Introduction to Nuclear Physics

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Advanced Nuclear Science and Technology Techniques Workshop

18 – 22 May 2026, iThemba LABS, Cape Town, South Africa

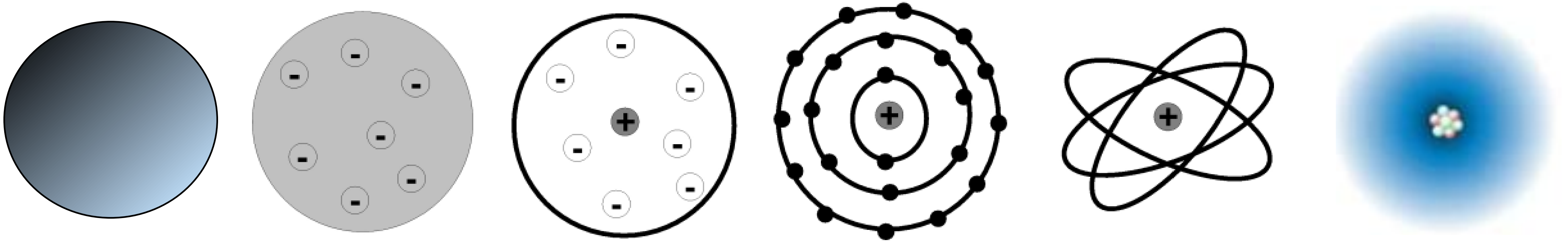
Learning objectives

By the end of this session, the learner should be able to:

- ❑ describe the atom and the nucleus
- ❑ differentiate between stable and unstable atoms
- ❑ describe radioactivity and the common modes of radioactive decay
- ❑ explain the term half-life in radioactive decay
- ❑ illustrate the radioactive decay curve
- ❑ use the chart of nuclides
- ❑ access and use nuclear data

Development of the knowledge about the atom

1803 | 1904 | 1911 | 1913 | 1916 | 1926

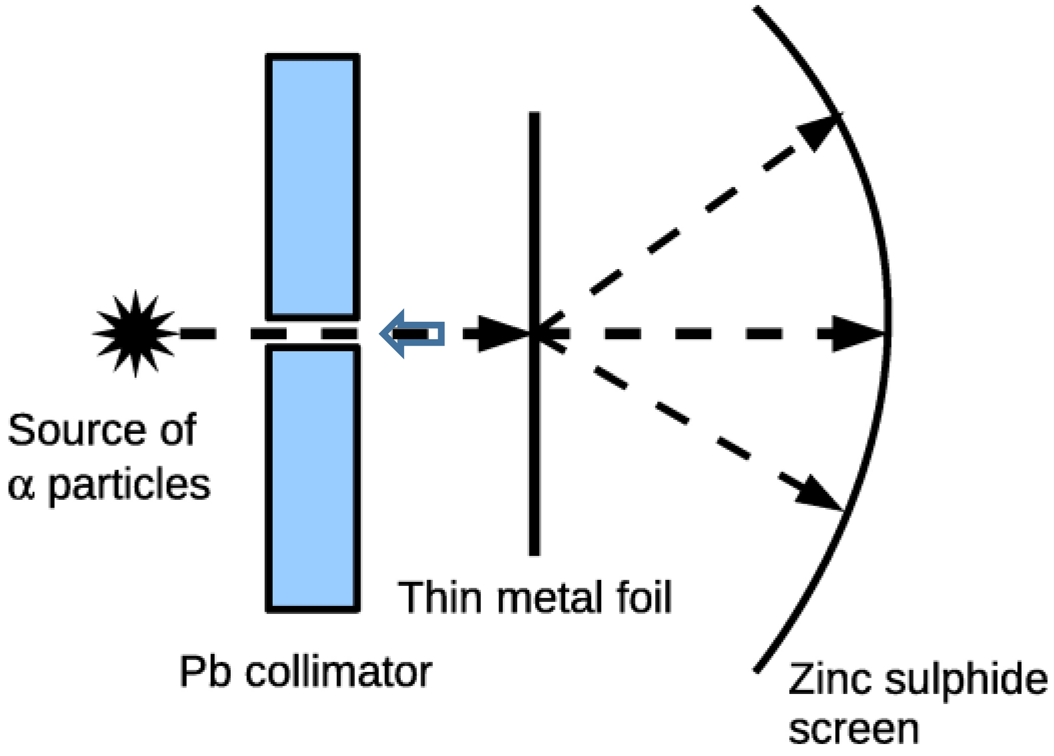


Dalton | **Thomson** | **Rutherford** | **Bohr** | **Sommerfeld** | **Schroedinger**

1803 – J. Dalton - the atom as the smallest indivisible part of matter
1904 – J.J. Thomson and L Kelvin – the atom contains electrons in random order - “plum-pudding model”
1911 – E. Rutherford – the atom is largely empty space and contains a massive core of matter at the centre
1913 – N. Bohr – the electrons orbit round the nucleus without emitting radiation - “planetary model”
1916 – A. Sommerfeld – introduced elliptical orbits, finite mass corrections and relativistic effects for the electrons
1926 – E. Schroedinger – introduced the concept of electron clouds
1932 – J. Chadwick – presence of neutrons in the nucleus of the atom

Discovery of the atomic nucleus

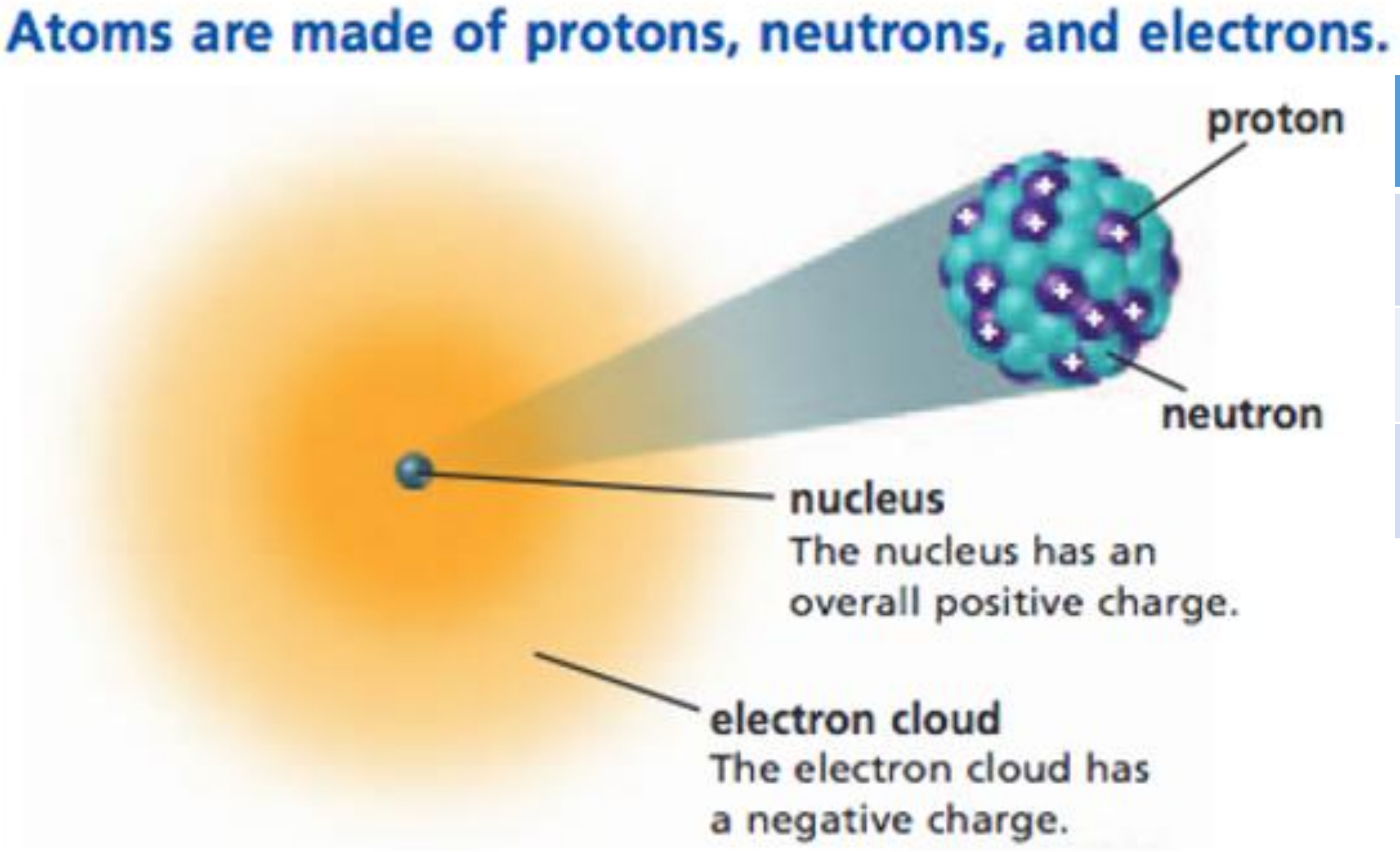
Rutherford experiment



Observations	Conclusions
• most of the α – particles went through un-deflected	• the atomic space is largely empty
• few of the α – particles were scattered in the forward direction	• there is a region of net positive charge in the atom
• very few of the α – particles were scattered back to the source	• there is a massive core of matter in the atom – the nucleus

More information: E. Rutherford. The scattering of α and β particles by matter and the structure of the atom. Philosophical Magazine. Series 6, 21 (May 1911) p. 669-688

The current atomic model



Particle	Mass	Charge (e)
electron	9.1×10^{-31} Kg 0.511 MeV/c^2	-1
proton	1.672×10^{-27} Kg 938.3 MeV/c^2	+1
neutron	1.675×10^{-27} Kg 939.6 MeV/c^2	0

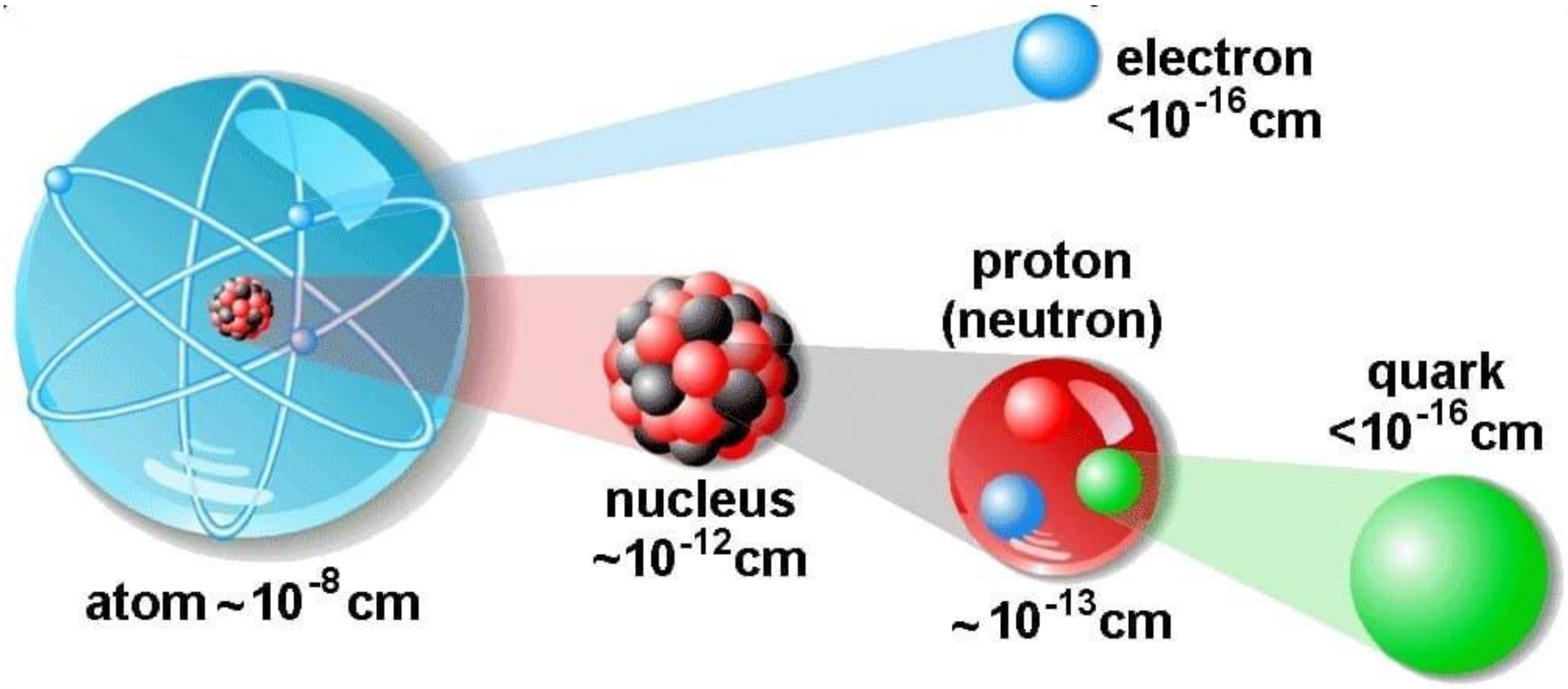
Nuclei are identified by:

Z = no. of protons

N = no. of neutrons

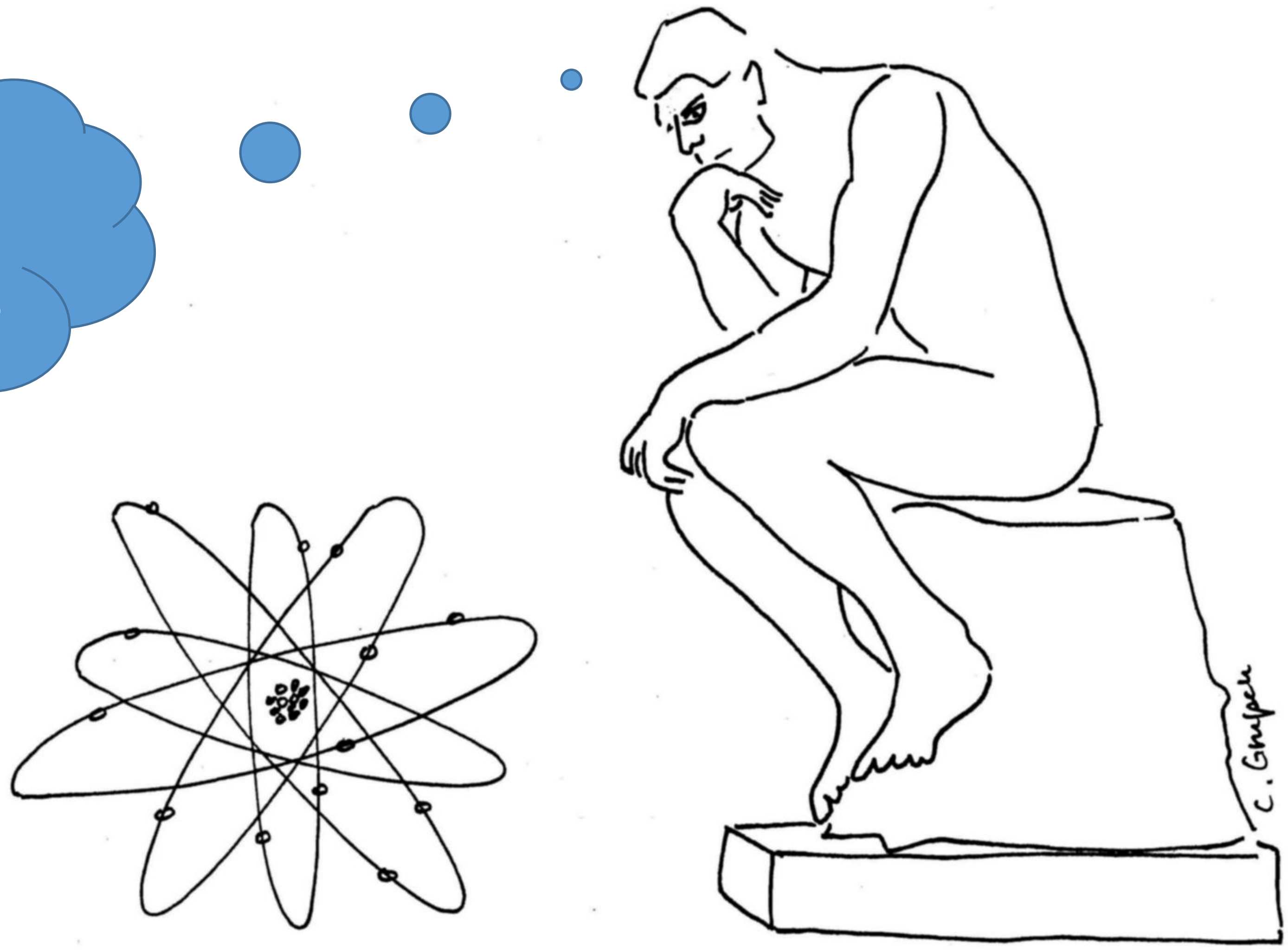
A = Z + N = mass number

The current atomic model

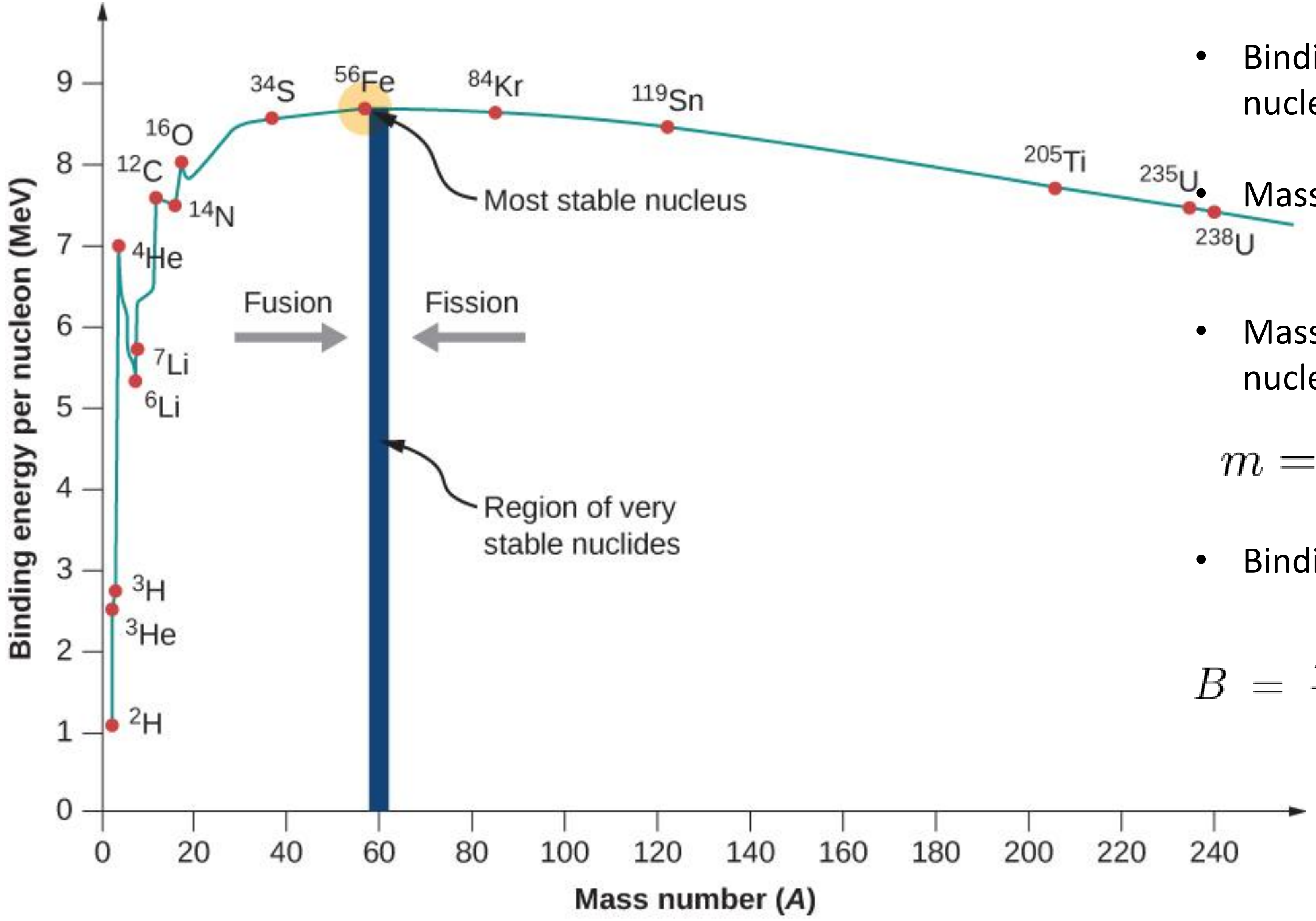


https://www.nuclear-power.com/nuclear-power/reactor-physics/atomic-nuclear-physics/atomic-nuclear-structure/volume-atom-nucleus/

What keeps
the nucleons
in the nucleus?



The Binding Energy Curve



- Binding energy is the energy that keeps the nucleons inside the nucleus
- Mass of nucleus < mass of nucleons
- Mass defect = mass of nucleons – mass of nucleus

$$m = Zm_p + (A - Z)\, m_n - m_{\text{nuc}}$$

- Binding energy per nucleon is given by

$$B = \frac{Zm_p + (A - Z)m_n - M(Z, A)}{A}$$

The Binding Energy per Nucleon

Example 1: The mass of the nucleus of ${}^{10}_{5}\mathrm{B}$ is 10.0165u.

The mass of protons is $5 \times m_p = 5 \times 1.00728\mathrm{u} = 5.03641\mathrm{u}$

the mass of neutrons is $5 \times m_n = 5 \times 1.00867\mathrm{u} = 5.0433\mathrm{u}$

so that the total mass of nucleons is $5.03641 + 5.0433 = 10.0797\mathrm{u}$.

The mass deficit is therefore $10.0797\mathrm{u} - 10.0165\mathrm{u} = 0.0637\mathrm{u}$

and the binding energy per nucleon is,

$$\frac{B}{A} = \frac{0.0637\mathrm{u}}{10} \times 931\mathrm{Mev/u} = 5.93\,\mathrm{MeV/nucleon}.$$

Nuclear Mass Density

The volume and radius of the nucleus depend on the number of nucleons

$$V \propto A \qquad R = R_0 A^{1/3}$$

… where $R_0 = 1.2 \times 10^{-15}\text{m} = 1.2\text{fm}$

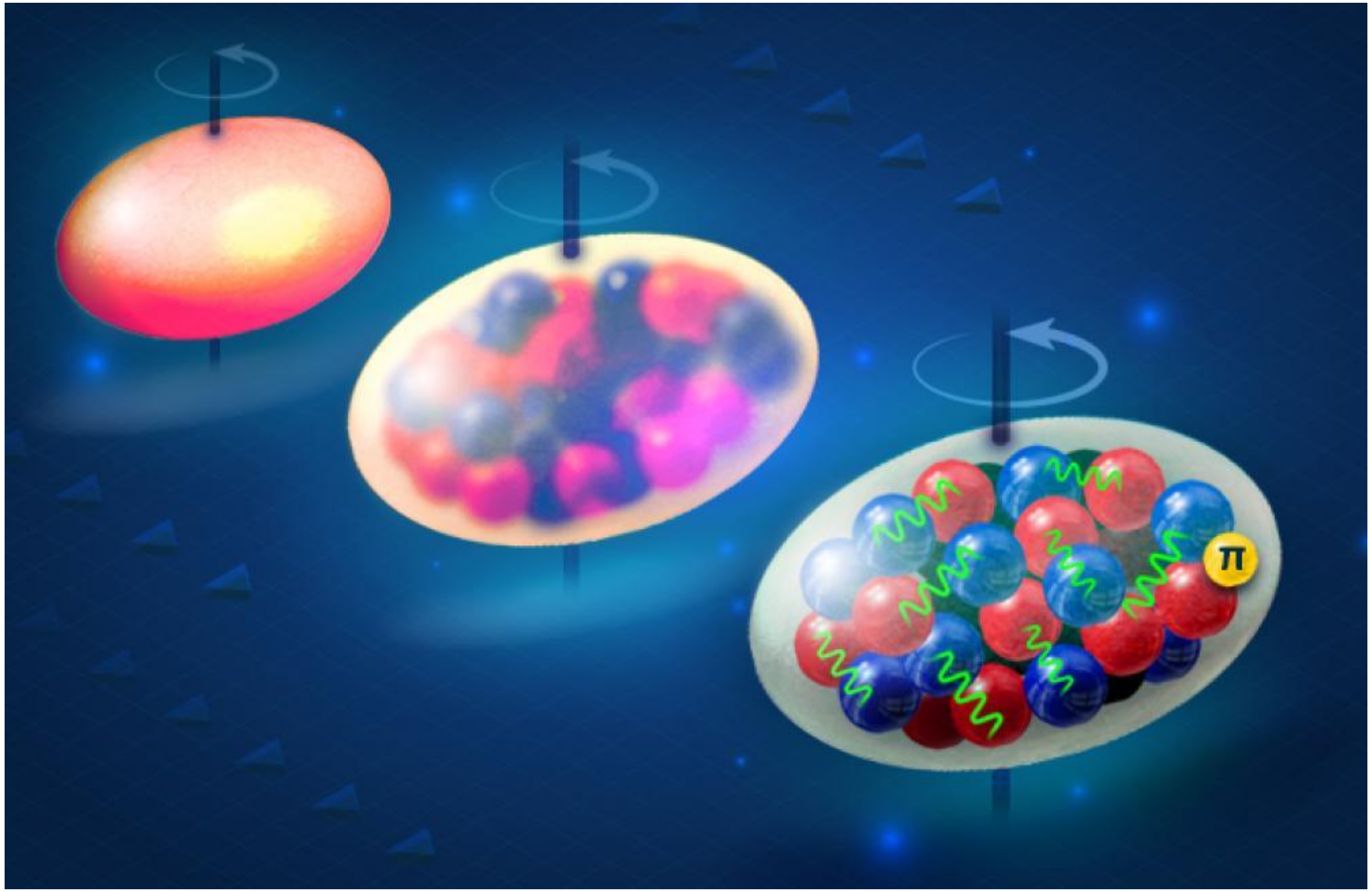
Example 2: Consider the isotope ${}^{12}_{6}\text{C}$. The radius of the nucleus is estimated as follows,

$$R \simeq 1.2(12)^{1/3}\text{fm} = 2.75\text{fm}$$

and hence the nuclear density can be calculated as follows,

$$\rho = \frac{m}{v} = \frac{(12\text{u})(1.66 \times 10^{-27}\text{kg/u})}{(4/3)\pi(2.7 \times 10^{-15}\text{m})^3} = 2.4 \times 10^{17}\text{kg/m}^3 \,.$$

Nuclear Models



OAK RIDGE National Laboratory

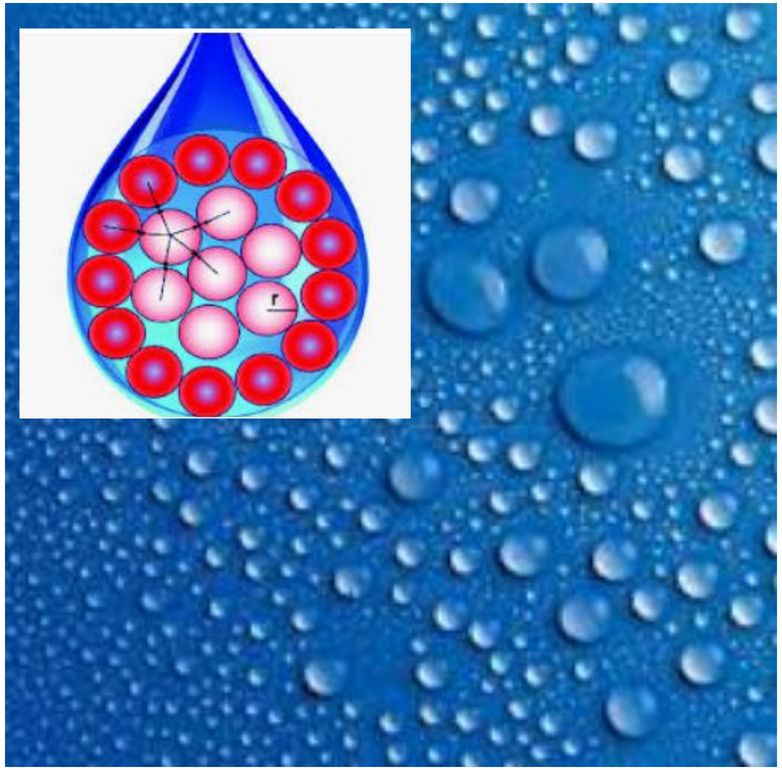
- ❖ Liquid Drop Model
- ❖ Fermi Gas Model
- ❖ Shell Model
- ❖ Collective Model
- ❖ …

No single model explains all known nuclear phenomena!

The Liquid Drop Model of the Nucleus

This model assumes that all nuclei have similar mass densities with binding energy approximately proportional to their masses just as in a classical charged liquid drop

volume energy	$E_v = a_1 A$	$a_1 = 14.1\text{MeV}$
surface energy	$E_s = -a_2 A^{2/3}$	$a_2 = 13.0\text{MeV}$
Coulomb energy	$E_C = -a_3 \dfrac{Z(Z-1)}{A^{1/3}}$	$a_3 = 0.595\text{MeV}$
assymetry energy	$E_a = -a_4 \dfrac{(A-2Z)^2}{A}$	$a_4 = 19.0\text{MeV}$
pairing energy	$E_p = (\pm, 0) \dfrac{a_5}{A^{3/4}}$	$a_5 = 33.5\text{MeV}$



Semi – empirical binding energy formula:

$$E_b = E_v + E_s + E_C + E_a + E_p$$

The Liquid Drop Model of the Nucleus

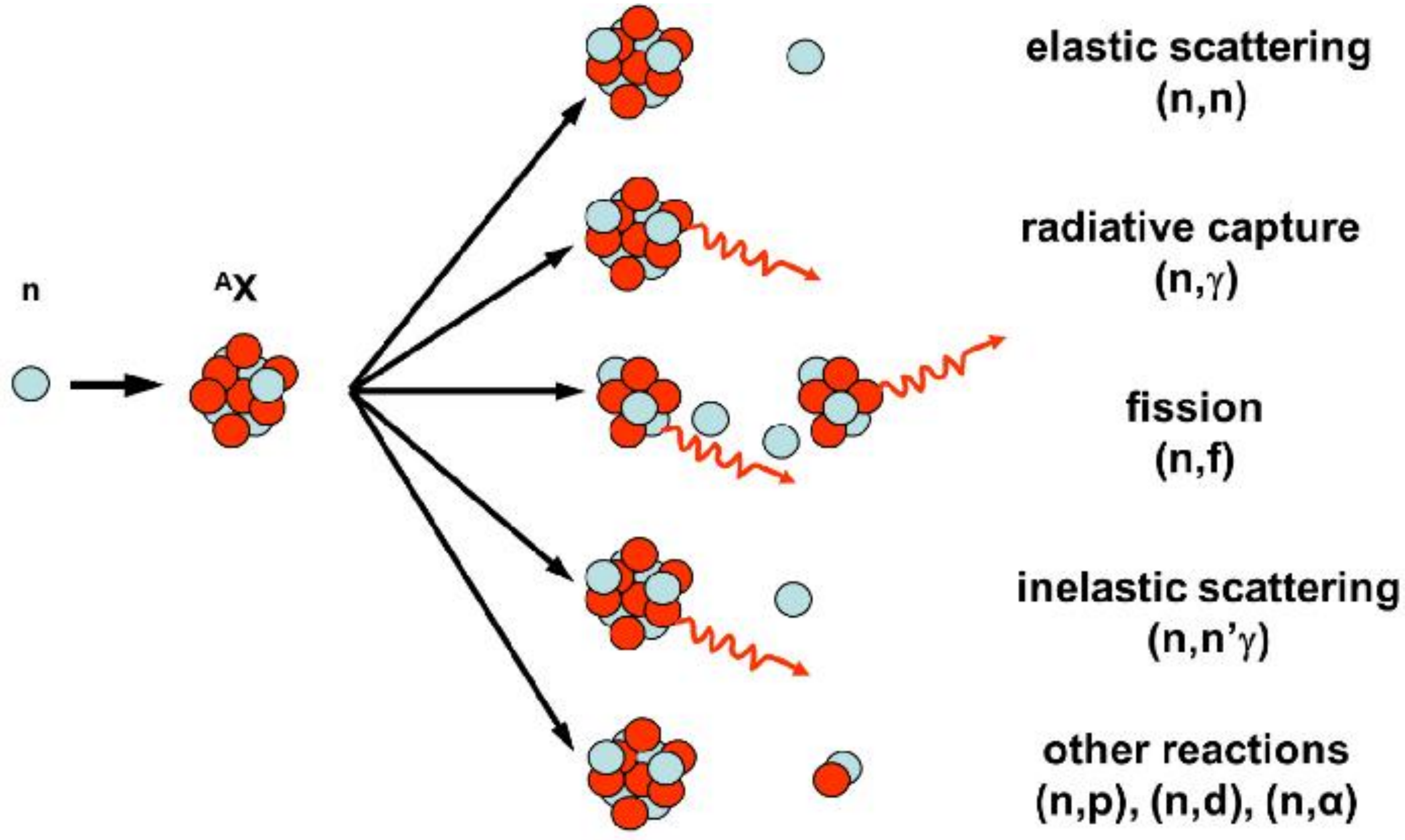
Example 3: Consider the zinc isotope $^{64}_{30}\mathrm{Zn}$ with atomic mass 63.929u. The binding energy is given by,

$$B = \Big[(30)(1.007825\mathrm{u}) + (34)(1.0088665\mathrm{u}) - 63.929\mathrm{u}\Big](931.49\mathrm{MeV/u}) = 559.1\mathrm{MeV}$$

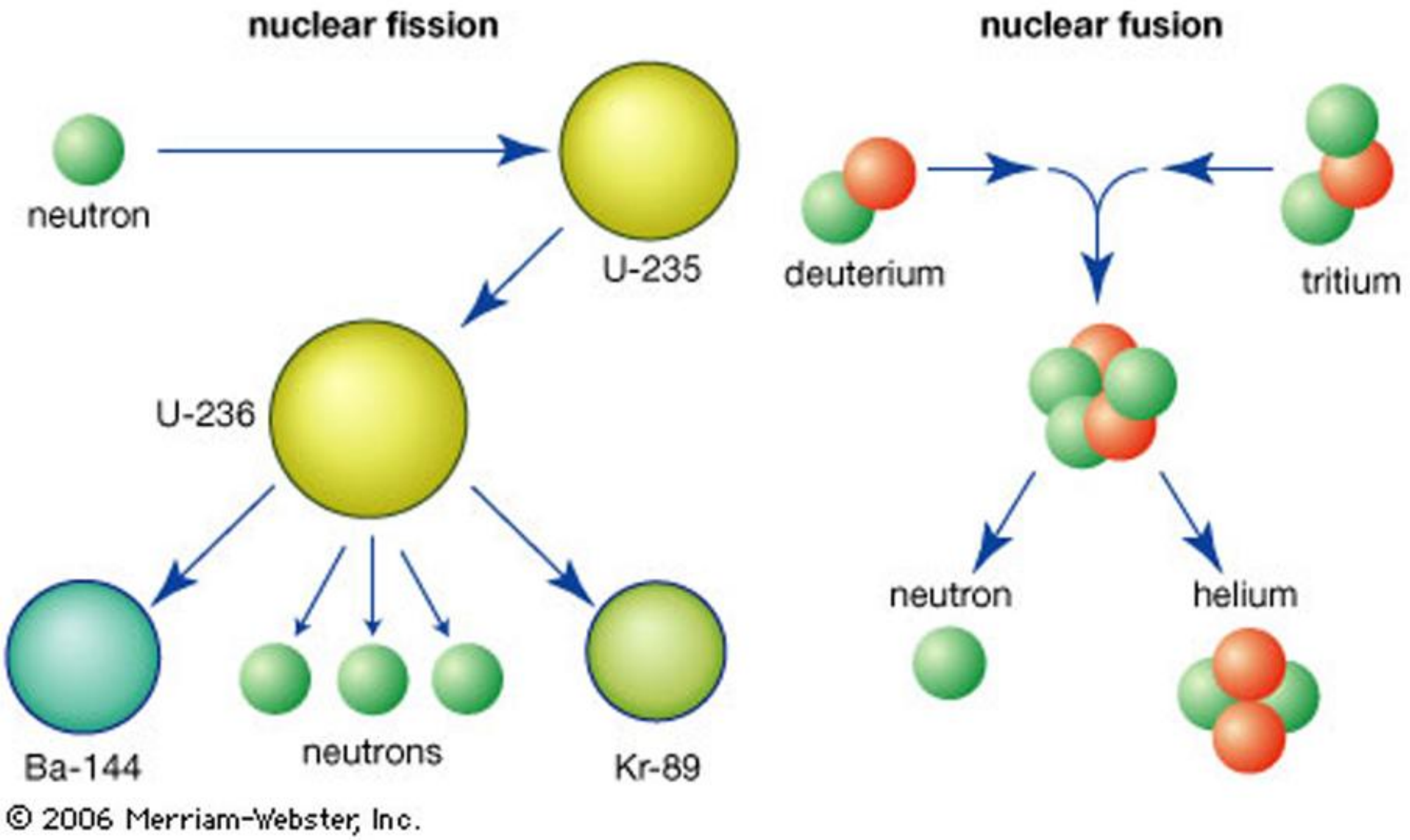
Using the semi-empirical binding energy formula,

$$E_b = (14.1\mathrm{MeV})(64) - (13.0\mathrm{MeV})(64)^{2/3} - \frac{(0.595\mathrm{MeV})(30)(29)}{(64)^{1/3}} - \frac{(19.0\mathrm{MeV})(16)}{64} + \frac{33.5\mathrm{MeV}}{(64)^{3/4}} = 561.7\mathrm{MeV}$$

Neutron – Nuclear Interactions



Nuclear Fission and Nuclear Fusion



- **Nuclear Fission** is the splitting of heavy nuclei to produce lighter ones, e.g.

$$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U$$
$$\rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr$$
$$+ \text{ neutrons, gamma} - \text{rays}, \ldots$$

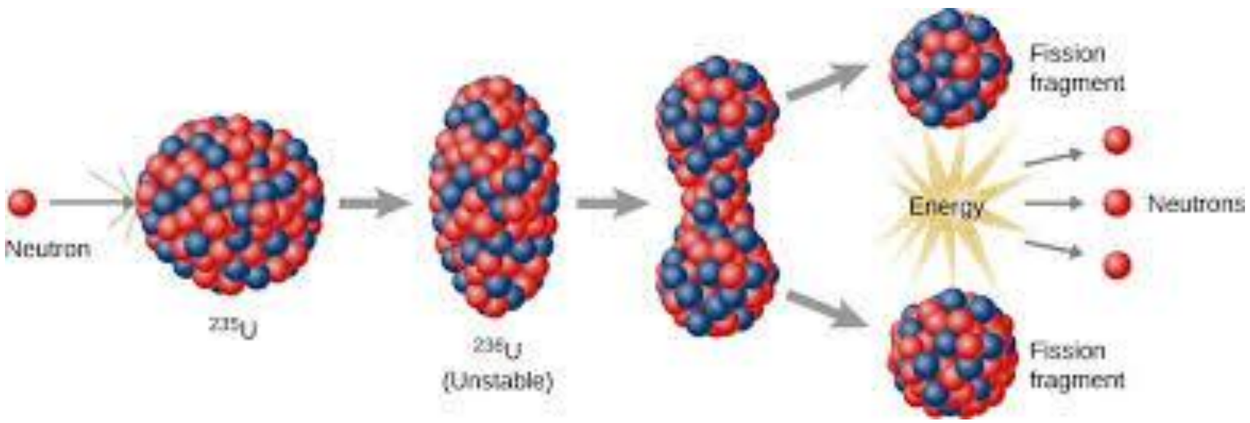
- **Nuclear Fusion** is the joining of lighter nuclei to form heavy ones, e.g.

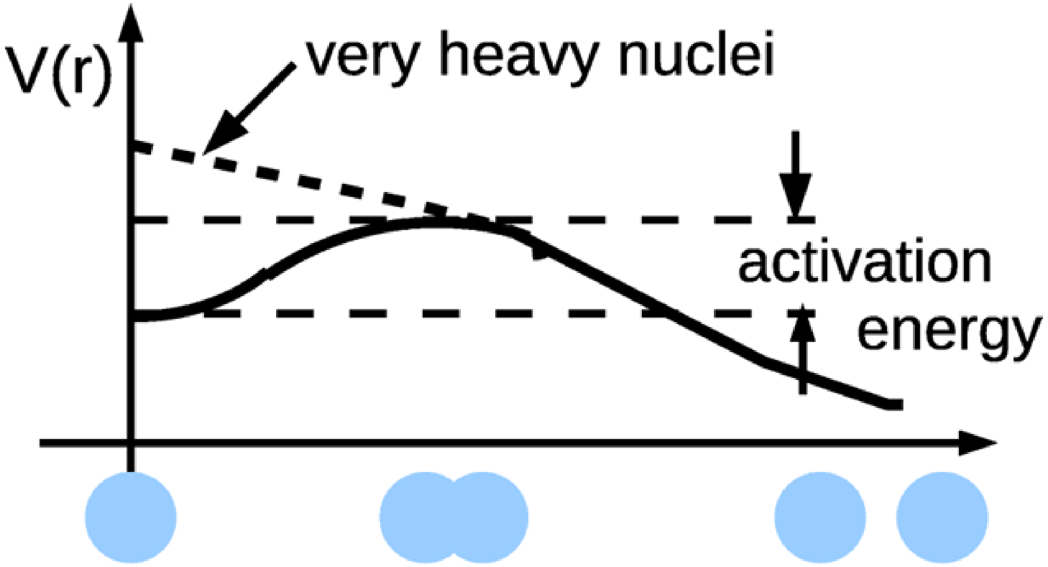
$${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{4}_{2}He + 23\text{MeV}$$

- Main process of energy production in the sun

Induced Fission

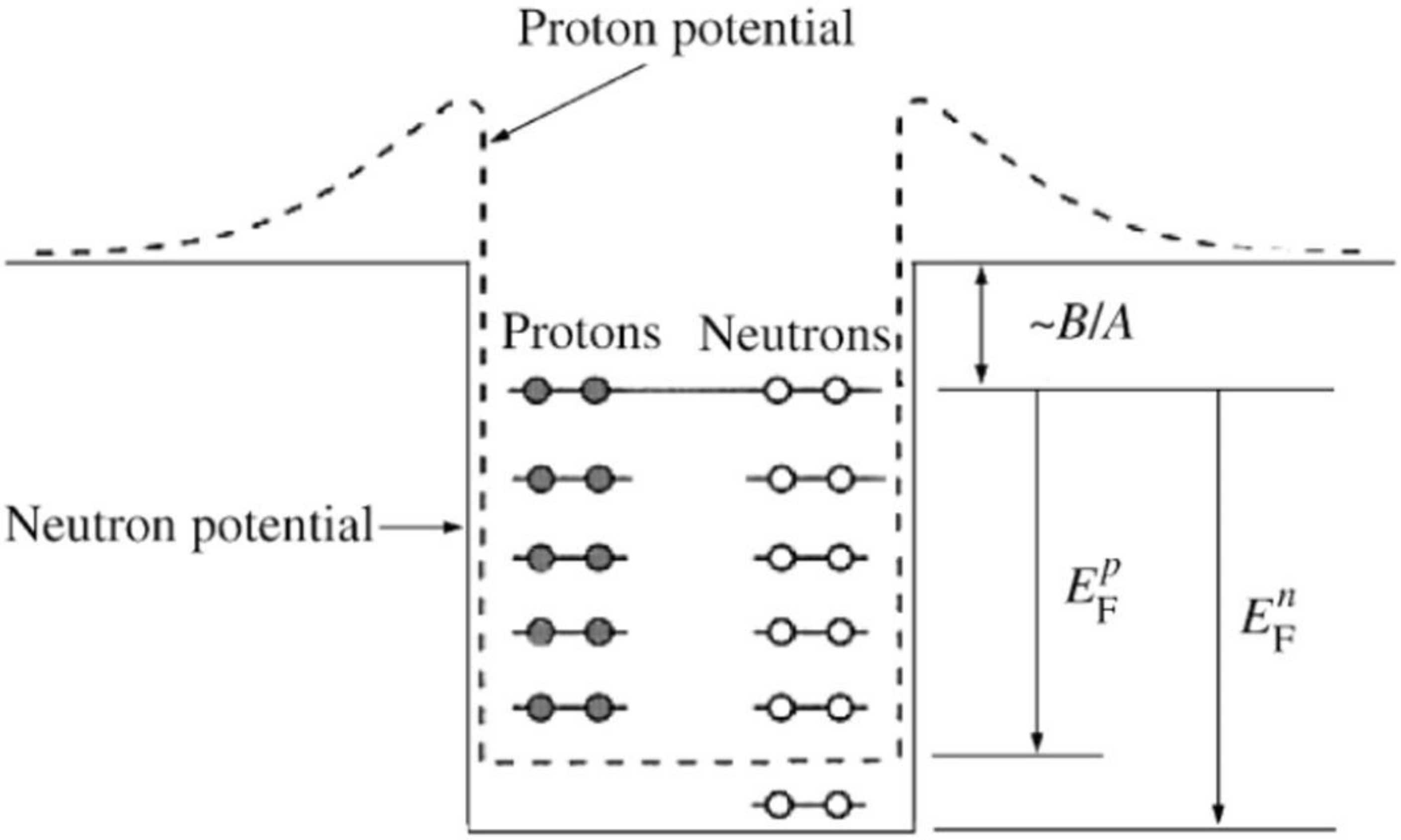
Induced fission: In order to induce fission in nuclei, some energy called *activation energy* must be provided to excite the parent nucleus above the fission barrier and split up into smaller nuclei. Figure 4.11 illustrates the process of induced fission using the liquid drop model. Neutrons are commonly used to induce fission.





The Fermi Gas Model of the Nucleus

Fermi Gas Model: the protons and neutrons that make up the nucleus are assumed to comprise two independent systems of nucleons, each freely moving inside the nuclear volume subject to the constraints of the Pauli principle.



Fermi energy:

$$E_F = \frac{P_F^2}{2M} \approx 33\text{MeV}$$

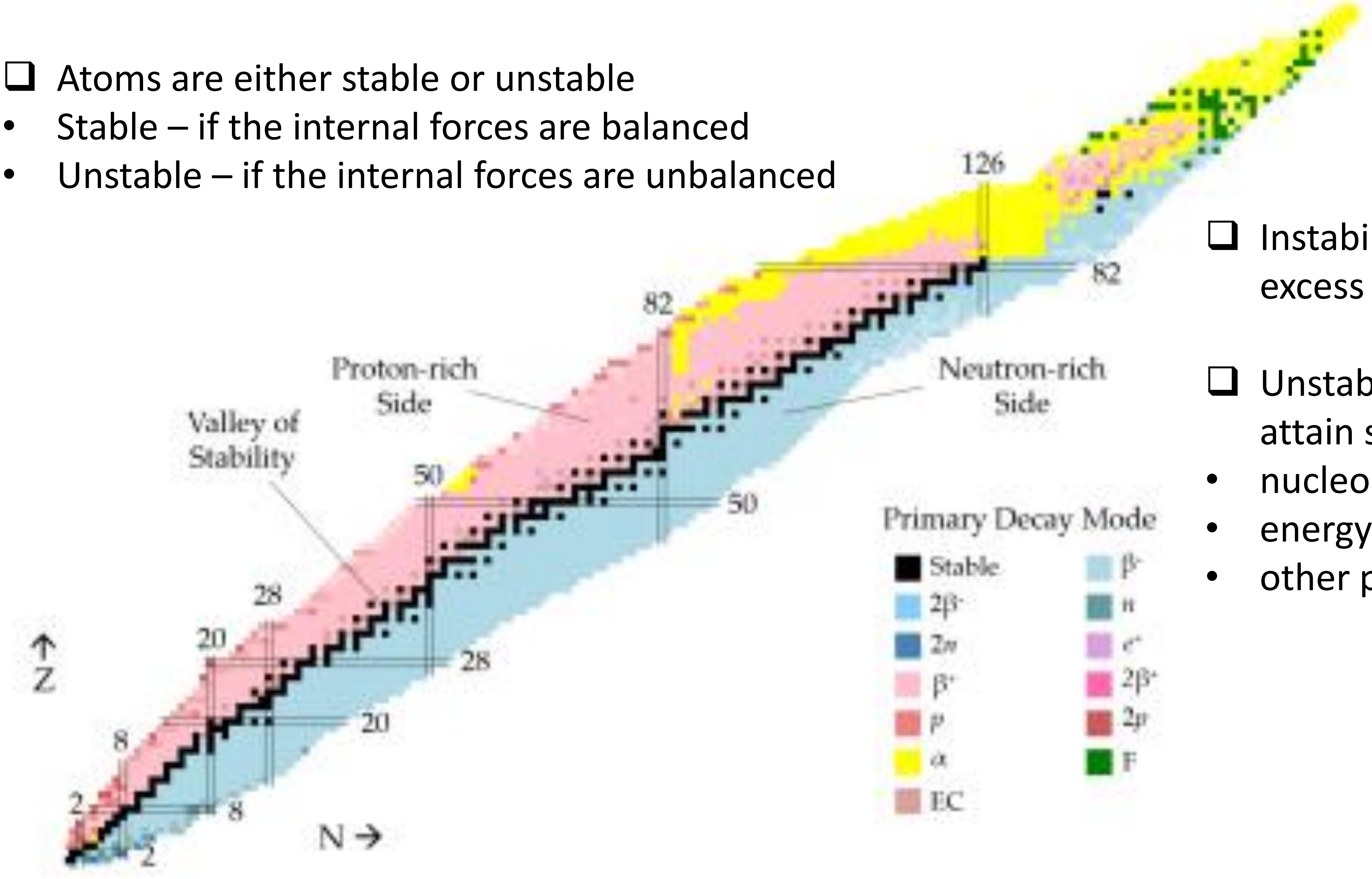
Potential depth:

$$V_o = E_F + \overrightarrow{B} \approx 40\text{MeV}$$

The potential felt by every nucleon is the superposition of the potentials due to all the other nucleons

Stability of atomic nuclei

- Atoms are either stable or unstable
- Stable – if the internal forces are balanced
- Unstable – if the internal forces are unbalanced



- Instability may be caused by excess of neutrons or protons

- Unstable (radioactive) atoms attain stability by ejecting:
- nucleons (protons, neutrons)
- energy (gamma-ray photons)
- other particles

Common modes of radioactive decay

Mode	Equation	Example	Changes in A,Z
alpha	${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$	${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$	A decreases by 4 Z decreases by 2
beta -	${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e$	${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-}$	A remains unchanged Z increased by 1
beta +	${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu_e$	${}^{64}_{29}Cu \rightarrow {}^{64}_{28}Ni + e^{+}$	A remains unchanged Z decreases by 1
e – capture	${}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \nu_e$	${}^{64}_{29}Cu + e^{-} \rightarrow {}^{64}_{28}Ni$	A remains unchanged Z decreases by 1
gamma	${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}Y + \gamma$	${}^{87}_{38}Sr^{*} \rightarrow {}^{87}_{38}Sr + \gamma$	A remains unchanged Z remains unchanged

Radioactive decay and radioactivity

- Radioactive decay is a random event.
- The rate of radioactive decay is directly proportional to the amount of radioactive substance

$$-\frac{dN}{dt} \propto N \quad \text{or} \quad -\frac{dN}{N} = \lambda dt$$

where λ is the decay constant.

- The amount of radioactive nuclei is given by:

$$N(t) = N_0\, e^{-\lambda t}$$

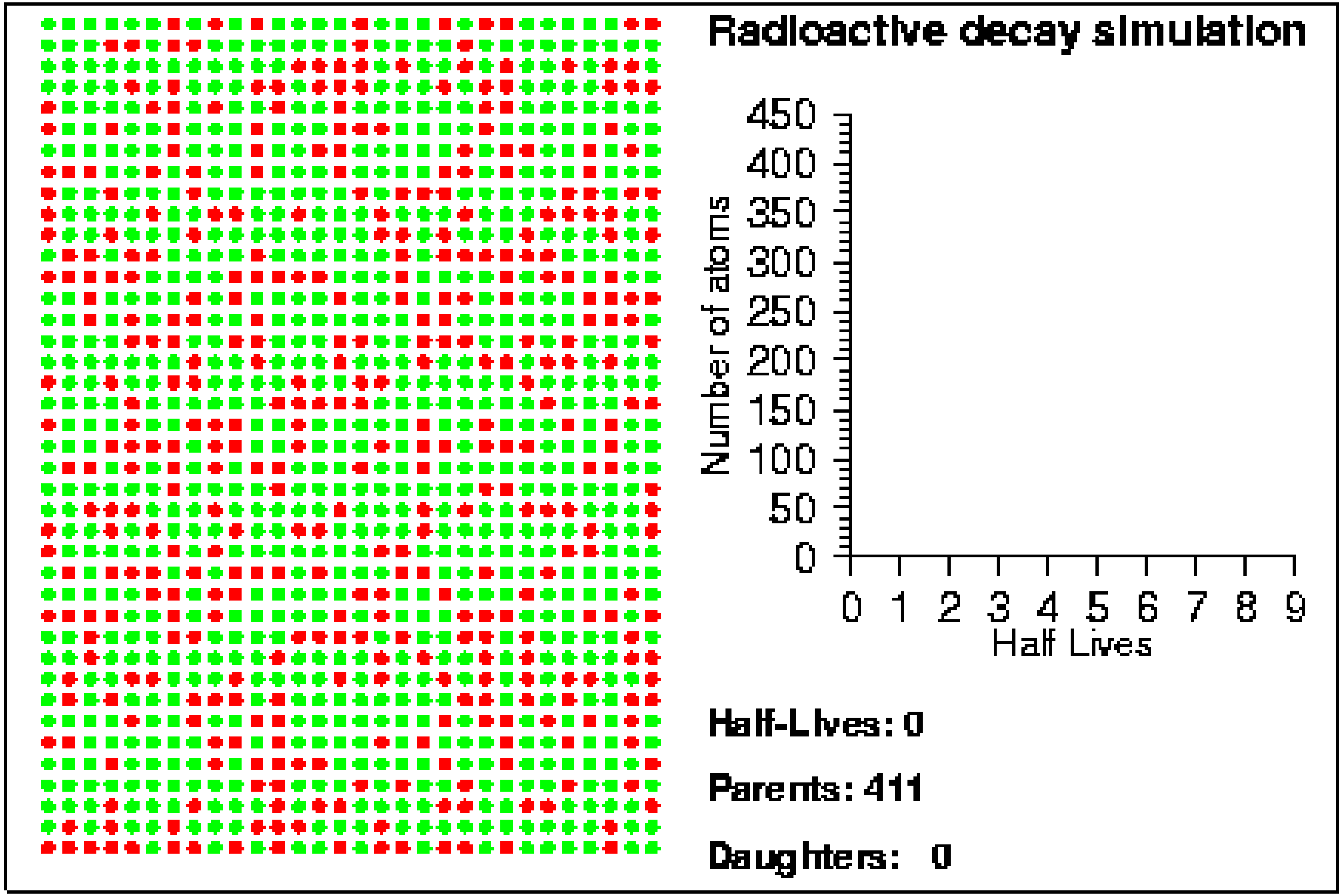
Radioactive decay depends only on time

- The activity of a radioactive substance is given by:

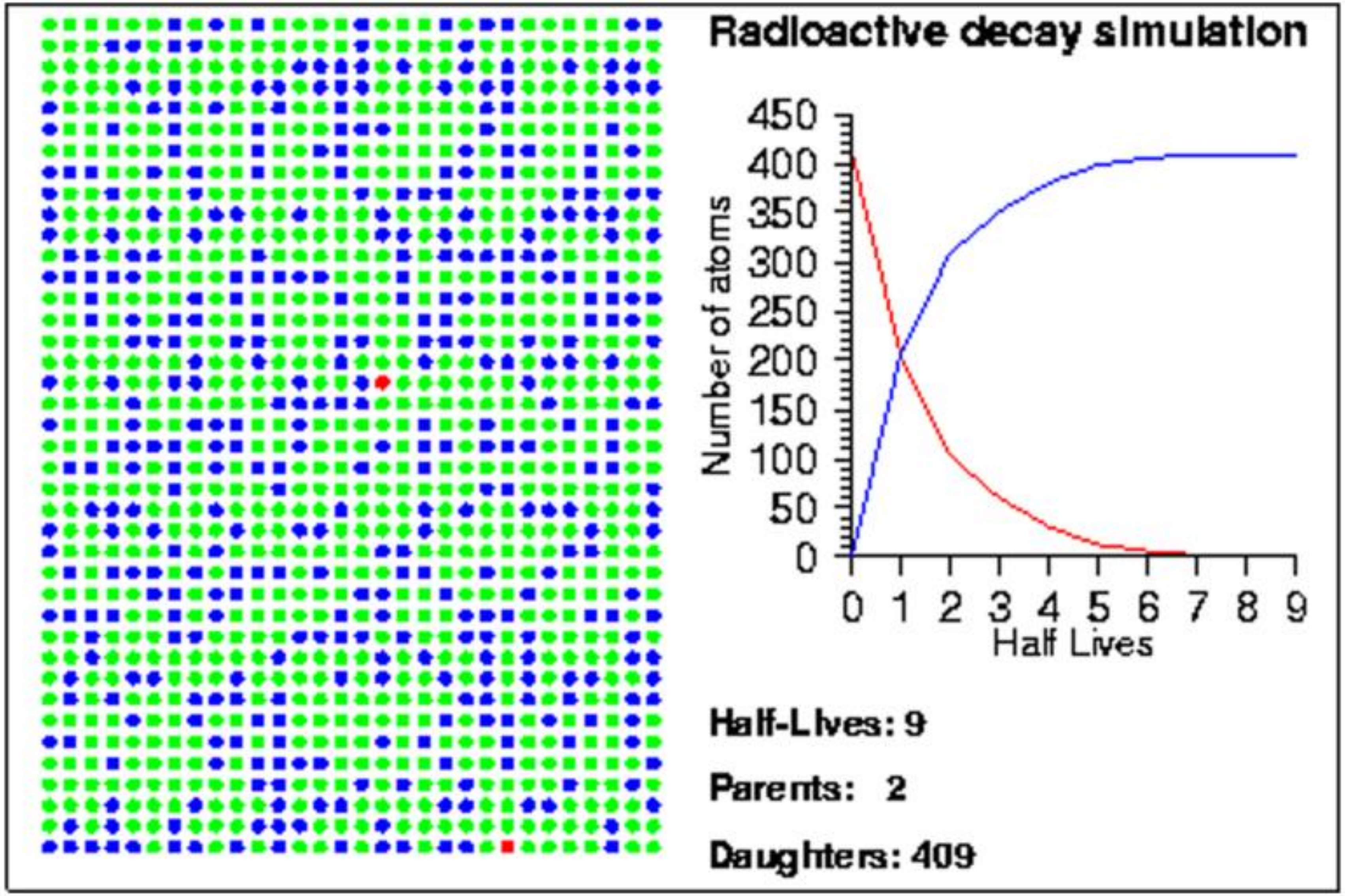
$$A = -\frac{dN}{dt} = \lambda N$$

$$1\,\text{Curie} = 1\,\text{Ci} = 3.7 \times 10^{10}\,\text{decays/s} = 3.7 \times 10^{10}\,\text{Bq}$$

Growth of daughter in radioactive decay



Growth of daughter in radioactive decay



Half-life of a radioactive substance

- Half – life $T_{1/2}$ is the time it takes for the amount of a radioactive substance to reduce by half of it's initial value.
- At $t = T_{1/2}$ we have $A = A_0/2$

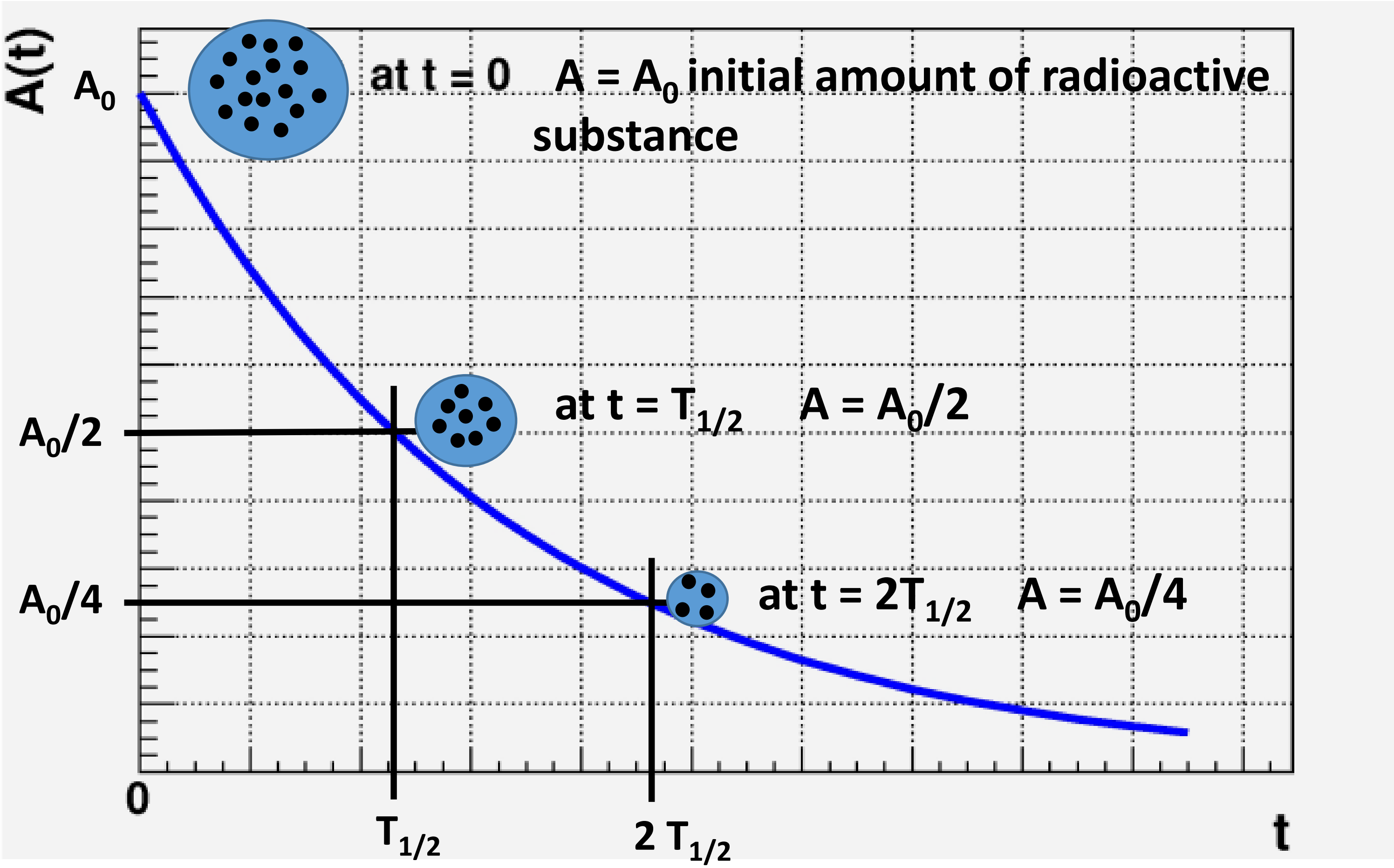
so that:

$$\frac{A_0}{2} = A_0 \exp(-\lambda T_{1/2})$$

which gives the following expression for the half life:

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

- The decay constant λ determines the rate of decrease of the radioactive substance.



Radioactivity

Example 4: Calculate the activity of 1mg of radon, ^{222}Rn, whose atomic mass is 222u. Calculate the activity of the radon sample at one week later.

Radon gas has a half-life of 3.8 days, hence the decay constant is,

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{(3.8\text{d})(86400\text{s/d})} = 2.11 \times 10^{-6}\text{s}$$

The number of atoms in 1mg of ^{222}Rn is,

$$N = \frac{1.00 \times 10^{-6}\text{kg}}{(222\text{u})(1.66 \times 10^{-27}\text{kg/u})} = 2.71 \times 10^{18}\text{atoms}$$

Hence the activity of the sample is,

$$A = \lambda N = (2.11 \times 10^{-6}\text{s})(2.71 \times 10^{18}\text{nuclei}) = 5.72 \times 10^{12}\ \text{decays/s}$$

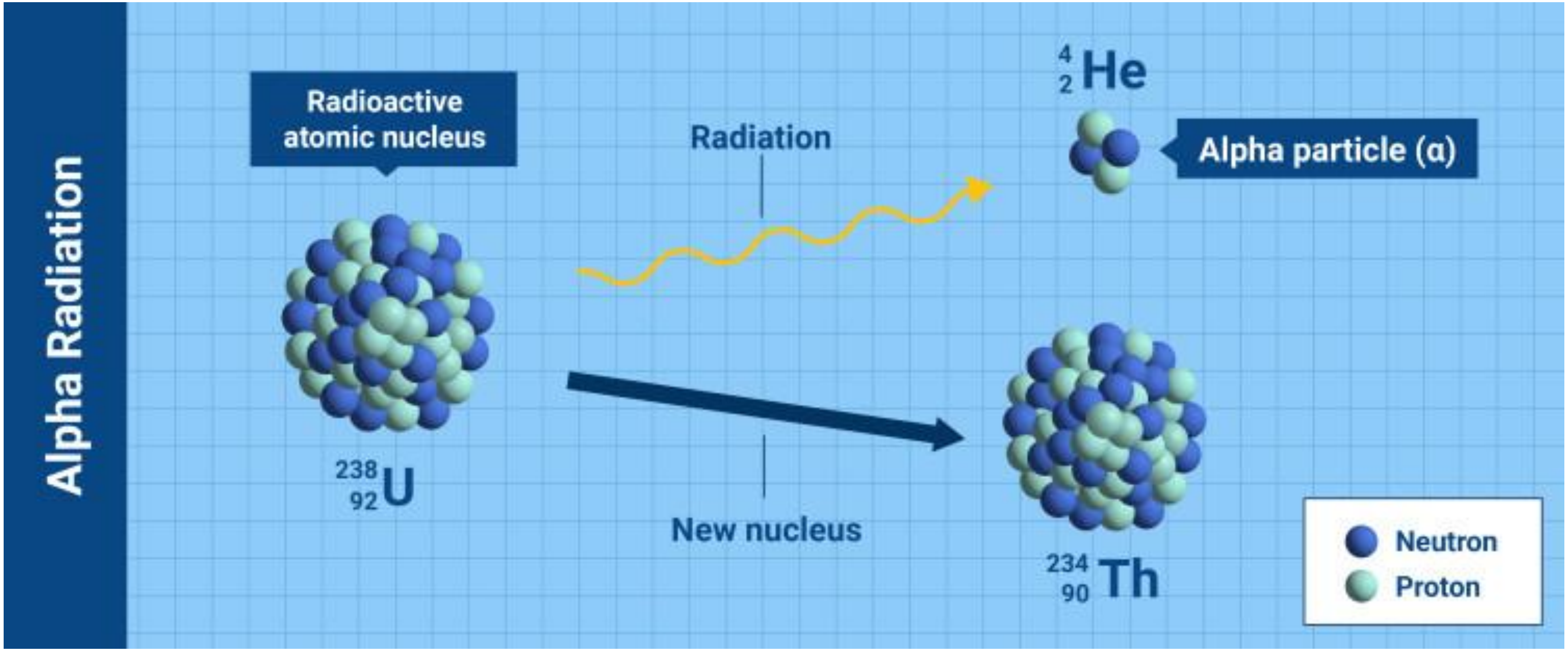
$$= 155\text{Ci}$$

Alpha radiation

- The decaying nuclei release heavy, positively charged alpha particles in order to attain stability
- Alpha radiation:
  - can easily be stopped by piece of paper
  - cannot penetrate our skin
  - can cause damage to internal organs if ingested

Examples:
uranium – 238 found in rocks
americium – 241 used in smoke detectors

Alpha radiation



https://www.iaea.org/newscenter/news/what-is-radiation

Alpha decay of uranium - 238

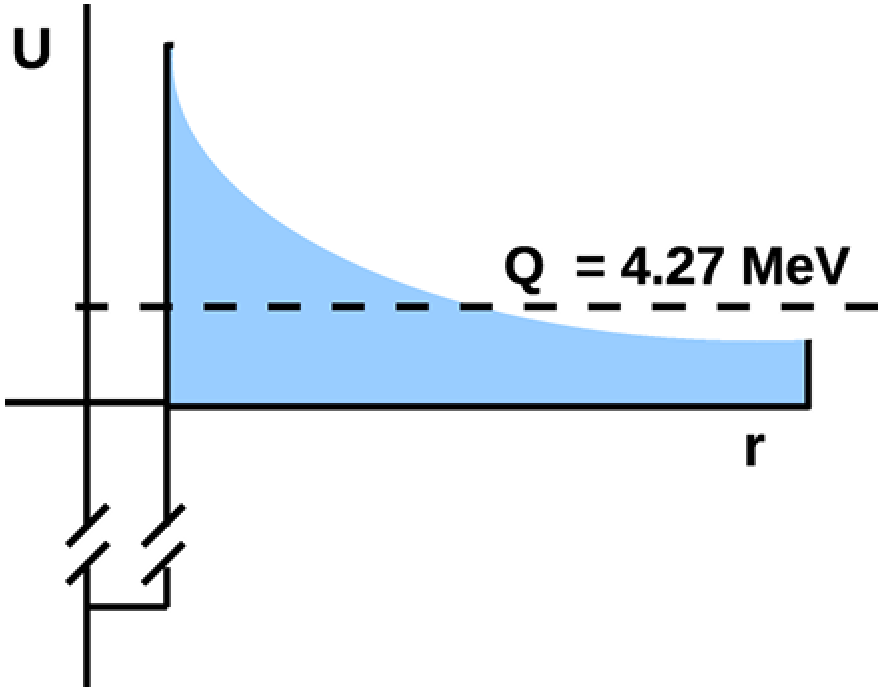


Illustration of the deep potential well for alpha particles in nuclei

decay equation: $^{238}_{92}\mathrm{U} \rightarrow ^{234}_{90}\mathrm{Th} + ^{4}_{2}\mathrm{He}$

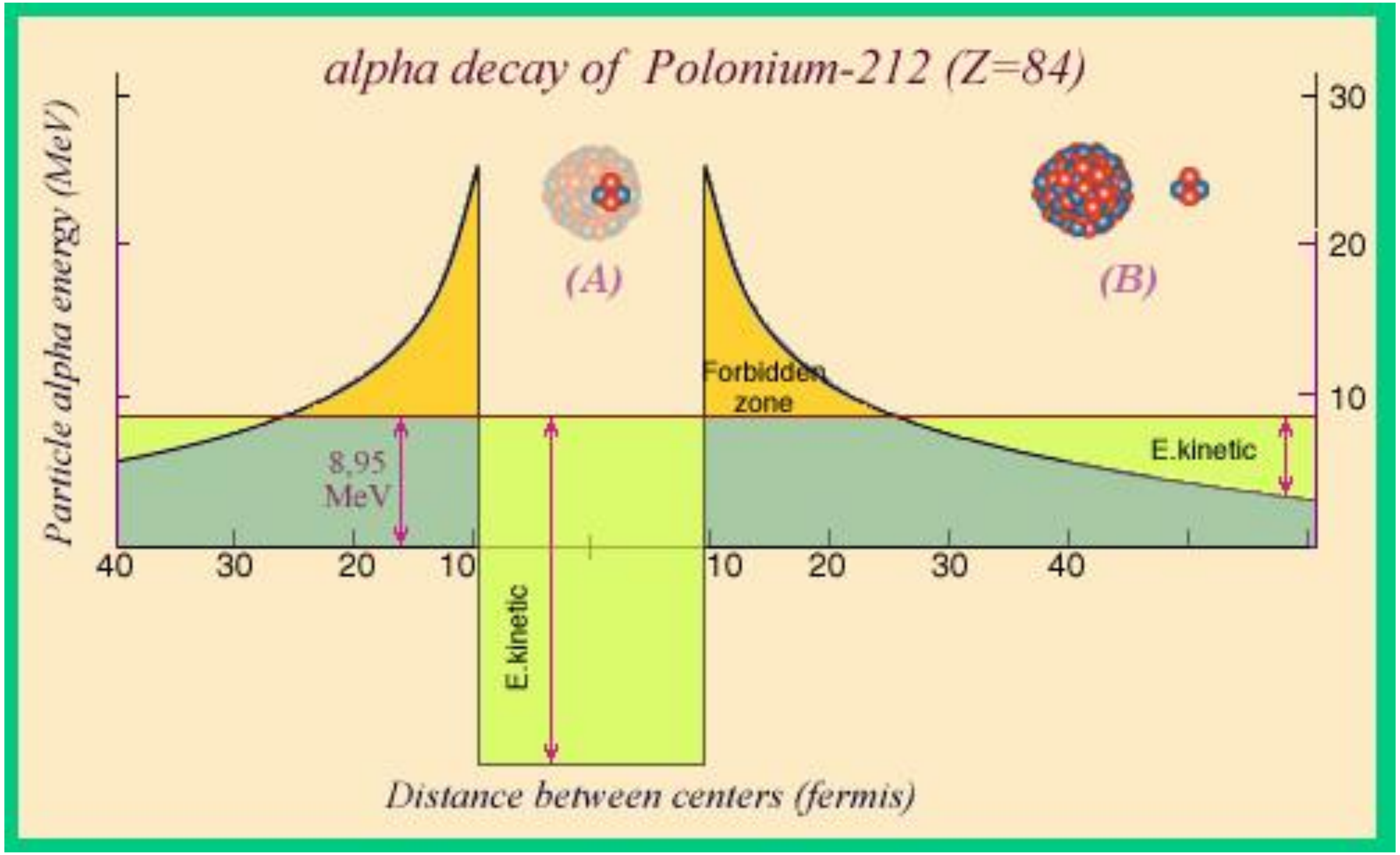
disintegration energy:

$$Q_\alpha = \Delta mc^2 = (0.004589\mathrm{u})(931.5\mathrm{MeV/u}) = 4.27\mathrm{MeV}.$$

Classically: the alpha particles would never be able to overcome the deep potential well

Quantum mechanically: the alpha particles tunnel through the potential well and are released from the parent nuclei

Alpha decay of polonium – 212

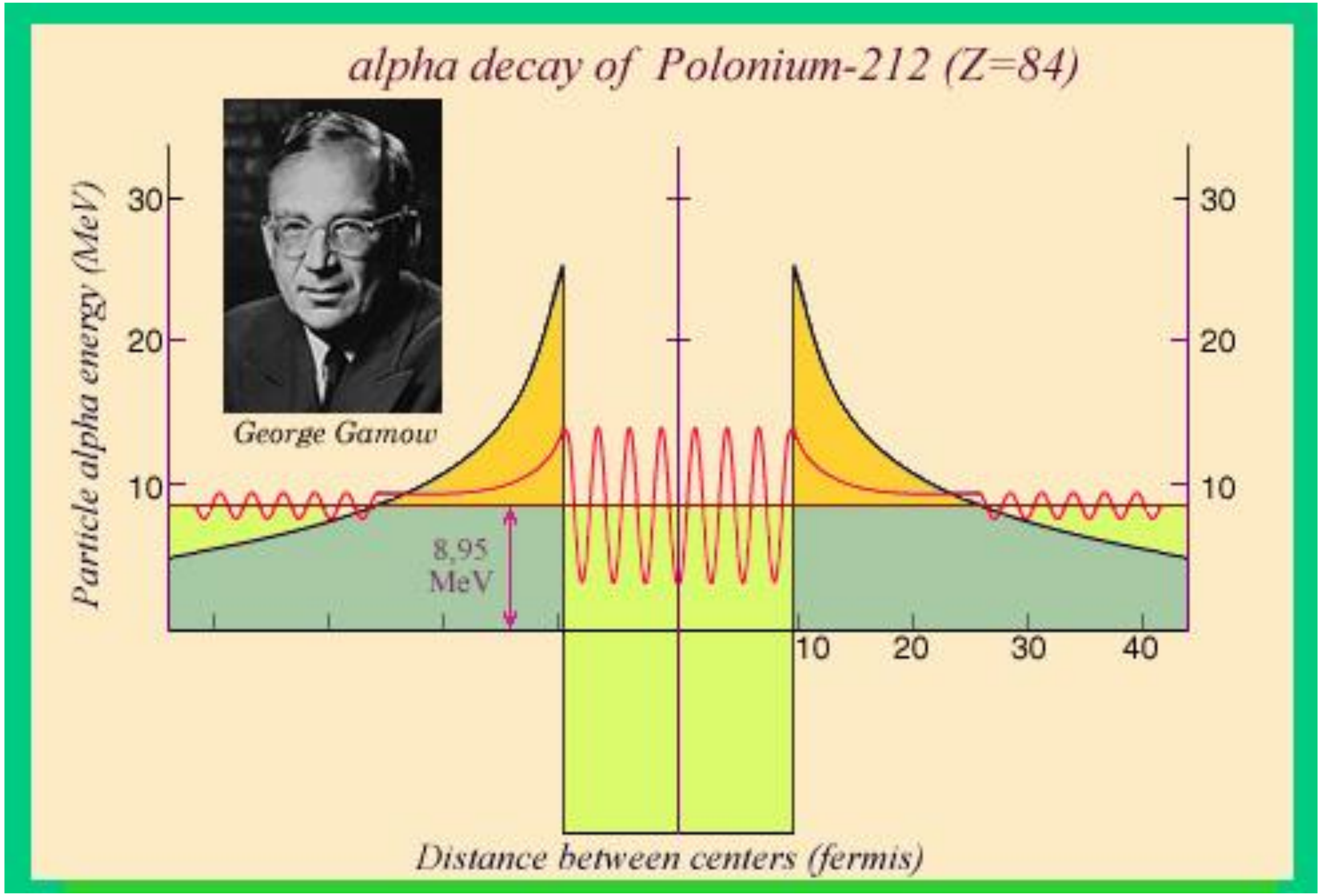


https://radioactivity.eu.com/articles/phenomenon/tunnel_effect

Energy released = 8.95 MeV

Classically:
it would be impossible for the alpha particles trapped at the bottom of the well to escape the potential barrier

Alpha decay of polonium – 212



https://radioactivity.eu.com/articles/phenomenon/tunnel_effect

Energy released = 8.95 MeV

Quantum mechanically: the alpha particle is represented by a superposition of wave. There is a probability for emission of the alpha particle.

Q-value of a decay process

Consider the general decay process:

$$X \dashrightarrow Y + x$$

Q- value of a decay process is given by the difference in mass between the parent (X) and the daughter with the emitted particle (Y + x)

$$Q = [m_X - (m_Y + m_x)]c^2$$

If the Q-value is positive then the decay takes place spontaneously

If the Q-value is negative then the decay must be induced

Alpha-decay of polonium - 212

The decay equation is as follows:

$$^{212}Po \text{ -----}\rightarrow {}^{208}Pb + {}^{4}He$$

Q- value of this decay process is given by the difference in mass between the parent (^{212}Po) and the daughter with the emitted particle (^{208}Pb + ^{4}He)

$$Q = [m_{Po} - (m_{Pb} + m_{He})]c^2 = [211.9889 - (207.9767 + 4.002603)](931.5)$$

$$= 8.94 \text{ MeV}$$

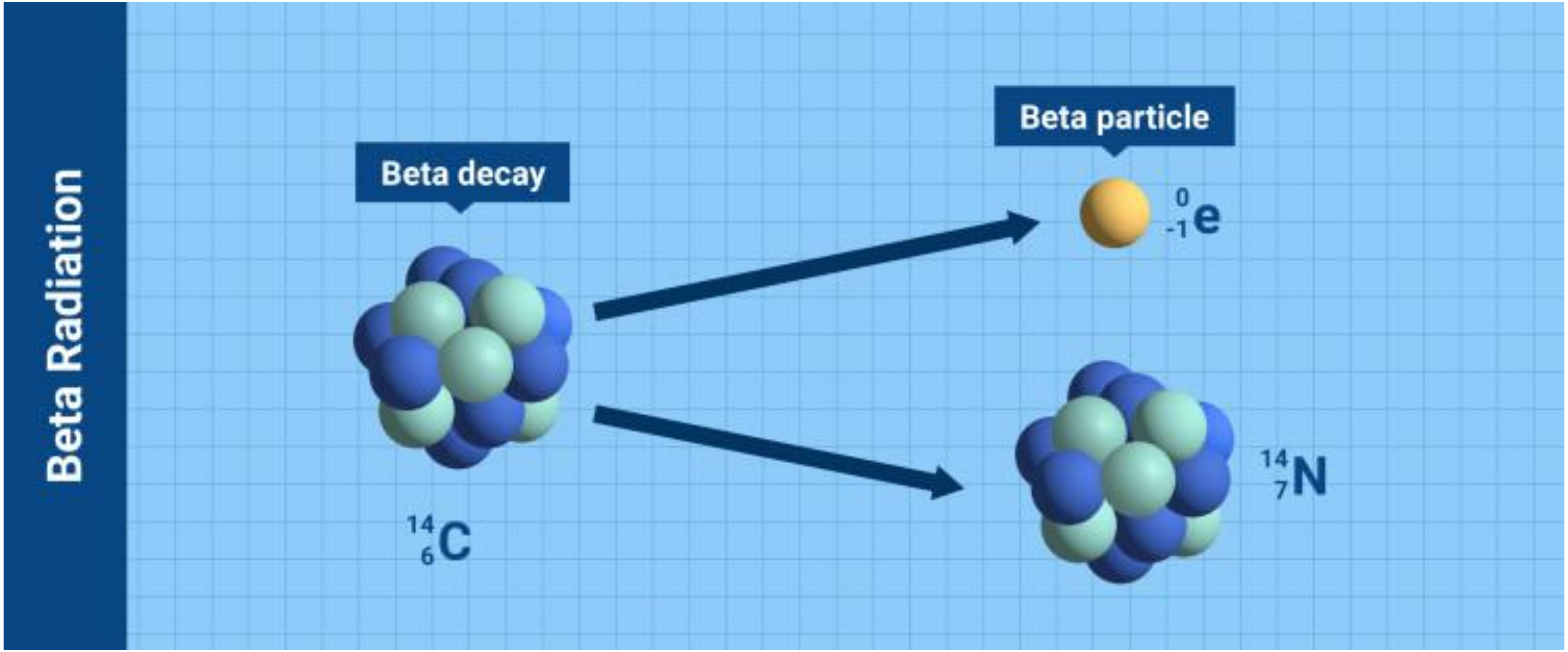
The Q-value is positive, the decay takes place spontaneously

Beta radiation

- The decaying nuclei release smaller particles (electrons or positrons) in order to attain stability
- Beta radiation:
  - is more penetrating than alpha radiation
  - can pass through 1 – 2 cm of water depending on energy
  - can be stopped by a few mm of aliuminium

Examples:
hydrogen - 3 (tritium) – used in emergency lights
carbon – 14 – used to determine age of objects

Beta radiation



https://www.iaea.org/newscenter/news/what-is-radiation

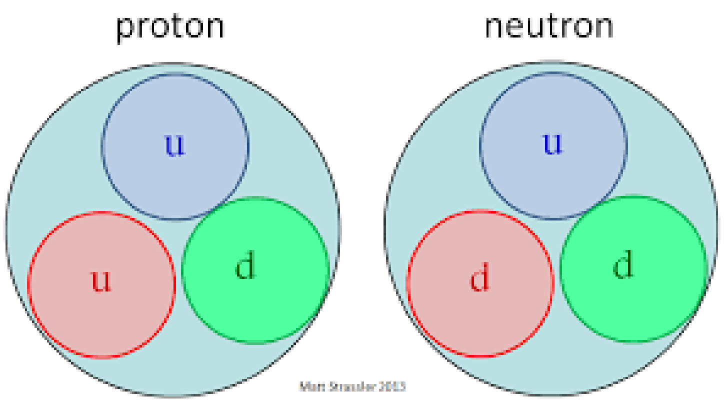
Decay of protons and neutrons

The decay equations are as follows:

$$n \longrightarrow p + e^- + \bar{\nu}_e \qquad (\beta^- \text{ decay})$$

$$p \longrightarrow n + e^+ + \nu_e \qquad (\beta^+ \text{ decay})$$

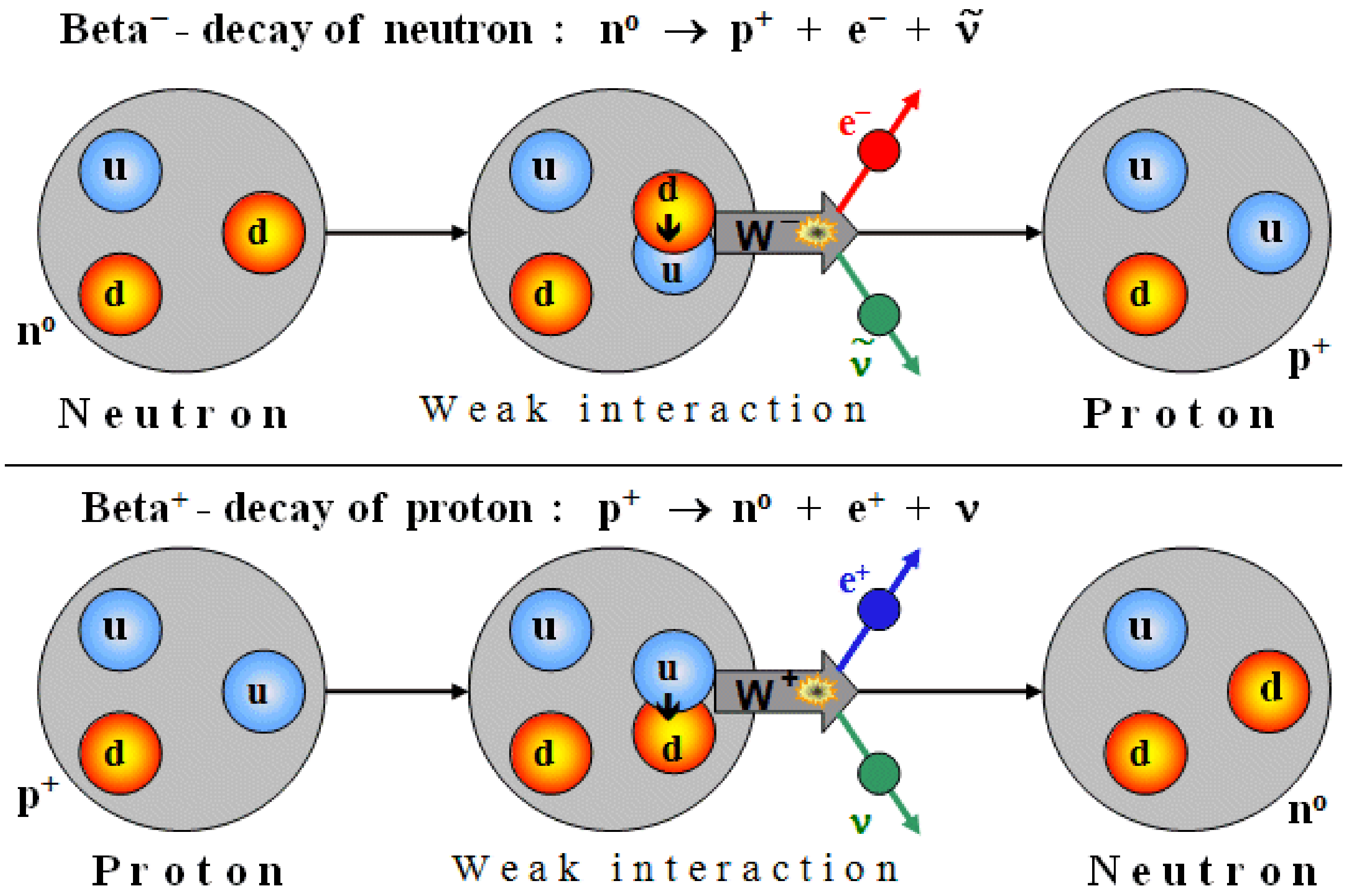
These decays are well understood by taking into account the quark content of the protons and neutrons as follows:



The decay of protons into neutrons and vice versa involves the transformation of the quarks in them. The up-quark and down-quark are transformed via weak interaction process with the emission of W-bosons.

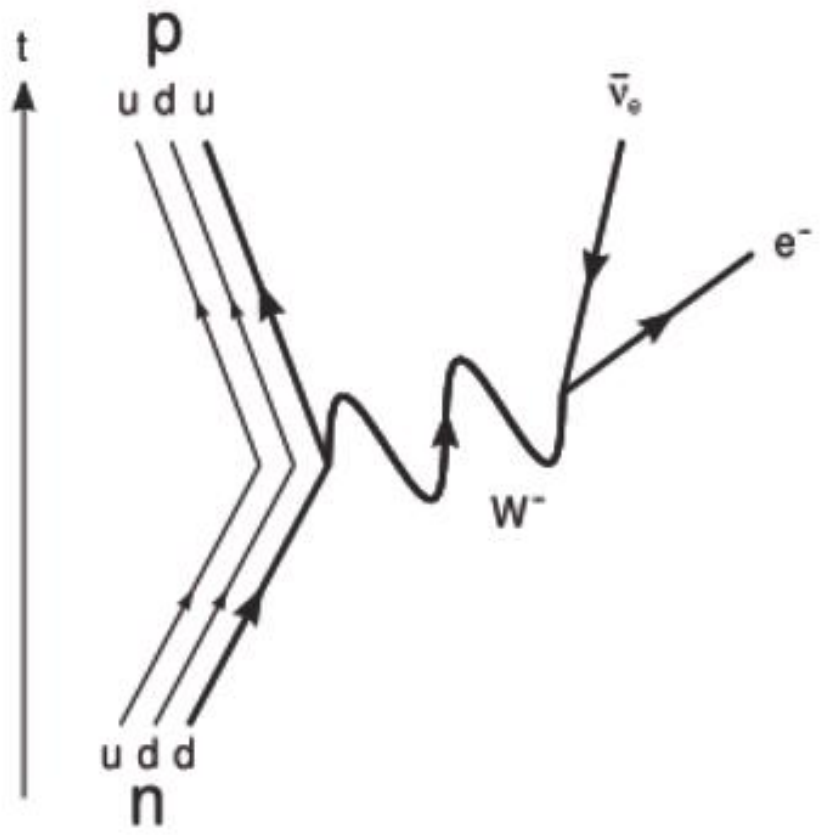
Decay of protons and neutrons

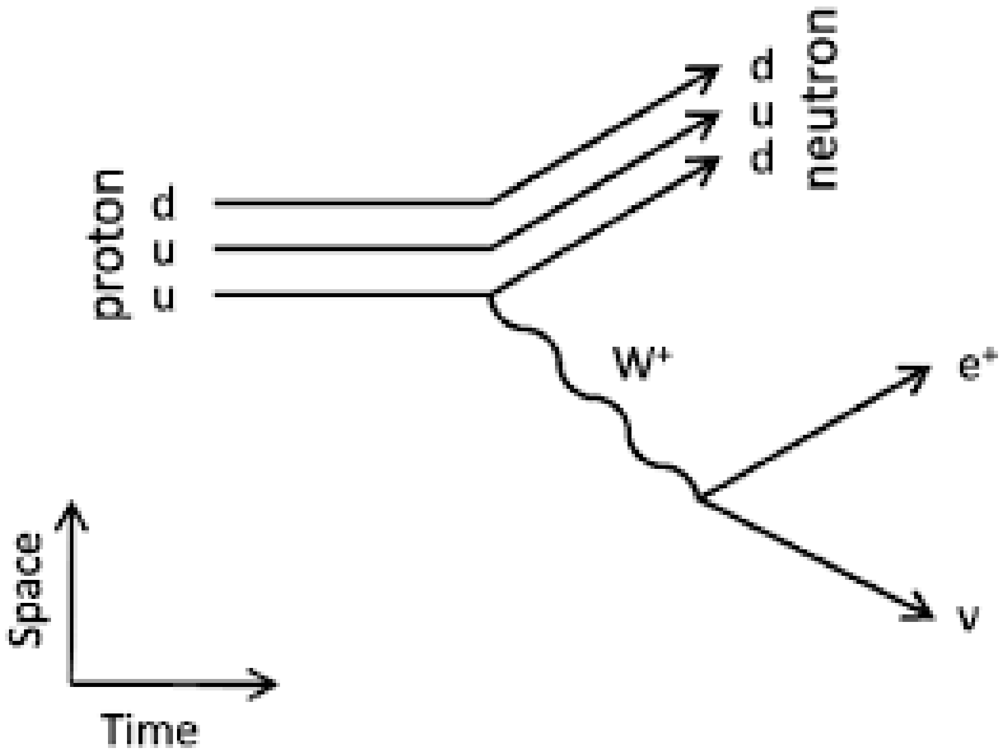
The decays involve transformation of quarks as follows:

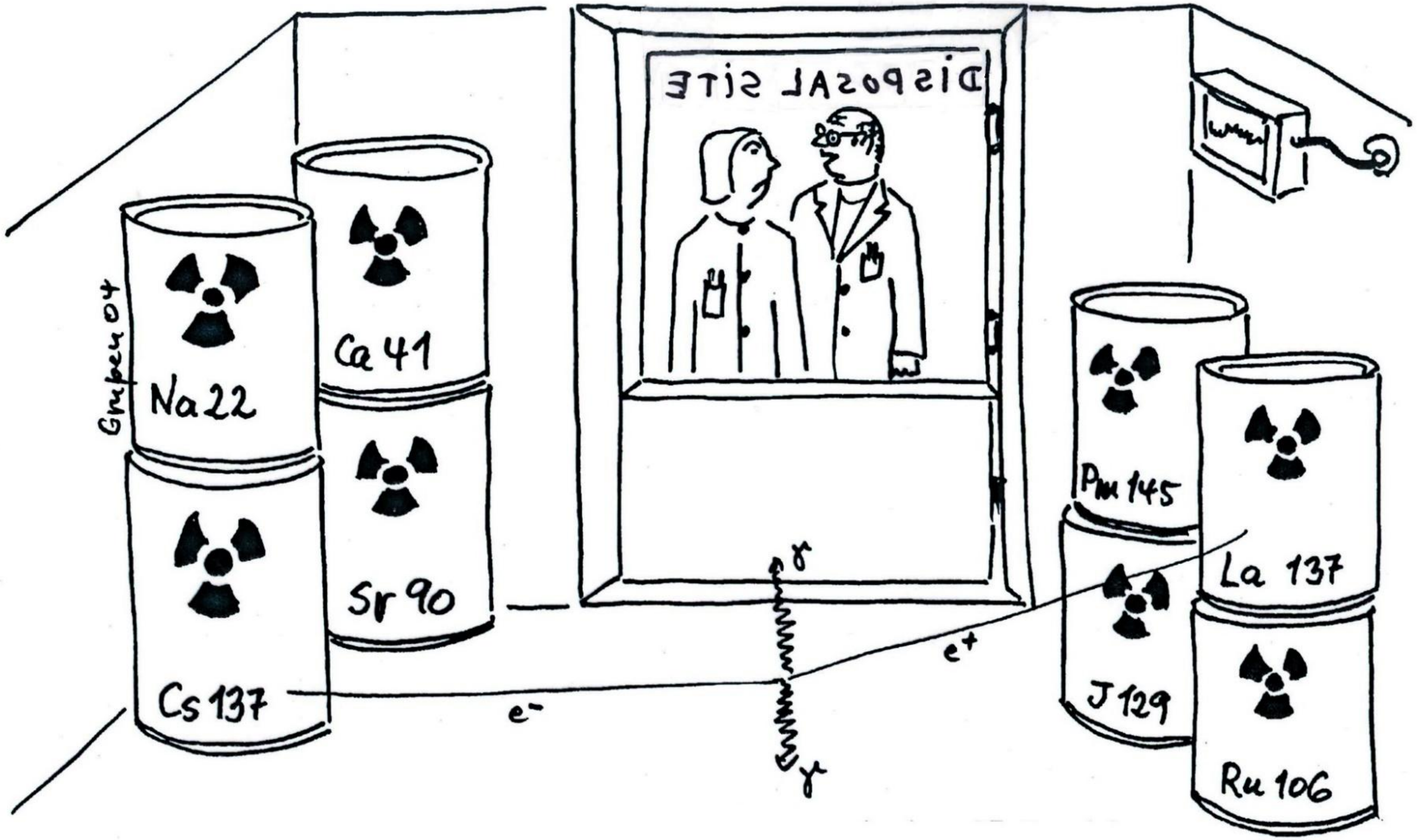


Decay of protons and neutrons

The decays involve transformation of quarks as follows:







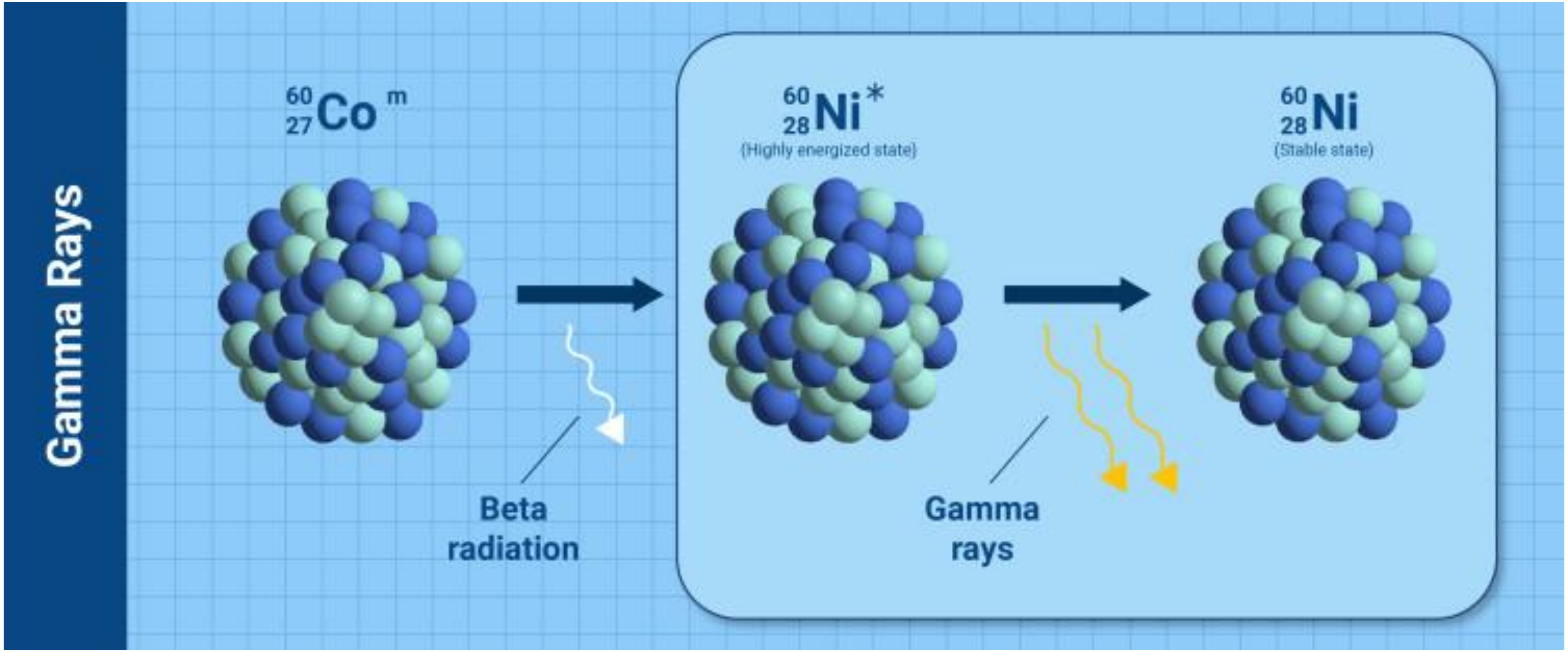
"We store the beta+ emitters together with the beta- emitters so that they can annihilate each other!"

Gamma radiation

- The decaying nuclei release gamma radiation in order to attain stability
- gamma radiation:
  - is electromagnetic radiation similar to X-rays
  - is more penetrating than alpha and beta radiation
  - can cause damage in the body
  - is attenuated by suitable materials like concrete, lead

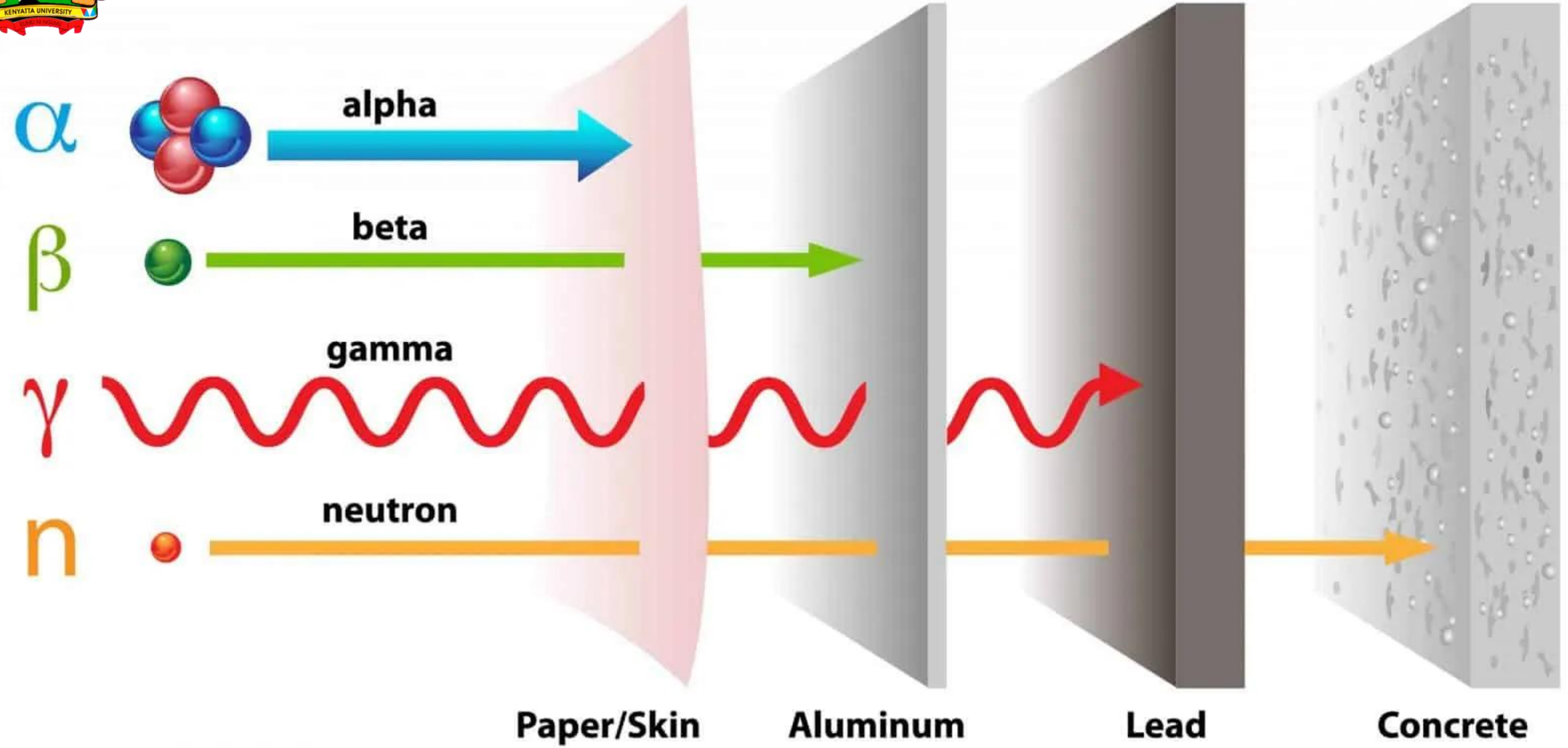
Examples:
cobalt – 60 – used in treatment of tumours
cesium -137

Gamma radiation



https://www.iaea.org/newscenter/news/what-is-radiation

Nuclear radiation



Source: SARWEB

Q – value in nuclear reaction

The Q-value of a nuclear reaction: Consider the general form of a nuclear reaction,

$$A + B \rightarrow C + D\,.$$

The Q-value of the nuclear reaction is defined as the difference between the rest energies of A and B and the rest energie of C and D,

$$Q = (m_A + m_B - m_C - m_D)\mathrm{c}^2$$

If Q is a positive quantity, energy is given off by the reaction. If Q is a negative quantity, enough kinetic energy in the center-of-mass system KE_{cm} must be provided by the reacting particles so that $KE_{cm} + Q \geq 0$. The kinetic energy in the center-of-mass system is given by,

$$\mathrm{KE_{cm}} = \left(\frac{\mathrm{m_B}}{\mathrm{m_A} + \mathrm{m_B}}\right)\mathrm{KE_{lab}}$$

where KE_{lab} is the kinetic energy in the laboratory system.

Q – value in nuclear reaction

Example 5: Consider the nuclear reaction $^{14}N(\alpha, p)^{17}O$. The minimum kinetic energy in the laboratory system needed by an alpha particle to cause the reaction is calculated by the Q-value using the individual masses as follows,

$$\text{mass of } ^{14}\text{N} \simeq 14.00307\text{u}, \qquad \text{mass of } ^{4}\text{He} \simeq 4.00260\text{u}$$

$$\text{mass of } ^{1}\text{H} \simeq 1.00783\text{u}, \qquad \text{mass of } ^{17}\text{O} \simeq 16.99913\text{u}$$

$$\text{Q} = (14.00307\text{u} + 4.00260\text{u} - 1.00783\text{u} - 16.99913\text{u})(931.5\ \text{MeV/u})$$

$$= -1.20\ \text{MeV}$$

The minimum kinetic energy KE_{cm} in the center-of-mass system must therefore be 1.20 MeV in order for the reaction to occur. In the laboratory system,

$$\text{KE}_{\text{lab}} = \left(\frac{14.00307 + 4.00260}{14.00307}\right)(1.20\ \text{MeV}) = 1.54\ \text{MeV}$$

Q-value in radioactive decay

Example 6: If the nuclide ^{238}U were to emit a proton, the decay process would be,

$$^{238}\mathrm{U} \rightarrow {}^{237}\mathrm{Pa} + {}^{1}\mathrm{H}$$

Given the following masses,

mass of $^{237}\mathrm{Pa} \simeq 237.051143\mathrm{u}$

mass of $^{1}\mathrm{H} \simeq 1.007825\mathrm{u}$

the total mass of decay products ^{237}Pa and $^{1}\mathrm{H} \simeq 238.058968\mathrm{u}$

the difference in mass between parent and decay products $\Delta m = -0.008183\mathrm{u}$

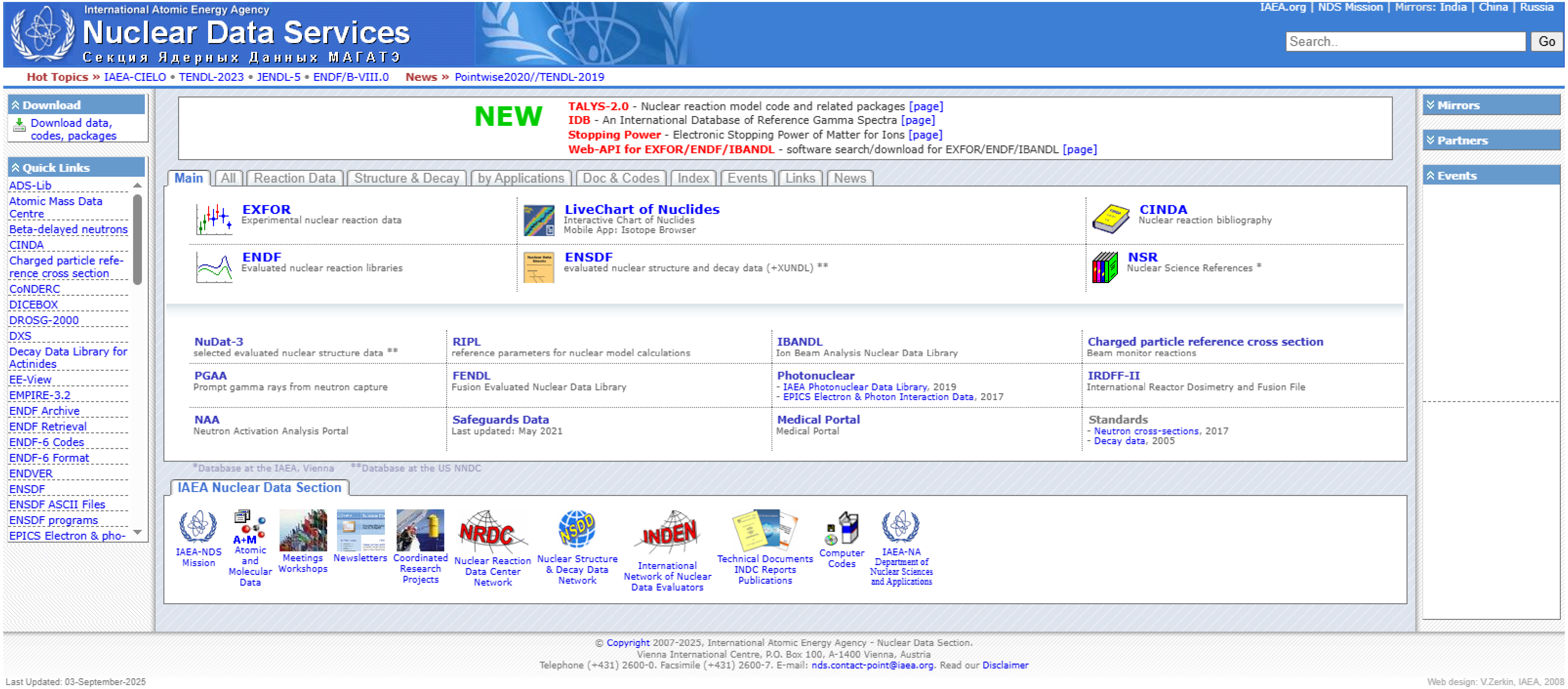
hence, $Q_p = \Delta mc^2 = (-0.008183\mathrm{u})(931.5\mathrm{MeV/u}) = -7.622\mathrm{MeV}$.

U-238 is stable against spontaneous emission of protons

Nuclear Data Services at the IAEA

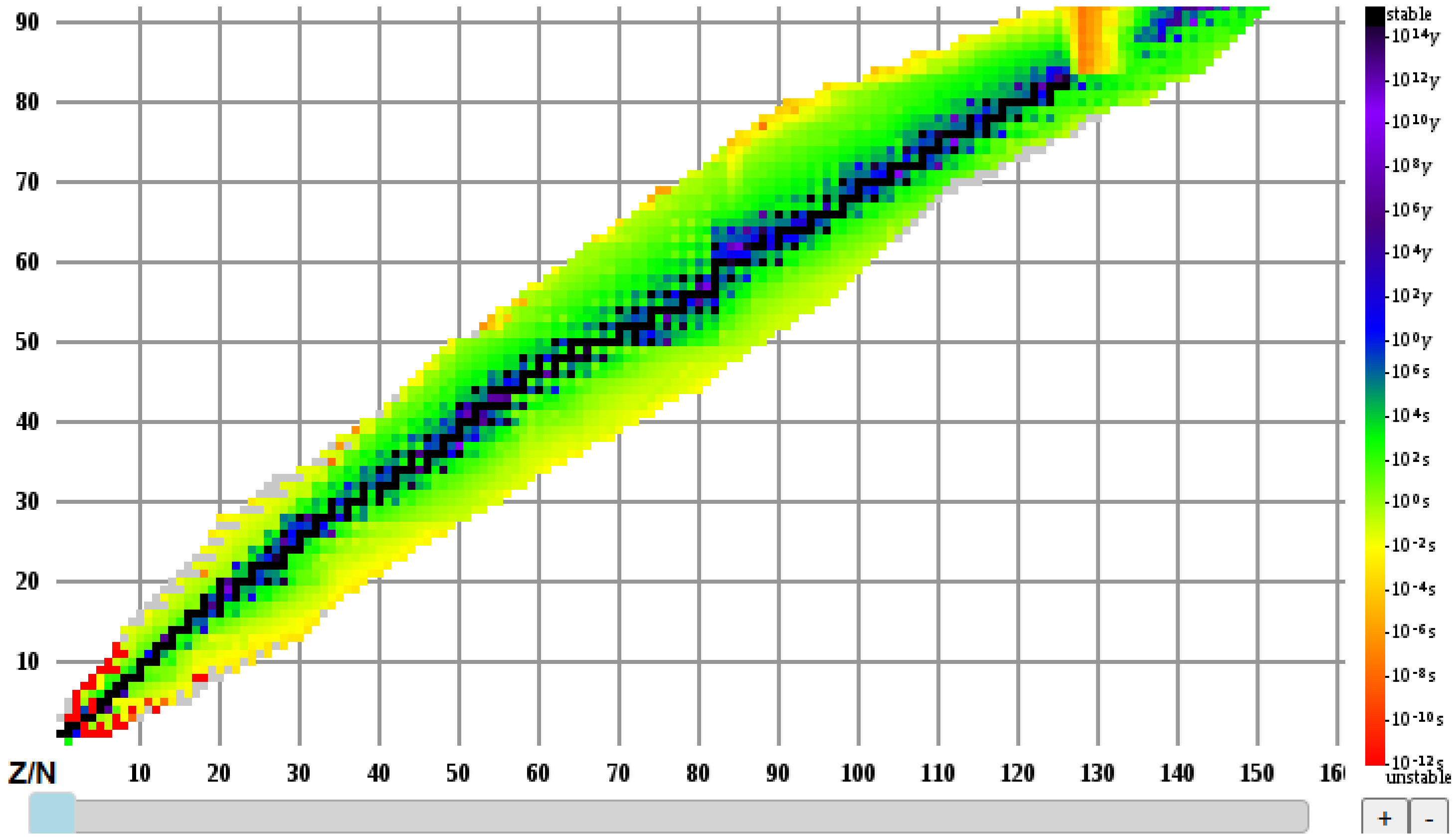
- EXFOR – Experimental nuclear reaction data
- ENDF – evaluated nuclear reaction libraries
- LiveChart of Nuclides
- ENSDF – Evaluated nuclear Structure and decay data
- CINDA – Nuclear reaction bibliography
- NSR – Nuclear Science Reference
- NuDat-3 – selected evaluated nuclear structure data
- PGAA – prompt gamma rays from neutron capture
- NAA – Neutron Activation Analysis Portal
- RIPL – Reference parameters for nuclear model calculations
- …

Nuclear Data Services at the IAEA



https://www-nds.iaea.org/

Nuclide chart at KAERI



Nuclide name | Find

Directions for Using Table of Nuclides

1. Locate the desired nuclide by dragging the chart or the horizontal slider.
2. Click the nuclide to see its nuclear property and list of evaluations.
3. On the list of evaluated nuclear data libraries, click the '+' sign to see the list of available reactions for the desired evaluation.
4. Click the reaction name to see the plot. To compare the two or more plots, click the 'Add to XSViewer' button for the desired plots and then click the 'Open XSViewer' button.

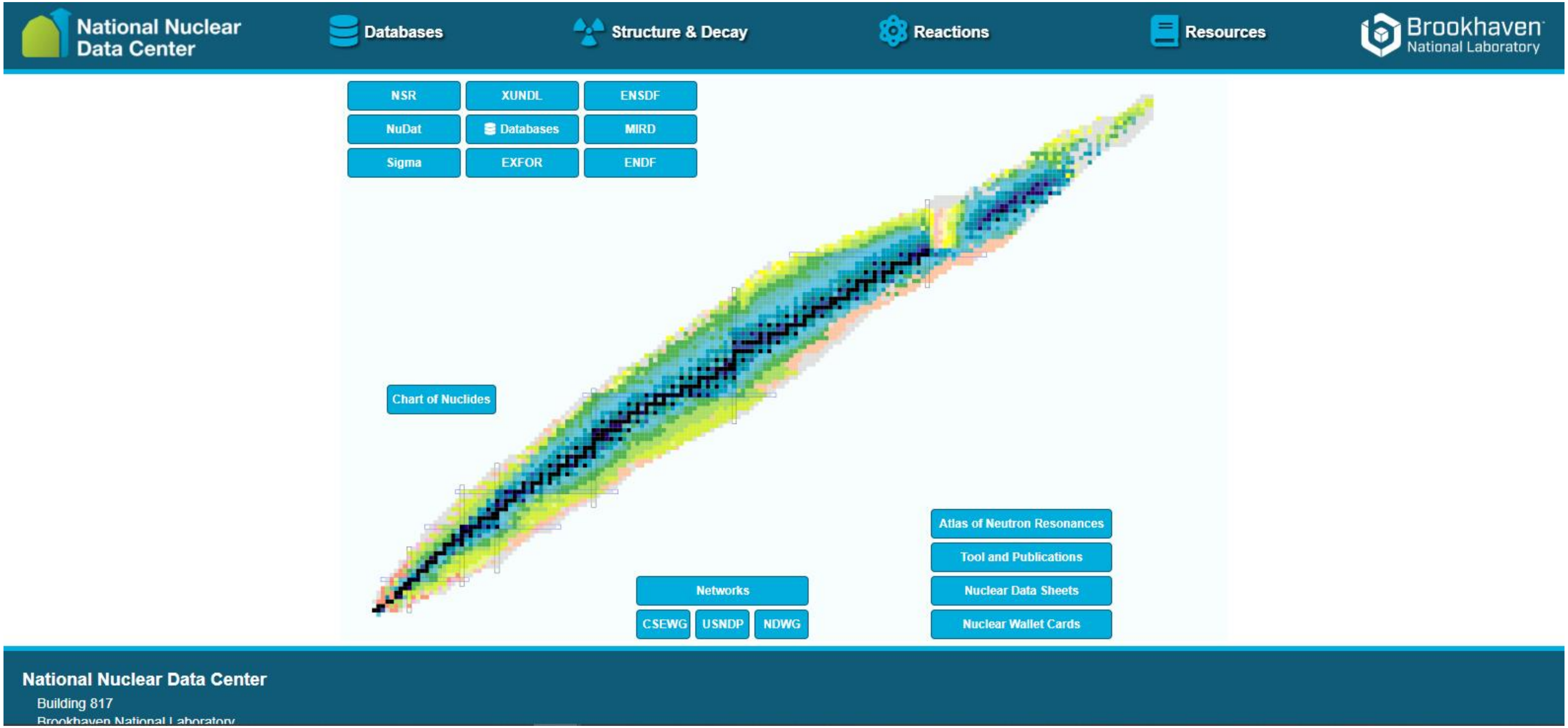
- Other information can be found here.

https://atom.kaeri.re.kr/nuchart/

Nuclide chart at Karlsruhe

https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/joint-research-centre-publishes-new-knowledge-elements-radioactivity-and-decay-user-friendly-chart-2022-03-17_en

National Nuclear Data Centre at BNL



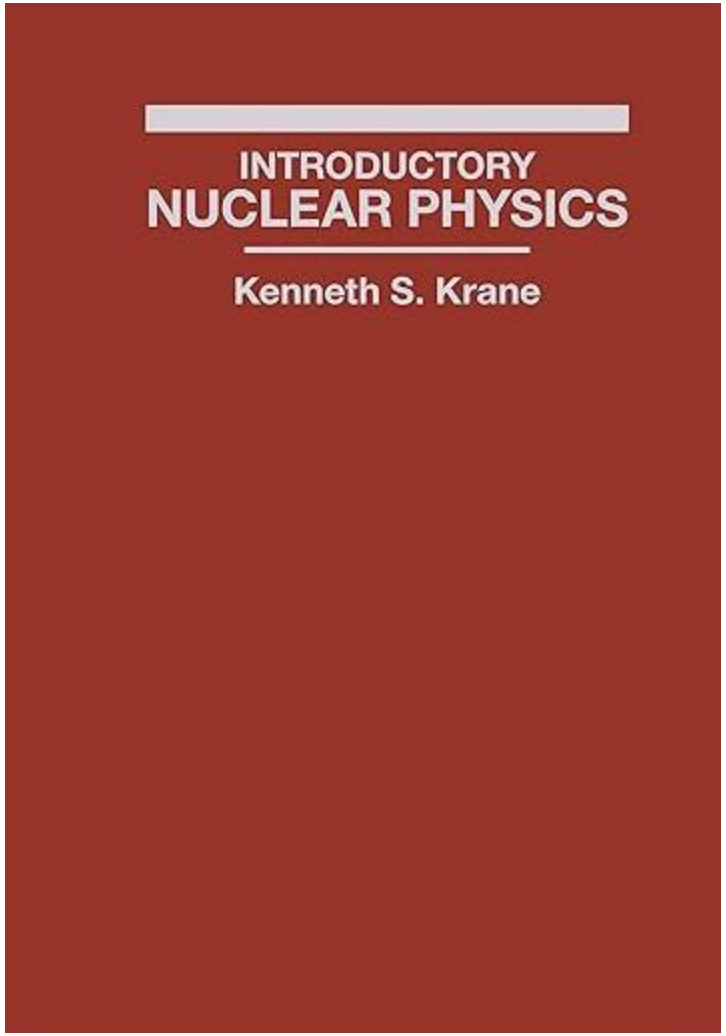
https://www.nndc.bnl.gov/

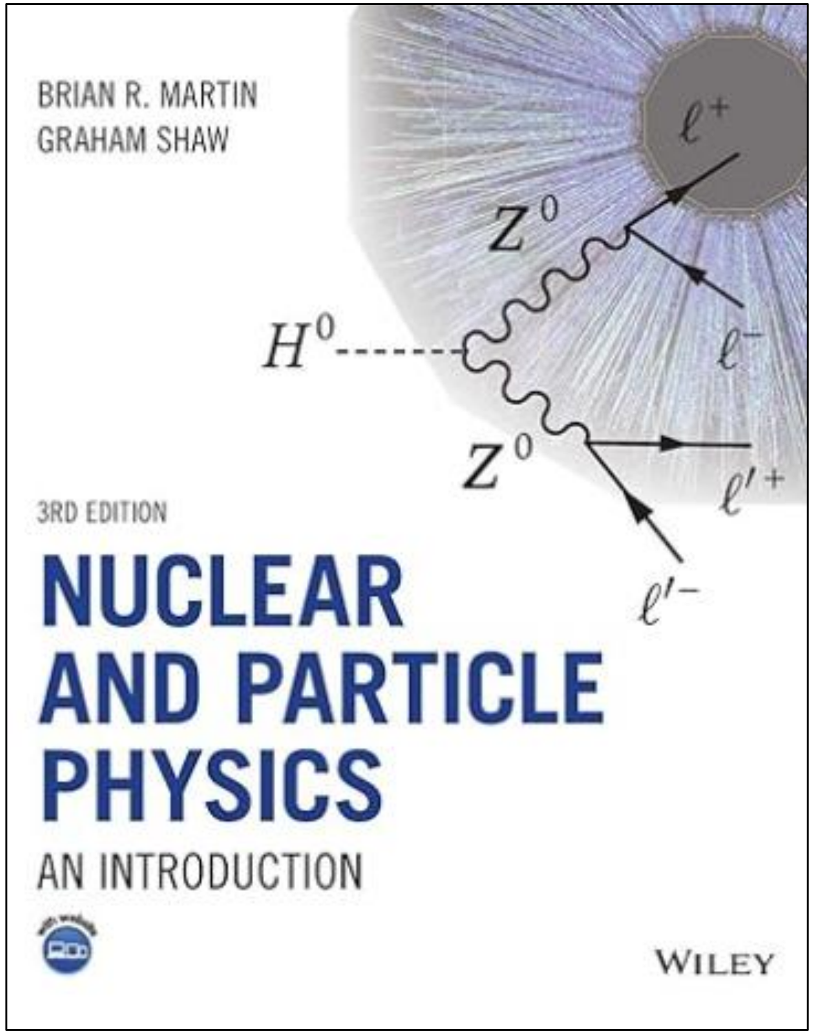
Summary

The following was discussed during this session:

- ✓ the structure of the atom and nucleus
- ✓ stability of atoms
- ✓ radioactivity
- ✓ common modes of radioactive decay
- ✓ the half-life in radioactive decay
- ✓ chart of nuclides
- ✓ accessing nuclear data

Further reading

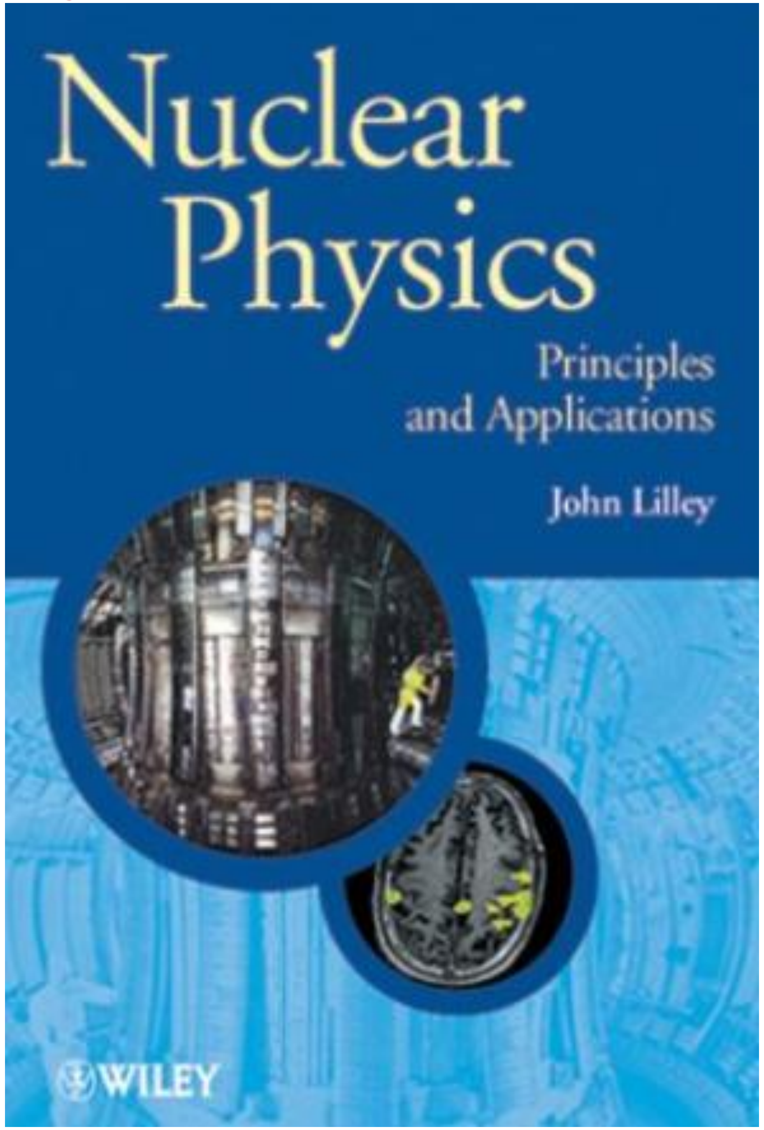


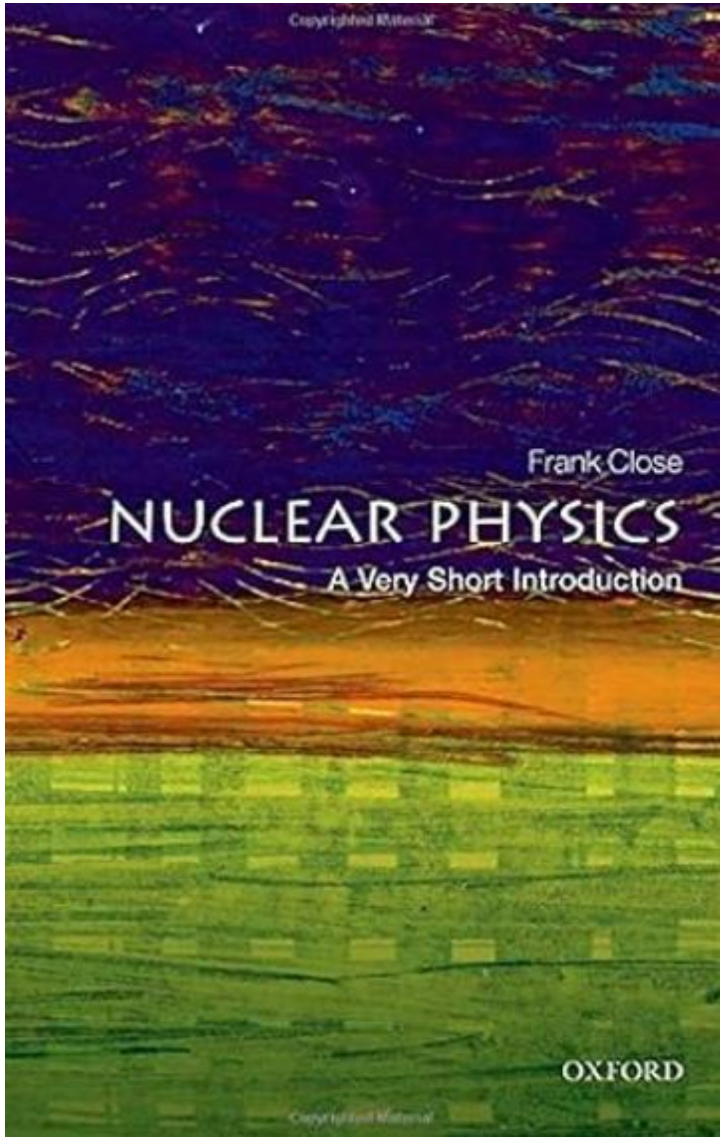


Kenneth S. Krane (1991) Introductory Nuclear Physics. Wiley. 3rd Edition
ISBN-10 : 047180553X
ISBN-13 : 978-0471805533

Brian R. Martin, Graham Shaw (2019). Nuclear and Particle Physics: An Introduction. Wiley. 3rd Edition
ISBN-10 : 1119344611
ISBN-13 : 978-1119344612

Further reading

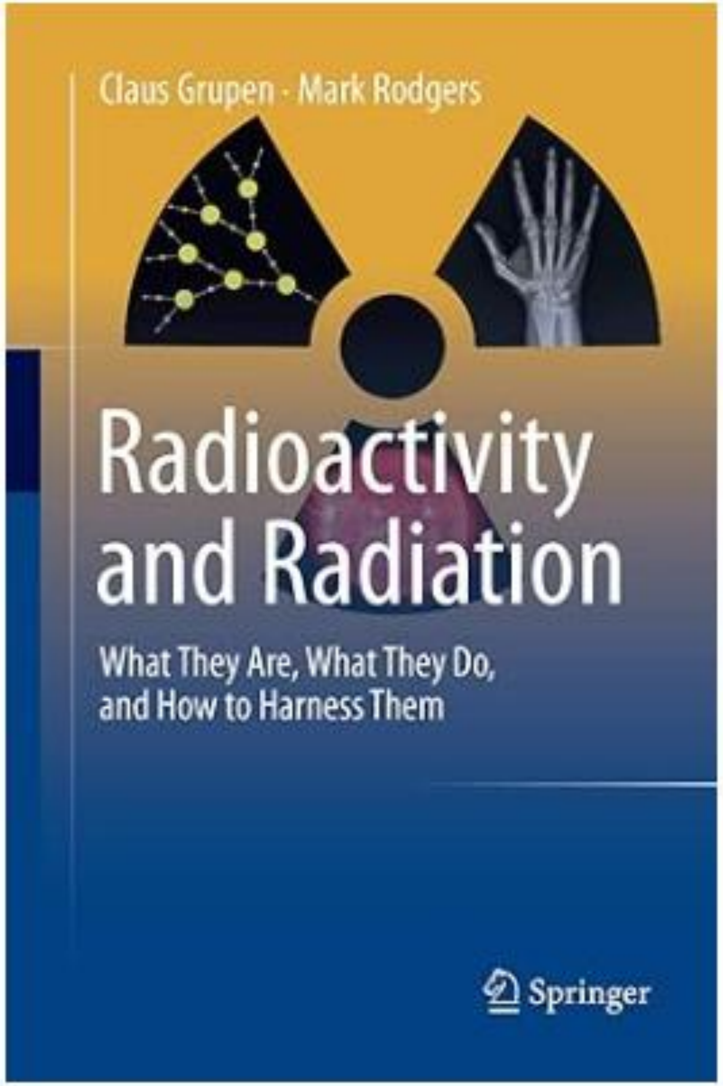


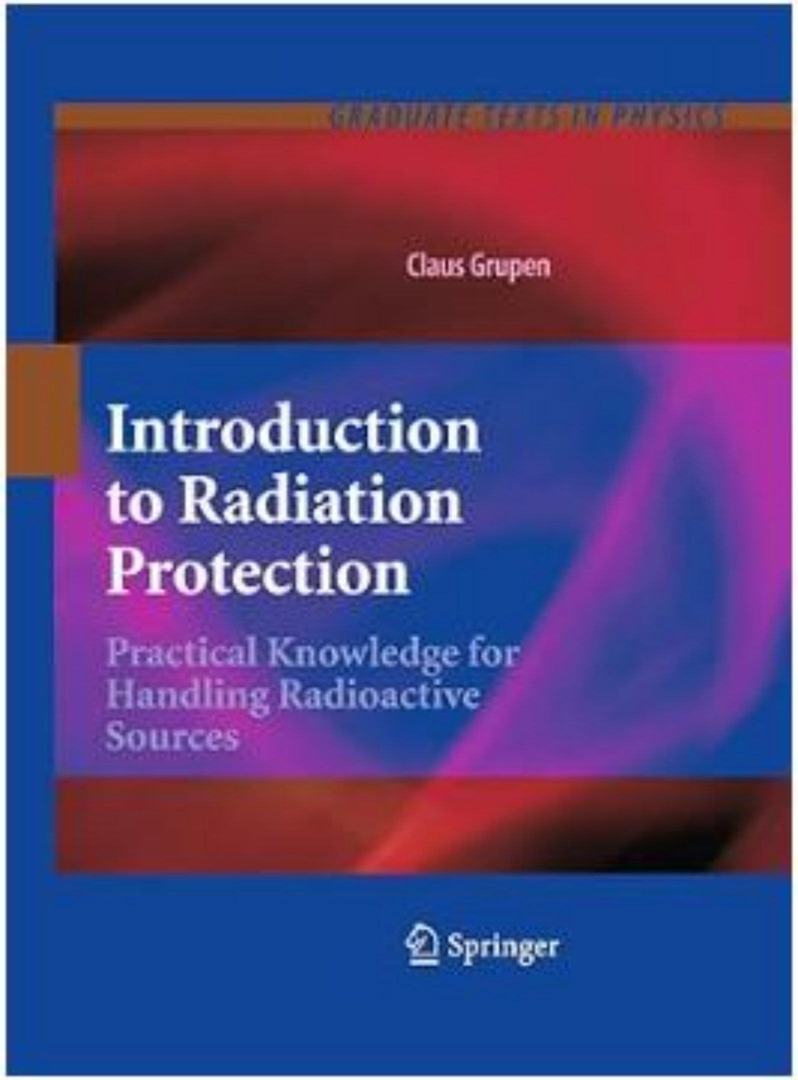


John Lilley (2013). Nuclear Physics: Principles and Applications (Manchester Physics Series Book 44) Wiley 1st Edition, Kindle Edition
ISBN-13 : 978-1118723333

Frank Close (2015) Nuclear Physics: A Very Short Introduction 1st Edition. Oxford University Press
ISBN-10 : 9780198718635
ISBN-13 : 978-0198718635

Further reading





Claus Grupen, Mark Rodgers (2018). Radioactivity and Radiation: What They Are, What They Do, and How to Harness Them. Springer; Softcover reprint of the original 1st ed. 2016 edition.
ISBN-10 : 3319825542
ISBN-13 : 978-3319825540

Claus Grupen (2010). Introduction to Radiation Protection: Practical Knowledge for Handling Radioactive Sources (Graduate Texts in Physics). Springer; 2010th edition.
ISBN-10 : 3662496038
ISBN-13 : 978-3662496039

Further reading:

https://www-nds.iaea.org/

https://atom.kaeri.re.kr/nuchart/

https://joint-research-centre.ec.europa.eu/training-programmes/karlsruhe-nuclide-chart_en

https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/joint-research-centre-publishes-new-knowledge-elements-radioactivity-and-decay-user-friendly-chart-2022-03-17_en

https://www.nndc.bnl.gov/

Useful illustrations

https://www.youtube.com/watch?v=UtZw9jfIxXM

https://www.youtube.com/watch?v=s7zPzBnf6Us

https://www.youtube.com/watch?v=V4PFQpCCqzk

https://www.youtube.com/watch?v=R2XWlhNz6WU

https://www.youtube.com/shorts/Ih9JfllFg24

https://www.youtube.com/watch?v=P_SD5Rt6XMk&t=95s

https://www.youtube.com/watch?v=QCZQCi_uKpM

https://www.youtube.com/watch?v=iGr6atucsBw

https://www.youtube.com/watch?v=ksLNmLQbNT4

https://www.youtube.com/watch?v=gDpyBifg6-s

https://www.youtube.com/watch?v=m3dpUk1emms

Thank you for the attention