Medical University of Białystok
Department of Biophysics

PRE-COURSE (PHYSICS)

RADIOACTIVITY 1.1

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dr Agnieszka Raciborska

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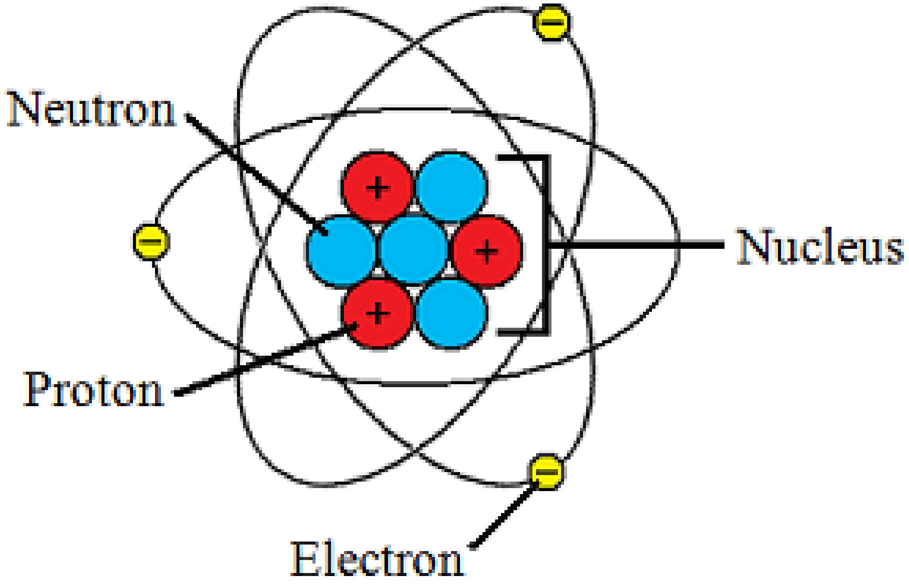
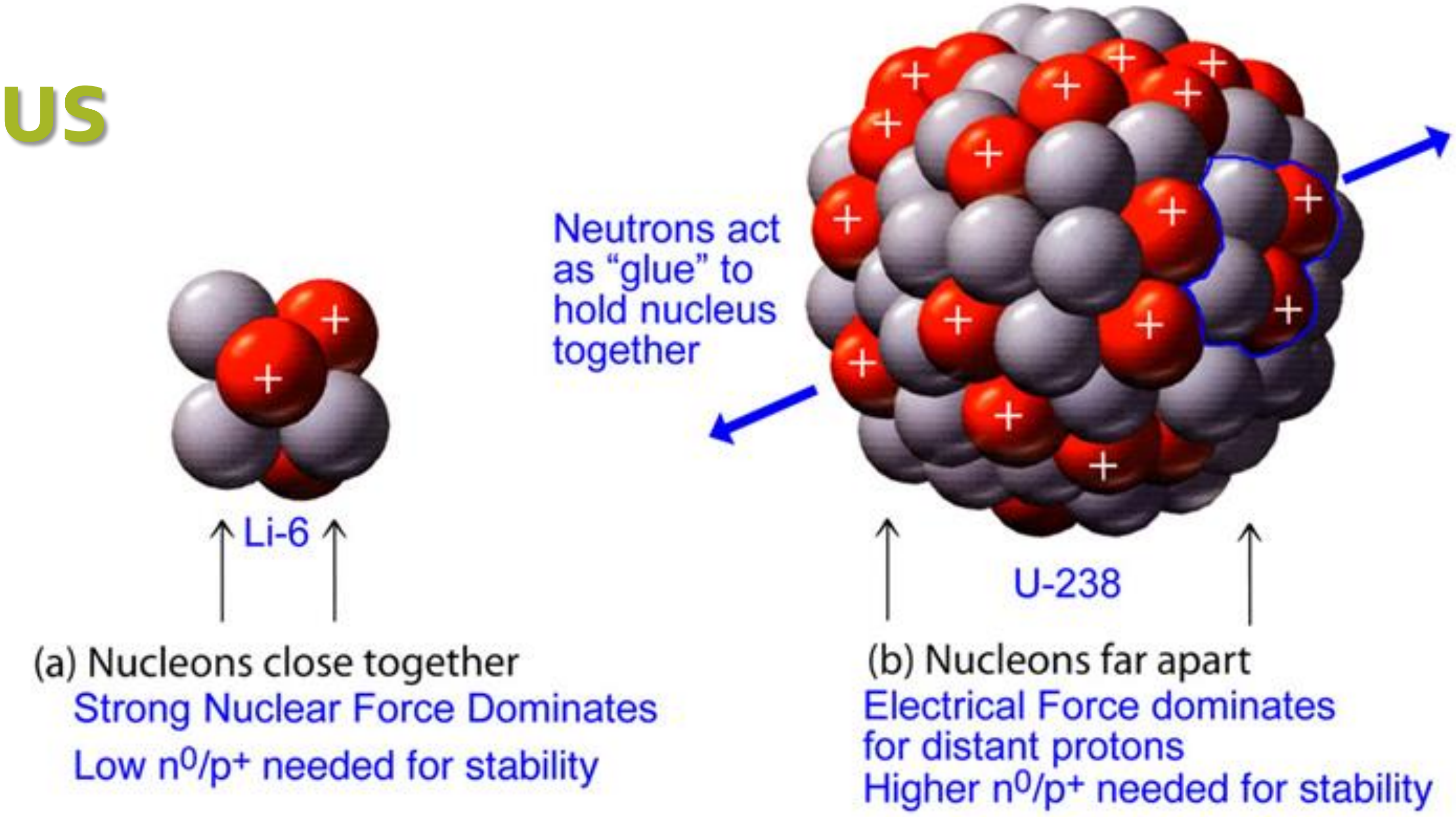
Atom

The atom is the smallest particle of an element. It consists of a positively charged nucleus surrounded by negatively charged electrons, which move in orbits similar to the way in which planets move round the Sun. The positive charge on nucleus exactly balances the total negative charge of all the surrounding electrons when the atom is neutral.



Nucleus



The nucleus consists of two types of particle very strongly held together - protons and neutrons. A proton carries one unit of positive charge.
A neutron has no charge and the mass of a neutron is very slightly more than the mass of a proton.

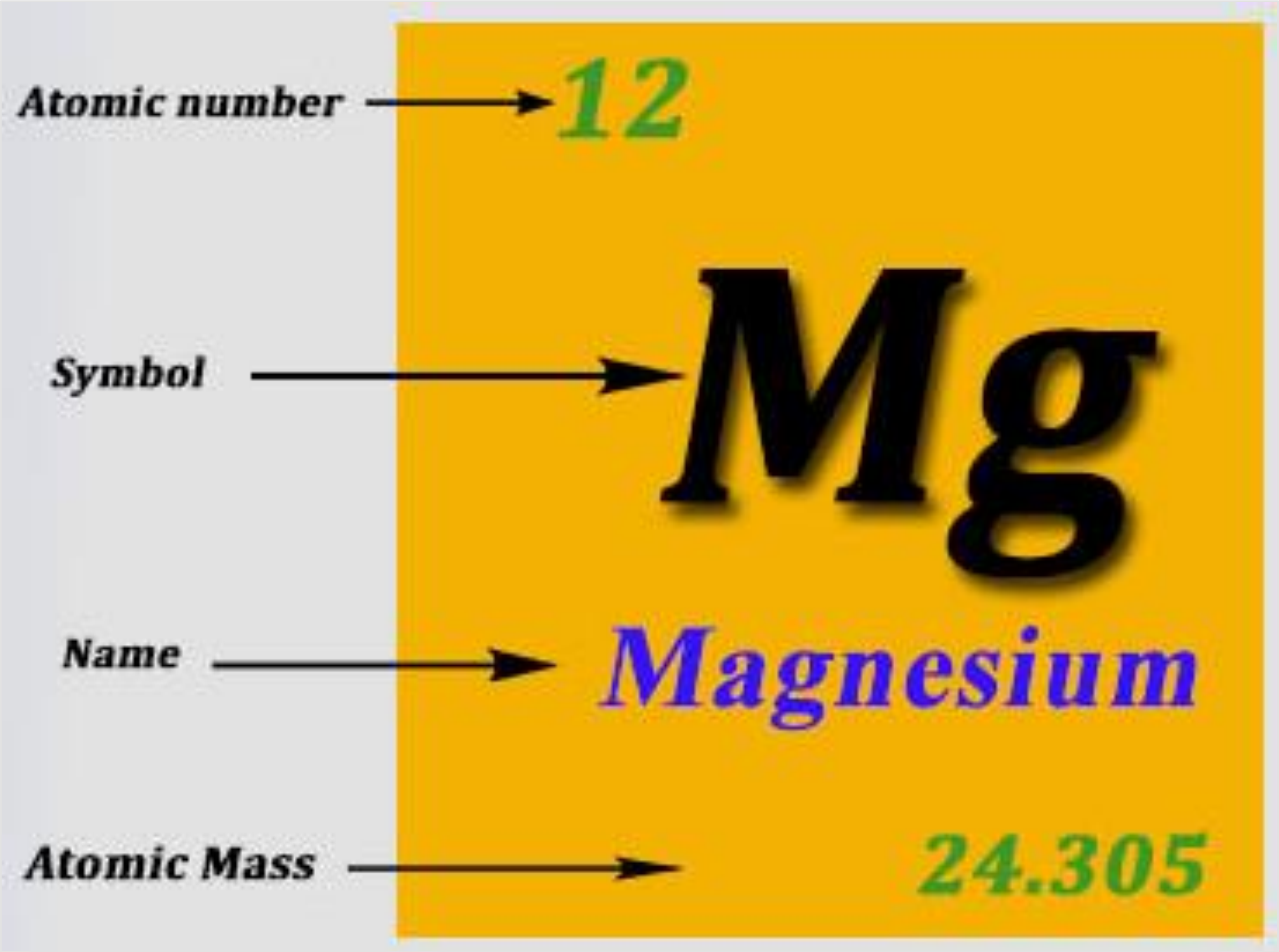
Elements

$${}^{A}_{Z}X$$

- **Z- Atomic Numer** - the number of protons (number of electrons) determines the element
- **A – Atomic Mass** - the number of nucleons in an atom. (the integer of the mass of element)
- **N – (N=A-Z)** - The number of neutrons in an atom.

Elements (e.g.)

Z



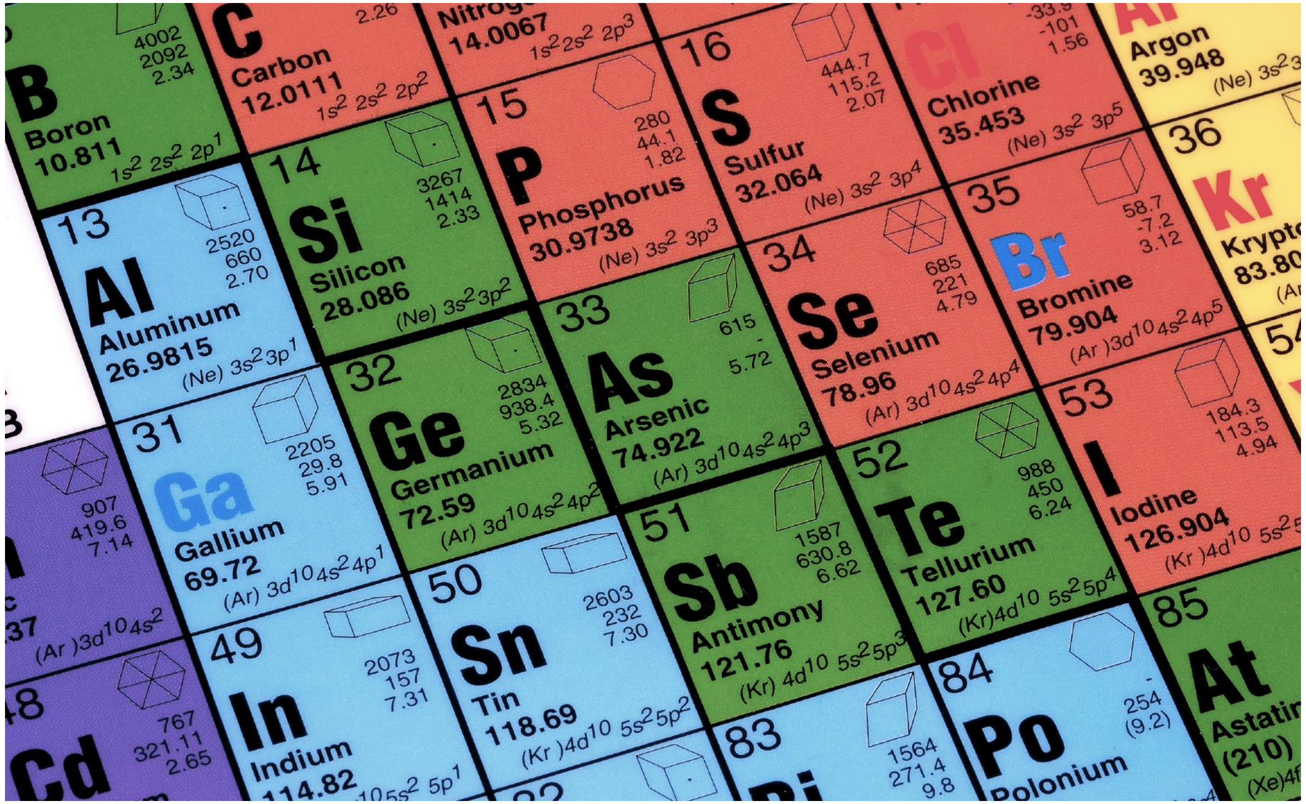
A

$$^{A}_{Z}X$$

$$^{24}_{12}Mg$$

Elements

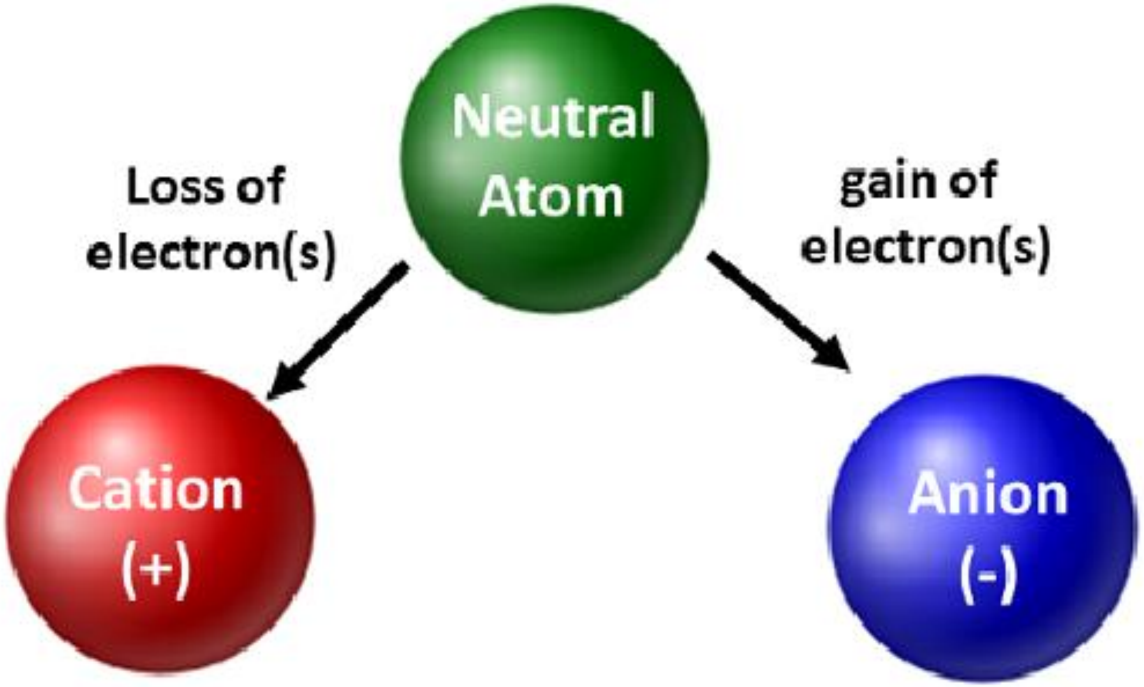
The number of protons (and the corresponding number of electrons) determines the element (atomic number, Z). So if a proton is removed from nucleus (or added to) the nucleus of an atom is no longer the same element.



https://www.ptable.com/?lang=en#Isotope

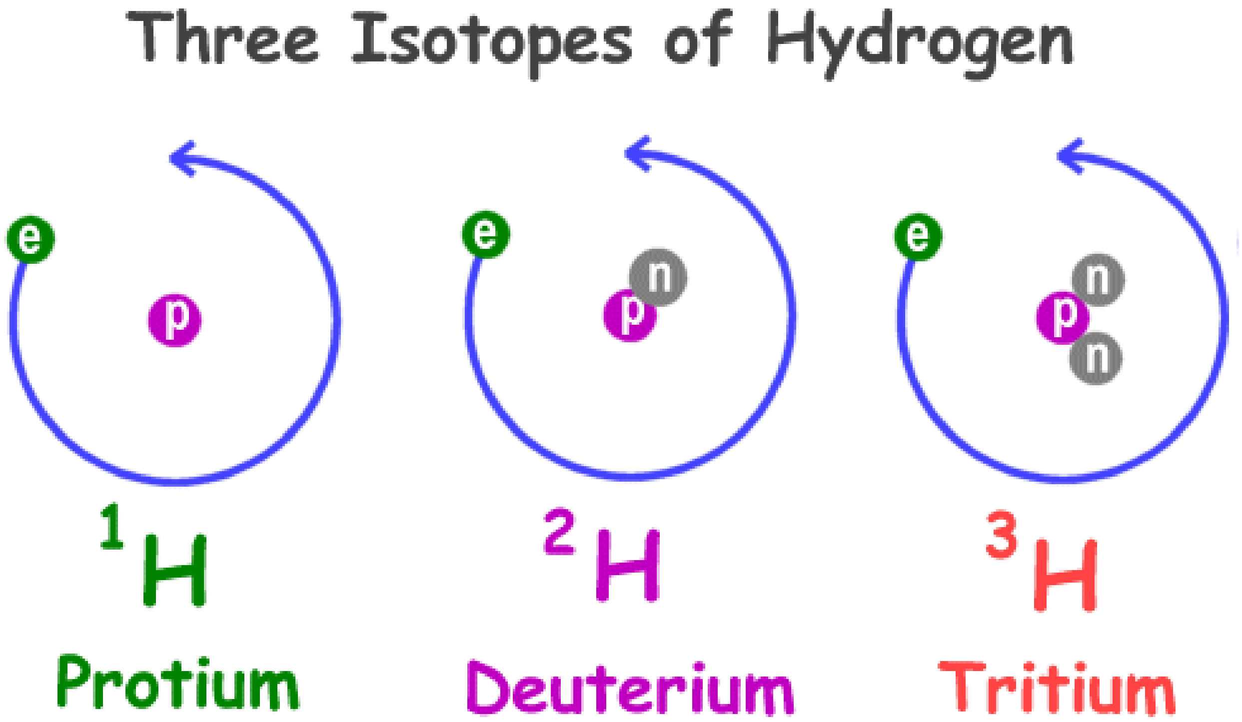
Elements

- if an electon is removed from the atom (or added to) the atom is no longer neutral. An ion is formed.
- When we add an electron (one or more), an anion forms, when we remove an electron (one or more), a cation forms.



Isotopes

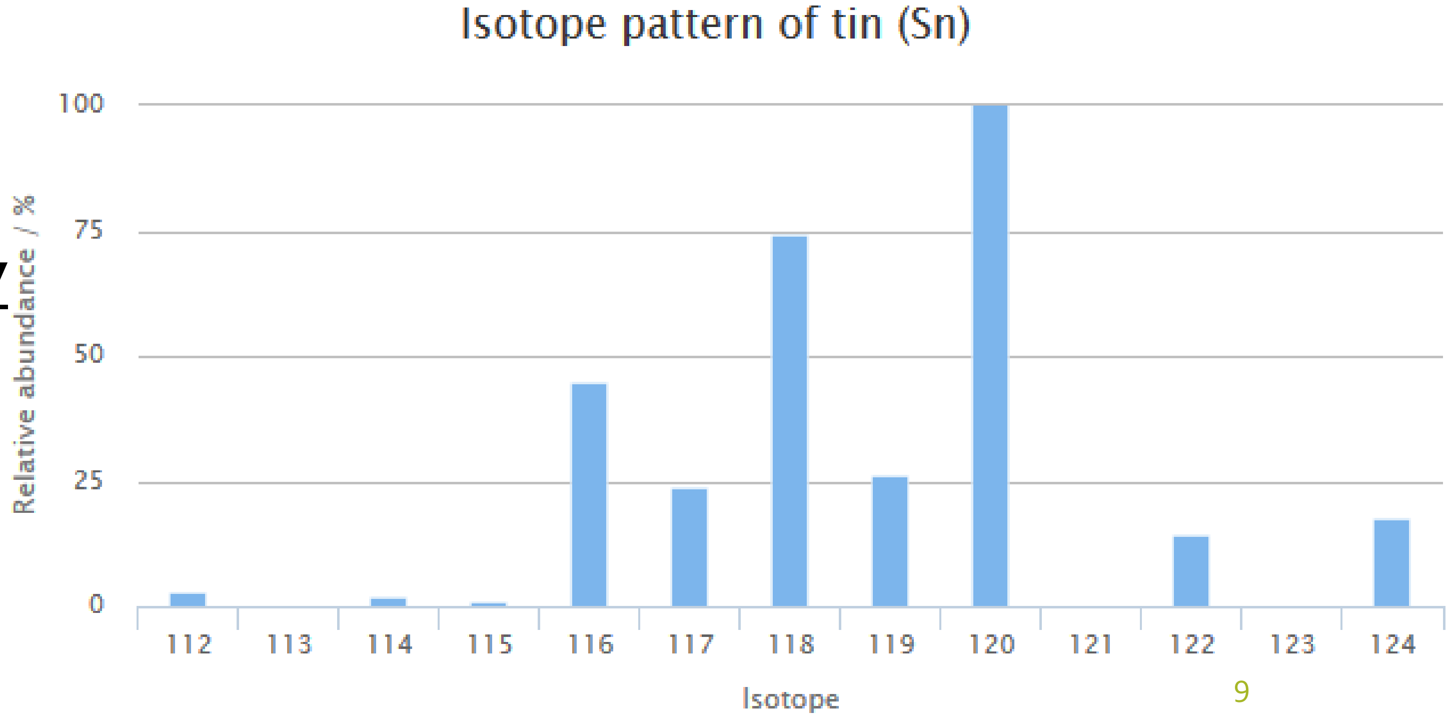
Chemical elements can create one, two or more forms differing only in atomic weight, which are called isotopes. The difference is due entirely to the addition or subtraction of neutrons from the nucleus. **The number of neutrons (N) determines the isotope of the element** (Z). Mass number (A=Z+N) determines the number of nucleons in an atom.



Radioisotopes

Many elements have several stable isotopes (e. g. tin (Sn) has 10). Every element can be made to have radioactive isotopes (radioisotopes) by adding or removing neutrons to the nucleus. The easiest way of producing many neutron-induced nuclear transformations is to place the material to be irradiated within a nuclear reactor which it can be subjected to intense neutron flux.

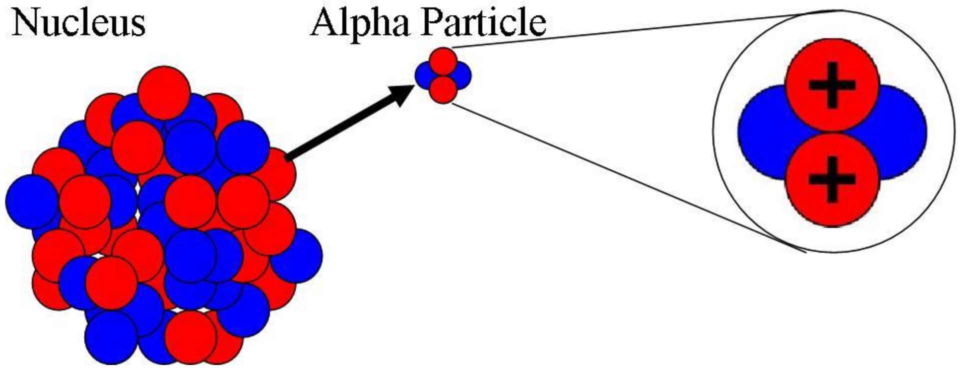
A few elements have naturally occurring radioisotopes.

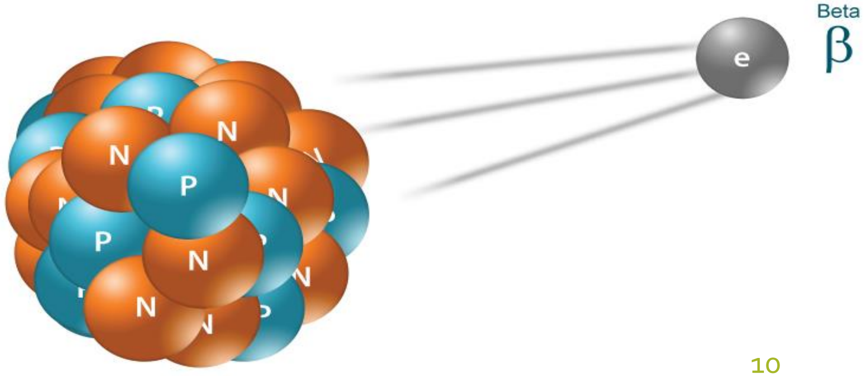


Transmutation of the nuclei

A radioactive nucleus is a nucleus having a certain probability (λ - the decay constant) to undergo a transmutation, either by the emission of:

1. **a positively charged $^{4}_{2}He$ - nucleus (called α-radiation),**
2. **a negatively charged electron e^{-} (called β^{-}-radiation),**
3. **a positively charged electron (positron) e^{+} (called β^{+}-radiation)**
4. **by capturing a negatively charged atomic electron E_C,**
5. **by spontaneous fission SF (called fission fragments).**





Transmutation of the nuclei

- **The mass difference between the neutral atoms before and after the transmutation is found back under form of:**
  - the mass and the kinetic energy of the emitted particles,
  - the recoil energy of the emitting nucleus and
  - the γ-radiation energy.
- **A neutrino ν or an anti-neutrino $\bar{\nu}$ is also emitted during the β-process. These are neutral, weightless particles carrying also part of available energy so that the β-particles have a continuous energy distribution.**

Table 1. The transmutations of the nuclei affect the atomic number Z and neutron number N

Radioactivity	Emitted particle	Change of Z	Change of N	Change of A
α	^{4}He nucleus	Z-2	N-2	A-4
β-	e- (+ $\bar{\nu}$)	Z+1	N-1	A
β+	e^+ (+ ν)	Z-1	N+1	A
EC	(+ν)	Z-1	N+1	A
SF	fragments			

The nuclear equations

- **α-radiation**

$$ {}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha \qquad {}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha $$

- **β^{-}-radiation**

$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \bar{\nu} \qquad {}^{24}_{11}Na \longrightarrow {}^{24}_{12}Mg + {}^{0}_{-1}e + \bar{\nu} $$

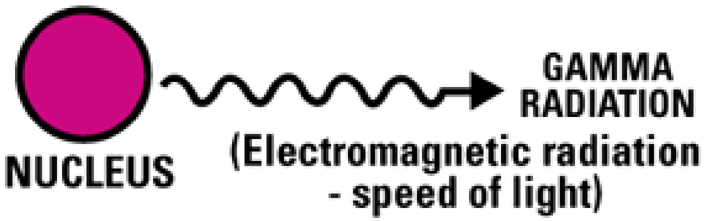
- **β^{+}-radiation**

$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \nu \qquad {}^{11}_{6}C \longrightarrow {}^{11}_{5}Be + {}^{0}_{+1}e + \nu $$

These radioactive phenomena may leave the daughter nucleus in an excited state. It may lose its excitation energy in (mostly) three different ways:

1) **by γ-emission,**
2) **by internal conversion,**
3) **by particle emission (neutrons and protons).**

In the case of internal conversion the nucleus gives its excitation energy to an atomic electron which is ejected from its shell (γ -ray emission is always accompanied by internal conversion).



When a nuclear state has a measurable life-time it is called an isomeric state. An isomeric state may either Decay:

- **by particle emission**
- **by electron capture**
- **by more or less converted isomeric γ-transition (IT) to a lower excited state.**

One or several decay modes are possible for one and the same nucleus, each having its own transition probability: λ_1, λ_2, λ_3, ...

The observed transition probability λ is given by the sum:

$$\lambda = \lambda_1 + \lambda_2 + \lambda_3 + \ldots$$

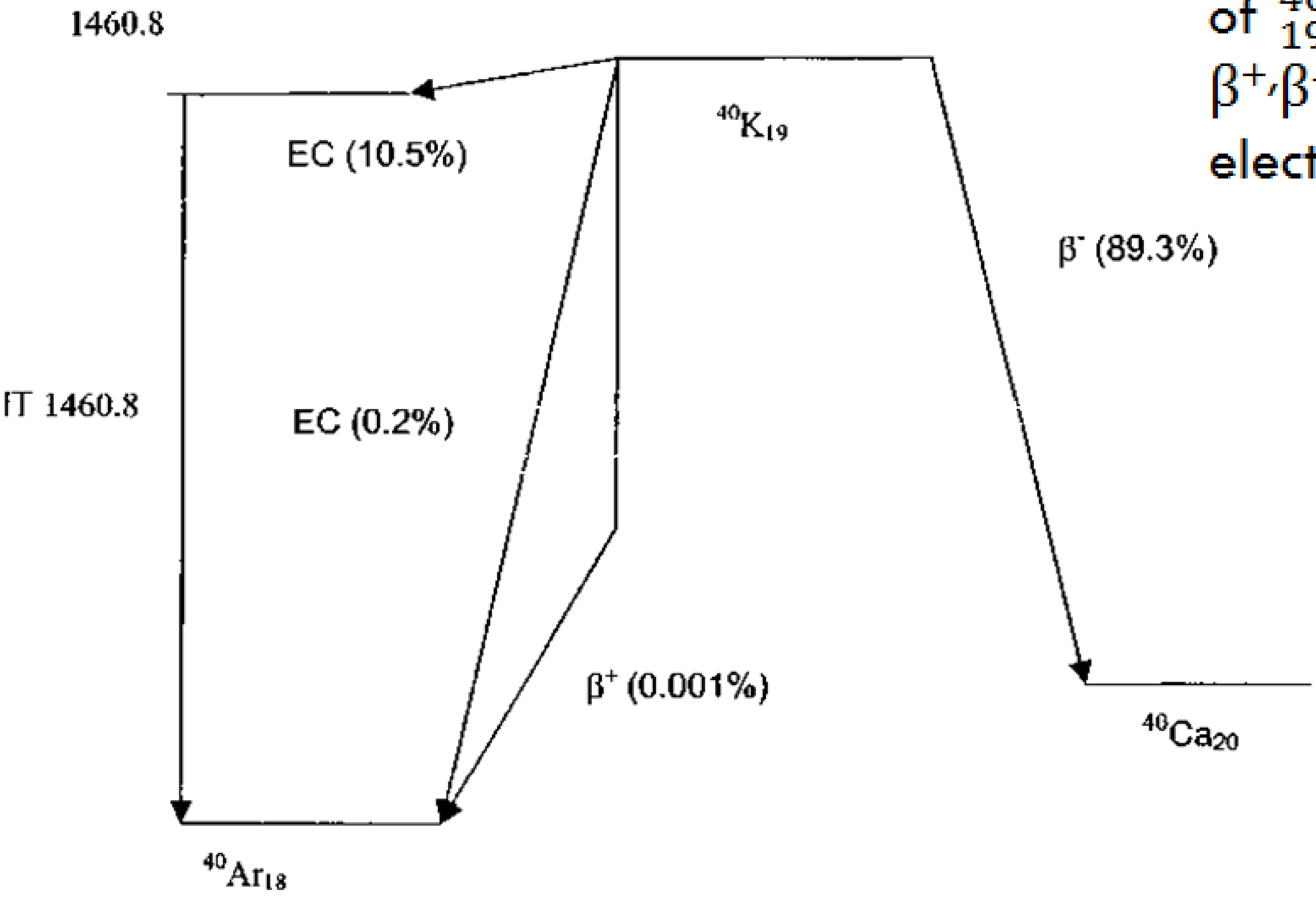
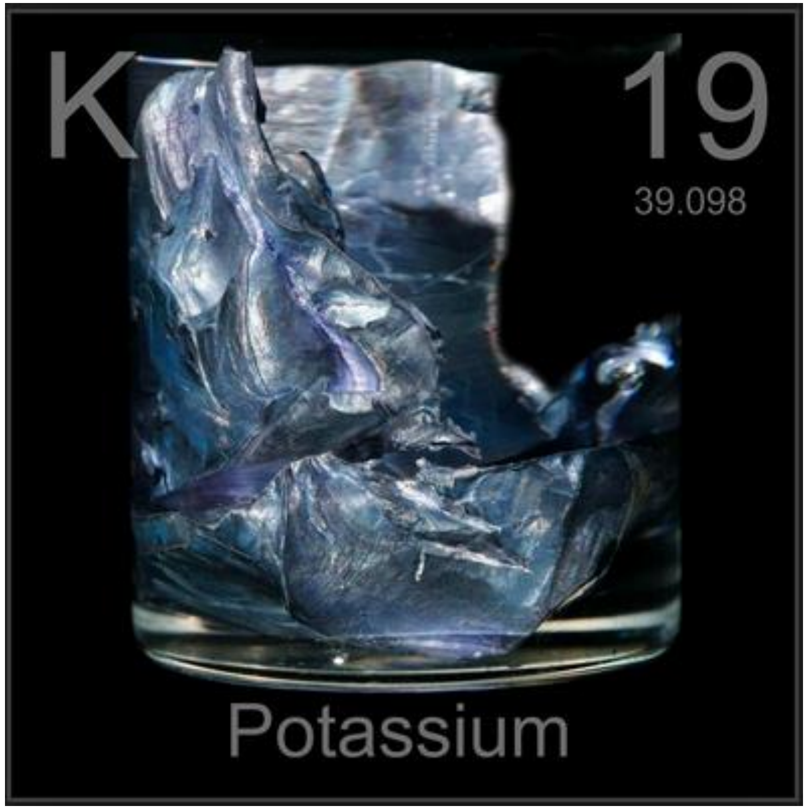


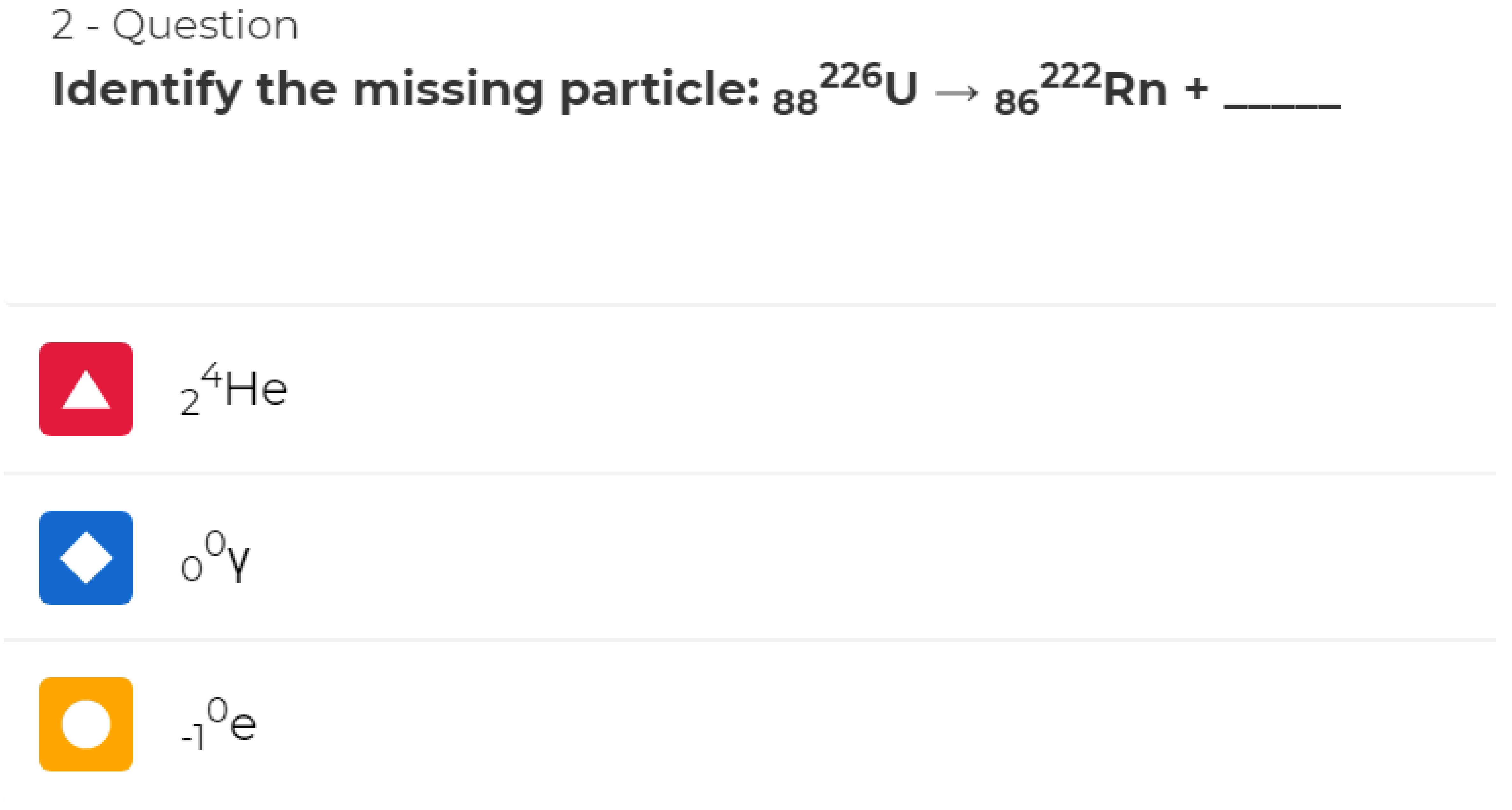
Figure 1 shows the decay modes of $^{40}_{19}K$ – isotope decaying by β^+,β^- and the capturing of an electron.



1 - Question

Identify the missing particle: ${}_{92}^{238}\mathrm{U} \rightarrow$ ____ $+ {}_{2}^{4}\mathrm{He}$

- ▲ ${}_{90}^{234}\mathrm{Th}$
- ◆ ${}_{90}^{234}\mathrm{Po}$
- ● ${}_{90}^{232}\mathrm{Th}$
- ■ ${}_{94}^{242}\mathrm{Pu}$



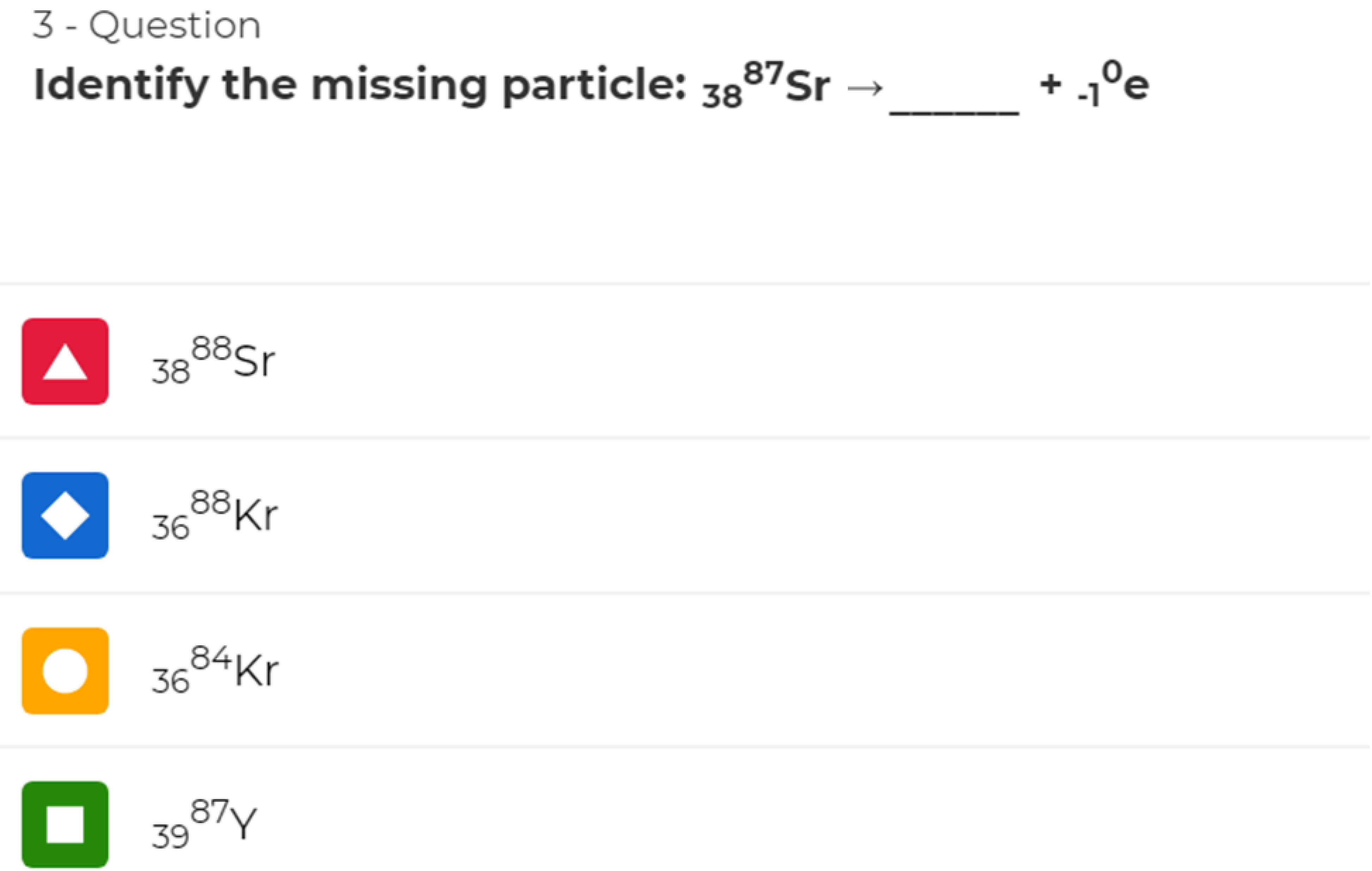
2 - Question

Identify the missing particle: ${}_{88}^{226}\mathrm{U} \rightarrow {}_{86}^{222}\mathrm{Rn}$ + _____

▲ ${}_{2}^{4}\mathrm{He}$

◆ ${}_{0}^{0}\gamma$

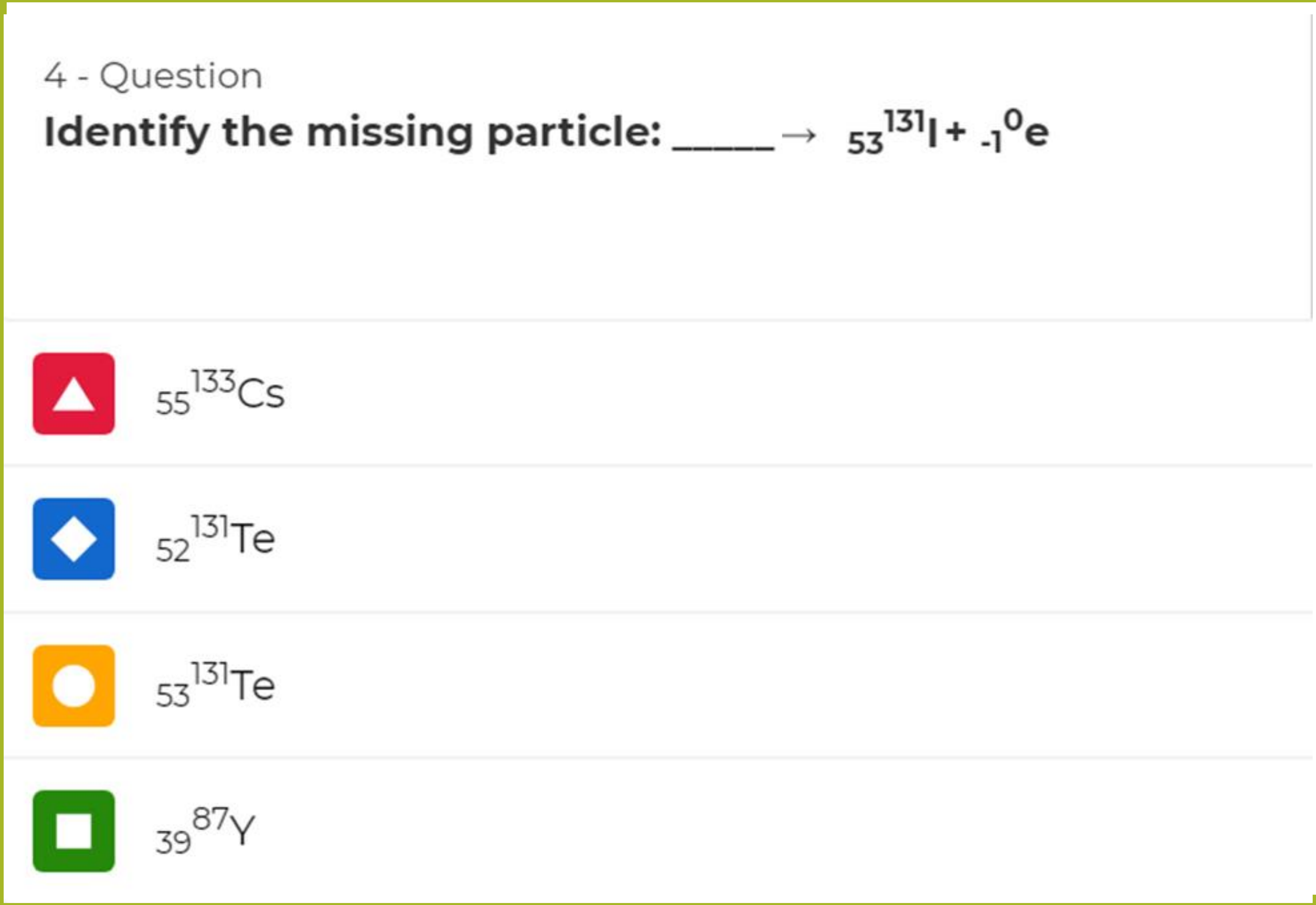
● ${}_{-1}^{0}\mathrm{e}$



3 - Question

Identify the missing particle: $_{38}^{87}\mathrm{Sr} \rightarrow$ ______ + $_{-1}^{0}\mathrm{e}$

- ▲ $_{38}^{88}\mathrm{Sr}$
- ◆ $_{36}^{88}\mathrm{Kr}$
- ● $_{36}^{84}\mathrm{Kr}$
- ■ $_{39}^{87}\mathrm{Y}$



4 - Question

Identify the missing particle: _____ → ${}_{53}^{131}\mathrm{I} + {}_{-1}^{0}\mathrm{e}$

- ▲ ${}_{55}^{133}\mathrm{Cs}$
- ◆ ${}_{52}^{131}\mathrm{Te}$
- ● ${}_{53}^{131}\mathrm{Te}$
- ■ ${}_{39}^{87}\mathrm{Y}$

The transformation theory

The number of atoms of a radioactive element which decay at any instant is proportional to the number of present atoms.
In mathematical form it becomes:

$$\mathbf{A} = \frac{dN}{dt} = (-)\ \lambda \cdot N \qquad (1)$$

where:

- dN/dt - the instantaneous rate of decay - activity (A),
- λ - the decay constant (characteristic of the radioactive substance), a probability to undergo a nucleus transmutation,
- N - the number of atoms present.
- The minus sign indicates that the number of atoms is decreasing.

The transformation theory

- If N_0 is the number of atoms originally present then the solution of the formula is:

$$N=N_0 \cdot e^{-\lambda \cdot t} \qquad (2)$$

where:

- $e \cong 2.72$ is the base of natural logarithms,
- λ - decay constant
- t – decay time,
- N – number of atoms present.

Half-life $(T_{1/2})$

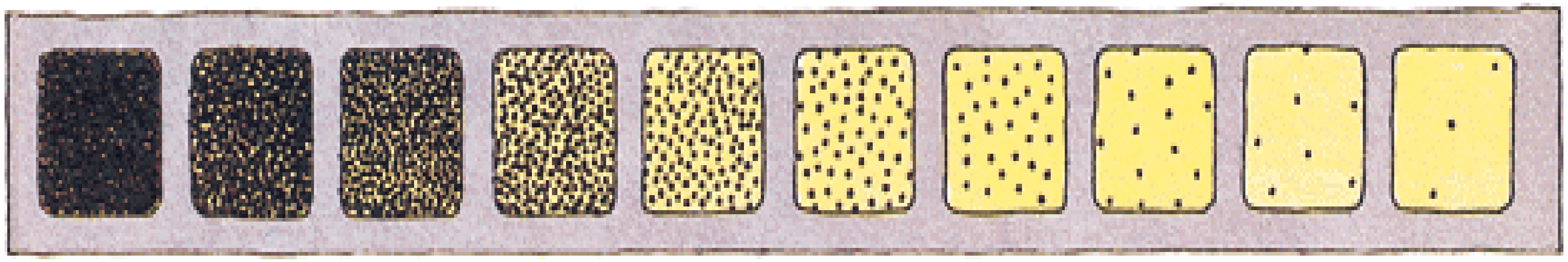
- $T_{1/2}$-the time for half of the nuclei in a sample to decay.

It is used as an indication of the rate of decay.

Half-life ranges from a fraction of second for some (man-made) isotopes to 4510 million years for Uranium 238.

The radioactive materials used in diagnostic medicine have half-lives ranging from a few hours to a few weeks.

Decay rate of radioactivity: After ten half lives, the level of radiation is reduced to one thousandth



Half-life $\left(T_{1/2}\right)$

For a time equal to the *half-life* equation (2) becomes:

$$\frac{N_0}{2} = N_0 \cdot e^{-\lambda \cdot T_{1/2}} \qquad (3)$$

$$\frac{1}{2} = e^{-\lambda \cdot T_{1/2}} \qquad (4)$$

$$2 = e^{\lambda \cdot T_{1/2}}$$

Half-life $\left(T_{1/2}\right)$ and decay constant (λ)

- The relation between the decay constant, λ,

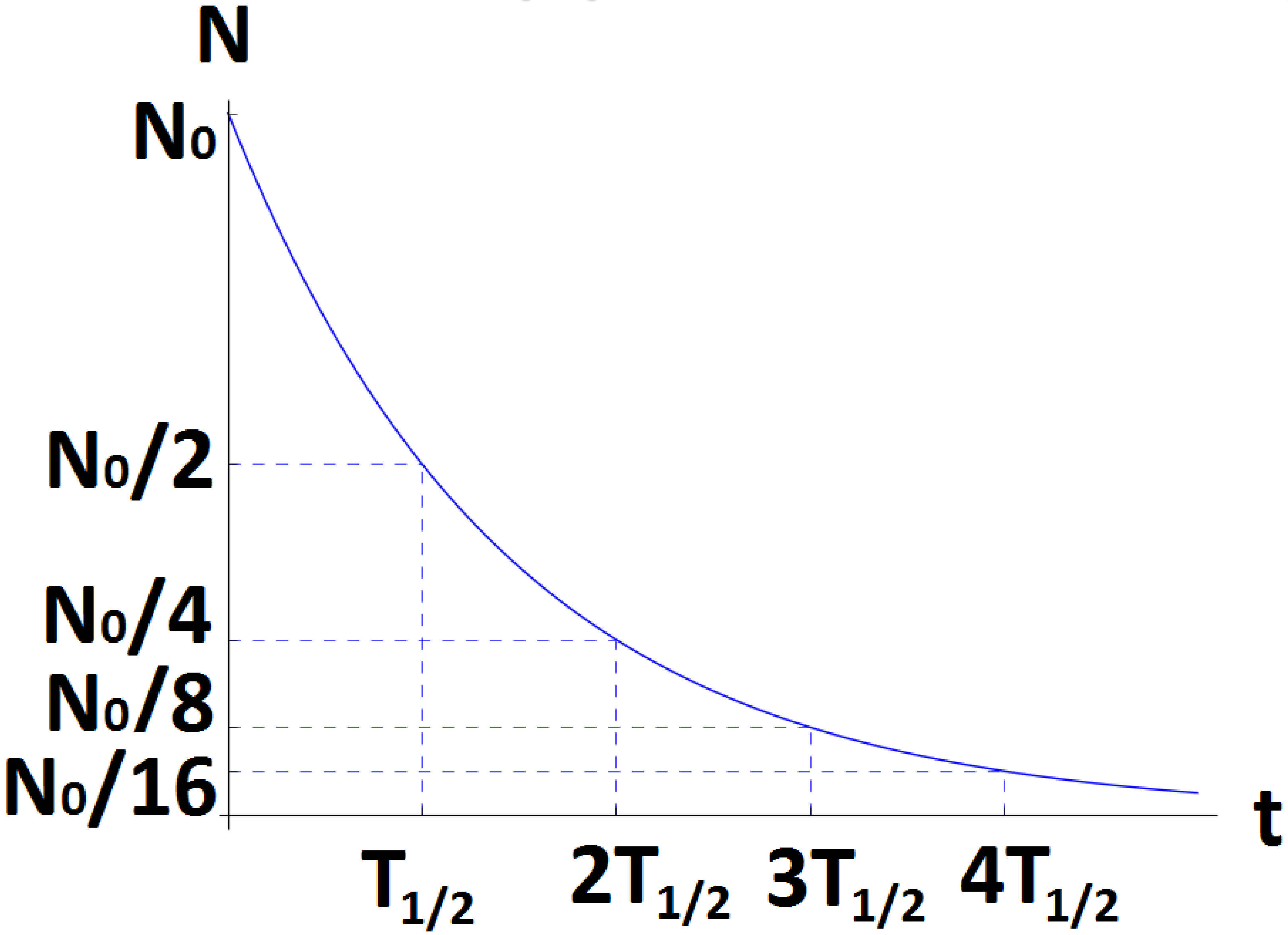
and the half-life, $T_{\frac{1}{2}}$ is established as follows:

$$\lambda \cdot T_{1/2} = log_e 2 \approx 0.693$$

$$\lambda \cdot T_{1/2} = ln2 \qquad (5)$$

- At the begining (t=0): $N=N_0$
- After $t = T_{1/2}$ remains $N = \frac{N_0}{2}$ decays $\frac{N_0}{2}$
- After $t = 2 \cdot T_{1/2}$ remains $N = \frac{N_0}{4}$ decays $\frac{3\,N_0}{4}$
- After $t = 3 \cdot T_{1/2}$ remains $N = \frac{N_0}{8}$ decays $\frac{7\,N_0}{8}$
- After $t = 4 \cdot T_{1/2}$ remains $N = \frac{N_0}{16}$ decays $\frac{15\,N_0}{16}$
- After $t = 5 \cdot T_{1/2}$ remains $N = \frac{N_0}{32}$ decays $\frac{31\,N_0}{32}$

The numbers of nuclei (N) as a function of decay time (t)



Effective half-life (T_{eff})

In medicine and biology to describe a process of losing the radioisotopes from a body not only in radioactive decay, but by biological processes too, we use the term effective half-life.
The effective half-life (T_{eff}) is obtained by combining the biological half-life (T_b) and the radioactive (physical) half-life (T_p) according to the formula:

$$\frac{1}{T_{eff}} = \frac{1}{T_b} + \frac{1}{T_p} \qquad (5a)$$

From *Formula (5)* we have:

$$\lambda \cdot T_{1/2} = ln2$$

so:

$$\frac{1}{T_{1/2}} = \frac{\lambda}{ln\,2}$$

then:

$$\frac{\lambda_{eff}}{ln\,2} = \frac{\lambda_b}{ln\,2} + \frac{\lambda_p}{ln\,2}$$

Finally:

$$\frac{\lambda_{eff}}{ln\,2} = \frac{\lambda_b}{ln\,2} + \frac{\lambda_p}{ln\,2}$$

$$\lambda_{eff} = \lambda_b + \lambda_p \qquad (5b)$$

The effective half-life is shorter than either the biological or physical half-life. This happens because both processes are depleting the supply of the radionuclide.

Thank you for your attention