Khemis Miliana University – Djilali BOUNAAMA
Faculty of Material Sciences and Computer Science
Department of Physics

Nuclear Physics

L3 Fundamental Physics

By:
Dr. S.E. BENTRIDI

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Content

Nuclear Physics

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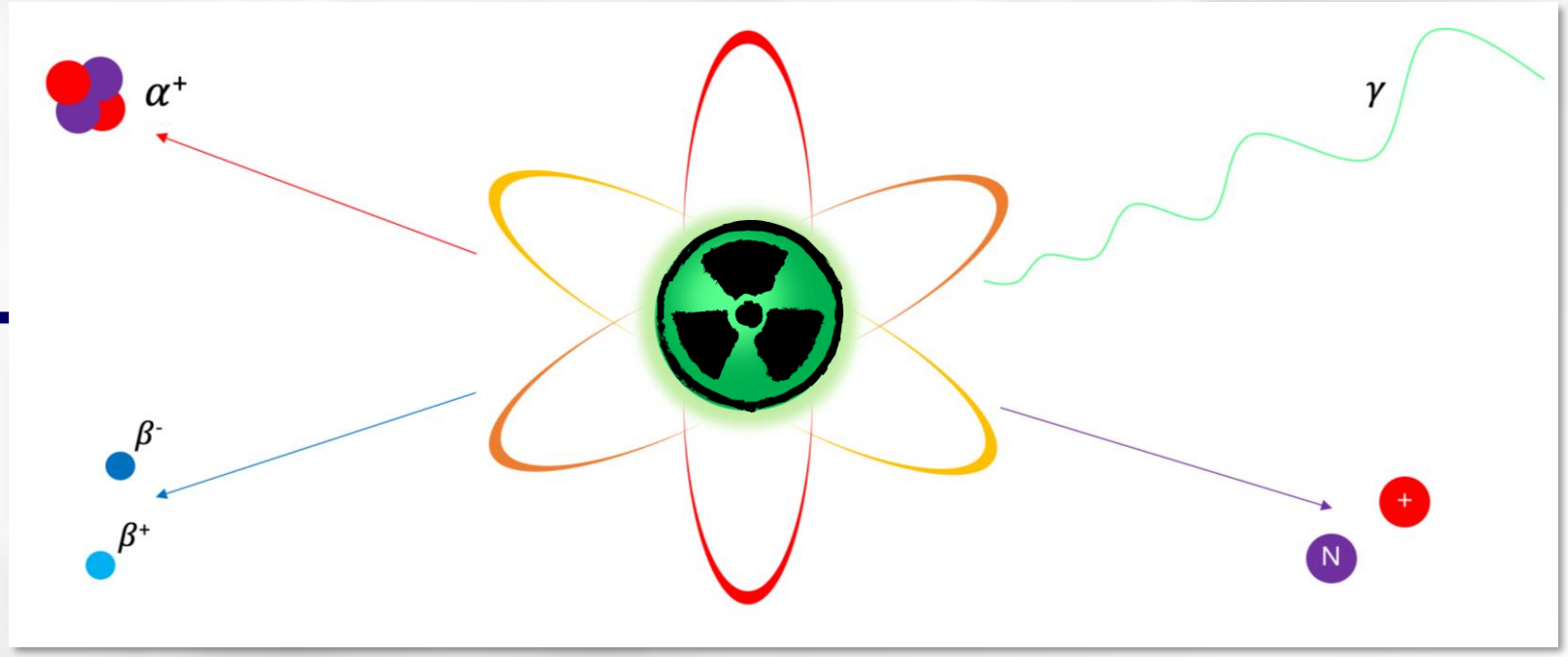
Chapter 02

Radioactivity



The Weak Interaction

The nuclear interaction that holds nucleons together to form nuclei cannot account for beta decay. Another short-range fundamental interaction turns out to be responsible: the **weak interaction.** Insofar as the structure of matter is concerned, the role of the weak interaction seems to be confined to causing beta decays in nuclei whose neutron/proton ratios are not appropriate for stability. This interaction also affects elementary particles that are not part of a nucleus and can lead to their transformation into other particles. The name "weak interaction" arose because the other short-range force affecting nucleons is extremely strong, as the high binding energies of nuclei attest. The gravitational interaction is weaker than the weak interaction at distances where the latter is a factor.

Thus four fundamental interactions are apparently sufficient to govern the structure and behavior of the entire physical universe, from atoms to galaxies of stars. In order of increasing strength they are gravitational, weak nuclear, electromagnetic, and strong nuclear. These inter-

II. Radioactivity

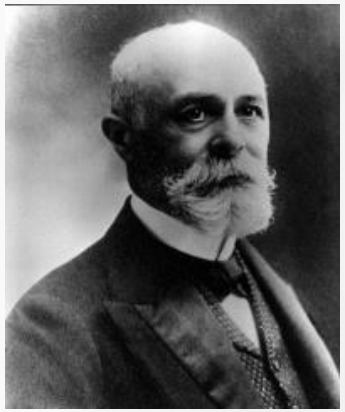
Radioactivity discovery timeline

Wilhelm Roentgen
Discovered X-rays in 1895

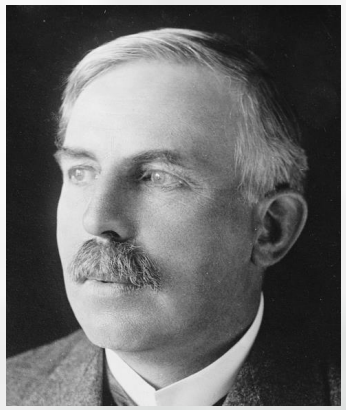
Marie Skłodowska-Curie
Discovered Po & Ra in 1898

Pau Villard
Discovered γ Rays in 1900

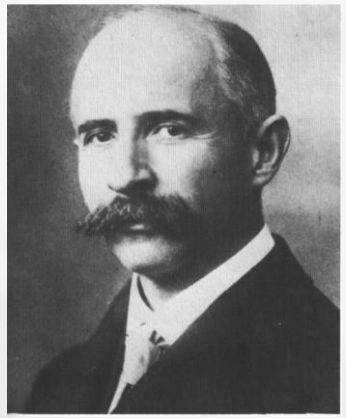
Wolfgang Ernst Pauli
Suggested neutrino 1931



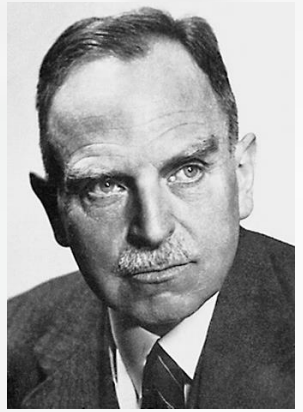
Antoine Henry BECQUEREL
Discovered U-decay in 1896



Ernest Rutherford
Discovered α & β in 1898
Confirmed in 1908 that $\alpha \equiv He$



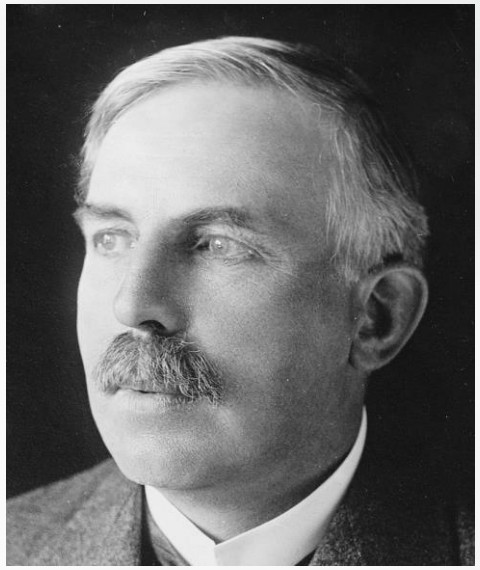
Walter Kaufmann
Confirmed in 1902 that $\beta \equiv e$



Otto Hahn
(with F. Strassmann & L. Meitner)
Discovered nuclear fission in 1938

II. Radioactivity

1. Nuclear decay



Ernest Rutherford
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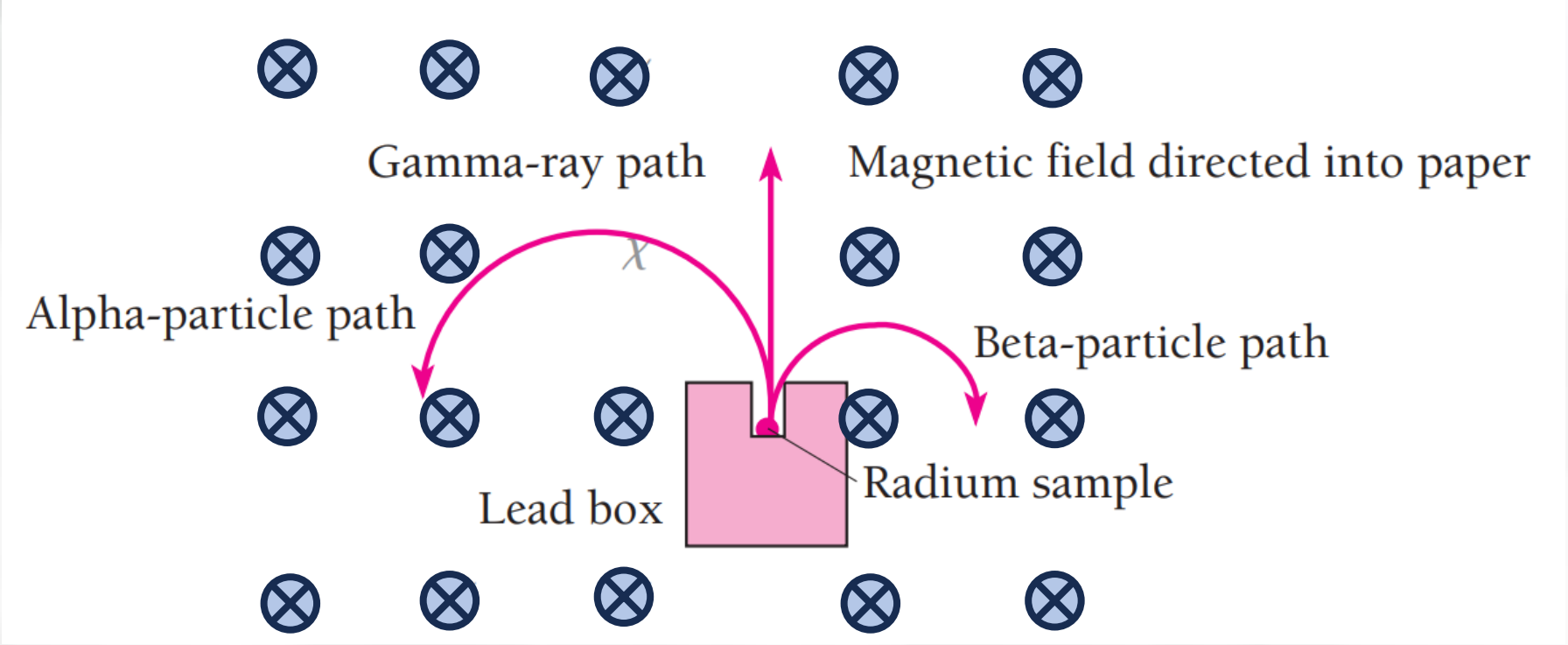
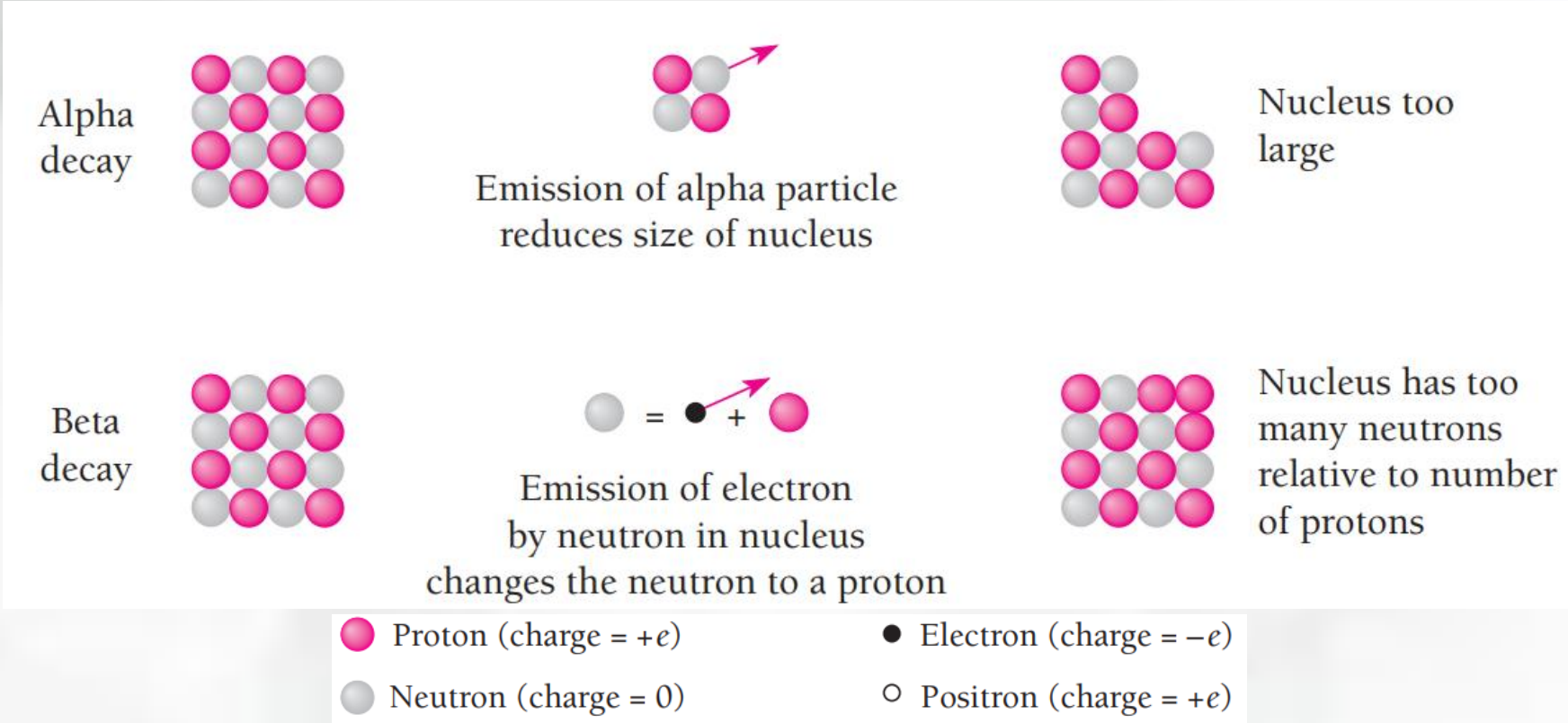


The early experimenters conducted by Rutherford and his coworkers, allowed the distinction of three components in the radiations from radionuclides. These components were called alpha, beta, and gamma, which were eventually identified as ^4_2He nuclei, *electrons*, and high-energy *photons* respectively. Later, positron emission and electron capture were added to the list of decay modes.

II. Radioactivity

1. Nuclear decay

Despite the strength of the forces that hold nucleons together to form an atomic nucleus, many nuclides are unstable and spontaneously change into other nuclides by radioactive decay.

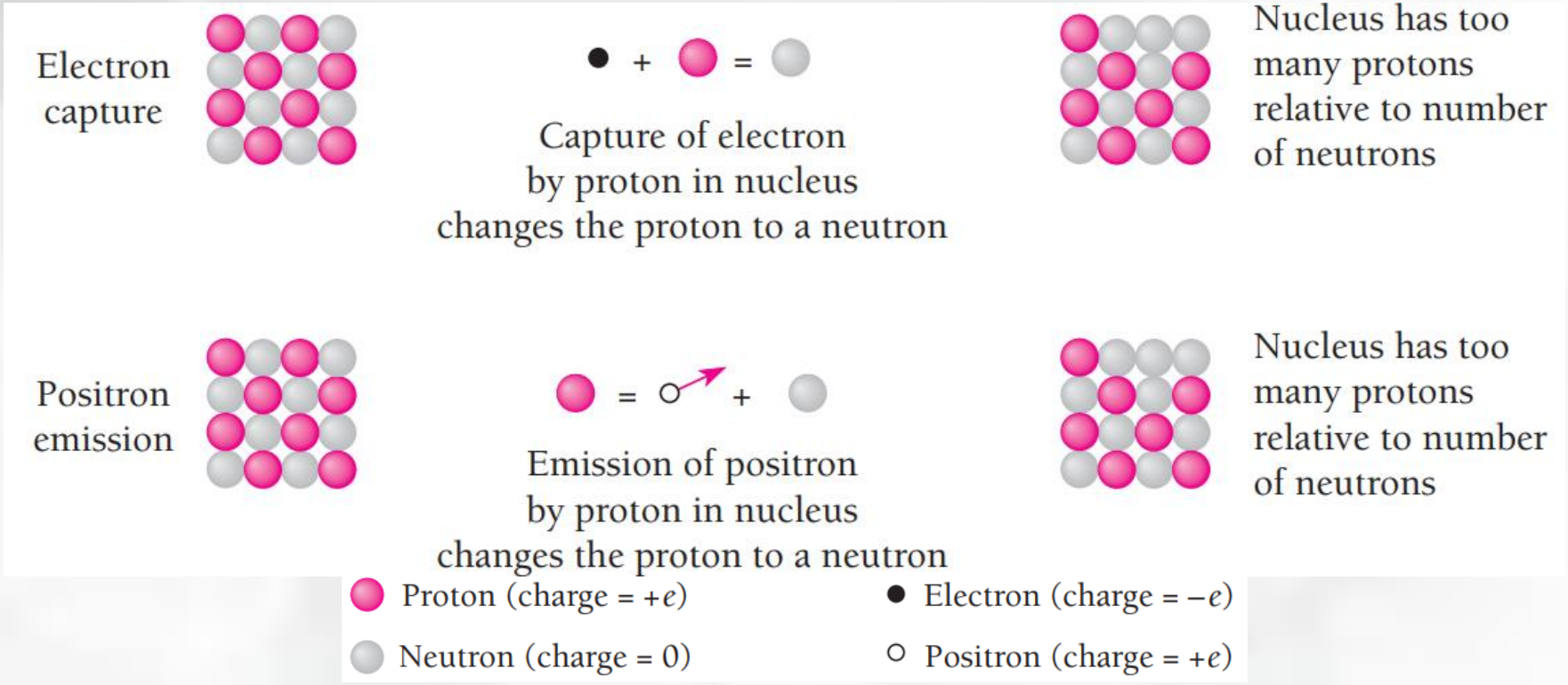


- ***When a nucleus undergoes alpha or beta decay, its atomic number Z changes and it becomes the nucleus of a different element: this means that elements are not immutable, although the mechanism of their transformation could not be explained by chemical processes.***

II. Radioactivity

1. Nuclear decay

Despite the strength of the forces that hold nucleons together to form an atomic nucleus, many nuclides are unstable and spontaneously change into other nuclides by radioactive decay.

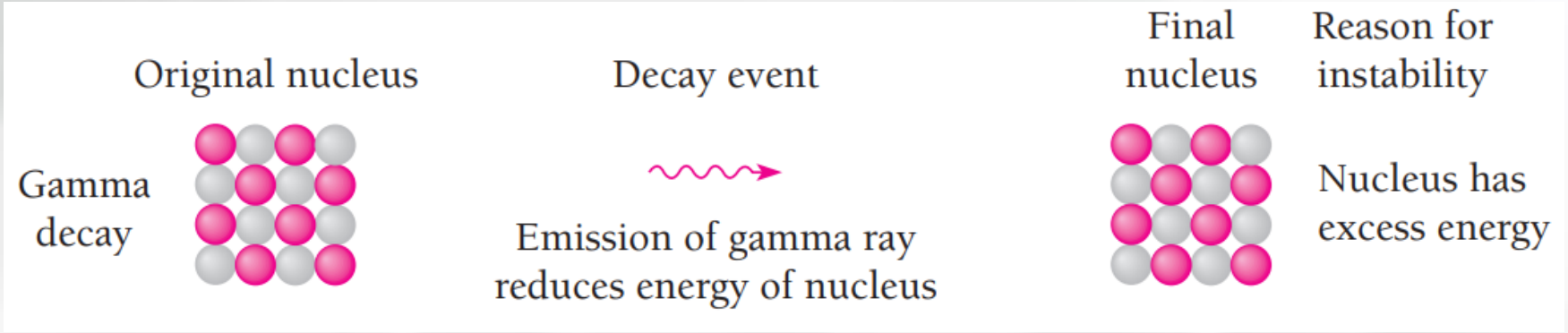


- ***Similarly, another decay modes were discovered, like electron capture and positron emission (positive Beta decay), transforming the initial nucleus into a new element with Z shifted by one unit.***

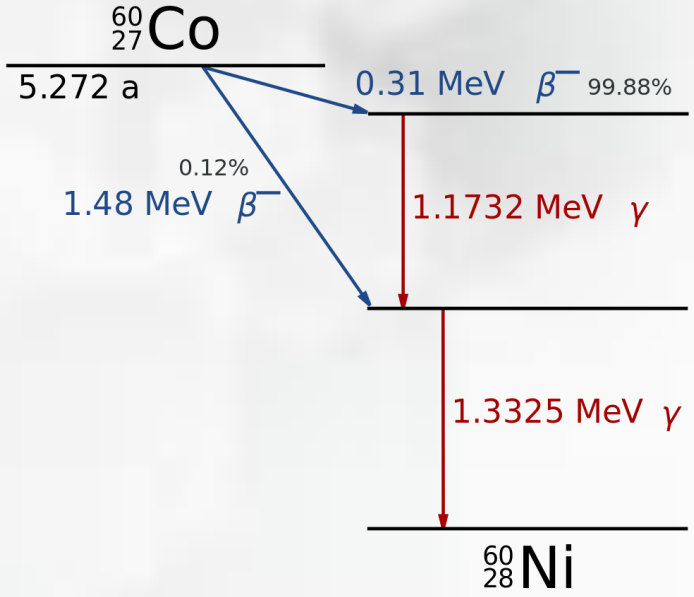
II. Radioactivity

1. Nuclear decay

Despite the strength of the forces that hold nucleons together to form an atomic nucleus, many nuclides are unstable and spontaneously change into other nuclides by radioactive decay.



- ***In other hand, the gamma decay left the nucleus unchanged. This mode is another proofing of the quantification of energy levels of nucleons within their nucleus, and gamma transitions (gamma spectrometry) is widely used to characterize (nucleus signature) a given isotope.***



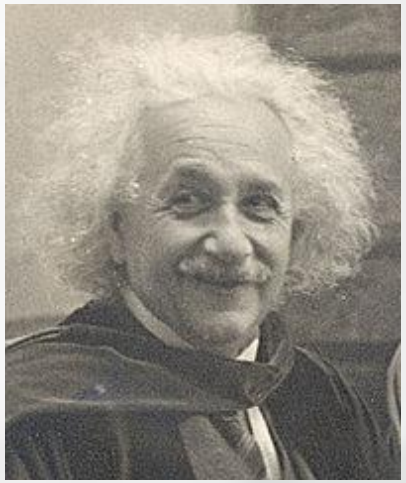
γ – rays is the result of deexcitation of an excited nucleus to get back to its ground state.

II. Radioactivity

1. Nuclear decay

- ***The energy liberated during radioactive decay comes from within individual nuclei without external excitation, unlike the case of atomic radiation. How can this happen? The answer could be given only when Einstein proposed the equivalence of mass and energy within its Special Relativity theory!!!***

$$\Delta E \equiv \Delta m c^2$$



Albert Einstein
(1879-1955) Swiss-Germany-USA

- **Radioactive decay is a statistical process that obeys the laws of chance. No cause-effect relationship is involved in the decay of a particular nucleus, only a certain probability per unit time. Classical physics cannot account for such behavior, although it fits naturally into the framework of quantum physics.**

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

II. Radioactivity

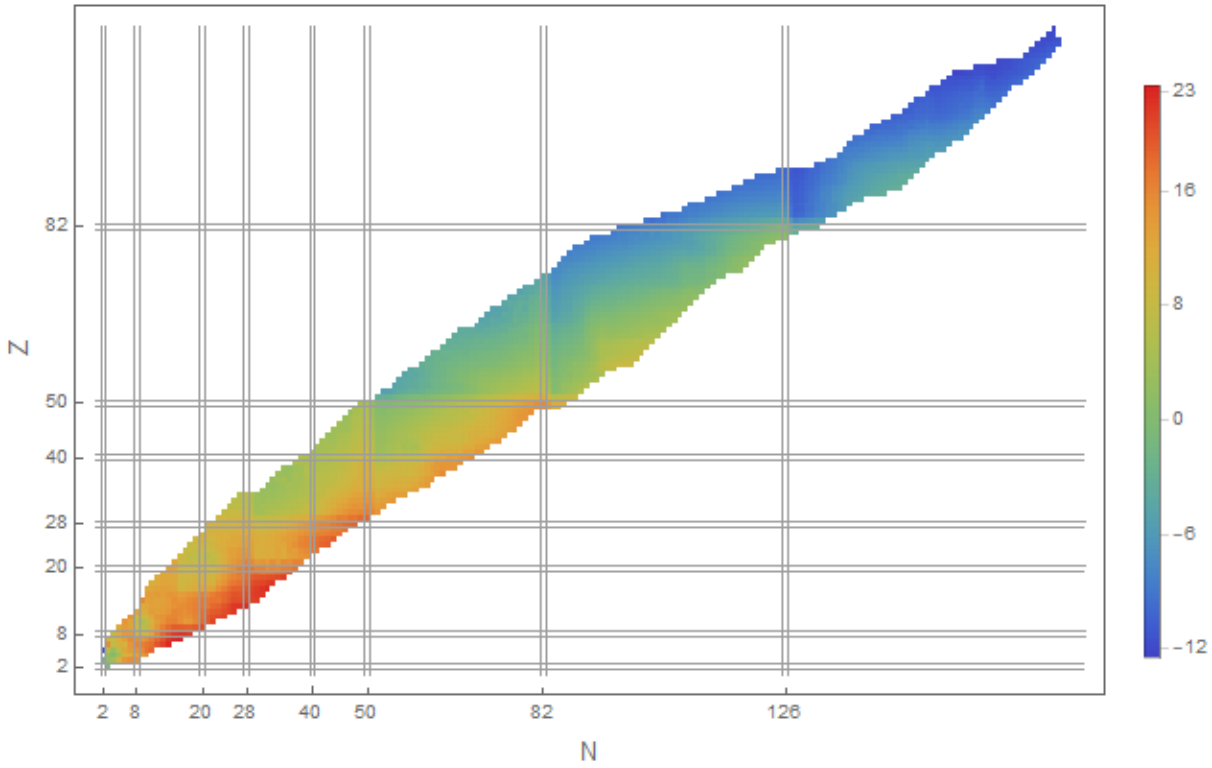
1.1. Alpha decay

Nuclei which contain 210 or more nucleons ($Z \geq 80$) are so large that the short-range nuclear forces that hold them together are barely able ($E_V \propto A$) to counterbalance the mutual repulsion of their protons ($E_C \propto Z^2$): *Coulomb repulsion grows much faster than nuclear cohesion force.*

Alpha decay occurs in such nuclei as a means of increasing their stability by reducing their size:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + Q_\alpha$$

The chart to the right shows the alpha separation energy distribution. It can be divided in 2 regions:



- The upper region: nuclei with $S_\alpha < 0$, i.e. nucleus gives out energy when emitting an alpha particle, thus, they are alpha-emitter.

- The lower region: nuclei with $S_\alpha > 0$, with some local minimum for the S_α ($^{8}_{4}Be$)

II. Radioactivity

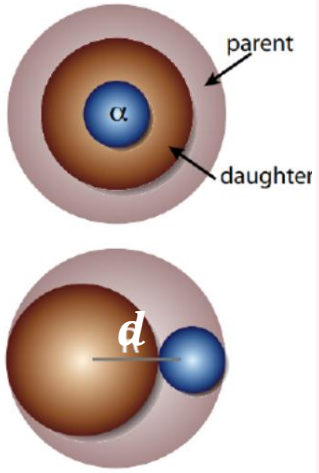
1.1. Alpha decay

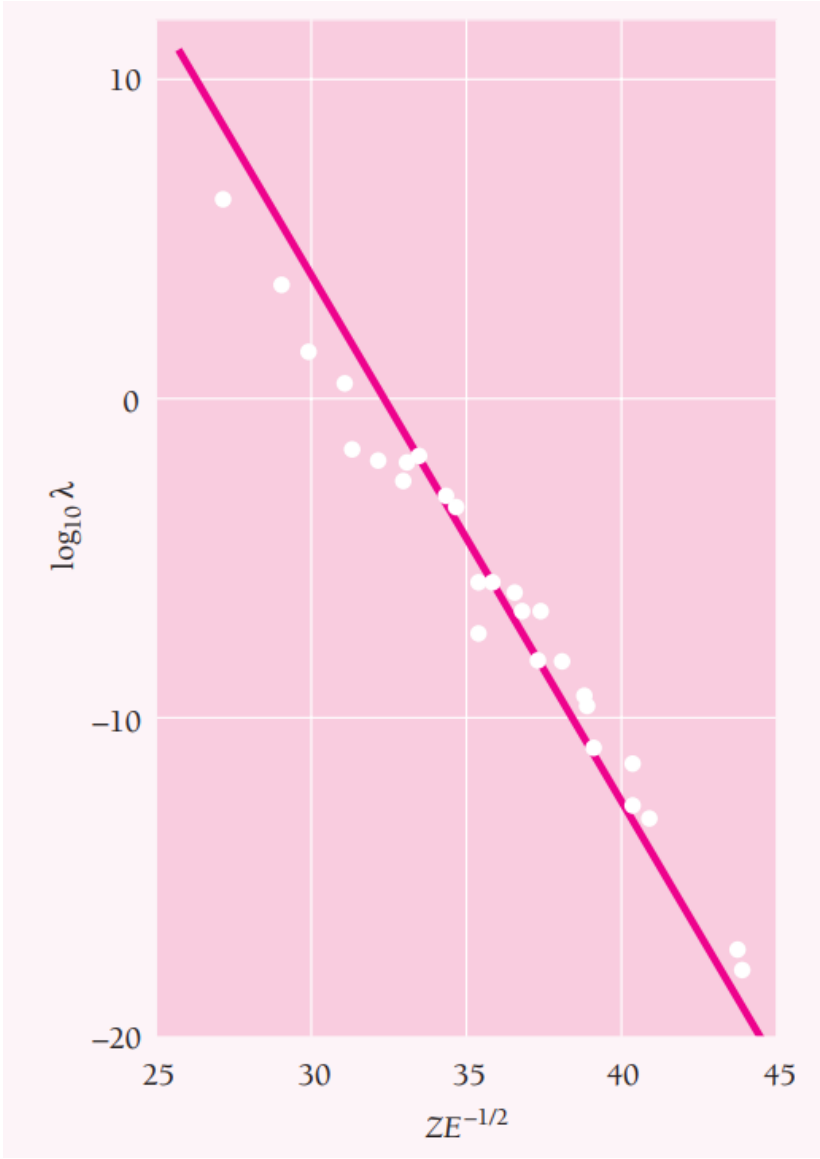
While a heavy nucleus can, in principle, spontaneously reduce its bulk by alpha decay, there remains the problem of how an alpha particle can actually escape the nucleus.

Indeed, the work that must be done against the repulsive electric force to bring an alpha particle from infinity to a position adjacent to the nucleus $(A = 210, Z = 80)$:

$$W_\alpha = U_C \equiv ke^2 \frac{(Z-2)2}{d} \cong 25MeV$$

$$With\ d = R_0\left((A-4)^{1/3} + 4^{1/3}\right) \cong 9fm$$





Experimental law of the alpha decay constant could be established in 1911 by Geiger and Nuttall, known as Geiger-Nuttall law of alpha decay:

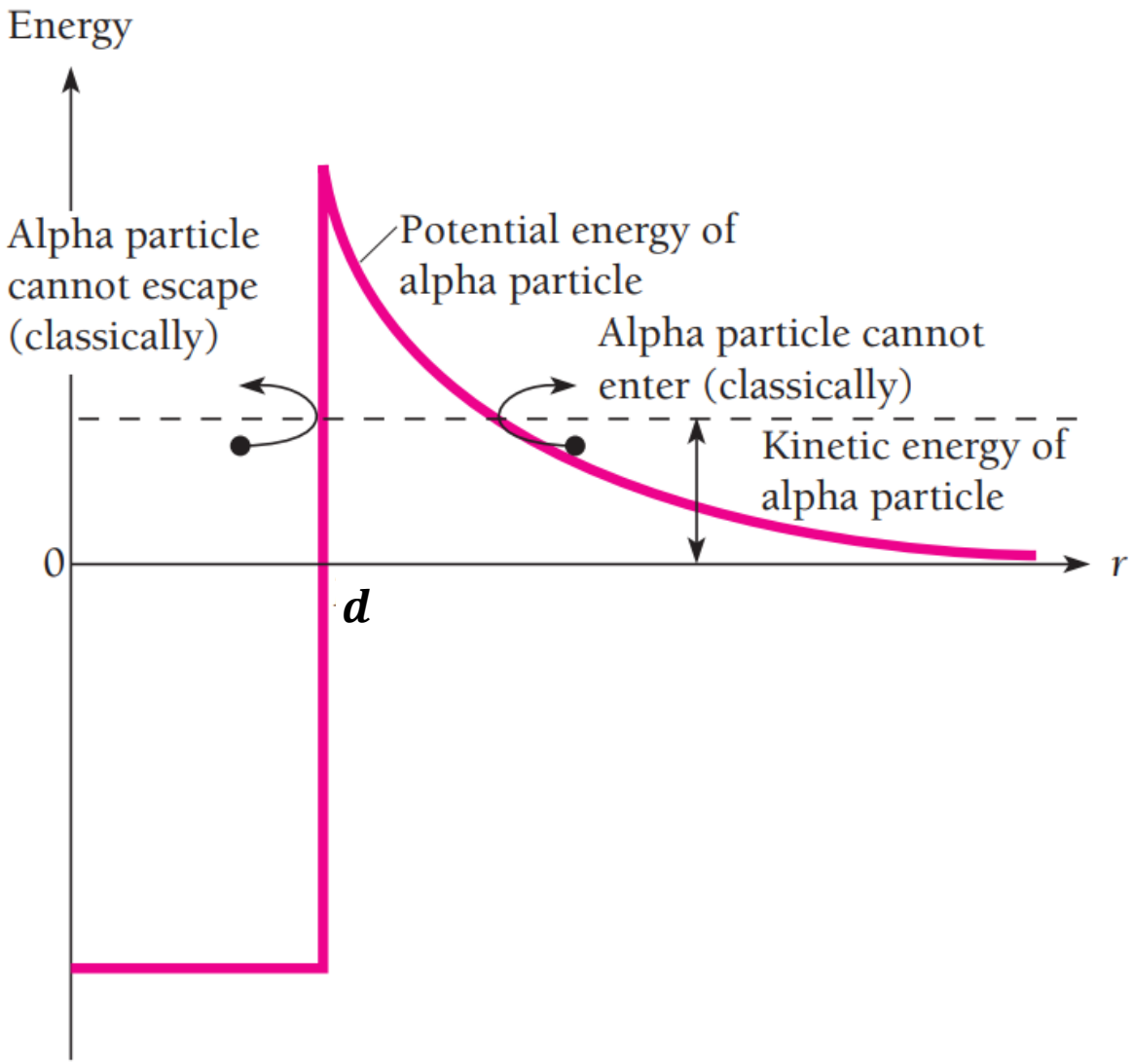
$$log_{10}\lambda \propto ZE^{-1/2}$$

II. Radioactivity

1.1. Alpha decay

We may therefore regard an alpha particle in such a nucleus as being inside a box whose walls require an energy of 25 MeV to be surmounted. However, decay alpha particles have energies that range from 4 to 9 MeV, depending on the particular nuclide involved—16 to 21 MeV short of the energy needed for escape.

In classical physics, an alpha particle whose kinetic energy is less than the height of the potential barrier around a nucleus cannot enter or leave the nucleus, whose radius is *d*.

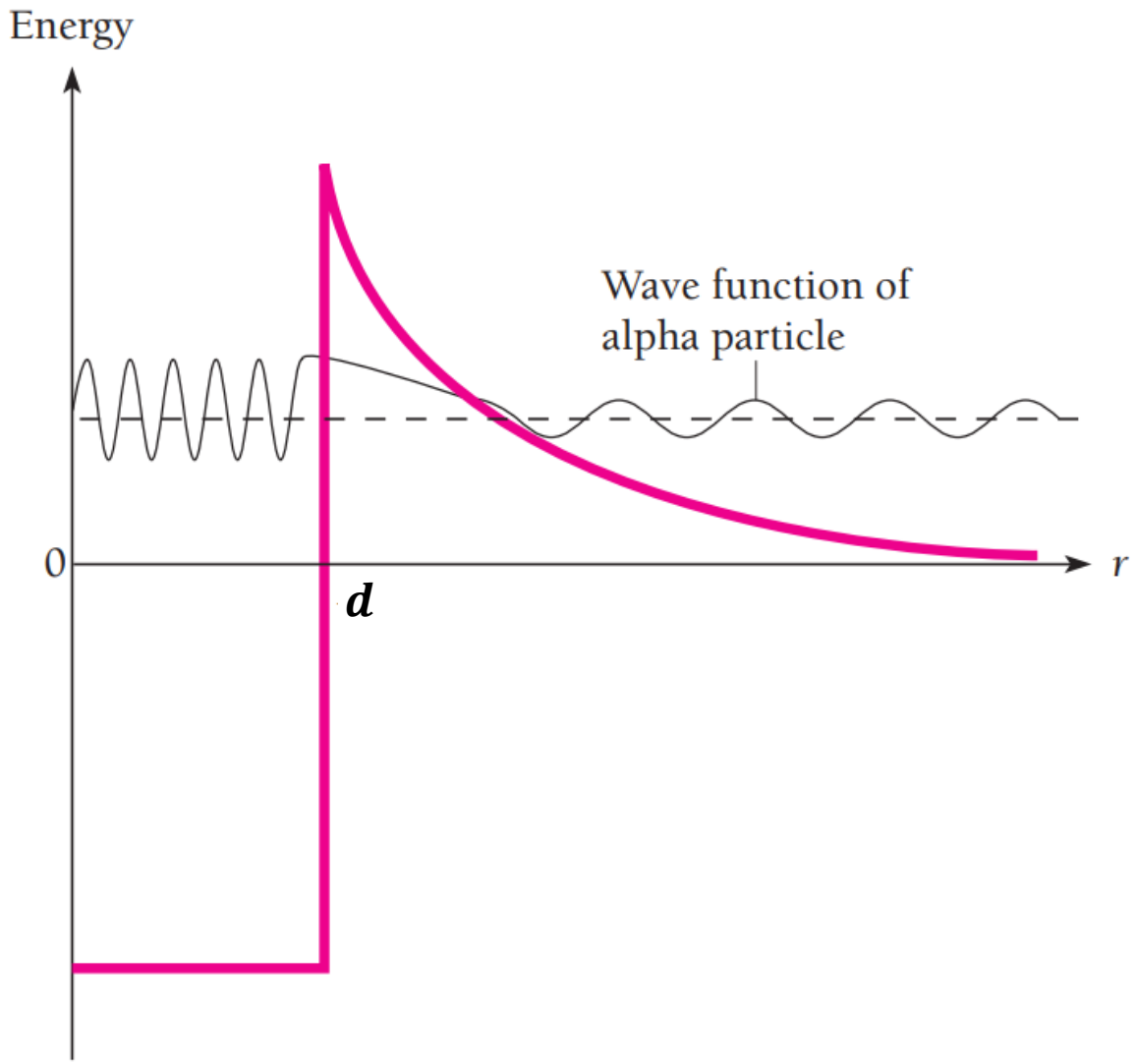


II. Radioactivity

1.1. Alpha decay

Although alpha decay is inexplicable classically, quantum mechanics provides a straightforward explanation. In fact, the theory of alpha decay, developed independently in 1928 by Gamow and by Gurney and Condon, was greeted as an especially striking confirmation of quantum mechanics.

In quantum physics, such an alpha particle can tunnel through the potential barrier with a probability that decreases with the height and thickness of the barrier.

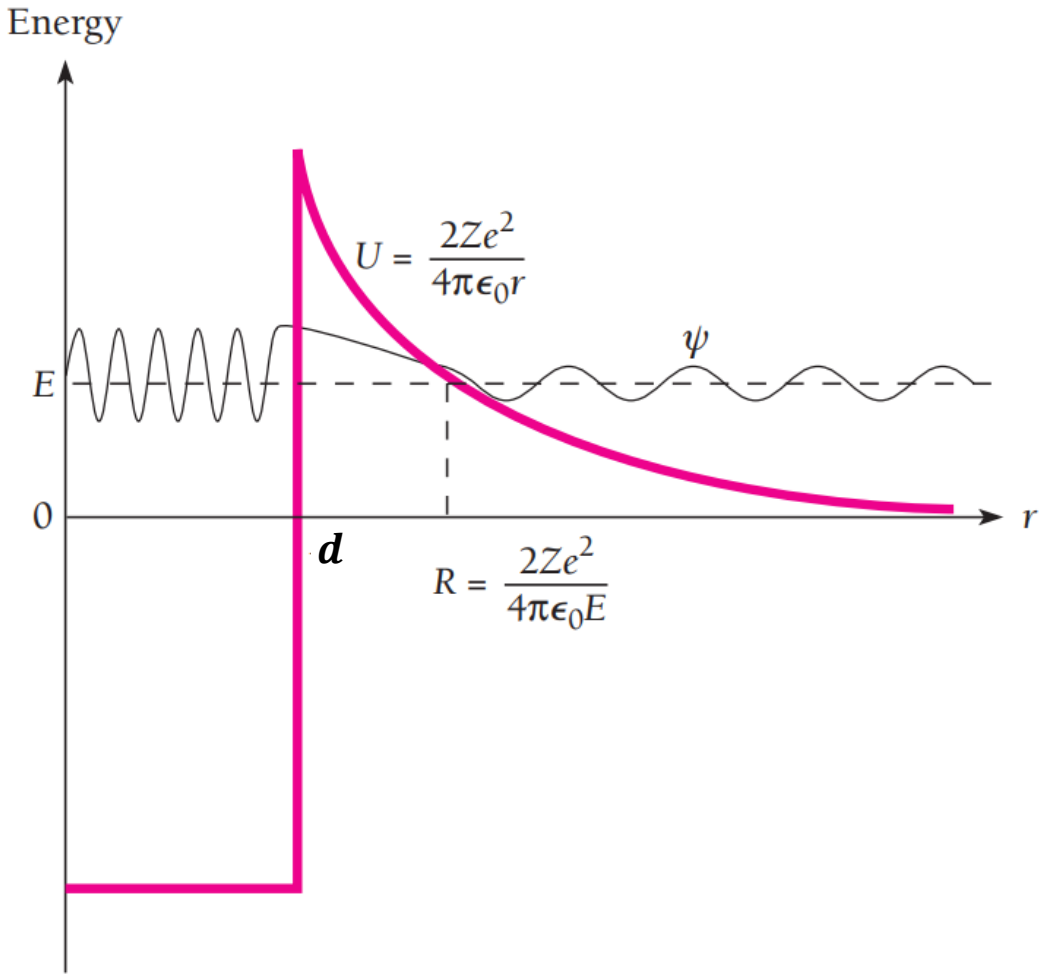


II. Radioactivity

1.1. Alpha decay

The basic notions of this theory are:

- **An alpha particle may exist as an entity within a heavy nucleus.**
- **Such a particle is in constant motion and is held in the nucleus by a potential Barrier.**
- **There is a small—but definite—likelihood that the particle may tunnel through the barrier (despite its height) each time a collision with it occurs.**



According to this theory, the alpha constant decay is given by the following formula:

$$log_{10}\lambda = log_{10}\left(\frac{v}{2d}\right) + 1.29Z^{1/2}.R_0^{1/2} - 1.72ZE^{-1/2}$$

Where $\frac{1}{2}m_\alpha v^2 = E \rightarrow v \sim 10^7 m/s$

II. Radioactivity

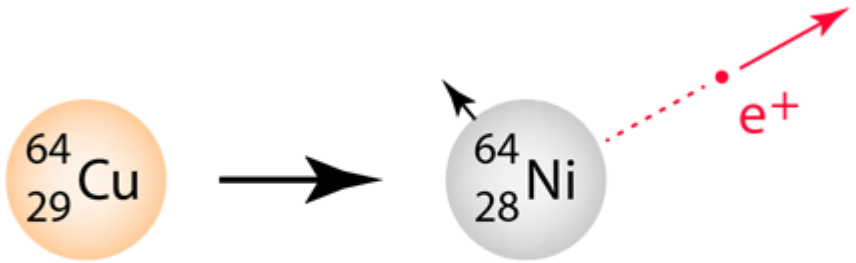
1.2. Beta decay

Like alpha decay, beta decay is a means whereby a nucleus can alter its composition to become more stable. Also like alpha decay, beta decay has its puzzling aspects conservation principles of energy, linear momentum, and angular momentum are all apparently violated in beta decay

- ***The electron energies observed in the beta decay of a particular nuclide are found to vary continuously :*** $T_e \in [0, T_{max}]$

Where the value $T_{max} = Q_\beta$ ***is a characteristic of the nuclide.***

- ***When the directions of the emitted electrons and of the recoiling nuclei are observed, they are almost never exactly opposite as required for linear momentum to be conserved.***
- ***The spins of the neutron, proton, and electron are all 1/2. If beta decay involves just a neutron becoming a proton and an electron, spin (and hence angular momentum) is not conserved.***



II. Radioactivity

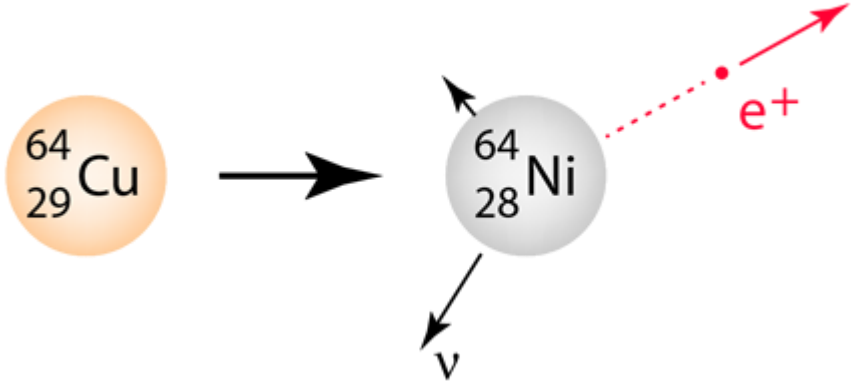
1.2. Beta decay

In 1930 Pauli proposed a "desperate remedy": if an uncharged particle of small or zero rest mass and spin 1/2 is emitted in beta decay together with the electron, the above discrepancies would not occur.

This particle, later called the neutrino ("little neutral one") by Fermi, would carry off an energy:

$$T_\nu = T_{max} - T_e$$

the difference between T_{max} and the actualT_e of the electron (the recoiling nucleus carries away negligible T). The neutrino's linear momentum also exactly balances those of the electron and the recoiling daughter nucleus.



Subsequently it was found that two kinds of neutrinos are involved in beta decay, the neutrino itself (symbol ν) and the antineutrino (symbol $\bar{\nu}$). Positrons were discovered in 1932 and two years later were found to be spontaneously emitted by certain nuclei. The properties of the positron are identical with those of the electron except that it carries a charge of $+e$ instead of $-e$.

1.2. Beta decay

In ordinary beta decay it is an antineutrino that is emitted:

$$n \rightarrow p + e^{-} + \overline{\nu}$$

Positron emission corresponds to the conversion of a nuclear proton into a neutron, a positron, and a neutrino:

$$p \rightarrow n + e^{+} + \nu$$

Closely connected with positron emission is electron capture, when a nucleus absorbs one of its inner atomic electrons, with the result that a nuclear proton becomes a neutron and a neutrino is emitted:

$$p + e^{-} \rightarrow n + \nu$$

By comparing these processes, we see that electron capture by a nuclear proton is equivalent to a proton's emission of a positron. Similarly the absorption of an antineutrino is equivalent to the emission of a neutrino, and vice versa.

The latter reactions are called inverse beta decays:

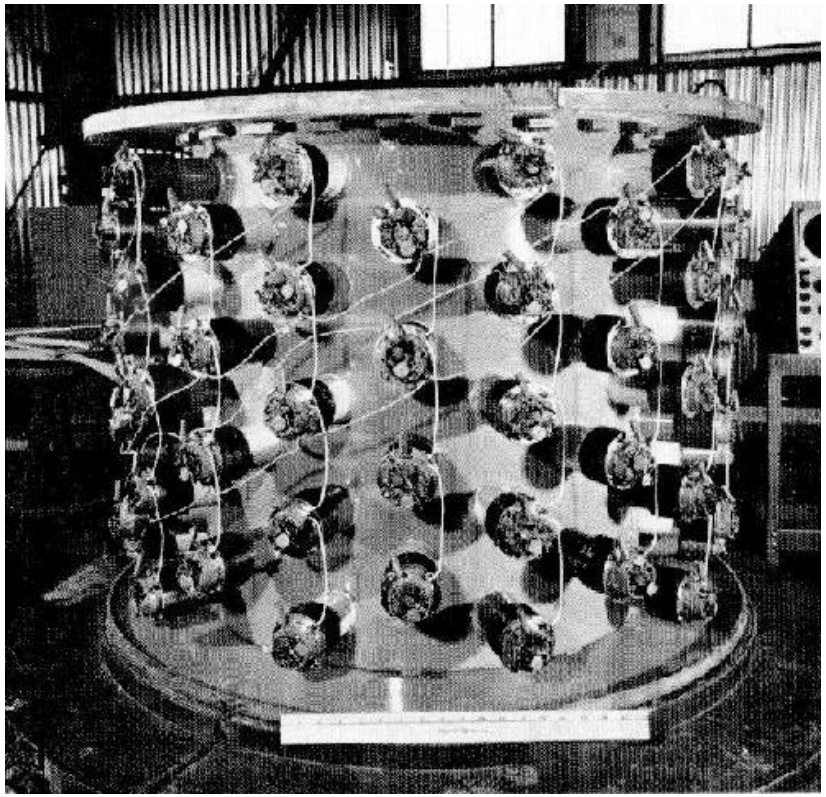
$$n + \nu \rightarrow p + e^{-}$$

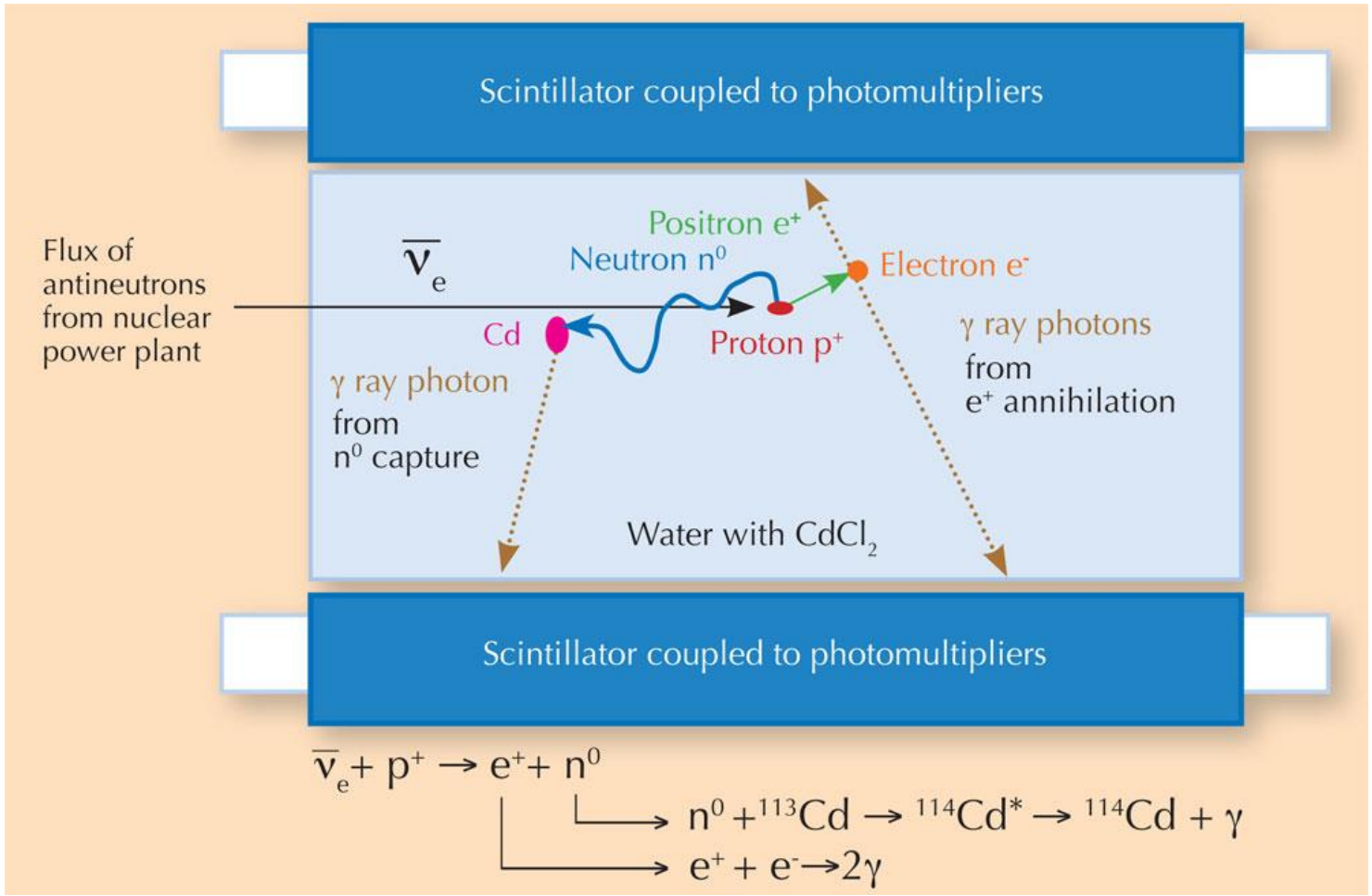
$$p + \overline{\nu} \rightarrow n + e^{+}$$

II. Radioactivity

1.2. Beta decay

Inverse beta decays have extremely low probabilities, which is why neutrinos and antineutrinos are able to pass through such vast amounts of matter, but these probabilities are not zero.





Starting in 1953, a series of experiments was carried out by F. Reines, C. L. Cowan, and others to detect the considerable flux of neutrinos (actually antineutrinos) from the beta decays that occur in a nuclear reactor.

1.3. Gamma decay

A nucleus can exist in states whose energies are higher than that of its ground state, just as an atom can.

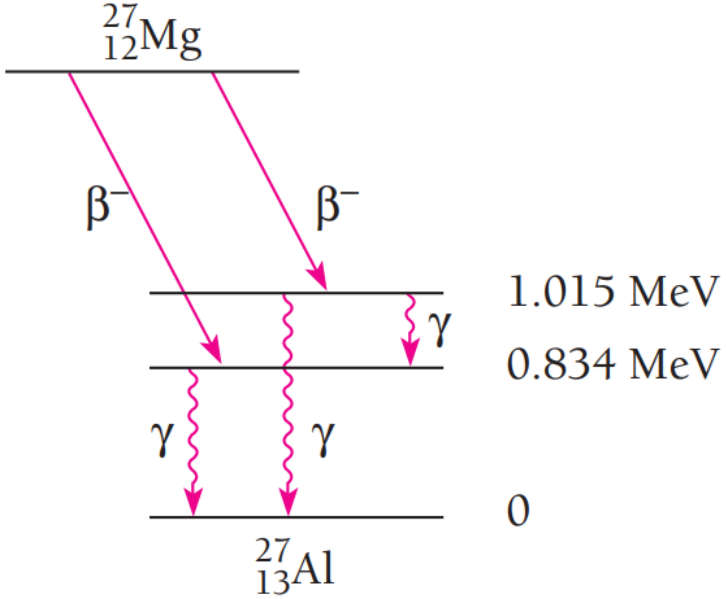
An excited nucleus is denoted by an asterisk after its usual symbol, for instance $^{27}_{12}Mg^{*}$.

Excited nuclei return to their ground states by emitting photons whose energies correspond to the energy differences between the various initial and final states in the transitions involved.

The photons emitted by nuclei range in energy up to several MeV, and are traditionally called gamma rays ($\gamma - rays$)

A simple example of the relationship between energy levels and decay schemes is shown in the figure below, which pictures the beta decay of $^{27}_{12}Mg^{*}$ to $^{27}_{13}Al^{*}$. The half-life of the decay is 9.5 min, and it may take place to either of the two excited states of $^{27}_{13}Al^{*}$.

The resulting nucleus $^{27}_{13}Al^{*}$ then undergoes one or two gamma decays to reach the ground state.

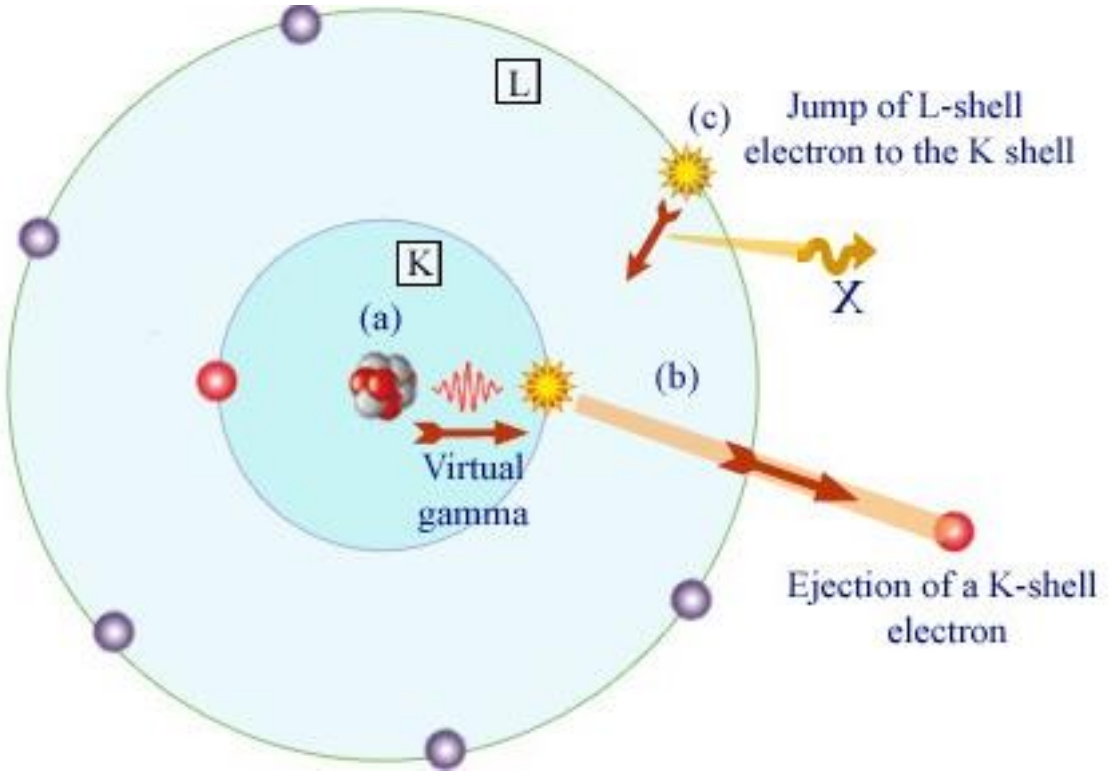


1.3. Gamma decay

As an alternative to gamma decay, an excited nucleus in some cases may return to its ground state by giving up its excitation energy to one of the atomic electrons around it.

While we can think of this process, which is known as "*internal conversion*", as a kind of photoelectric effect in which a nuclear photon is absorbed by an atomic electron, it is in better accord with experiment to regard internal conversion as representing a direct transfer of excitation energy from a nucleus to an electron.

The emitted electron has a kinetic energy equal to the lost nuclear excitation energy minus the binding energy of the electron in the atom.

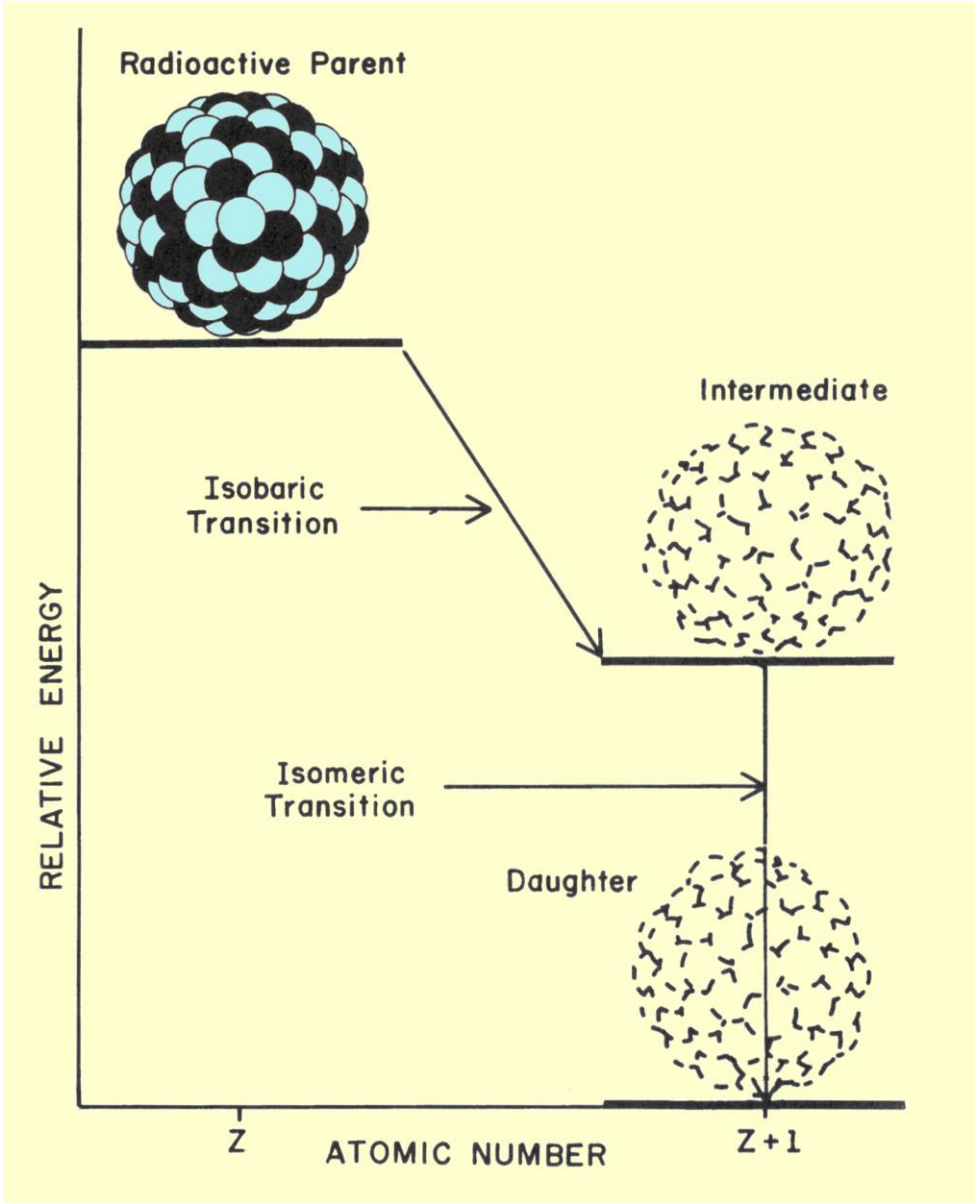


1.3. Gamma decay

Most excited nuclei have very short half-lives against gamma decay, but a few remain excited for as long as several hours.

The analogy with metastable atomic states is a close one. A long-lived excited nucleus is called an "*isomer*" of the same nucleus in its ground state.

For instance, The excited nucleus $^{87}_{38}Sr^{*}$ has a half-life of $T_{1/2} = 2.8\ h$ and is accordingly an isomer of $^{87}_{38}Sr$: $^{87m}_{38}Sr$



II. Radioactivity

2. Law of radioactive decay

The variation of nuclei number obey the following differential law:

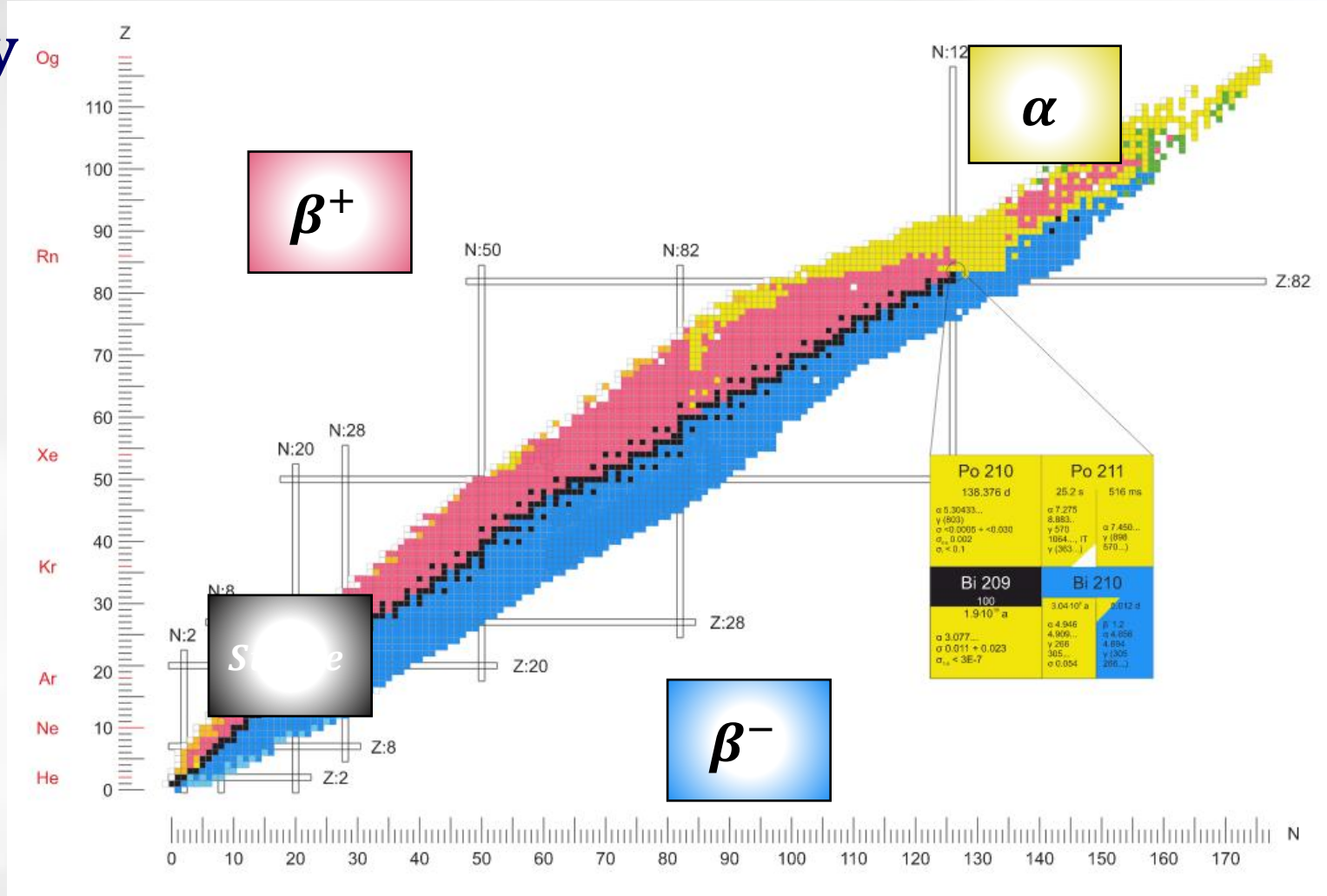
$$dN/dt = -\lambda N$$

After integration:

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_{0}^{t} dt \rightarrow N = N_0 e^{-\lambda t}$$

With the decay constant:

$$\frac{N}{N_0} = \frac{1}{2} = e^{-\lambda T_{1/2}} \rightarrow \lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

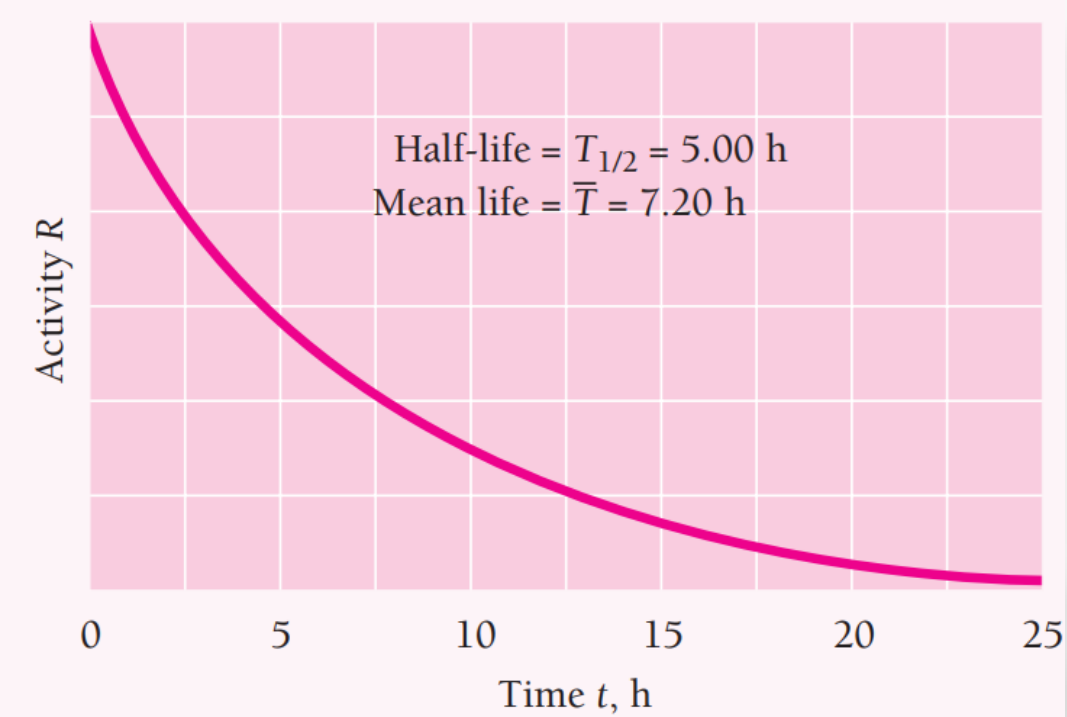


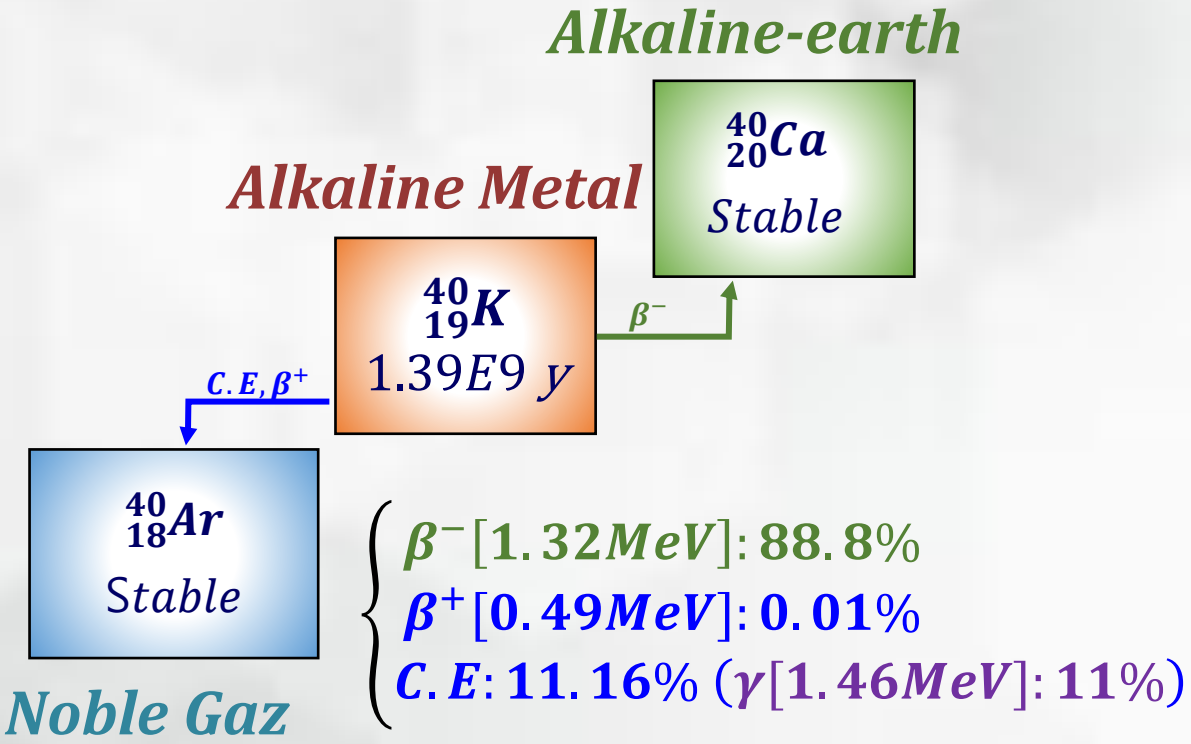
II. Radioactivity

2. Law of radioactive decay

Half life and mean life:

- $T_{1/2}$: is the time needed to reduce the number of radioactive nuclei to the half
- $\overline{T} = T_{1/2}/ln\ 2$: Is the time needed to reduce the number of radioactive nuclei to about 30%





II. Radioactivity

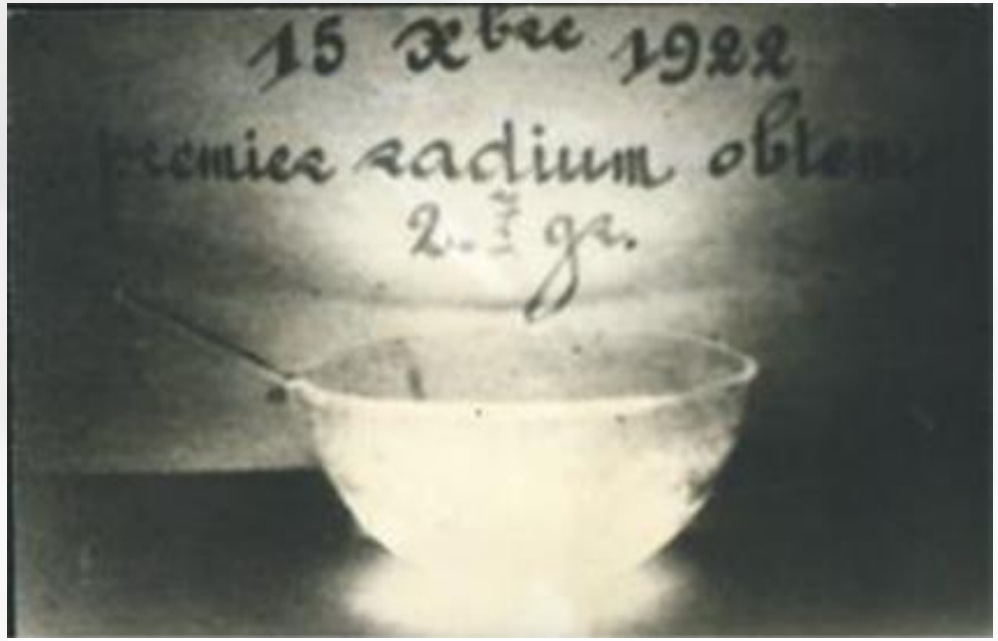
3. Radioactive activity

The activity of radioactive sample $A(t)$ is the rate at which the nuclei of its constituent atoms decay. It is given by:

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

Using $N = N_0 e^{-\lambda t}$ we obtain:

$$A(t) = -\frac{dN}{dt} = \lambda N = \lambda N_0 e^{-\lambda t}$$



The SI unit of activity is named after Becquerel: $1Bq = 1Bequerel = 1decay/s.$

The traditional unit of activity is used to be the curie (Ci), which was originally defined as the activity of 1 g of radium $(^{226}_{88}Ra)$*. Because the precise value of the curie changed as methods of measurement improved, it is now defined arbitrarily as:* $1Curie = 1Ci = 3.7 \times 10^{10}\ decay/s.$

4. Radioactive series

Most of the radionuclides found in nature are members of four radioactive series, with each series consisting of a succession of daughter products all ultimately derived from a single parent nuclide.

The reason that there are exactly four series follows from the fact that alpha decay reduces the mass number of a nucleus by 4. Thus the nuclides whose mass numbers are all given by $A = 4n$, where n is an integer, can decay into one another in descending order of mass number. The other three series have mass numbers specified by $A = 4n + 1$, $A = 4n + 2$, and $A = 4n + 3$. The members of these series, too, can decay into one another.

Mass number	Series	Parent	Half-life (years)	Stable end product
$4n$	Thorium	$^{232}_{90}Th$	1.39×10^{10}	$^{208}_{82}Pb$
$4n + 1$	Neptunium	$^{237}_{93}Np$	2.25×10^{6}	$^{209}_{83}Pb$
$4n + 2$	Uranium 238	$^{238}_{92}U$	4.47×10^{9}	$^{206}_{82}Pb$
$4n + 3$	Uranium 235	$^{235}_{92}U$	7.07×10^{8}	$^{207}_{82}Pb$

II. Radioactivity

4. Radioactive series

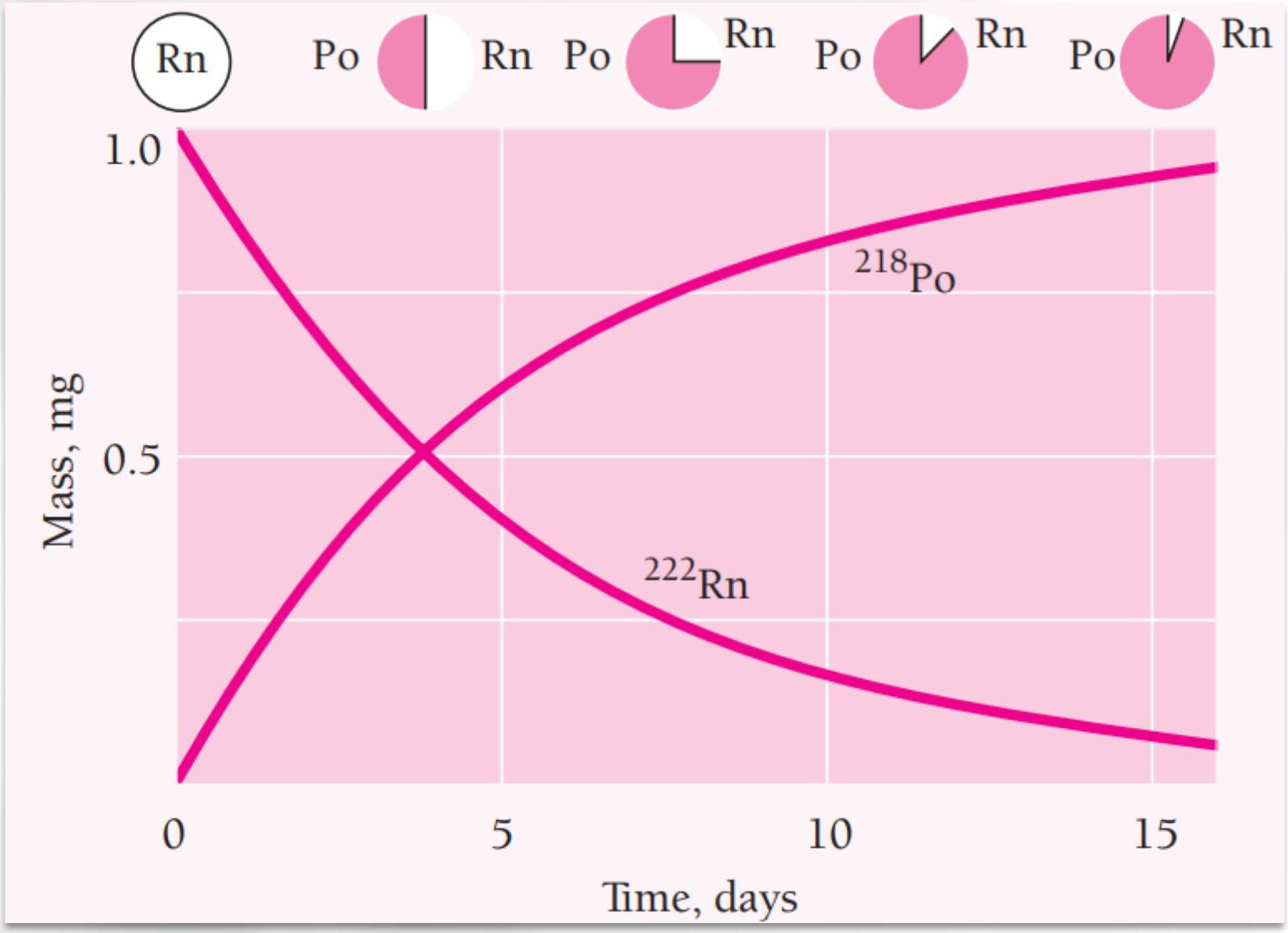
The most simple case in the radioactive series is the case where the parent (1) and daughter (2) nuclei are both radioactive.

In this case, it is easy to solve the differential equation system:

$$\begin{cases} dN_1/dt = -\lambda_1 N_1 \\ dN_2/dt = \lambda_1 N_1 - \lambda_2 N_2 \end{cases}$$

To find the solution of the form:

$$\begin{cases} N_1 = N_0 e^{-\lambda_1 t} \\ N_2 = \dfrac{\lambda_1 N_0}{\lambda_2 - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) \end{cases}$$



II. Radioactivity

4. Radioactive series

This could be generalized for a radioactive series with several radioactive successive daughter nuclei (like the U-series) and the number of nuclei for a daughter nucleus of order n is given by:

$$N_n = C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t} + \cdots + C_n e^{-\lambda_n t}$$

With:

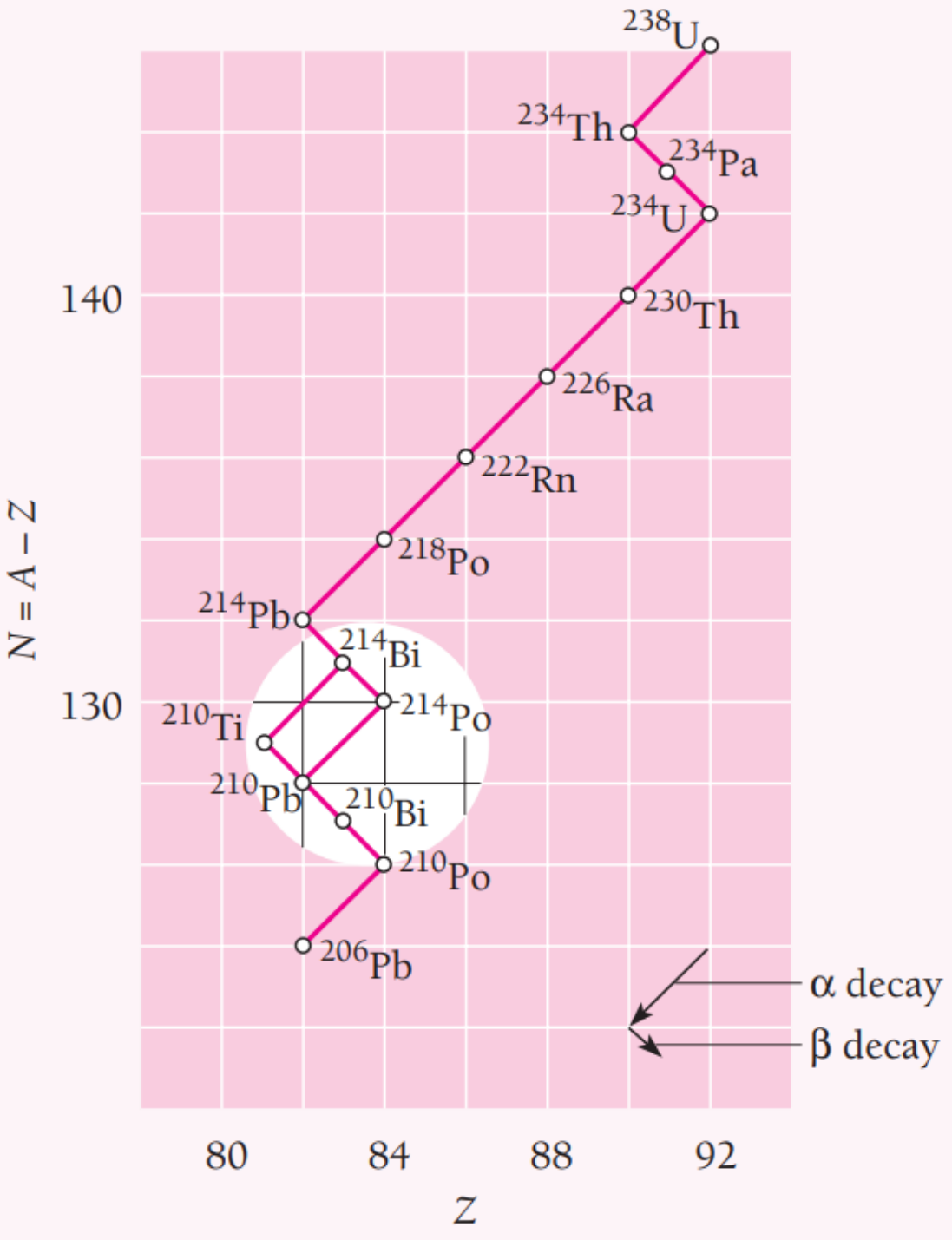
$C_i = \frac{K N_0}{\delta_i}$;

$K = \lambda_1 \lambda_2 \ldots \lambda_{n-1}$;

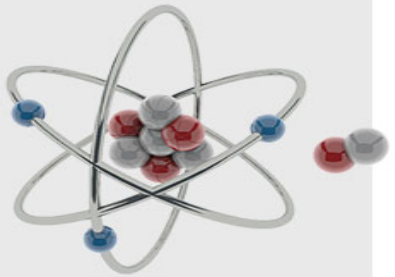
$\delta_i = (\lambda_1 - \lambda_i)(\lambda_2 - \lambda_i) \ldots (\lambda_n - \lambda_i)$

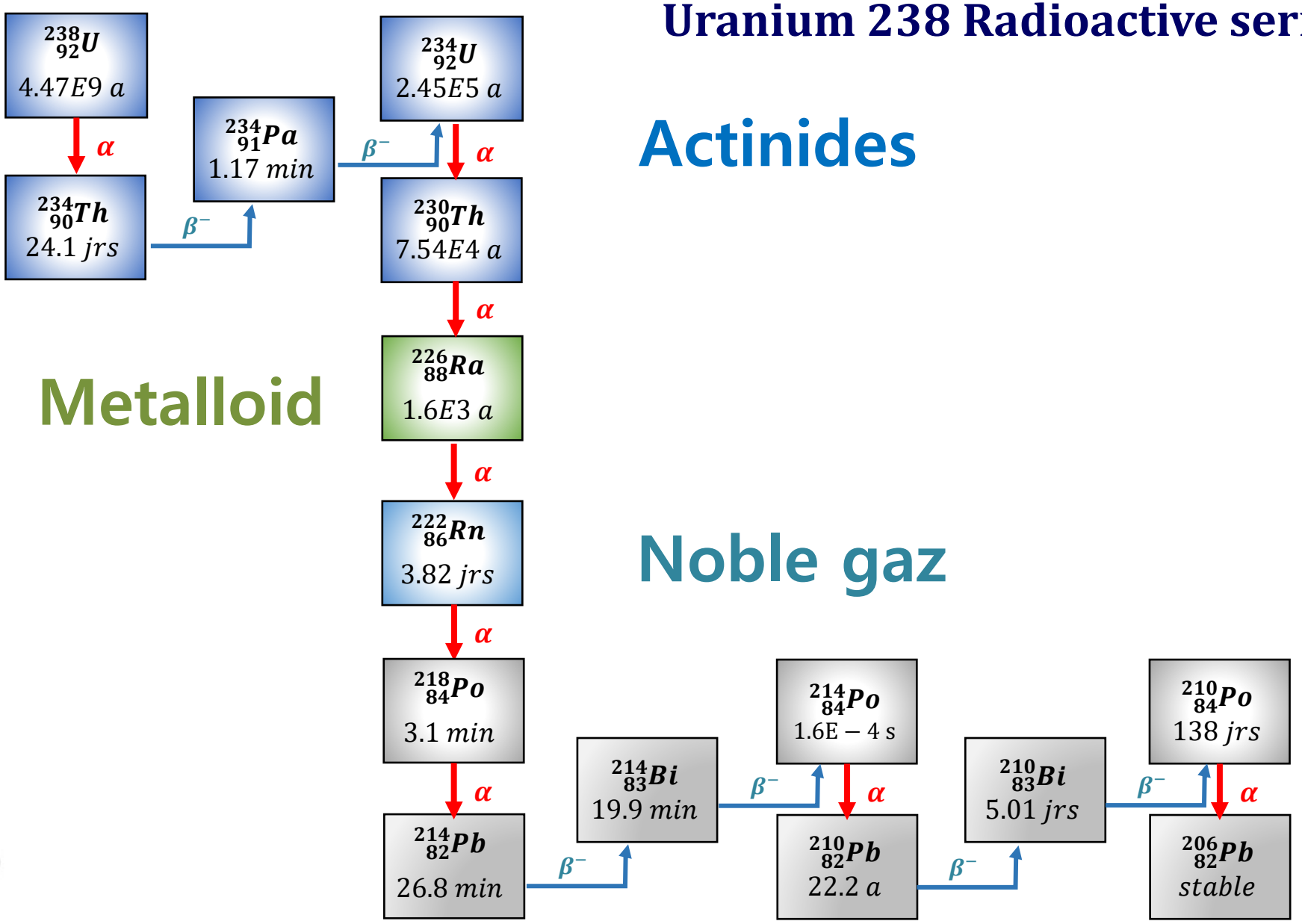
For a secular equilibrium (sufficient long period to obtain the equilibrium between all daughter nuclei of the same radioactive series), we get:

$$\lambda_1 N_1 = \lambda_2 N_2 = \lambda_3 N_3 = \cdots = \lambda_n N_n$$



Uranium 238 Radioactive series





Actinides

Metalloid

Noble gaz

post-transitional Metals

Radioactivity and the Earth

Most of the energy responsible for the geological history of the earth can be traced to the decay of the radioactive uranium, thorium, and potassium isotopes it contains. The earth is believed to have come into being perhaps 4.5 billion years ago as a cold aggregate of smaller bodies that consisted largely of metallic iron and silicate minerals that had been circling the sun. Heat of radioactive origin accumulated in the interior of the infant earth and in time led to partial melting. The influence of gravity then caused the iron to migrate inward to form the molten core of today's planet; the geomagnetic field comes from electric currents in this core. The lighter silicates rose to form the rocky mantle around the core that makes up about 80 percent of the earth's volume. Most of the earth's radioactivity is now concentrated in the upper mantle and the crust (the relatively thin outer shell), where the heat it produces escapes and cannot collect to remelt the earth. The steady stream of heat is more than enough to power the motions of the giant plates into which the earth's surface is divided and the mountain building, earthquakes, and volcanoes associated with these motions.

II. Radioactivity

1. Radiometric dating

Because the decay of any particular radionuclide is independent of its environment, the ratio between the amounts of that nuclide and its stable daughter in a specimen depends on the latter's age.

One of this radioelement used to date objects of biological origin is the radiocarbon, the beta-active carbon isotope ${}^{14}_{6}C$.

Radiocarbon has too many neutrons for stability and beta decays into ${}^{14}_{7}N$ with a half-life of about $T_{1/2} = 5760\ years$:

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \bar{\nu} $$

Although the radiocarbon decays steadily, the cosmic-ray bombardment constantly replenishes the supply. A total of perhaps 90 tons of radiocarbon is distributed around the world at the present time. When plants and animals die, however, they no longer take in radiocarbon atoms, but the radiocarbon they contain keeps decaying away to ${}^{14}_{7}N$.

This elegant method permits the dating of mummies, wooden implements, cloth, leather, charcoal from campfires, and similar artifacts from ancient civilizations as much as 50,000 years old, about nine half-lives of ${}^{14}_{6}C$.

II. Radioactivity

2. Geological dating

Radiocarbon dating is limited to about 50,000 years whereas the earth's history goes back toward 4.5 billion years. Geologists accordingly use radionuclides of much longer half-lives to date rocks. In each case it is assumed that all the stable daughter nuclides found in a particular rock sample came from the decay of the parent nuclide.

Although the thorium and uranium isotopes do not decay in a single step as do $^{40}_{19}K$ and $^{87}_{37}Rb$, the half-lives of the intermediate products are so short compared with those of the parents that only the latter need be considered.

If the number of atoms of a parent nuclide in a sample is N and the number of atoms of both parent and daughter is N_0, then :

$$t = \frac{1}{\lambda} ln\left(\frac{N_0}{N}\right)$$

The precise significance of the time t depends on the nature of the rock involved.

It may refer to the time at which the minerals of the rock crystallized, for instance, or it may refer to the most recent time at which the rock cooled below a certain temperature.

II. Radioactivity

2. Geological dating

The most ancient rocks whose ages have been determined are found in Greenland and are believed to be 3.8 billion years old. Lunar rocks and meteorites as well as terrestrial rocks have been dated by the methods cited below in the table. Some lunar samples apparently solidified 4.6 billion years ago, which is very soon after the solar system came into being.

Method	Parent Radionuclide	Stable Daughter Nuclide	Half-Life, Billion Years
Potassium-argon	^{40}K	^{40}Ar	1.3
Rubidium-strontium	^{87}Rb	^{87}Sr	47
Thorium-lead	^{232}Th	^{208}Pb	13.9
Uranium-lead	^{235}U	^{207}Pb	0.7
Uranium-lead	^{238}Pb	^{206}Pb	4.5

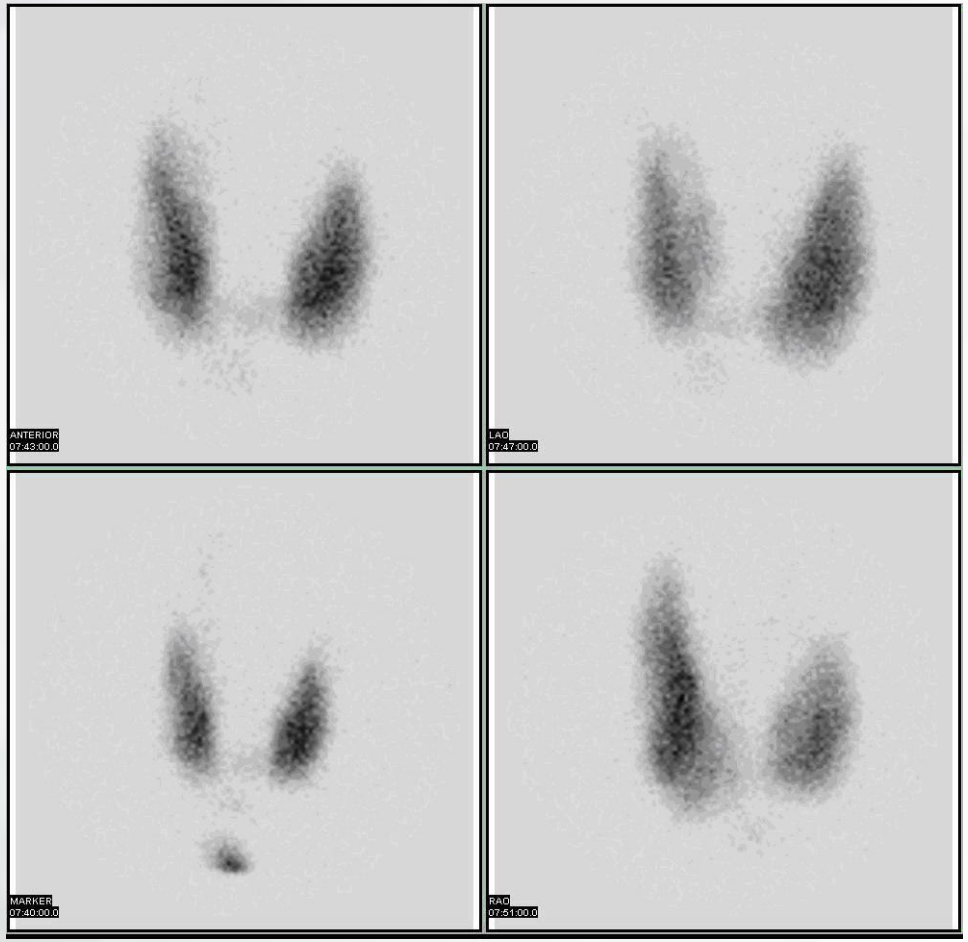
II. Radioactivity

3. Radio-tracers

Some radioactive isotopes are widely used as tracers because their decay activity is sufficiently detectable within short period. This includes a wide range of applications in medicine, including diagnostic and therapy (Chemotherapy).

One example of a diagnostic application is using radioactive Iodine-131 ($T_{1/2} \cong 8\,days$) to test for thyroid activity, (this organ has the most high concentration of iodine).

To evaluate thyroid activity (normal, hyperthyroidism or hypothyroidism), a measured dose of iodine-131 is administered to a patient, and the next day a scanner is used to measure the amount of radioactivity in the thyroid gland. Bones, the heart, the brain, the liver, the lungs, and many other organs can be imaged in similar ways by using the appropriate radioactive isotope.



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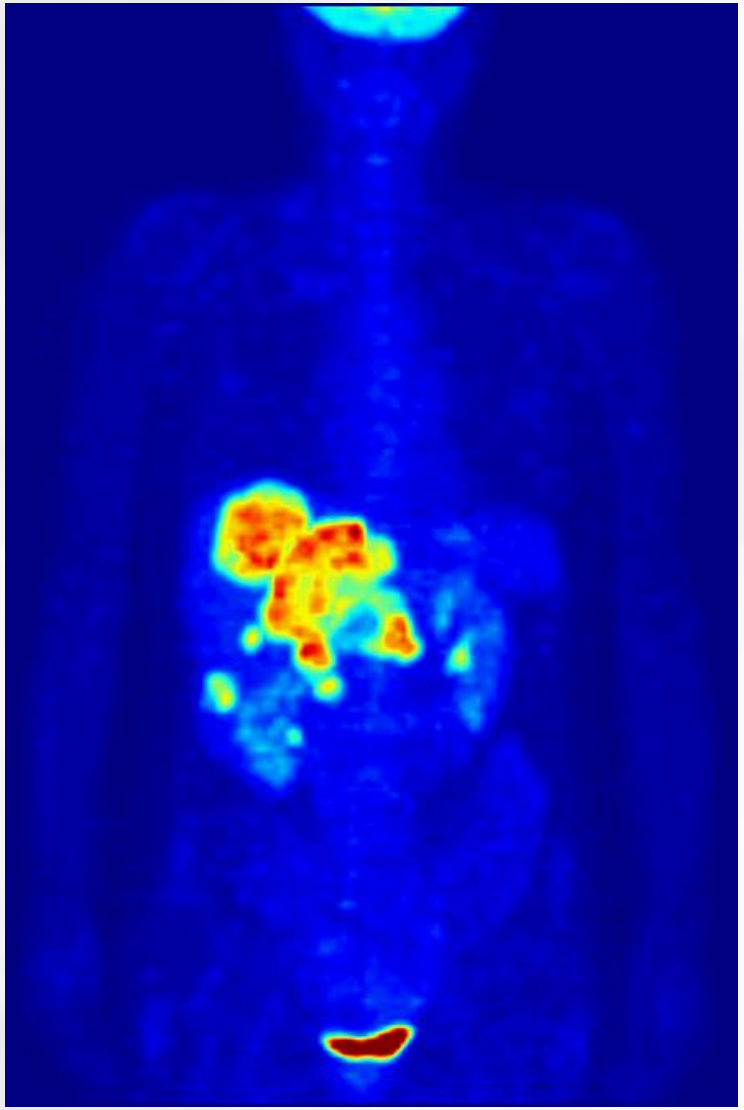
isotope	*Medical use*
${}^{32}_{15}P$	*cancer detection and treatment, especially in eyes and skin*
${}^{59}_{26}Fe$	*anemia diagnosis*
${}^{99m}_{43}Tc$	*brain, thyroid, liver, bone marrow, lung, heart, and intestinal scanning; blood volume determination*
${}^{133}_{54}Xe$	*lung imaging*
${}^{198}_{79}Au$	*liver disease diagnosis*

II. Radioactivity

3. Radio-tracers

One of the most sophisticated technique in medical imaging is known as Positron Emission Tomography (PET): which a functional imaging technique that uses radioactive substances known as radiotracers (positrons emitters, like $^{18}_{9}F$) to visualize and measure changes in metabolic processes, and in other physiological activities including blood flow, regional chemical composition, and absorption. Different tracers are used for various imaging purposes, depending on the target process within the body.



Isotopes used in PET scans

Isotope	^{11}C	^{13}N	^{15}O	^{18}F	^{68}Ga	^{64}Cu	^{52}Mn	^{55}Co	^{89}Zr	^{82}Rb
Half-life	20 min	10 min	2 min	110 min	67.81 min	12.7 h	5.6 d	17.5 h	78.4 h[47]	1.3 min

II. Radioactivity

1. Absorbed dose

When ionizing radiations ($E_{rad} \geq 13.6eV$) interact with matter, a partial or total radiation energy is transferred to the crossed volume.

To quantify this interaction, we define the absorbed dose of radiation per unit of mass :

$$D[Gy] = \frac{dE_{rad}[J]}{dm[kg]}$$

With usual unit $[Gray] \equiv [J/kg]$

The ancient unit of absorbed dose was:

$[rad]$: *Roentengen Absorbed Dose*

$$100[rad] = 1[Gy]$$

2. Dose rate

When the irradiation time is taken in consideration, the dose rate is calculated as:

$$\dot{D}[Gy/h] = \frac{dD[Gy]}{dt[h]}$$

Which is the quantity of radiation absorbed or delivered per unit time.

Bigger is the dose rate (time exposition), higher will be the involved risk of radiations.

II. Radioactivity

3. Equivalent dose

Since the Grey is defined with referential electromagnetic radiations (X-rays and Gamma rays), it is important to differentiate the effect of other radiations when compared to photonic ones: $\alpha, \beta,$ and $neutrons$. That's why an equivalent dose is considered which takes in consideration the nature of incoming radiations:

$$D_{eq} = H[Sv] = D[Gy] \times W_R$$

With :

$[Sievert] \equiv [Gray] \times W_R$

W_R: Radiation weight or radiation ponderation factor

The ancient unit of equivalent dose was:
$[rem]$:*Roentengen Equivalent Man*
$100[rem]=1[Sv]$

Radiation	Energy	W_R
Photons (X-rays, γ)	*The whole range*	**1**
Electrons (Beta)	*The whole range*	**1**
Neutrons	$< 100KeV$	**10**
	$100keV - 2MeV$	**20**
Alpha particles	*Internal absorb.*	**20**

II. Radioactivity

Dosimetry

4. Effective dose

The living tissues constituting the human body are not affected in the same way when exposed to the same radiation with the same energy.

This differentiation is taken into account when calculating the effective dose, where the tissue nature is considered. For a given tissue:

$$E_i[Sv] = H \times W_{Ti} = D \times W_R \times W_{Ti}$$

When the whole or a part of the human body is exposed, the effective absorbed dose is obtained by the sum:

$$E[Sv] = \sum_i E_i = \sum_i H \times W_{Ti}$$

Organ/Tissue	W_T
Stomach	0.12
Colon	0.12
Lung	0.12
Bone Marrow (red)	0.12
breast	0.12
gonads	0.08
urinary bladder	0.04
liver	0.04
thyroid	0.04
esophagus	0.04
Remainder tissues	0.12
bone surface	0.01
skin	0.01
brain	0.01
salivary glands	0.01
$\sum$	1.00

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II. Radioactivity

5. Radiation Hazards

The various radiations from radionuclides ionize matter through which they pass. X-ray ionize matter, too. All ionizing radiation is harmful to living tissue, although if the damage is slight, the tissue can often repair itself with no permanent effect. Radiation hazards are easy to underestimate because there is usually a delay, sometimes of many years, between an exposure and some of its possible consequences.

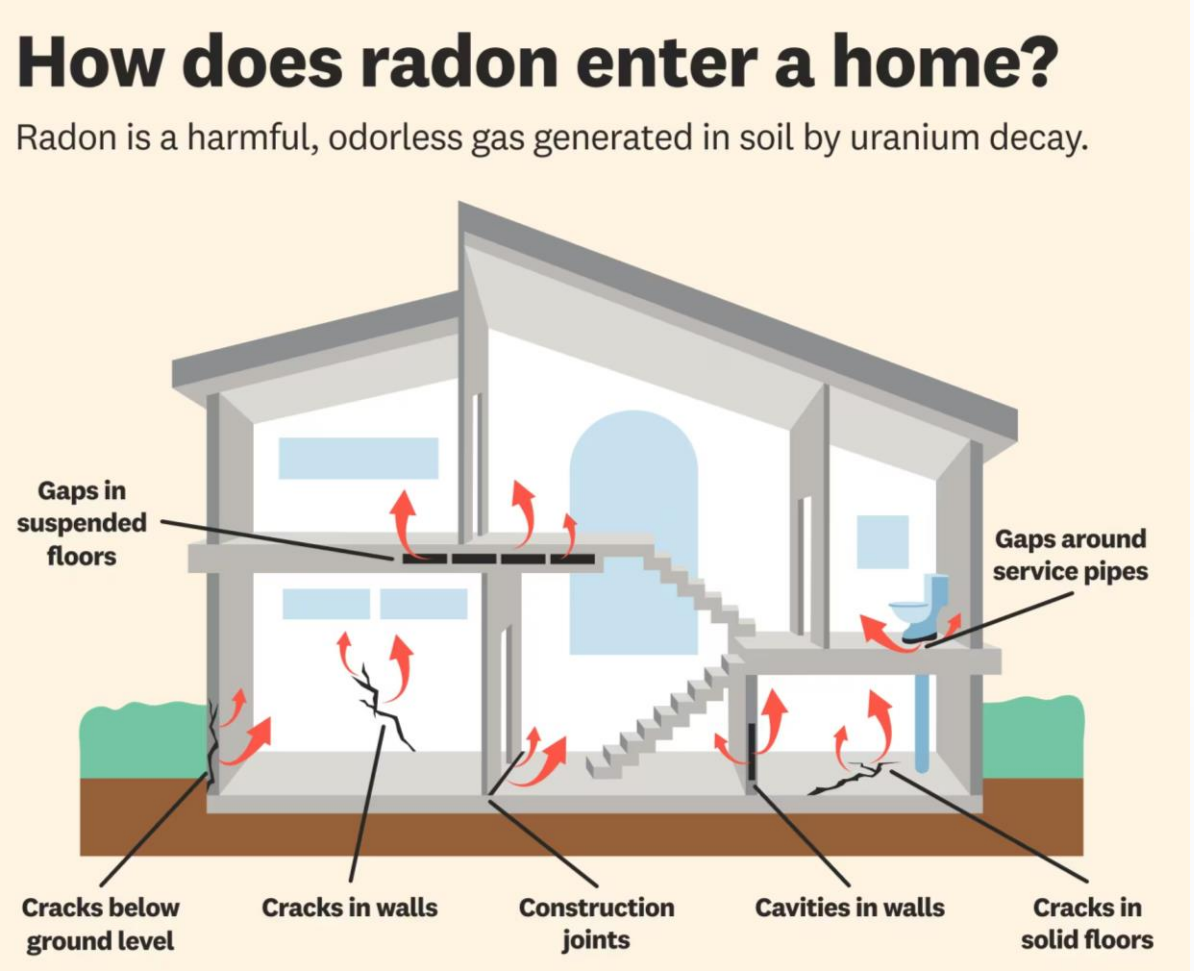
These consequences include cancer, leukemia, and changes in the DNA of reproductive cells that lead to children with physical deformities and mental handicaps

The International Commission on Radiation Protection estimates an average risk factor of $0.05\ Sv^{-1}$. This means that the chances of dying from cancer as a result of radiation are 1 in 20 for a dose of $1\ Sv$, 1 in 20,000 for a dose of $1\ mSv$, and so on.

II. Radioactivity

5. Radiation Hazards

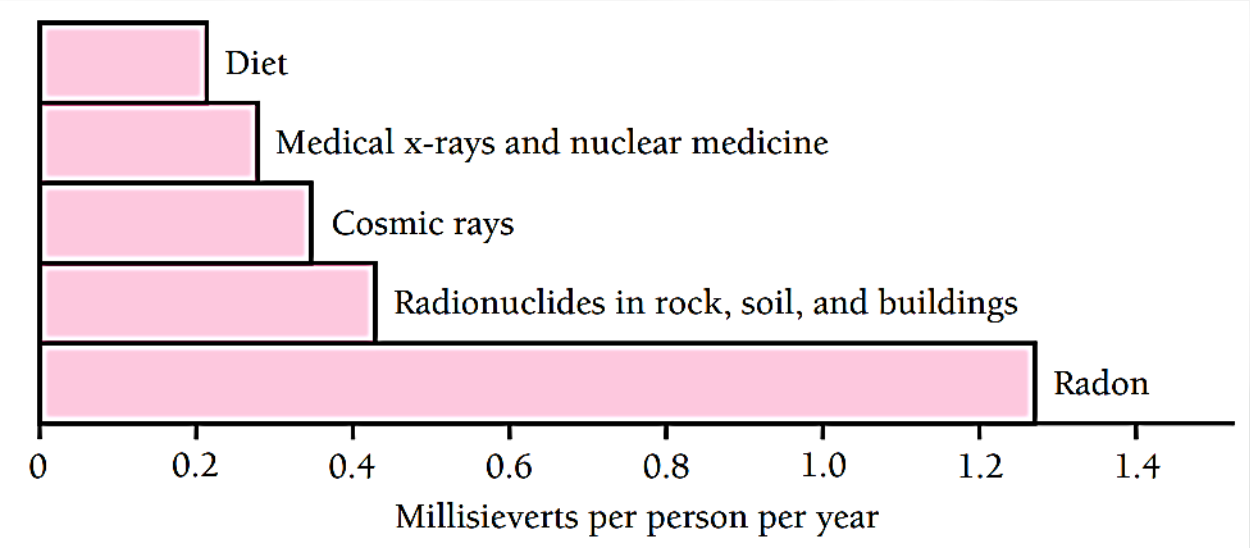
The most important single source is the radioactive gas radon, a decay product of radium whose own origin traces back to the decay of uranium. Uranium is found in many common rocks, notably granite. Hence radon, colorless and odorless, is present nearly everywhere, though usually in amounts too small to endanger health. Problems arise when houses are built in uranium-rich regions, since it is impossible to prevent radon from entering such houses from the ground under them.



II. Radioactivity

5. Radiation Hazards

Other natural sources of radiation dosage include cosmic rays from space and radionuclides present in rocks, soil, and building materials. Food, water, and the human body itself contain small amounts of radionuclides of such elements as potassium and carbon.



- ***Many useful processes involve ionizing radiation. Some employ such radiation directly, as in the x-rays and gamma rays used in medicine and industry.***
- ***In other cases the radiation is an unwanted but inescapable byproduct, notably in the operation of nuclear reactors and in the disposal of their wastes.***
- ***In many countries the dose limit for workers (about 9 million worldwide) whose jobs involve ionizing radiation is 20 mSv per year.***
- ***For the general public, which has no choice in the matter, the dose limit for no-background radiation is 1 mSv per year***

5. Radiation Hazards

- An appropriate balance between risk and benefit is not always easy to find where radiation is concerned.
- This seems particularly true for medical x-ray exposures, many of which are made for no strong reason and do more harm than good.
- Particularly dangerous is the x-raying of pregnant women, until not long ago another "routine" procedure, which dramatically increases the chance of cancer in their children.
- Of course, x-rays have many valuable applications in medicine. The point is that every exposure should have a definite justification that outweights the risk involved.
- An ordinary chest x-ray using modern equipment involves a radiation dose of about 0.017 mSv, much less than in the past.
- However, a CT chest scan (Sec. 2.5) involves the considerable dose of 8 mSv. CT scans of children pose especially serious risks and need equally serious justification

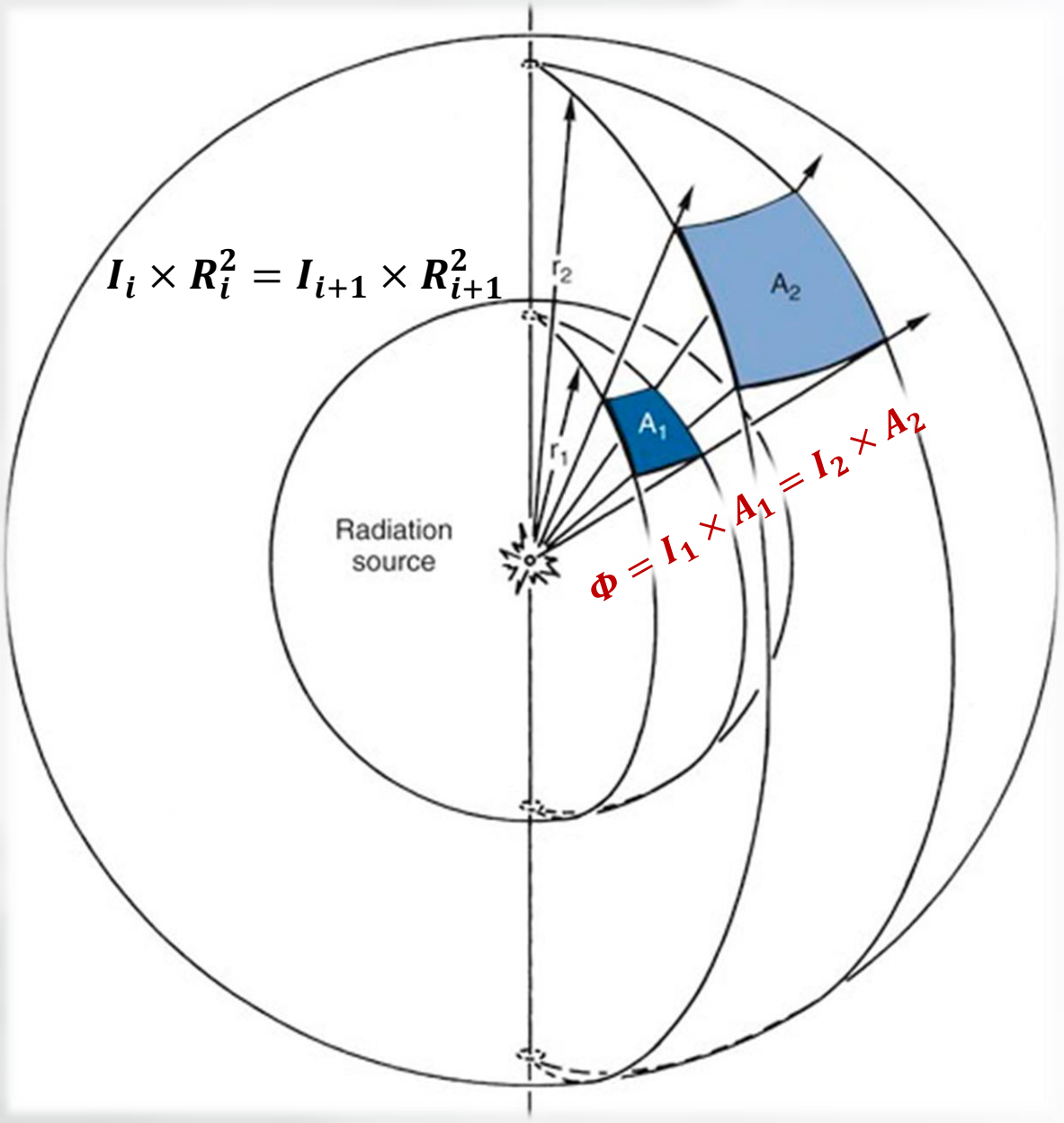
II. Radioactivity

1. Geometrical attenuation

To avoid a high exposure to ionizing radiations, it is important to protect ourselves from being exposed either for higher fluxes or for longer period time.

The most basic rule to prevent the high exposure to radiations is to run away from the radiation source. This is could be explained by the geometrical attenuation of the flux intensity as shown in the case of isotropic emission of a point source, Since $R_{i+1} > R_i$:

$$I_{i+1} \ll I_i$$

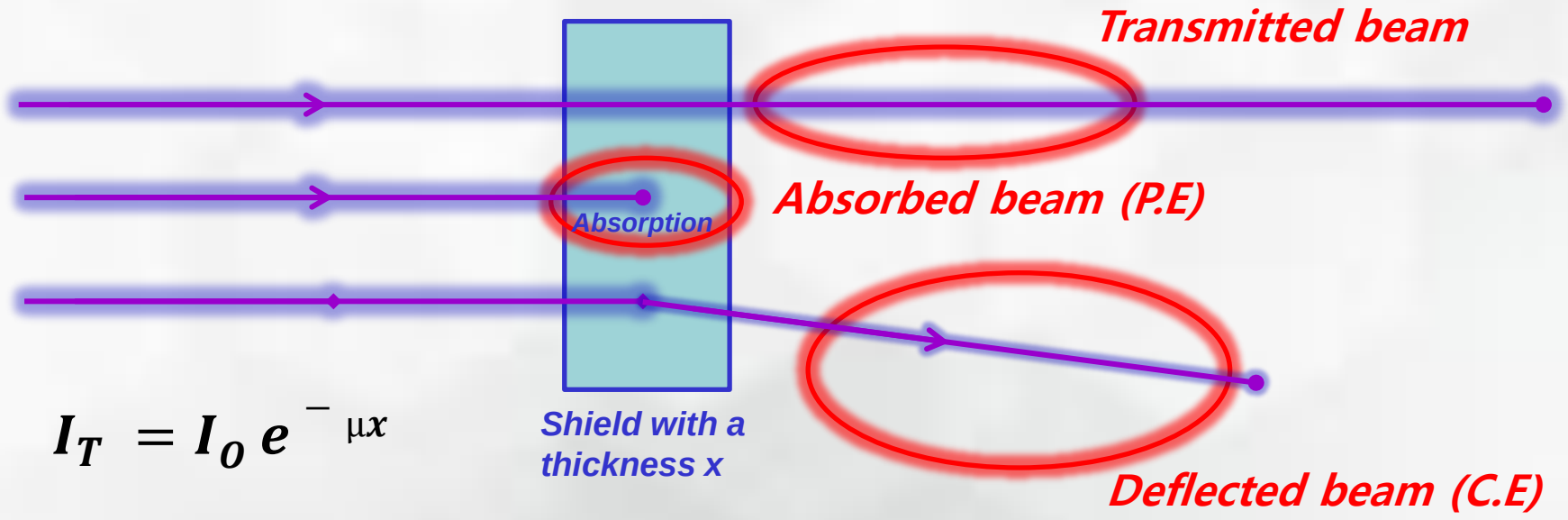


II. Radioactivity

2. Physical attenuation

Let's examine the case of the interaction of photons with matter. Three main interactions (P.E, C.E, P.C) will be translated by the following radiation beam components:

1. ***Transmitted beam: Passing photons through matter without interaction***
2. ***Absorbed beam: Photons are totally absorbed in the matter (final Photoelectric Effect)***
3. ***Deflected beam: Photons interact with matter and change their directions when getting out (Compton Effect)***



$$I_T = I_0 e^{-\mu x}$$

II. Radioactivity

2. Physical attenuation

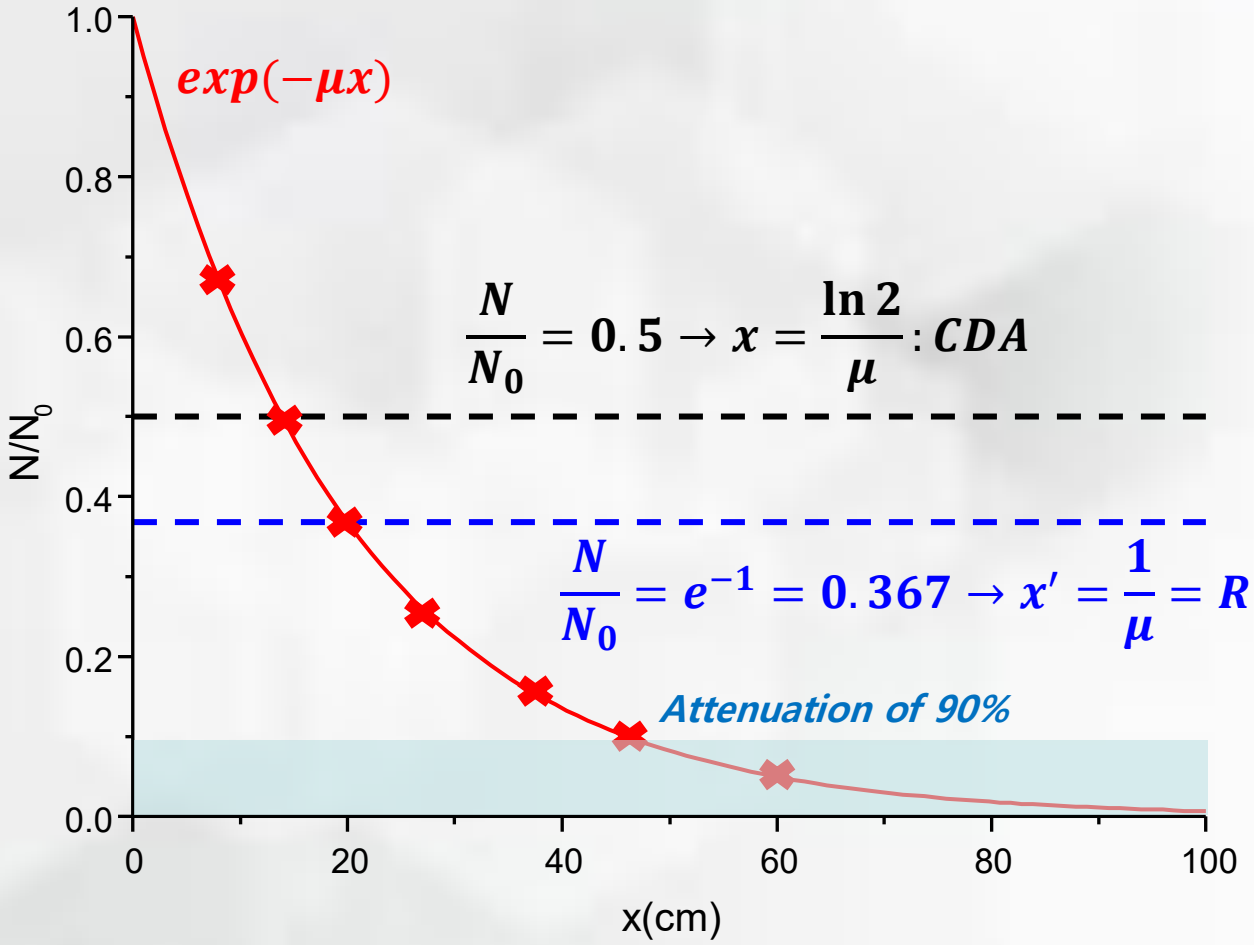
The physical attenuation of electromagnetic radiations depends on the different modes of photon-matter interaction: Photoelectric Effect, Compton Effect, and Pair creation.

The probability of interaction for each mode is given by its interaction cross-section σ_i. Thus, the total probability of photon interaction with the matter, including all possible modes:

$$\sigma_{TOT} = \sigma_{PE} + \sigma_C + \sigma_{CP}$$

For a given material with atomic density $n\left[\frac{atoms}{cm^3}\right]$, an attenuation factor is defined:

$$\mu = n\sigma_{TOT}[cm^{-1}]$$



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Mass attenuation factor could be also used:

$$\mu_m[cm^2.g] = \frac{\mu[cm^{-1}]}{\rho[g.cm^{-3}]}$$

1MeV	Pb	Fe	eau	béton ordinaire
μ (cm^{-1})	0,79	0,47	0,07	0,15
CDA (cm)	0,88	1,47	9,90	4,62
R (cm)	1,26	2,12	14,28	6,66
ρ ($g.cm^{-3}$)	11,30	7,85	1,00	2,30

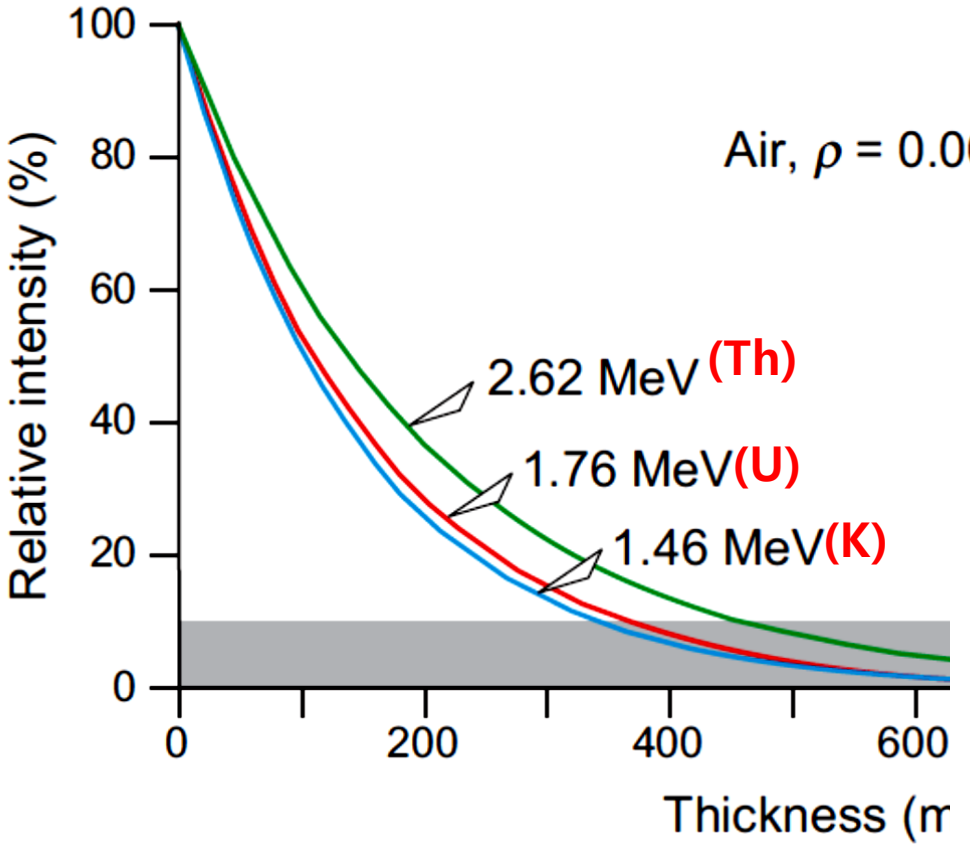
The attenuation factor is a function of:

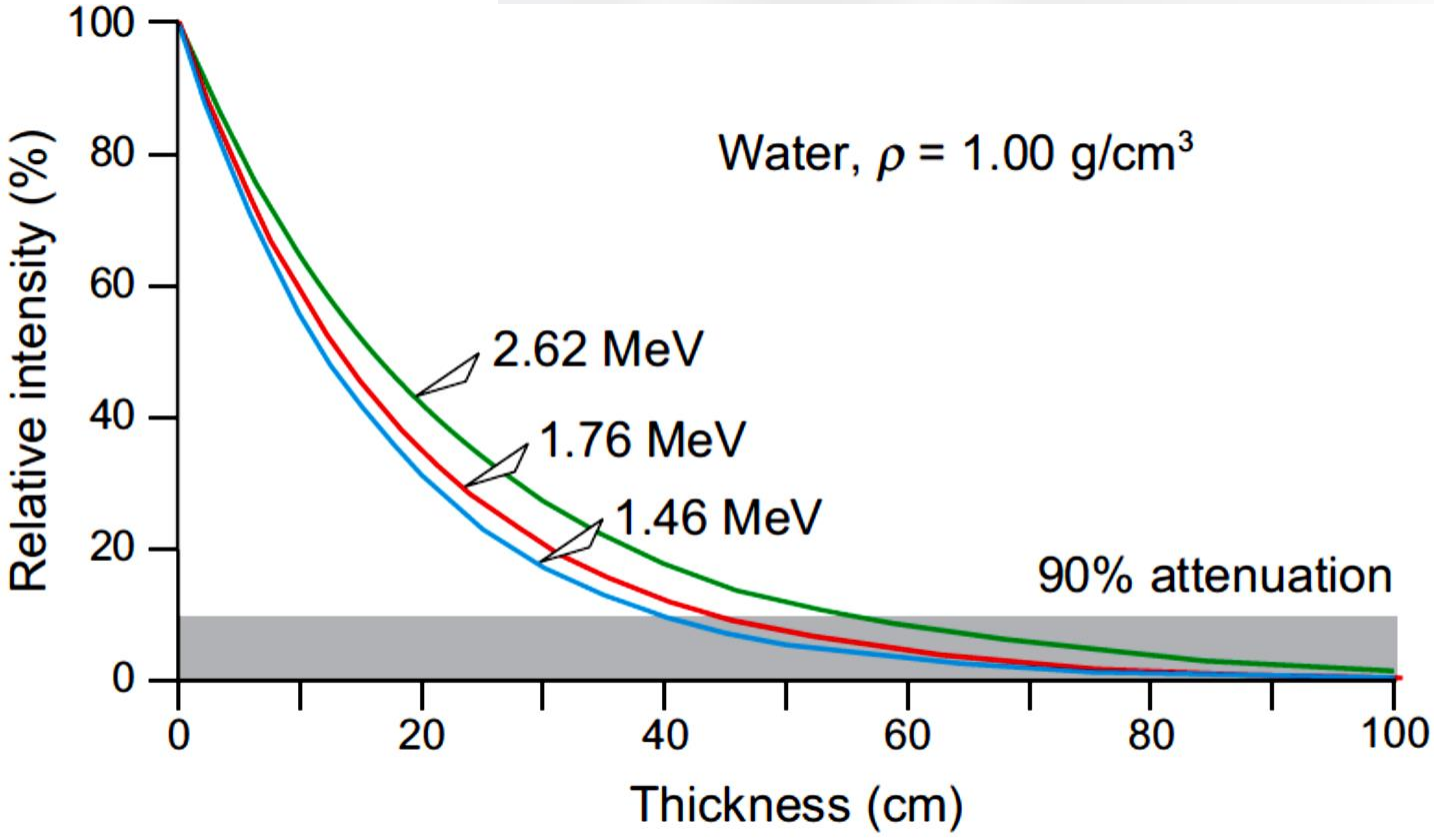
- *the energy of incoming radiation*
- *the elemental constitution of the target*
- *the density of the target*

$$\mu = f(E_{rad}, material)$$

II. Radioactivity

2. Physical attenuation





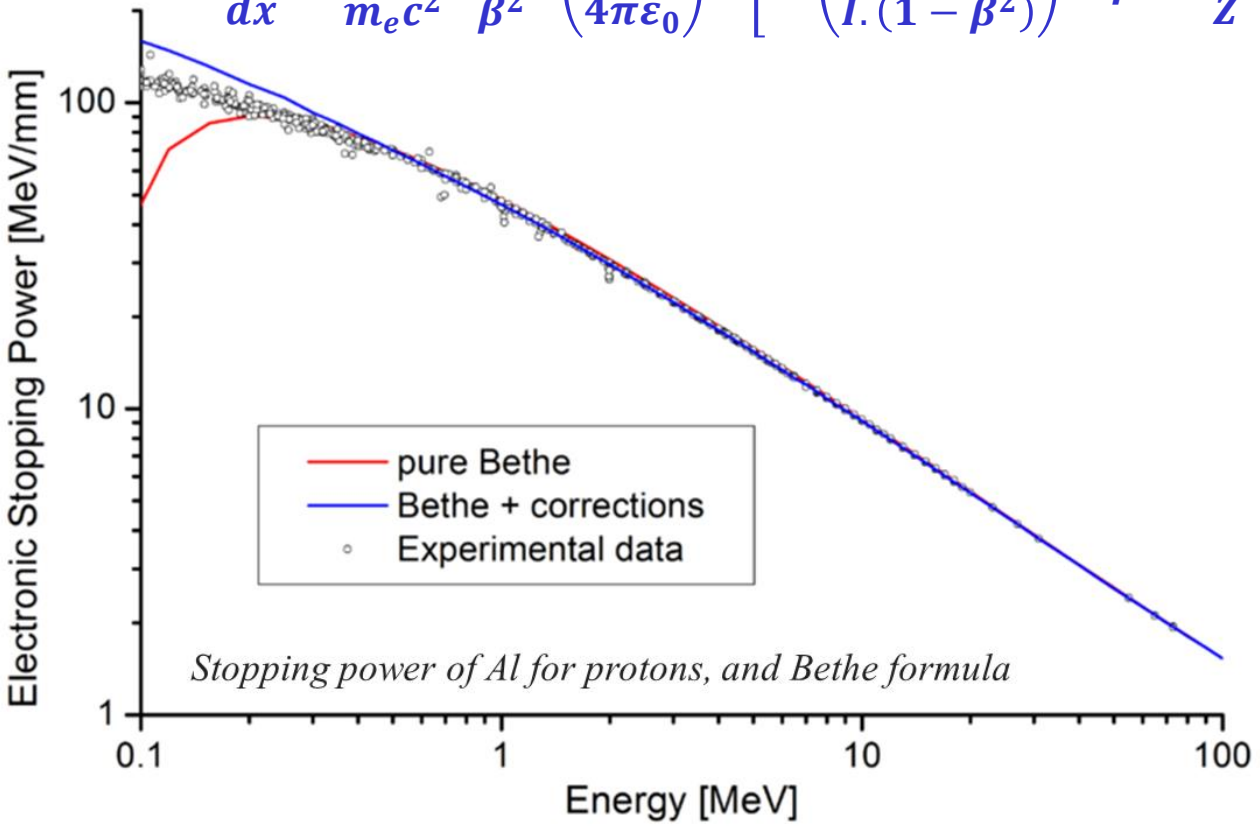
II. Radioactivity

3. Other radiations

The charged particle like α and β interact promptly with matter due to the Coulomb interaction law. They loose most of their energy when entering material medium on specific range of few:

- Microns for α
- Millimeters for β

$$-\frac{dE_c}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[ln\left(\frac{2m_e c^2 \beta^2}{I.(1-\beta^2)}\right) - \beta^2 - \frac{C}{Z} - \frac{\delta}{2}\right]$$



II. Radioactivity

3. Other radiations

Whereas, neutrons interact at nuclear levels with constituting nuclei with different modes:

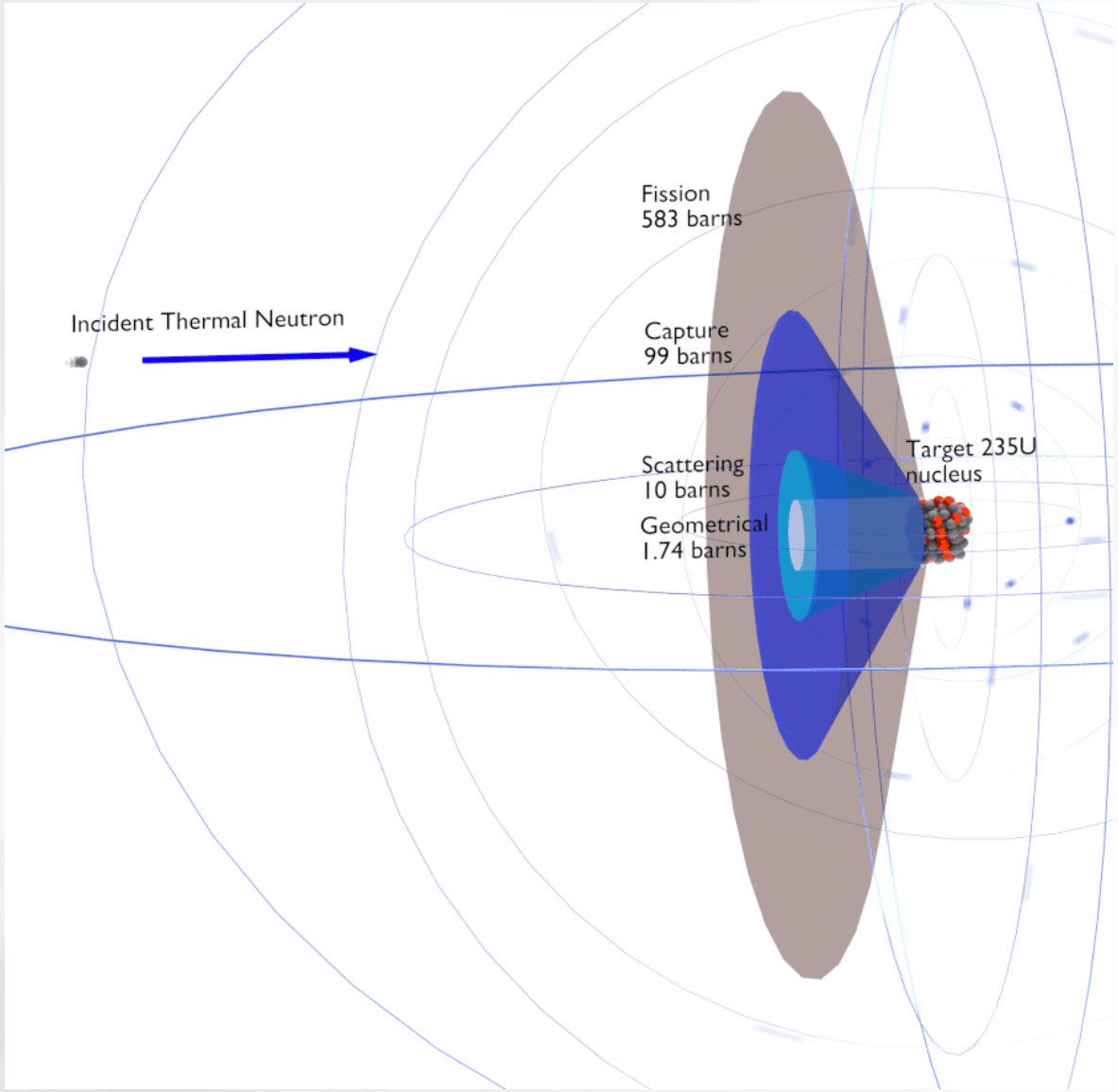
- Elastic Scattering (n, n)
- Non-elastic Scattering (n, n')
- Capture (n, γ)
- Fission $(n, FP + n)$

All the above contribution will provide the total probability of neutron-matter interaction:

$$\sigma_{TOT} = \sigma_S + \sigma_{inel} + \sigma_C + \sigma_f$$

We should notice that :

$$\sigma \equiv f(E_n, interaction, nucleus\ target)$$



II. Radioactivity

4. Shielding