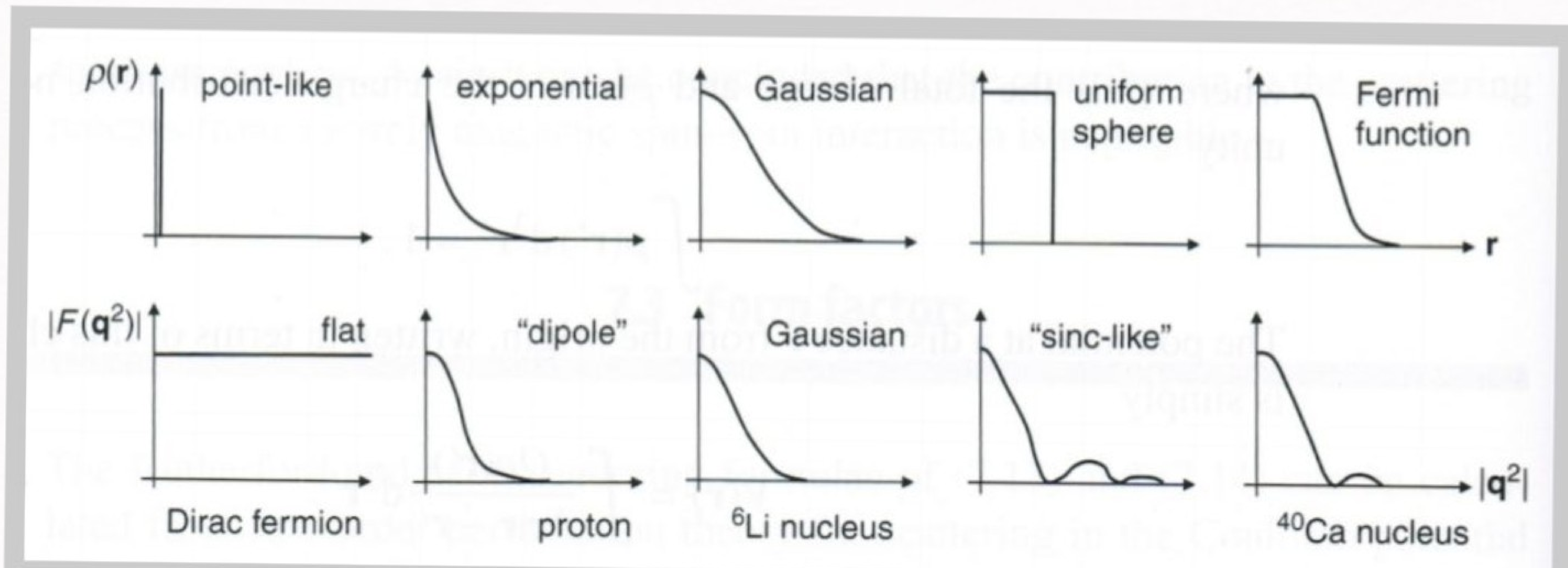
$$F(\vec{q}^{\,2}) = \int d^3\vec{r}\, \underbrace{|\psi(\vec{r})|^2}_{\rho(\vec{r}) \text{ or charge distribution}} e^{-i\vec{q}\cdot\vec{r}}$$

$F(\vec{q}^{\,2})$ is just the Fourier-transform of the charge distribution

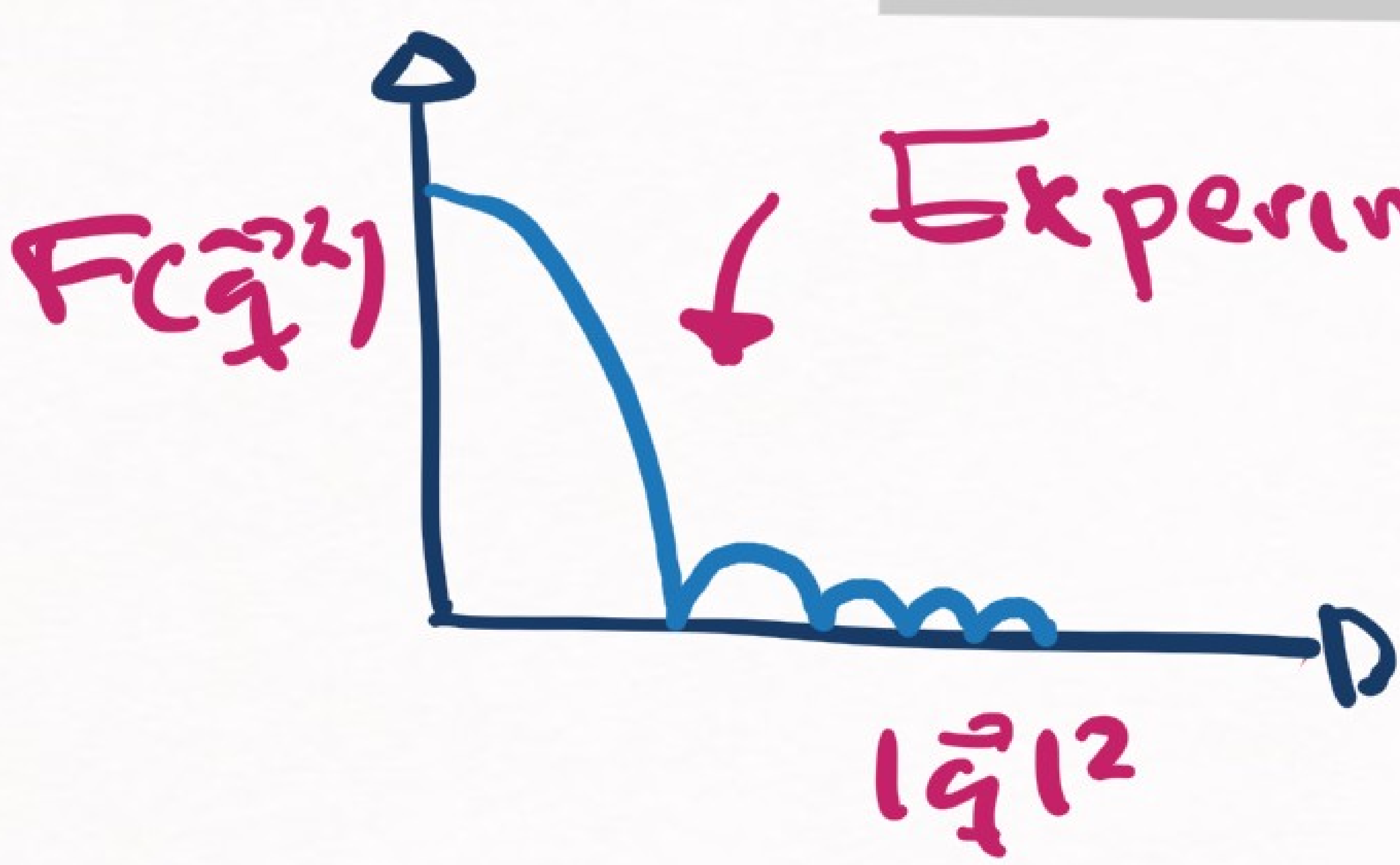
NUCLEAR SIZE (4)

$\Rightarrow$ Form factors and density : a few examples

Fourier transform



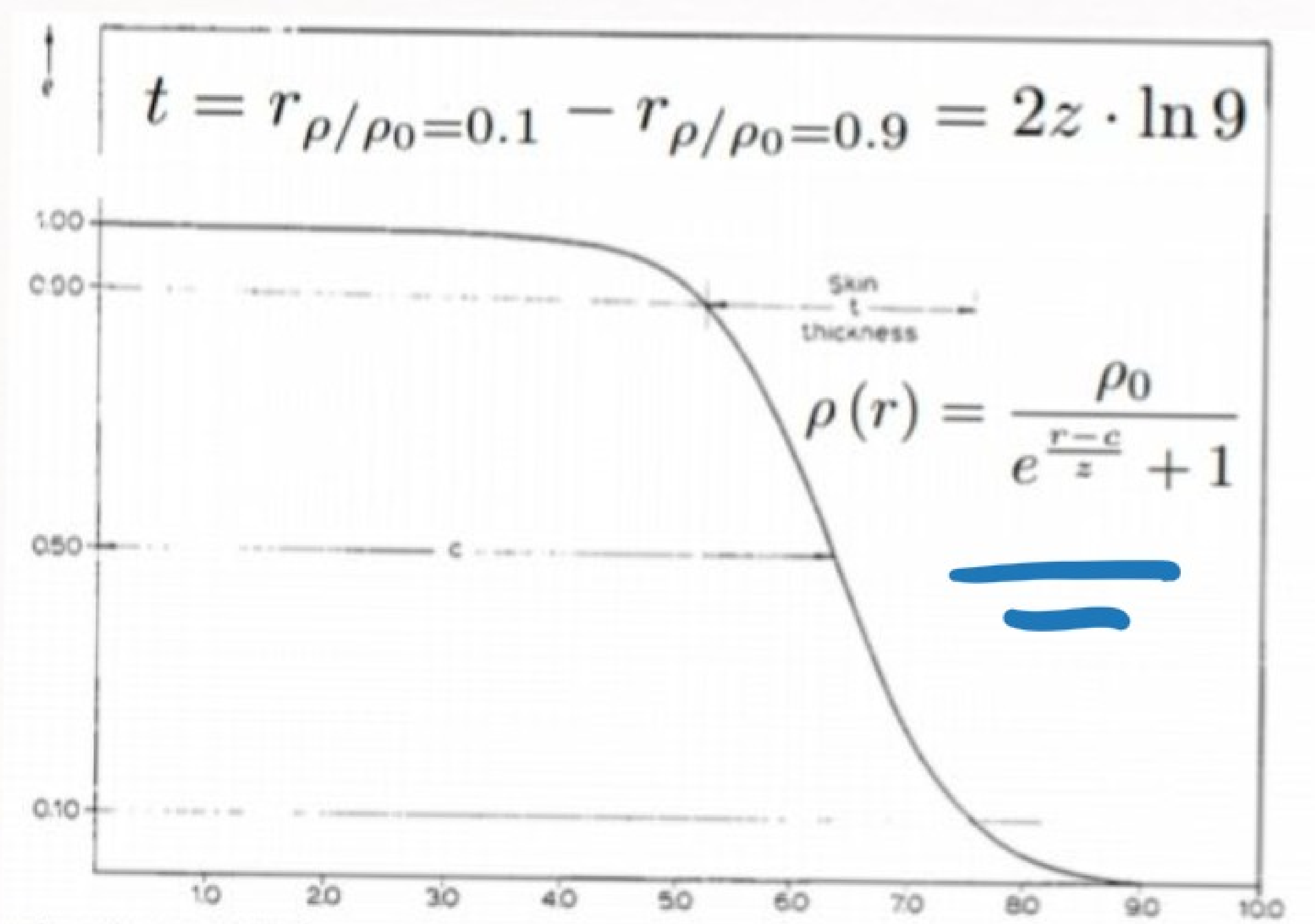
taken from ref. [2]



Experiment $\Rightarrow$ $\rho(\vec{r})$ should be "uniform" or "fermi-function-like"

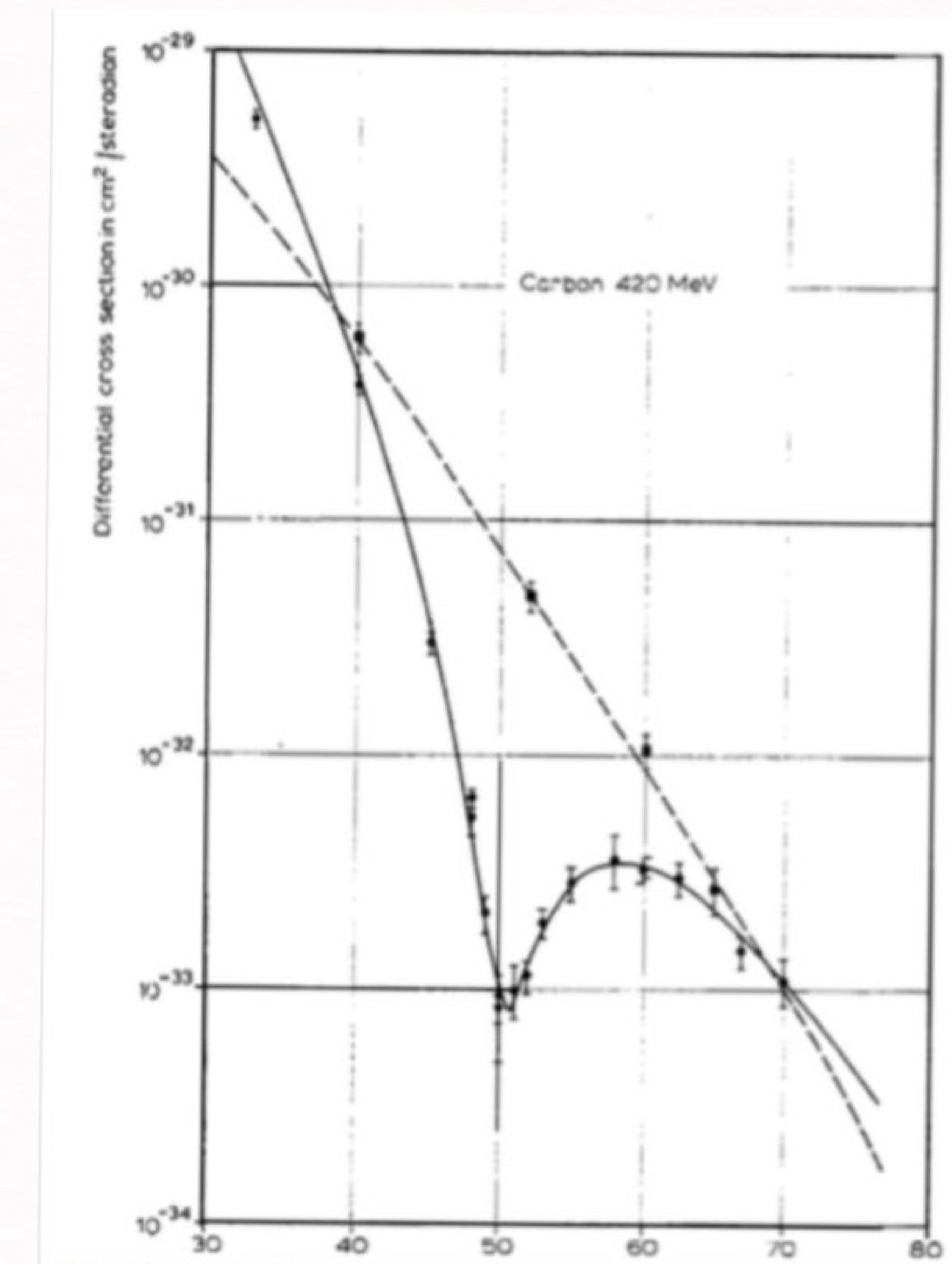
NUCLEAR SIZE (5)

⇒ In particular, Hofstadter found this:



taken from ref. [5]

From this $F(q^2)$ we can deduce the density here



taken from ref. [5]

⇒ a Woods-Saxon distribution

NUCLEAR SIZE (6)

⇒ Typical mass distribution:

$$\rho(r) = \frac{\rho_0}{1 + e^{(r-R_0)/a_0}}$$

with: $\rho_0 \simeq 0.17\ \mathrm{fm}^{-3}$ (nucleon density)

$a_0 \simeq 0.54\ \mathrm{fm}$

$R_0 \simeq 1.12\ A^{1/3}\ \mathrm{fm}$ $\quad \underline{\underline{(R \sim r_0 A^{1/3})}}$

[ANGULAR MOMENTUM AND PARITY] 3

=> Next nuclear property on the list

0) Nucleons & mesons: $J^P(\pi) = 0^-$, $J^P(\rho) = 1^-$, $J^P(\sigma) = 0^+$

[$J^P(N) = 1/2^+$] → $N = n, p$

1) Light nuclei:

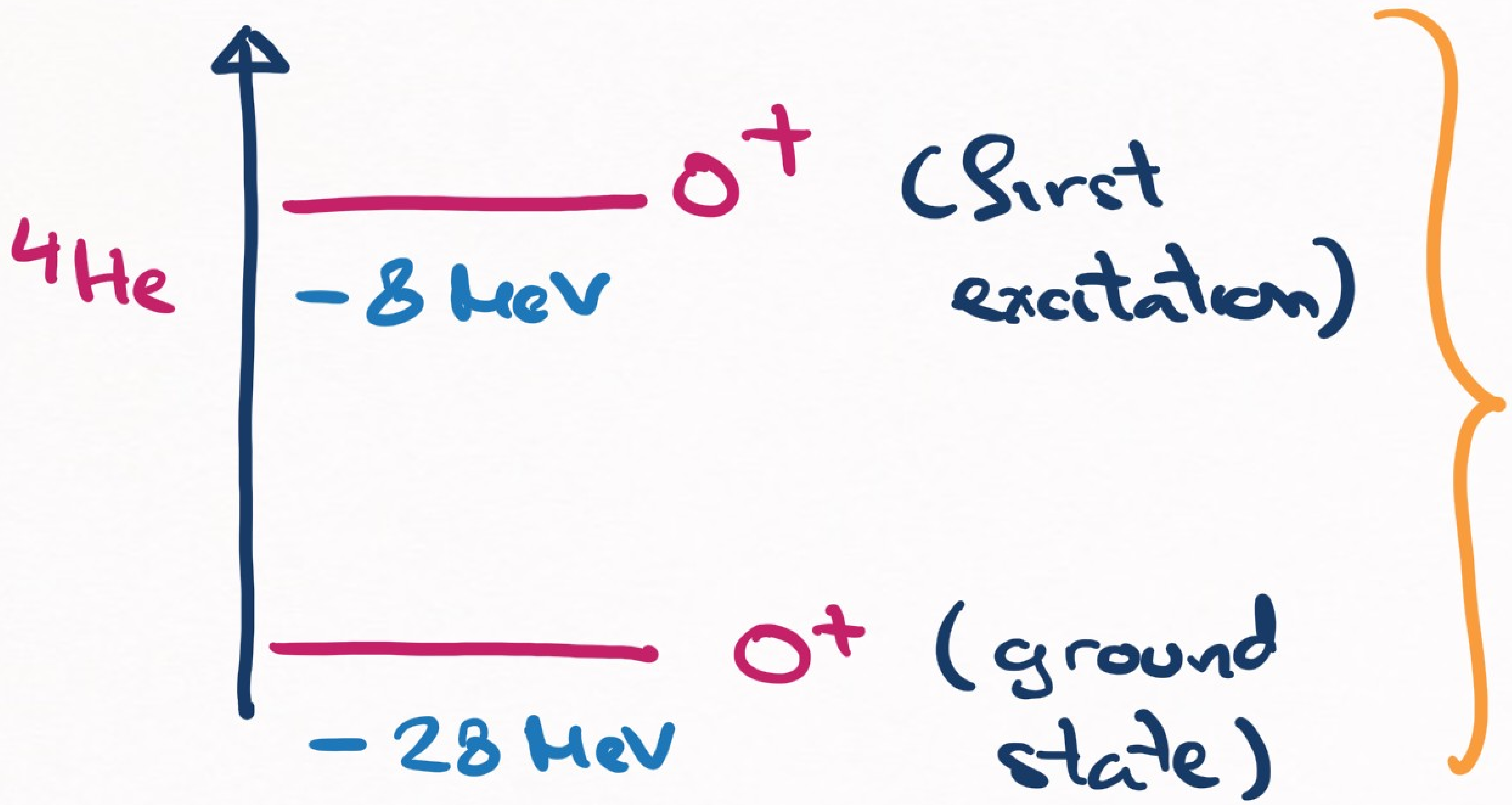
$J^P(\text{deuteron}) = 1^+$ (+ because it is S-wave)

$J^P(^3H / ^3He) = 1/2^+$

$J^P(^4He) = 0^+$

[ANGULAR MOMENTUM AND PARITY] (2)

⇒ Most nuclei have excited states:



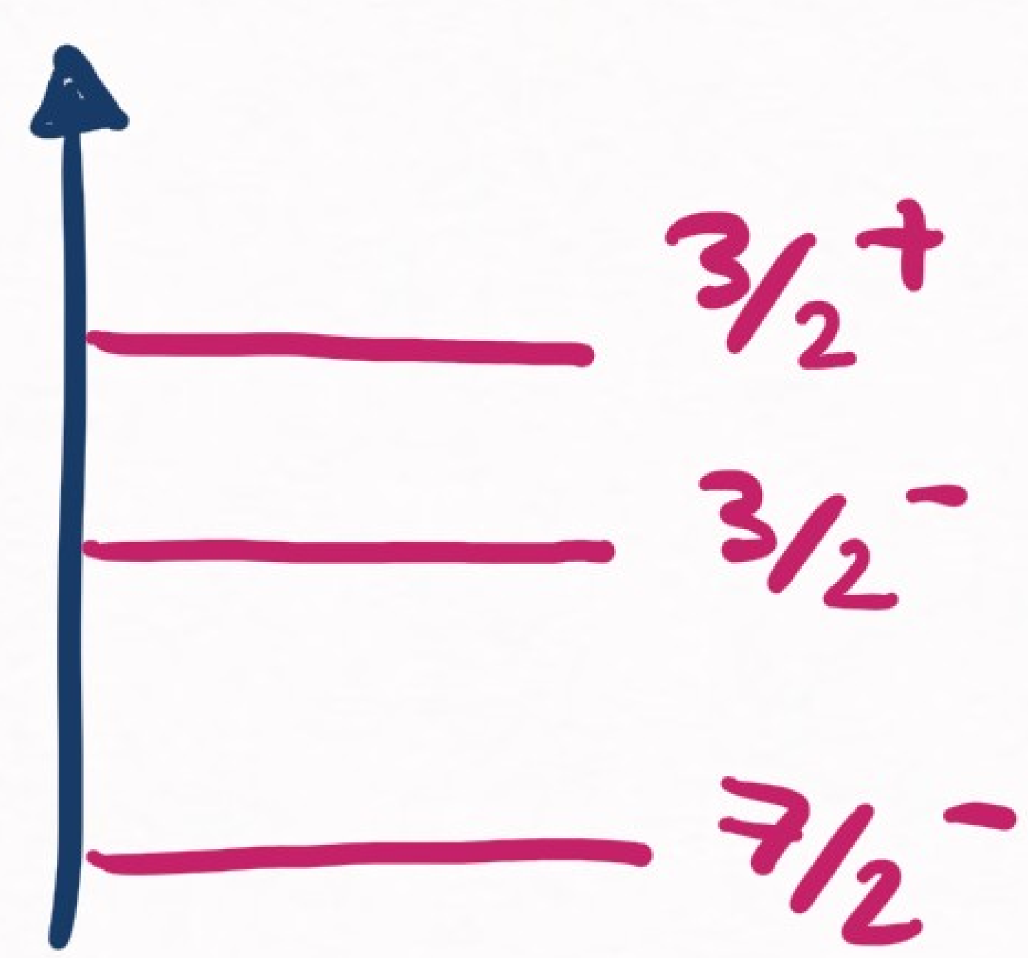
Explaining J^P of excited states will be a very important part of nuclear models

[ANGULAR MOMENTUM AND PARITY] 3

⇒ Excited states J^P and energy related to nuclear structure

1) ^4He $(0^+/0^+)$: "Breathing" mode of the collective model

2) ^{41}Ca :



typical shell-model spectrum

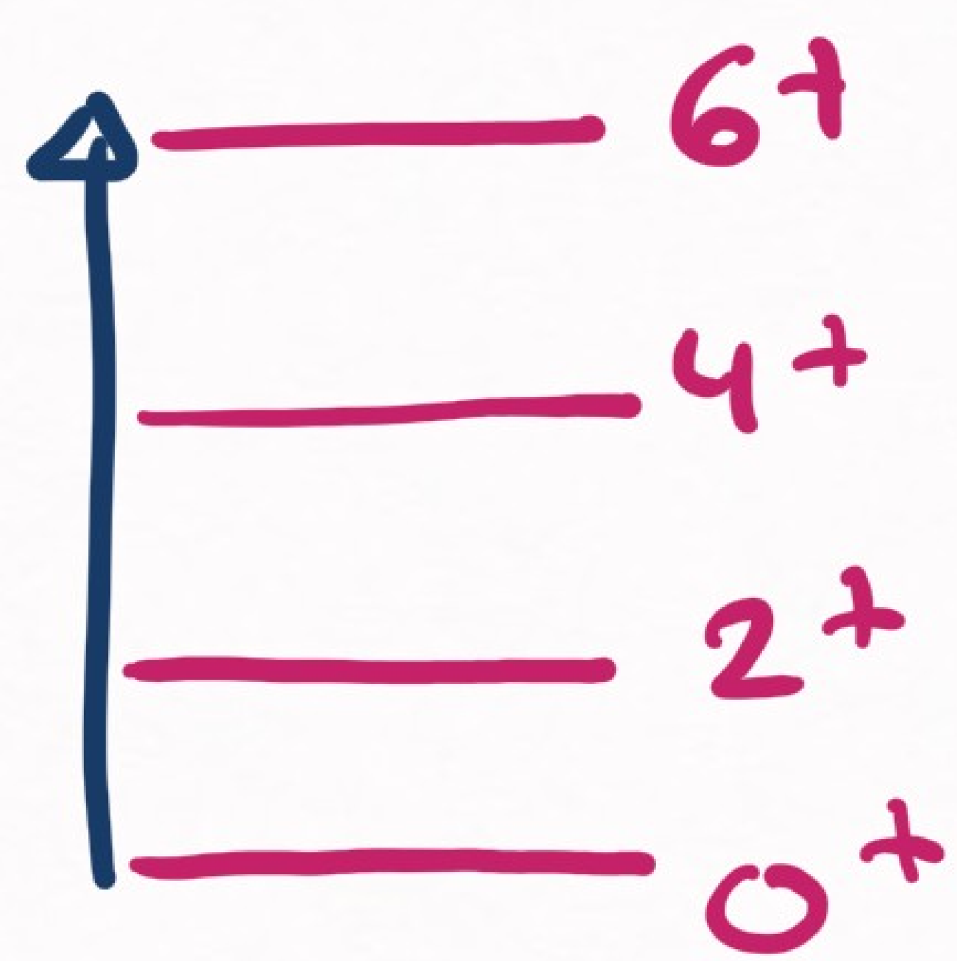
[ANGULAR MOMENTUM AND PARITY] (4)

⇒ Excited states J^P and energy related to nuclear structure

3) ^{122}Te:

typical vibrational spectrum (collective model)

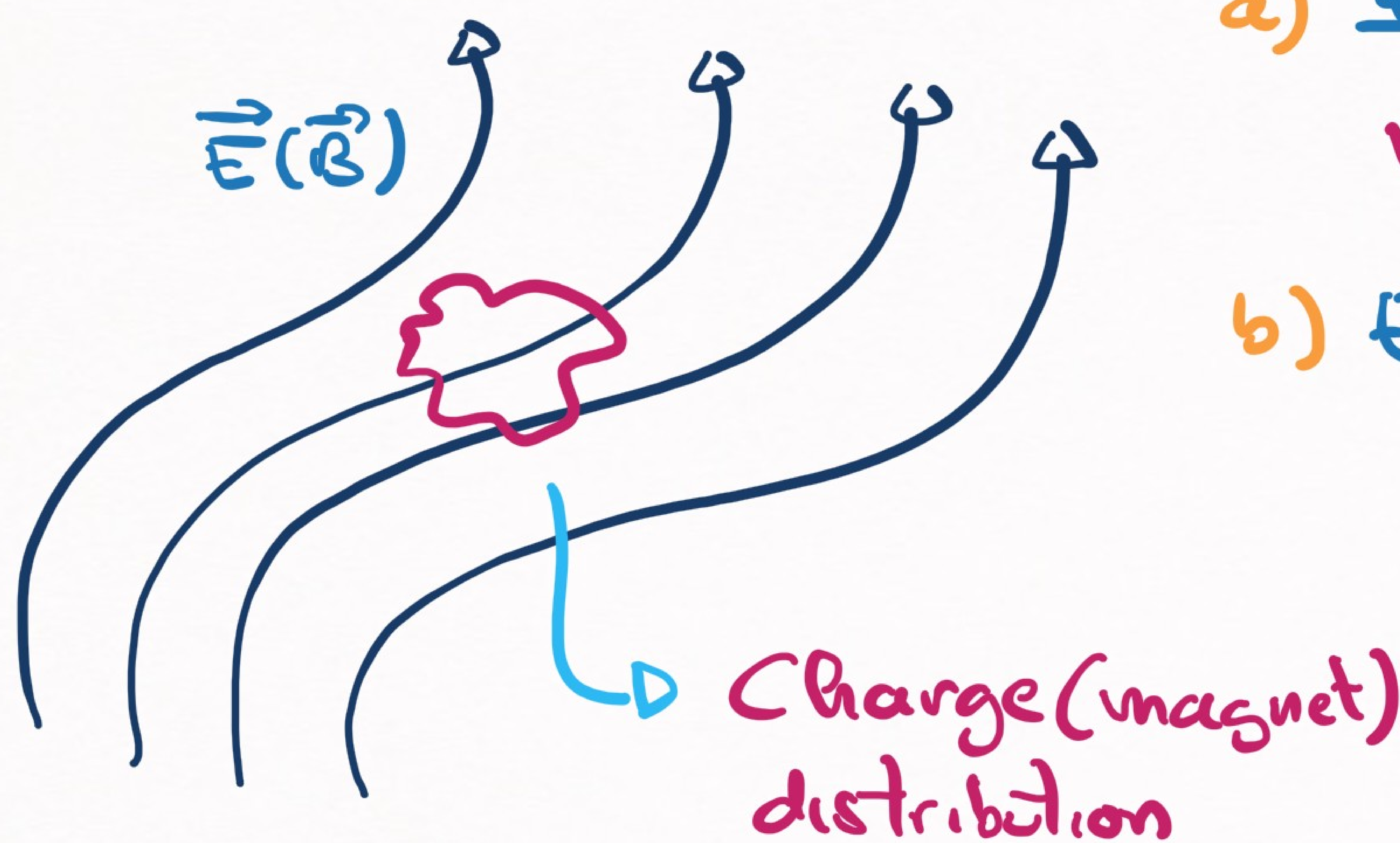
4) ^{166}Er:



typical rotational spectrum (collective model)

[ELECTROMAGNETIC MOMENTS] 1

⇒ Next important property: (nuclei are extended objects)



a) Point-like charge:

$$V(\vec{r}) = q\,\Phi(\vec{r})$$

b) Extended charge:

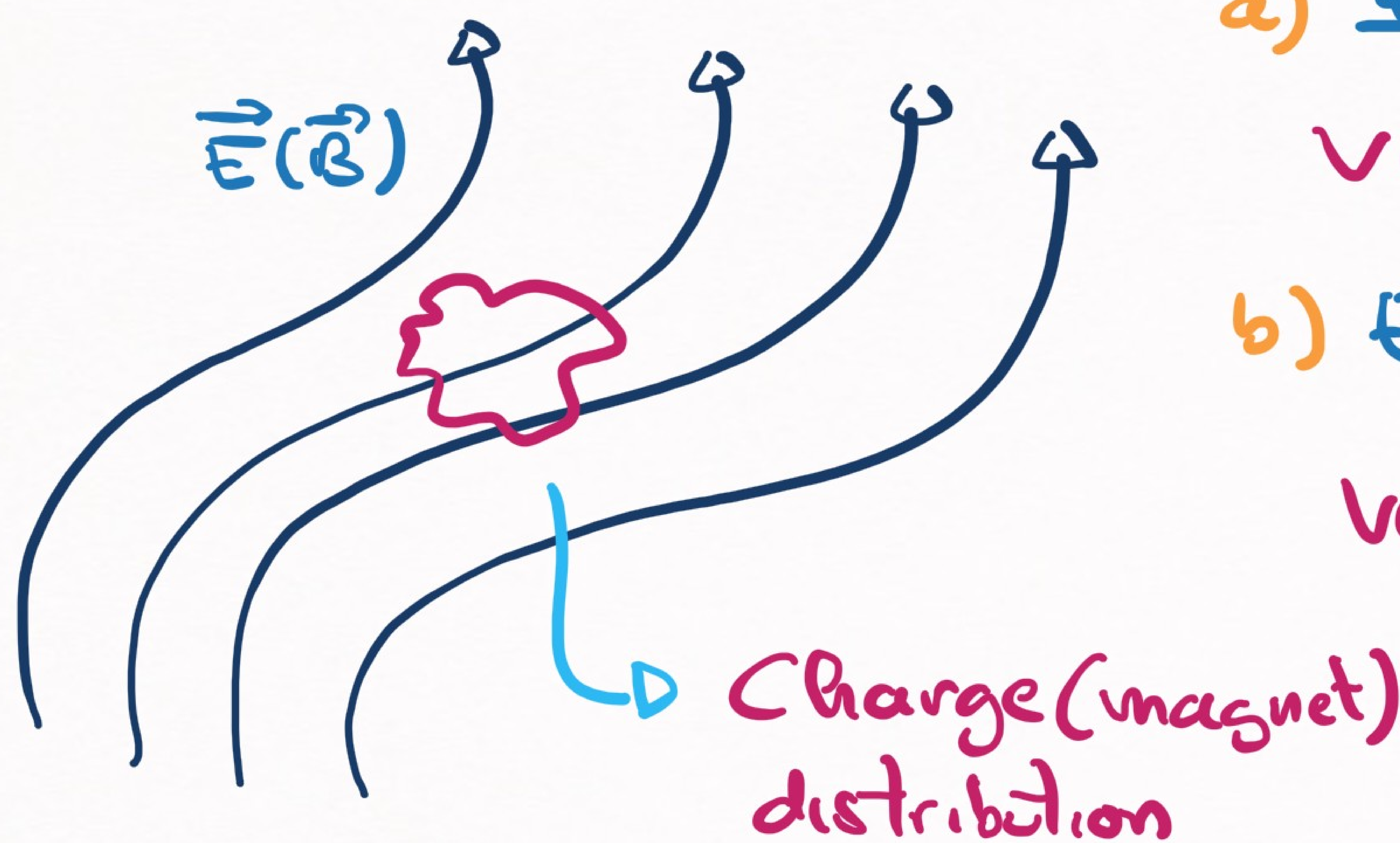
$$V(\vec{r}) = \int d^3\vec{r}\,\rho(\vec{r})\,\Phi(\vec{r})$$

$$\int d^3\vec{r}\,\rho(\vec{r}) = q$$

[CHECK LESSON 6]
slides 14/15

[ELECTROMAGNETIC MOMENTS] 2

⇒ Next important property : nuclei have a size



a) Point-like magnet :

$$V(\vec{r}) = -\vec{\mu} \cdot \vec{B}(\vec{r})$$

b) Extended magnet :

$$V(\vec{r}) = -\int d^3\vec{r}\; \vec{\mu}(\vec{r}) \cdot \vec{B}(\vec{r})$$

$$\int d^3\vec{r}\, \vec{\mu}(\vec{r}) = \vec{\mu}$$

($\vec{\mu} \rightarrow$ magnetic moment)

[CHECK LESSON 6]
slides 14/15

[ELECTROMAGNETIC MOMENTS] 3

⇒ Electric moments:

$$V = q\,\Phi + \vec{d}\cdot\vec{\nabla}\Phi + \frac{1}{6} Q_{ij}\,\partial_i \partial_j \Phi + \ldots$$

+ (slide 23)

$\phi(\vec{r}) \longrightarrow$ scalar potential

$\vec{\nabla}\phi(\vec{r}) = \vec{E} \longrightarrow$ electric field

a) $q = \int d^3\vec{r}\, \rho_c(\vec{r}) \rightarrow$ electric charge

b) $\vec{d} = \int d^3\vec{r}\, \vec{r}\, \rho_c(\vec{r}) \rightarrow$ electric dipole moment

c) $Q_{ij} = \int d^3\vec{r}\,(3 r_i r_j - \delta_{ij} r^2)\, \rho_c(\vec{r}) \rightarrow$ electric quadrupole moments

[ELECTROMAGNETIC MOMENTS] 4

⇒ Magnetic moments:

$$V = \vec{\mu}\cdot\vec{B} + \frac{1}{6} Q_{\mu ij}\,\partial_i B_j + \dots$$

(slide 24)

$\vec{B} = \vec{\nabla}\times\vec{A}$ → magnetic field

$\vec{A}$ → vector potential

a) $\vec{\mu} = \int d^3\vec{r}\,\vec{\mu}(\vec{r})$ → magnetic dipole moment

b) $Q_{\mu ij} = \int d^3\vec{r}\left[\frac{3}{2} r_i \mu_j(\vec{r}) + \frac{3}{2} r_j \mu_i(\vec{r}) - \vec{r}\cdot\vec{\mu}(\vec{r})\,\delta_{ij}\right]$

→ magnetic quadrupole moment

[ELECTROMAGNETIC MOMENTS] 5

⇒ Notice that for nuclei:

a) $\vec{d} = \vec{0}$ (electric dipole moment)

⇒ $\vec{d} = \int d^3\vec{r}\, \vec{r}\, \rho(\vec{r})$ but we have that $\rho(\vec{r}) = \rho(-\vec{r})$

b) $Q_{\mu ij} = 0$ (magnetic quadrupole moment)

⇒ $\mu(\vec{r}) = \mu(-\vec{r})$ but the integral contains $r_i \mu_j(\vec{r})$

[ELECTROMAGNETIC MOMENTS] 6

⇒ Important moments:

1) Electric charge (trivial) $\underline{\underline{Ze_p}}$

2) Electric quadrupole moment

3) Magnetic dipole moment

At higher orders we also have the electric hexadecupole moment & the magnetic octupole moment, but they are usually small

[ELECTROMAGNETIC MOMENTS] 7

1) Electric charge: $q = eZ$ with Z # of protons

2) Quadrupole moment:

$\Rightarrow$ Charge density: $\rho(\vec{r}) = \langle \psi_A | \sum_{k=1}^{A} e | \psi_A \rangle$

$= \langle \psi_A | \sum_k e_k \delta(\vec{r} - \vec{r}_k) | \psi_A \rangle$

$$Q_{ij} = \int d^3\vec{r} \, (3 r_i r_j - r^2 \delta_{ij}) \, \rho(\vec{r})$$

(5 moments) $\quad Q = \langle JJ | Q_{33} | JJ \rangle$

[ELECTROMAGNETIC MOMENTS] (8)

2) Quadrupole moment (cont'ed): $Q = \langle JJ|Q_{33}|JJ\rangle$

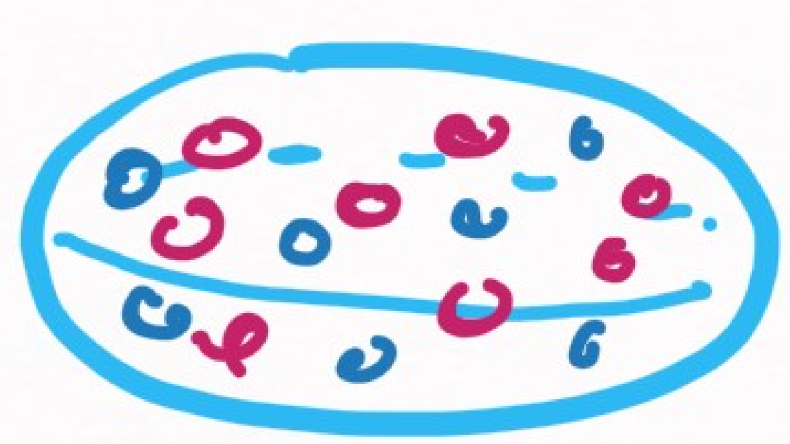
2.a) Deuteron: $Q_d = 0.256\, e\, fm^2$ [$Q_d > 0$ (prolate)]

2.b) Triton, ^3He: $Q(^3H) = Q(^3He) = 0$

2.c) ^4He: $Q(^4He) = 0$

2.d) Most heavy nuclei: $\boxed{Q < 0}$

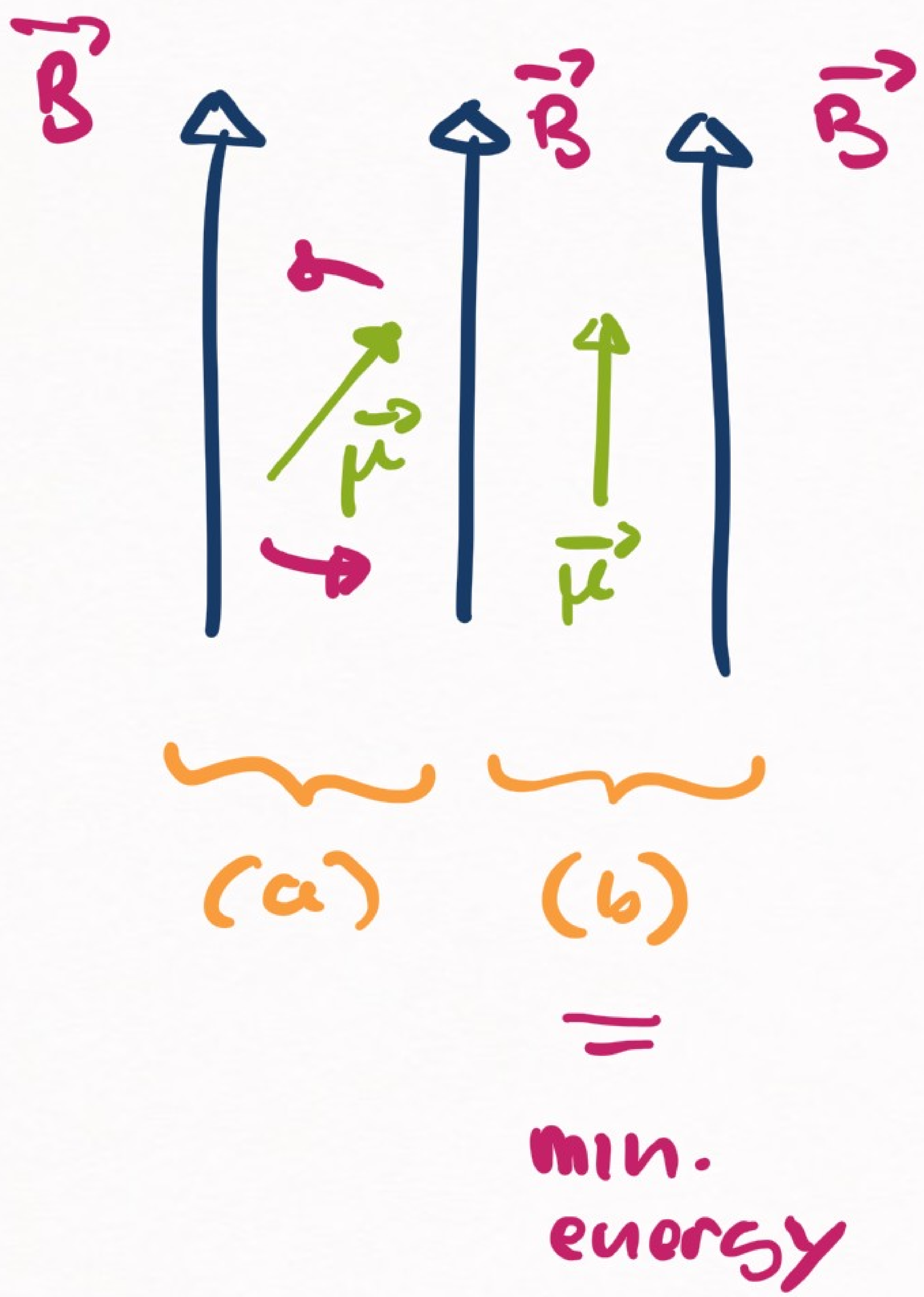
$Q \neq 0$ requires that $J \geq 1$



→ Oblate

[ELECTROMAGNETIC MOMENTS] 9

3) Magnetic moments: $H = -\vec{\mu}\cdot\vec{B}$



(a) If the magnet is not aligned with $\vec{B}$, it will feel a "torque" (an angular force)

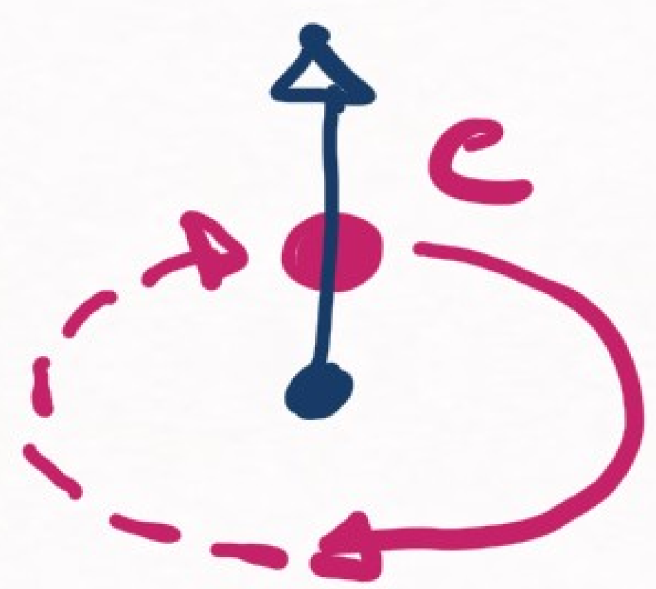
(b) Minimum energy state:

$$\vec{\mu} \parallel \vec{B}$$

(paralel)

[ELECTROMAGNETIC MOMENTS] (10)

a) Classical mechanics:



orbiting/spinning charge w/ angular momentum $\vec{L}$

$$\vec{\mu}_L = \frac{e}{2m}\vec{L}$$

b) Quantum mechanics: $\vec{J} = \vec{L} + \underline{\underline{\vec{S}}} \rightarrow \vec{\mu} = \vec{\mu}_L + \vec{\mu}_S$

new

Q: How to write $\vec{\mu}_S$?

A (naive): $\vec{\mu}_S = \frac{e}{2m}\vec{S}$ (in analogy to $\vec{\mu}_L$)

→ this will be wrong

[ELECTROMAGNETIC MOMENTS] (11)

b) Magnetic moment in quantum mechanics:

$$\vec{J} = \vec{L} + \vec{S} \Rightarrow \vec{\mu} = \vec{\mu}_L + \vec{\mu}_S$$

naively: $\vec{\mu}_S = \frac{e}{2m}\vec{S}$ $\longrightarrow$ Wrong !!.

actually: $\vec{\mu}_S = \underbrace{g_S}_{} \frac{|e|}{2m}\vec{S}$

$\hookrightarrow$ gyromagnetic factor

what are its values? $\Rightarrow$

[ELECTROMAGNETIC MOMENTS] (32)

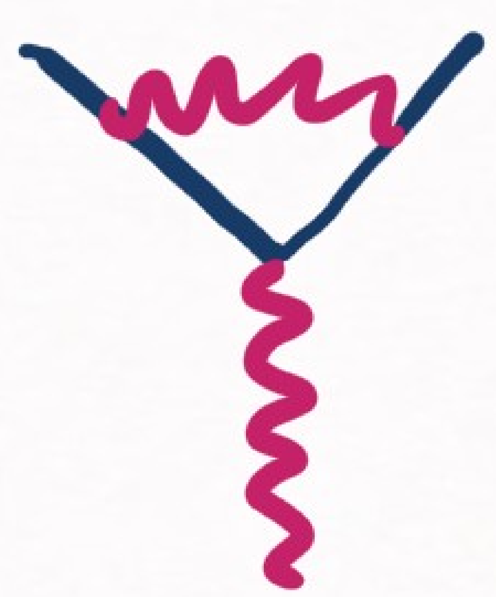
⇒ Gyromagnetic factor of the electron (fundamental):

a) Dirac equation:

$$g_s(e^-) = -2$$

(consequence of QM + relativity)

b) QED corrections:



$$g_s(e^-) = -2\left[1 + \frac{\alpha}{2\pi} + \mathcal{O}(\alpha^2)\right]$$

[ELECTROMAGNETIC MOMENTS] 13

$\Rightarrow$ Gyromagnetic factor of the proton & neutron:
(composite)

If they were fundamental,
we would have: $g(p) \simeq 2$, $g(n) \simeq 0$

But they are not. Experimentally we have:

$$g(p) = 5.586 \quad , \quad g(n) = -3.826$$
$$(\neq 2) \qquad\qquad\qquad (\neq 0)$$

[Because they are composite]

[ELECTROMAGNETIC MOMENTS] (54)

$\Rightarrow$ To summarize, we have:

$$\vec{\mu} = \mu_N \left(\frac{e_N}{e} \vec{L} + g_s \vec{S} \right)$$

with $\mu_N = \dfrac{e}{2m_N}$ } nuclear magneton (usual unit when talking about magnetic moments)

$\mu_s(p) = +2.793$

$\mu_s(n) = -1.919$

$\rightarrow \mu_p = +2.793\,\mu_N$

$\rightarrow \mu_n = -1.919\,\mu_N$

But also, we can write:

$$\vec{\mu} = \mu_N \left(\frac{e_N}{e} \vec{L} + \hat{\mu}_s \vec{\sigma} \right)$$

$$\hat{\mu}_s = \frac{g_s}{2}$$

} Sometimes this is more convenient

[ELECTROMAGNETIC MOMENTS] 15

⇒ Example: the magnetic moment of the deuteron 1

Definition:

$$\mu({}^A_Z X_N) = \langle JJ | \hat{\mu}_3 | JJ \rangle$$

$$\hat{\vec{\mu}} = \sum_{i=1}^{A} \hat{\vec{\mu}}_i$$

Experiment:

$$\mu_{d,exp} = 0.8573\ \mu_N$$

(deuteron)

For the deuteron:

$$\hat{\vec{\mu}}_d = \hat{\vec{\mu}}_p + \hat{\vec{\mu}}_n = \bar{\mu}_N \vec{L}_p + \mu_p \bar{\sigma}_p + \mu_n \bar{\sigma}_n \quad , \quad \mu_d = \langle 11 | \hat{\mu}_{d3} | 11 \rangle$$

$(J=1)$

[ELECTROMAGNETIC MOMENTS] 16

⇒ Example: the magnetic moment of the deuteron 2

Pure S-wave deuteron:

$$\mu_d = \langle 11 | \mu_p \sigma_{p3} + \mu_n \sigma_{n3} | 11 \rangle$$

$$= \mu_p + \mu_n \simeq 0.88\ \mu_N \neq \mu_{d,exp} = 0.8573\ \mu_N$$

⇒ Discrepancy → Cause? → ∃ some angular momentum we have forgotten (D-wave component)

[ELECTROMAGNETIC MOMENTS] 17

⇒ Example: the magnetic moment of the deuteron 3

Solution: include the D-wave contribution ←

$$|\psi_d\rangle = a_s|^3S_1\rangle + a_d|^3D_1\rangle$$

$$|a_s|^2 + |a_d|^2 = 1$$

⇒ $\mu(^3S_1) = \mu_p + \mu_n = 0.88\,\mu_N$ (prev. slide)

$$\mu(^3D_1) = \frac{3}{4}\mu_N - \frac{1}{2}(\mu_p + \mu_n) = 0.31\,\mu_N$$

[ELECTROMAGNETIC MOMENTS] 18

⇒ Example: the magnetic moment of the deuteron 4

We have that:
$$\mu_d = |a_S|^2 \mu(^3S_1) + |a_D|^2 \mu(^3D_1)$$
$$= P_S\, \mu(^3S_1) + P_D\, \mu(^3D_1)$$
$$= \mu_{d,exp}$$

$P_S + P_D = 1$

⇓

$$\left[P_S \simeq 0.96\,,\; P_D \simeq 0.04 \right]$$ → 4% D-wave probability

[ELECTROMAGNETIC MOMENTS] 39

$\Rightarrow$ But, at this point, if you are a purist of quantum mechanics...

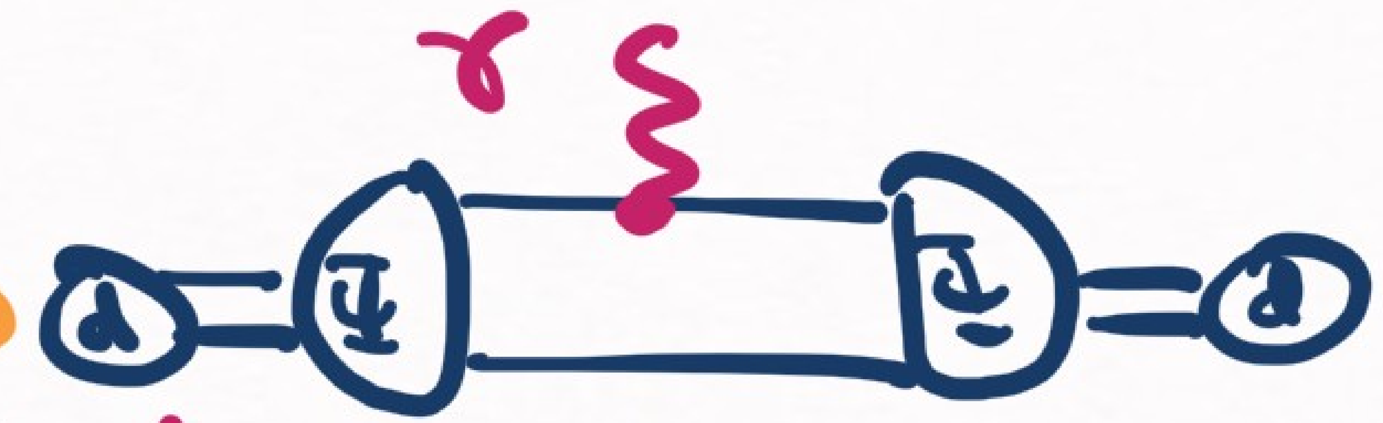
a) The wave function is not an observable

b) P_S and P_D cannot be determined (they should be arbitrary)

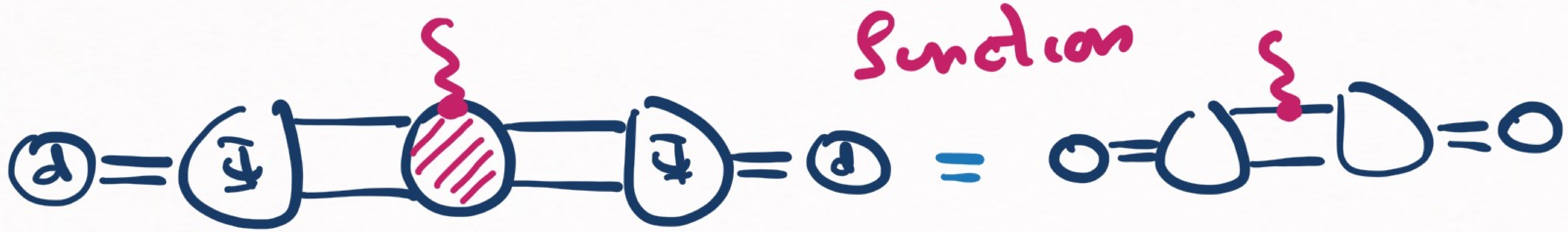
c) Thus, there's something missing in our previous calculation

[ELECTROMAGNETIC MOMENTS] (20)

⇒ What we are missing are two-body currents

a) $P_S = 0.96$
$\underline{\underline{P_D = 0.04}}$ } ⇒ 

} This assumes the photon interacts directly & uniquely with the <u>nucleons</u>

b) 

Real world: the photon can hit other things (e.g. in-flight pion)

\+ 

} TWO BODY CURRENT

\+ ...

[ELECTROMAGNETIC MOMENTS] 21

⇒ [TWO-BODY CURRENTS]

→ They are complicated to calculate, but luckily they are small

Example: deuteron quadrupole moment

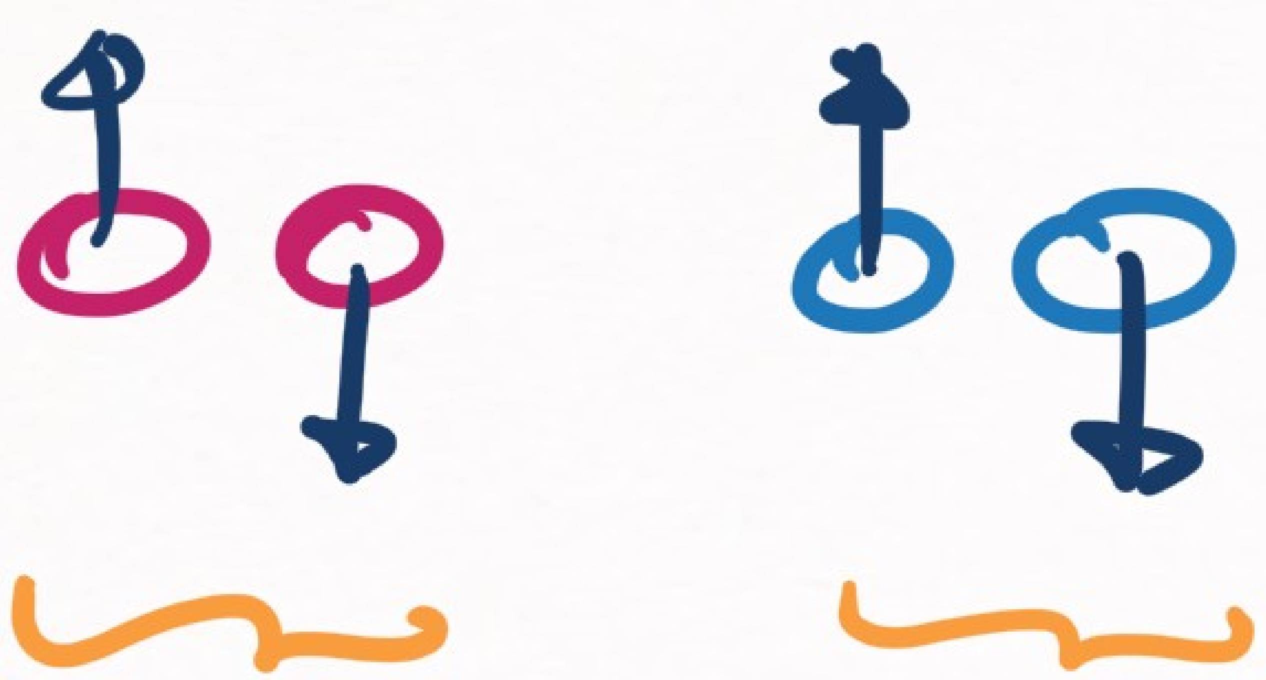
$$Q_{d,exp} = 0.2859(3)\ e\,fm^2$$

$$Q_d = \underbrace{Q_d^{1B}}_{0.276\ e\,fm^2} + \underbrace{Q_d^{2B}}_{0.010\ e\,fm^2} + \dots \quad \Big\}\ |Q_d^{1B}| \gg |Q_d^{2B}|$$

[MAGNETIC MOMENTS OF NUCLEI] (1)

⇒ There is a really important simplification:

[PAIRING]



$S=0$ $\qquad$ $S=0$

the spin of pairs of neutrons or protons couples to zero

^{3}He, $^{3}H \rightarrow J = 1/2$

$^{4}He \rightarrow J = 0$

$$\vec{\mu}_{pair} = \vec{\mu}_1 + \vec{\mu}_2$$

$$= \mu_{n/p}(\vec{\sigma}_1 + \vec{\sigma}_2) = \vec{0}$$

[MAGNETIC MOMENTS OF NUCLEI] 2

a) even-even nuclei : $\vec{\mu}(\text{even-even}) = 0$

even # of protons & neutrons

b) even-odd nuclei : even-odd = even-even + odd nucleon

$$\mu(A) = \underbrace{\cancel{\mu(\text{core})}}_{\text{even-even core}}^{\;0} + \mu_N = \mu_N$$

$\Rightarrow$ We only have to study the odd nucleon

[MAGNETIC MOMENTS OF NUCLEI] 3

b) even-odd nuclei: SCHMIDT VALUES

odd nucleon → $\vec{J}, \vec{L}, \vec{S}$, $S = 1/2 \Rightarrow J = L \pm 1/2$

$$\mu_N (J = L + 1/2) = g_l (J - 1/2) + \frac{1}{2} g_s$$

$$\mu_N (J = L - 1/2) = g_l \frac{J(J+3/2)}{J+1} - g_s \frac{J}{2(J+1)}$$

c) odd-odd nuclei: case-by-case base (e.g. deuteron)

S stable nuclei

RECAP | ELECTROMAGNETIC MOMENTS

1) Most important moments: electric quadrupole & magnetic dipole ✓

electric dipole
magnetic quadrupole } vanish

2) Electric quadrupole moment:

2.a) Deuteron: $Q_d = 0.286\ e\,fm^2$ $(Q_d > 0)$

2.b) Most heavy nuclei: $Q < 0$

RECAP | ELECTROMAGNETIC MOMENTS

3) Magnetic moments → probably the moment containing more information

3.a) Deuteron D-wave component:

$\mu_d({}^3S_1) = 0.88\,\mu_N \neq \mu_{d,exp}$ ⇒ We need a D-wave

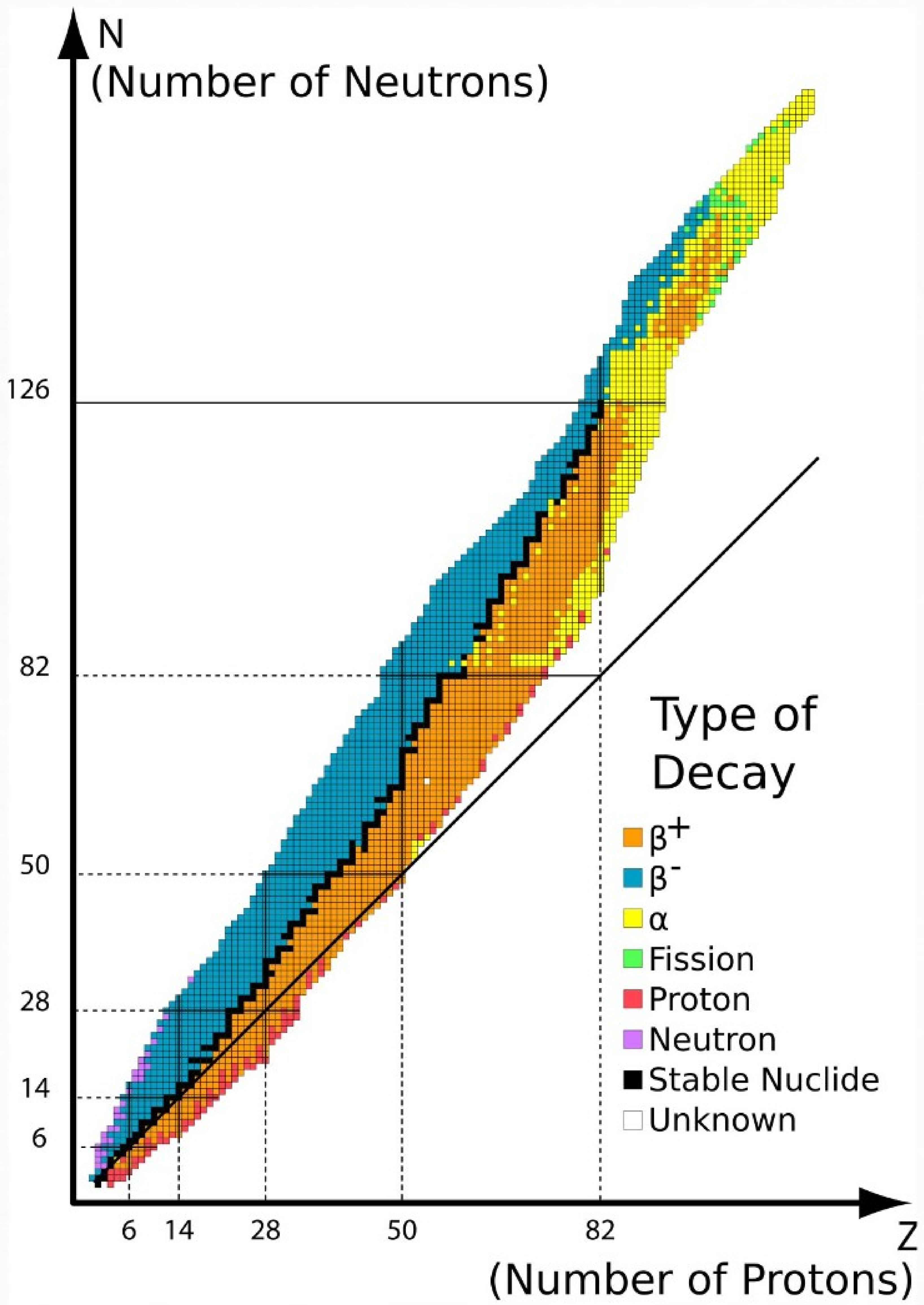
3.b) Nuclei ⇒ Great simplification due to pairing

→ Even-even nuclei: $\mu = 0$

→ Even-odd nuclei: $\mu(A) = \mu_{core} + \mu_N = \mu_N$

SCHMIDT VALUES

NUCLEAR STABILITY ①



⇒ Very few nuclei are stable (most nuclei will decay)

⇓

Q: which one?

A: every nuclei for which decaying is energetically allowed

(unless there is some conservation law protecting a nucleus)

NUCLEAR STABILITY ②

If E(initial nucleus) > E(final products)

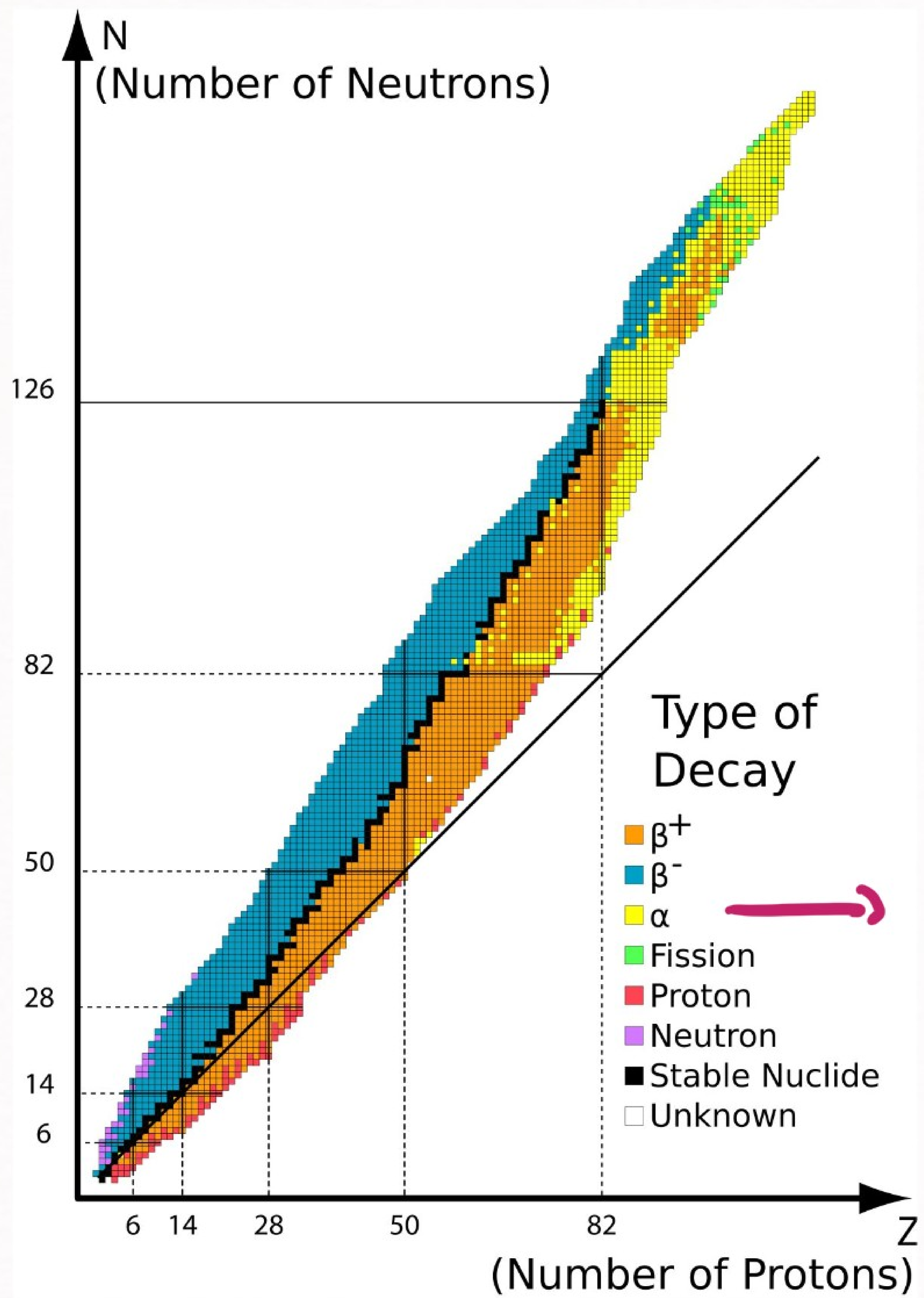
$\Rightarrow$ then, decay will happen
(unless forbidden by some symmetry)

1) α-decay : ${}^{A}_{Z}X_{N} \rightarrow {}^{A-4}_{Z-2}X_{N-2} + \alpha$

Energy balance : $S_\alpha(Z,N) = B(Z,N) - B(Z-2,N-2)$
$- B(2,2)$

Most heavy nuclei : $S_\alpha < 0$

NUCLEAR STABILITY ③



3) α-decay (cont'd):

It is indeed pretty common

→ α-decay nuclei

NUCLEAR STABILITY ④

2) β^- and β^+ decay (electron/positron emission):

$$\left.\begin{aligned} \beta^- &: {}^A_Z X_N \to {}^{A}_{Z+1}X_{N-1} + e^- + \bar{\nu}_e \\ \beta^+ &: {}^A_Z X_N \to {}^{A}_{Z-1}X_{N+1} + e^+ + \nu_e \end{aligned}\right\}$$

Simplest example: $n \to p + e^- + \bar{\nu}_e$

Possible because: $Q = m_n + m_e + m_{\bar{\nu}_e} - m_p$

$\simeq 1.29\ \text{MeV} \quad (Q > 0)$

NUCLEAR STABILITY (5)

2) $\beta^{\pm}$ decay (cont'ed):

Fermi-type decay

Gamow-Teller decay

$$\Gamma(n \to p e^- \bar{\nu}_e) = 2\pi G_V^2 (1 + 3 g_A^2) \Pi(Q)$$

$$\Pi(Q) = \frac{m_e^5}{4\pi^4} f\left(\frac{Q}{m_e}\right) \quad , \quad f(x) = \int_0^{\sqrt{x^2-1}} \left(x - \sqrt{1+y^2}\right)^2 y^2 \, dy$$

$m_e = 0.511$ MeV, $Q = 1.293$ MeV, $G_V = 1.14939 \cdot 10^{-11}$ MeV,

$g_A = 1.2654$

$$\Rightarrow \quad \tau = \frac{\hbar c}{\Gamma} \frac{1}{c} = 934.83 \text{ s}$$

$\boxed{\text{NUCLEAR STABILITY}}$ 6

2) $\beta^{\pm}$ decay : the triton $^3H \to {}^3He + e^- + \bar{\nu}_e$

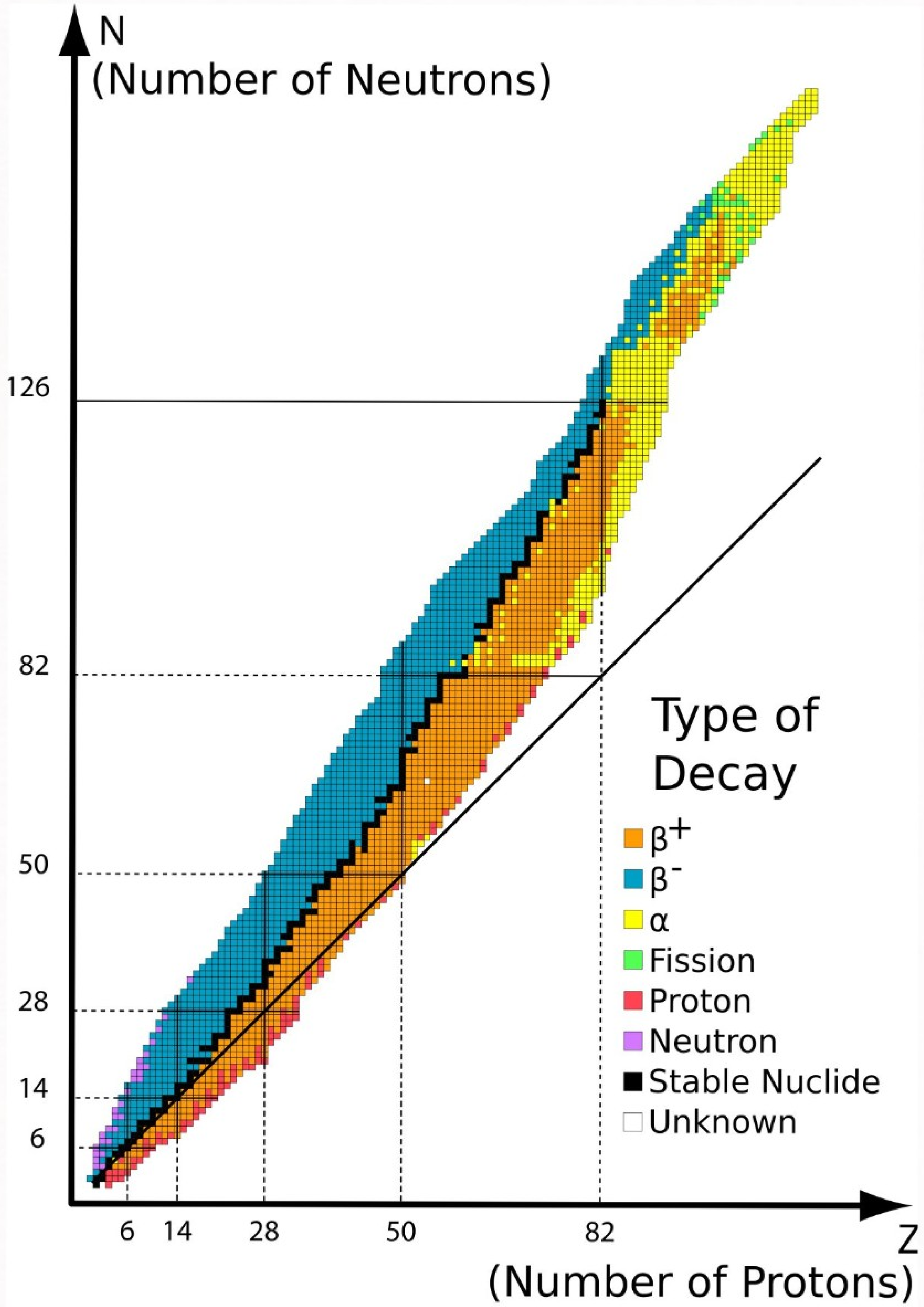
$$Q = -B(^3H) + (m_n - m_p) - B(^3He) - m_e \geq 0$$

$Q \simeq 0.0186$ MeV (small) $\Rightarrow \tau \simeq 10$ years (large)

3) γ decay : $^A_Z X^*_N \to {}^A_Z X_N$

happens very fast, and it involves a transition from an excited to a lower energy state of the same nuclei

NUCLEAR STABILITY 7



$\alpha, \beta, \gamma \rightarrow$ cover most of the decays

but other types of decay are possible:

spontaneous fission
$\rightarrow$ liquid drop model

single neutron/proton emission

+ other exotic types

RECAP!

1) Binding energies → Saturation: $B/A \sim (8\text{-}9)\,\mathrm{MeV}$

(liquid drop model)

→ Magic numbers: $N = 2, 8, 20, 28, 50, \ldots$

(shell model)

2) Nuclear size → $R \simeq A^{1/3} r_0$, $r_0 \sim (1.2\text{-}1.3)\,\mathrm{fm}$

→ Hofstadter experiment:

Nuclear density almost constant and then decays fast

Woods-Saxon distribution

RECAP

3) Angular momentum and parity : shell-model
collective model

4) Electromagnetic moments

→ Electric dipole & magnetic quadrupole vanish ✓

→ Electric quadrupole usually negative (unless it vanishes: $J = 0, \frac{1}{2}$)

→ Magnetic moments

→ Two-body currents

5) Decays : α, β, γ

See you on Friday

15:50