Modern Physics

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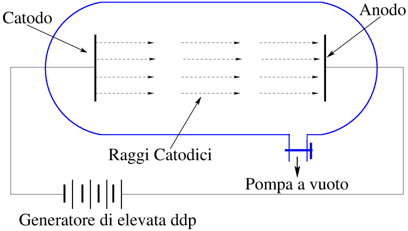
DIMES

Atomic model

Electron discovery



- Electric discharges in gas (end 1800): glass ampoule with little gas and two electrodes: **Cathode** and **Anode**.
- High ΔV between the two electrodes generates a **bright spot** at the anode, controllable by collimators
- hypothesis of propagation of **cathode rays**.
- Electric and magnetic fields modify the spot by deflection of the cathode rays ⇒ particles with negative charge
- Determination of the charge/mass ratio; the term **electron** is coined

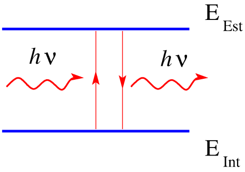
Atomic nucleus discovery

- In the early 1900s Ernest Rutherford led the famous experiment with which he proved the existence of the atomic nucleus.
- In this experiment, a very thin gold plate was targeted with α particles
- α particles (helium nuclei composed of two protons and two neutrons) have a mass thousands of times greater than that of the electron.
- part of the α particles were not deflected, and that only a small part was deflected or even bounced back
- this proved the existence of a central zone in atoms with a very high density surrounded by a large, substantially “empty” region: **the atomic nucleus**

Atomic models

- Thomson’s model, defined as “panettone”, since the atom is represented as an extended mass with “immersed” the electrons (like the raisins in the panettone, in fact)
- Rutherford “planetary” model, developed according to its experimental observations, in which around a positive nucleus the electrons rotate like satellites around a planet.
- Bohr model “quantum”, not directly interpretable with analogies of classical macroscopic phenomena such as the orbits of the planets (but still semiclassical), which however foresees that the electronic “orbits” are in discrete number with energy values precise.

Discrete energy states



- The electron absorbs energy (photons) when it passes from an orbit closer to one furthest from the nucleus, while in the opposite case it emits energy

$$\Delta E = E_n - E_m$$

- These exchanges of energy that move the electron from one orbit to another are therefore discrete and with precise values that depend on the difference in energy between the two orbitals.
- If we supply the atom with a lower amount of energy, $E < \Delta E$, there is no orbital transition.

Quantum Mechanics

- The period in which the greatest number of changes in Physics occurred was in the first twenty years of the twentieth century.
- Dual nature of light and particles (wave-particle dualism, wave properties to matter and corpuscular to energy).
- Shrodinger equation: *wave function* for the electron or proton, the module to the square gives the chance to observe an electron in a certain orbit with some energy and momentum.

Quantum Mechanics

- The Shrodinger equation is a fundamental equation for physics, comparable to the Newton equation $F = ma$ in classical mechanics.
- We pass from a description **deterministic** of natural phenomena to a **probabilistic** description in which for an object it is only possible to estimate the probability of being in a certain state
- for example to a moving object it is not possible to associate precisely at the same time position, velocity and acceleration (uncertainty principle).

Photons

- material wave (De Broglie material waves) and corpuscular energy (photons).
- Electromagnetic waves; energy packs, **photons** (γ).
- Amount of energy transported: classically with continuous values (like amplitudes).

$$E \propto A^2$$

- In quantum mechanics, on the other hand, the energy of a wave is given by the sum of the energies of the single photons, each with an energy directly proportional to the oscillation frequency:

$$E_\gamma = h\nu$$

- This law was verified by the photoelectric effect experiment (Einstein)

Photoelectric effect

- Some materials, if irradiated with electromagnetic waves, emit electrons.
- By irradiating with electromagnetic waves of different frequencies and intensities it is observed that if the frequency is lower than a threshold value, there is no electron emission, regardless of the intensity of the wave;
- if the frequency exceeds the threshold the electron emission (amuont of electrons) returns to be proportional to the intensity of the wave.
- if one measures the initial kinetic energy of each electron, it does not depends on the wave intensity but only on the frequency

Photoelectric effect

- The explanation is of a quantum nature: if the energy (frequency) of every single photon E_γ is lower than the ΔE_e energy of extraction $E_\gamma = h\nu < \Delta E_e = h\nu_C$ no emission is observed.
- if instead $E_\gamma > \Delta E_e$, the number of electrons emitted depends on the number of incident photons, proportional to the intensity of the wave.
- The higher the frequency, the greater the energy carried by each single photon, and therefore the greater the effects.

Atomic Nuclei

Atomic nuclei properties

- Rutherford proves experimentally that, at the center of each atom, there is a very small, positive nucleus, with a slightly lower mass than that of the entire atom.
- Since the atoms are electrically neutral, an atom containing Z electrons must have a charge core of $+Ze$
- Atoms described like miniature “solar systems” where around Z negative electrons rotate around the orbits around the nucleus.
- The atom is about $10^{-10}m$ and the nucleus $10^{-14}m$
- if you enlarge a nucleus to give it mass and size of the sun, the mass of electrons would become about that of the earth and their distance from the sun about 10 times that of the most distant planets in the solar system: atoms are practically “empty”.

Atomic nuclei properties

- The mass of a nucleus grows with its charge, but (1913, JJ Thomson) the atoms of a given chemical species do not all have the same mass, but they have nuclei of different mass and of equal charge called “isotopes”.
- In each nucleus there are “protons” +, and zero charge neutrons.
- Protons and neutrons have almost equal masses about 2000 (1836) times that of the electron.

$$m_P = 1.6726 \times 10^{-27} kg = 938.256 MeV$$

$$m_N = 1.6749 \times 10^{-27} kg = 939.550 MeV$$

Isotopes

- The isotopes of a particular chemical species have the same number Z of protons (equal to the number of electrons), but different number N of neutrons.
- Z is called *atomic number*, $A = N + Z$ is called *atomic mass number*.
- A nucleus is identified by the symbol of the chemical element corresponding to its charge Z, with apex its mass number A.
- Example: Li^7 indicates a nucleus with $Z = 3$ (Lithium), $A = 7$ and then $N = A - Z = 4$.

Isotopes

- Isotopes have the same atom symbol, but different mass numbers A.
- C^{10}, C^{11}, C^{12}, C^{13}, C^{14}, C^{15} are the different carbon isotopes ($Z = 6$)
- The protons and neutrons of the nuclei are held together by very intense forces (**strong interactions**)
- this overhang the electrostatic repulsion between charges of the same sign.
- it is necessary to perform some work to reduce a nucleus to all its constituents sufficiently far from each other to be unaffected by the forces of mutual attraction.

mass defect and nuclear bonding energy

- If we measure the mass of an atomic nucleus, we observe that it is less than the sum of the masses of its individual isolated constituents (protons and neutrons).
- The reason for this lies in Einstein's famous report: $E = mc^2$
- E and m are the energy and mass of a particle and c is the speed of light in a vacuum.
- Mass is a form of energy, and vice versa: if we have to provide energy to separate the constituents of a nucleus, then the mass of the separated constituents will be greater than the mass of the nucleus, which is given by the mass of the constituents plus the mass "(negative) energy of binding".

mass defect and nuclear bonding energy

- For a core of Z mass protons m_P and N mass neutrons m_N the mass of the separated constituents is $Zm_P + Nm_N$.
- The mass difference $\Delta m = Zm_P + Nm_N - m_{nucleus}$ takes the name of "mass defect".
- For example, the C^{12} mass is $19.921 \times 10^{-27} kg$.
- This core is composed of 6 protons and 6 neutrons, so $6m_P + 6m_N = 20.085 \times 10^{-27} kg$
- from which $\Delta m = 1.7 \times 10^{-28} kg$.
- The equivalent of Δm in terms of energy is worth $E = \Delta mc^2$ and takes the name of "nuclear bonding energy"

Energy measures

- To measure the energies of nuclear processes, we use the electron-Volt (eV)
- the eV is energy acquired by an electron accelerated by the potential difference of 1 V; $e = 1.6 \times 10^{-19}C$,
- $1eV = 1.6 \times 10^{-19}J$).
- Some multiples of the eV are in common use in nuclear physics, and also in medicine when we refer to the production of X-rays:
  - keV ($10^3 eV$)
  - MeV ($10^6 eV$)
  - GeV ($10^9 eV$)

Energy measures

- In the Large Hadron Collider (LHC) accelerator at CERN in Geneva it is possible to obtain collisions between protons with energies of the order of TeV , that is $10^{12}eV$.
- Using $E = mc^2$ to convert mass into energy, the energy associated with the proton is given by:

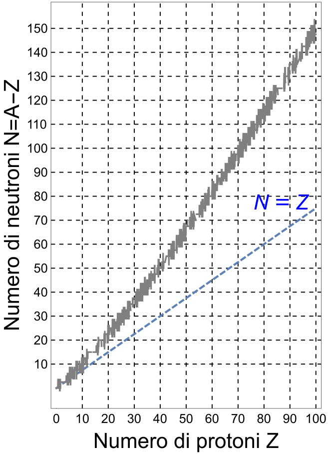
$$\begin{aligned} E_{Prot} &= 1.6726 \times 10^{-27}kg \times 9 \times 10^{16}m/s \\ &= 14.4 \times 10^{-11}J \\ &= 9 \times 10^{8}eV = 900MeV \end{aligned}$$

nuclear stability

- The binding energy of a nucleus determines its stability
- a nucleus is stable with respect to its subdivision into two or more fragments when its mass is less than the sum of the masses of the fragments.
- A nucleus is “stable” if its mass is less than the sum of the masses of the fragments for any possible fragmentation.

nuclear stability

- Distribution of stable nuclei in terms of N and Z.
- While for the lighter elements $N \approx Z$, as Z increases, N is always larger than Z.
- For example, for Z = 10, $N \approx Z$ while for Z = 70, N = 100.
- This neutron excess is necessary to balance the electrostatic repulsion between protons.



Radioactive Decay

Radioactive decay

- When stability conditions are not verified, a nucleus is unstable and decays into two or more fragments.
- The decay does not happen instantaneously, there is a finite probability that it decays in a given time interval.
- Said λ the probability per unit of time that a nucleus decays, if you have N nuclei, the number of those that decay over time dt is equal to the dN decrease of N, ie :

$$dN = -N\lambda dt$$

Radioactive decay

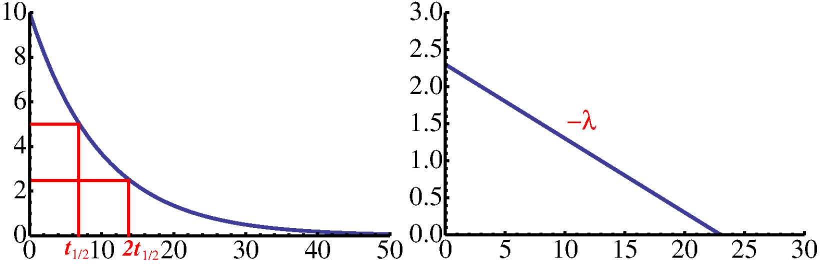
- from this the exponential decay law is obtained:

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

- where N_0 is the number of cores initially present (initial condition), and $N(t)$ the number of nuclei remaining after a time t.
- We define "average life" τ of a nucleus, the inverse of probability of decay per unit of time: $\tau = 1/\lambda$ and then:

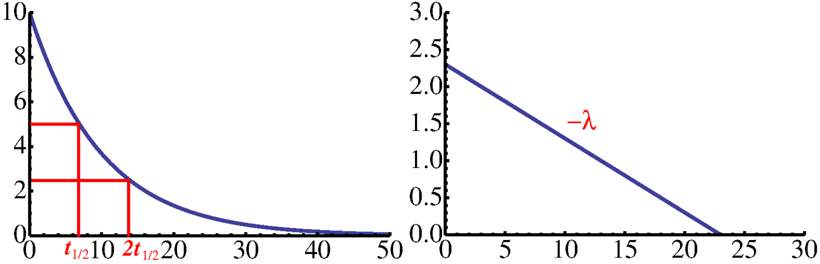
$$N(t) = N_0 e^{-t/\tau}$$

Radioactive decay



- Law of radioactive decay in linear and logarithmic scale on the y axis.
- The decay products can be:
  - heavy particles (α)
  - electrons ($\beta^- \ \beta^+$)
  - photons (γ) rays.

Radioactive decay



- The average life is the time when N_0 nuclei are reduced to N_0/e.
- Average lives vary between 10^{-6} s to 10^{14} years.
- The **half-life** $t_{1/2}$ is the time when N_0 nuclei are reduced to $N_0/2$.
- The link between $t_{1/2}$ and τ is:

$$t_{1/2} = \tau log(2) = 0.69\tau.$$

Heavy particles emission (α)

- The nuclei can decay by emitting particularly stable heavy particles, above all particles α (that is, nuclei of He^4).
- These decays occur through a quantum mechanism known as the “tunnel effect”
- this is based on which there is a finite probability for a particle of a certain energy to overcome a barrier of greater energy potential.

Heavy particles emission (α)

- The average lives of the α emitters are extremely variable and depend on the energy of the α emitted particles
- for example the Rn^{216} has an average life of 10^{-6} sec, while the U^{236} has $\tau = 2.4 \times 10^{7}$ years.
- There is also the possibility of spontaneous fission, that is the breaking of the nucleus into two fragments of comparable mass.
- One example is that of U^{238} which fission with an average life of 4.5×10^{9} years.

Electrons emissions (β^- e β^+)

- The emission of an electron by a nucleus is known as decay β.
- In these decays the mass number of the nucleus does not change, while the atomic number varies by one unit.
- Everything happens as if a neutron of the nucleus were transformed into a proton plus an electron or vice versa:

$$n \to H^1 + e^-$$

$$H^1 \to n + e^+$$

Electrons emissions (β^- e β^+)

- In fact, in these decays another neutral particle called "neutrino" is also emitted, whose mass is much smaller than that of the electron and is practically non-interacting with the other particles (hence its name). .

$$n \rightarrow H^1 + e^- + \bar{\nu}$$

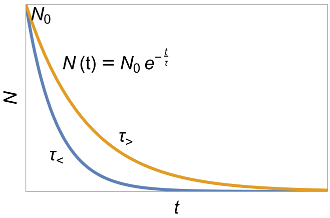
$$H^1 \rightarrow n + e^+ + \nu$$

- As a consequence, the emitted electrons have no fixed energy, but can have all energies between 0 and a value of E_{MAX}.
- Examples of β emitters are ^{130}I, ^{137}Cs, ^{142}Ba.

Photons emission (γ) rays

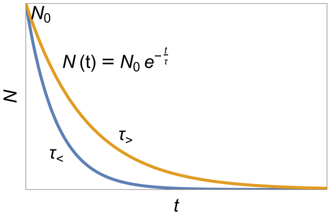
- nucleons have energy levels like the electron around them, and they can get excited in the same way
- When a nucleus passes from an energy state to a higher energy to a lower energy one it emits the difference in energy in the form of a quantum of EM wave, or photon.
- they usually happens in nuclei that derive from nuclear decays of other, heavier, nuclei
- These photons are called "γ rays" (the amount of energy carried is very high) and this type of decay is called decay γ.
- The energy of the γ photons emitted by the nuclei is of the order of MeV, and the average lives for this type of decay are usually very short ($10^{-17} - 10^{-12}s$).
- Only in cases where the angular moments of the two states between which the decay takes place are very different, the average lives become relatively long.

Measurements



- "Activity" of a radioactive sample is the number of disintegration in the time unit
- the shorter the average life τ., the fastest this decreases over time
- $N(t)$ for two different values of τ.
- The greater is τ the slower the radioactive nuclei are removed.

Measurements



- The unit of measure of the activity is the Bequerel (Bq) which corresponds to 1 disintegration per second: 1 $Bq = 1$ disintegration/s.
- An old unit of measurement is still in use, the Curie (Ci), which corresponds to 3.7×10^{10} disintegration per second, so 1 $\mu Ci = 37\ kBq$

X Rays

X rays in medicine and biology

- End 1800, Wilhelm Roentgen: new type of rays produced by the impact of cathode rays (electrons) with various substrates.
- X-rays are an important diagnostic and therapeutic tool in all fields of medicine.
- They are photons with high frequencies, but less than γ.

X rays in medicine and biology

- X-rays are invisible to the human eye, and therefore for their detection we use special tools such as ionization chambers, scintillation detectors, fluorescent screens and digital detectors.
- The methods of biomedical imaging based on X-rays: angiography, mammography, fluoroscopy, and allow non-invasive investigations of parts inside the body that would otherwise be unreachable only through surgery.
- The Computerized Axial Tomography (TAC), allows to obtain three-dimensional images of whole organisms, through multiple two-dimensional scans, then assembled into a single image through sophisticated algorithms.

X ray production

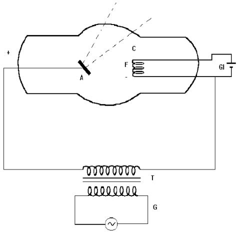
- If a beam of fast (and therefore energetic) electrons impinges on a target, X-rays are emitted.
- The emitted photons occupy a broad spectrum of energies, with different values depending on the mechanism that produced them and the material used.
- The **characteristic X-rays** have discrete energies and are produced by atomic transitions as electron excitations and subsequent return to the fundamental level, induced by the electron beam, with emission peaks characteristic of the materials used.
- The radiation of **Bremsstrahlung** (from the German "braking") is the mechanism that generates the component with continuous values of the emission spectrum X, (the majority of a typical X spectrum).

X ray production

- Materials with high atomic number Z are more efficient in producing X-rays.
- Tungsten ($Z = 74$) is often used as a target in X-ray tubes because it has a high emission output and a high melting point, which allows it to resist the increase in thermal energy due to the bombardment and the resulting phenomena.
- For example, for 100 keV electrons incident on a tungsten target, the radiation yield is about 1%: most of the energy is dispersed as heat.

The X-ray tube

- X-rays are energy photons $(1 - 100\,KeV)$ with wavelengths λ on the Angstrom order $(1\text{Å} = 10^{-10}m)$.
- The production apparatus is called a x-ray tube.
- The kinetic energy of the electrons on the cathode is almost null and therefore negligible, while near the anode is $K = 10\,keV$.

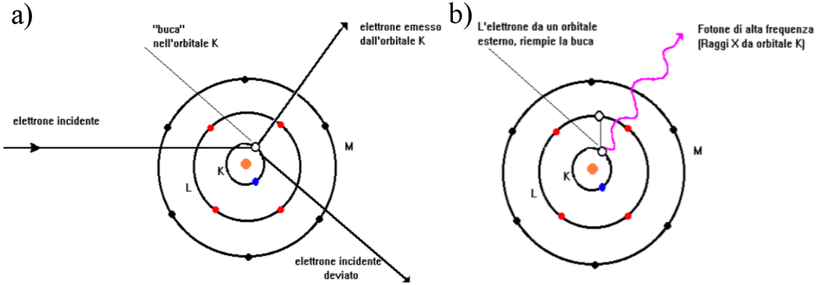


X-ray tube scheme:

- A anode
- C cathode
- F cathode filament
- GI current generator (secondary)
- GT voltage generator of the primary circuit.

Characteristic X rays

- a) The incident electron strikes an electron of an internal orbital and removes it, leaving a “gap”;
- b) the gap is filled by an outermost electron, with a greater energy and the difference in energy is released in the form of photons X.



Characteristic X rays - the energy gap

- The gap is usually filled with an electron of a higher energy level, and the difference in energy ΔE is expelled as quantum of radiation X.
- Thus a new gap is formed, which if filled by an external electron generates another photon X, or an Auger cascade
- The Auger effect consists in the emission of an external electron following an unused energy transfer for the production of X rays.

Characteristic X rays - the energy gap

- The characteristic production, being linked to the transition between energy levels, has two important characteristics:
    - Depends on the electronic structure of the cathode and therefore on its chemical nature, hence the name of characteristic radiation. Different cathodes originate different characteristic peaks.
    - The spectrum of the characteristic radiation is of a discrete type, ie it has peaks only at certain energies corresponding to the electronic transitions occurred
- The transitions between the various energy levels are indicated by the letters K, L, M and so on with any sub-levels (Ka, Kb, ...).

Bremsstrahlung X rays

- The other mechanism for producing X-rays is the acceleration of the electrons due to the interaction with the Coulomb electric field of the nucleus.
- When the electrons hit the anode, they also collide with the atoms of the material and lose most of their energy as heat (even 99% and so the X-ray tubes need to be cooled).

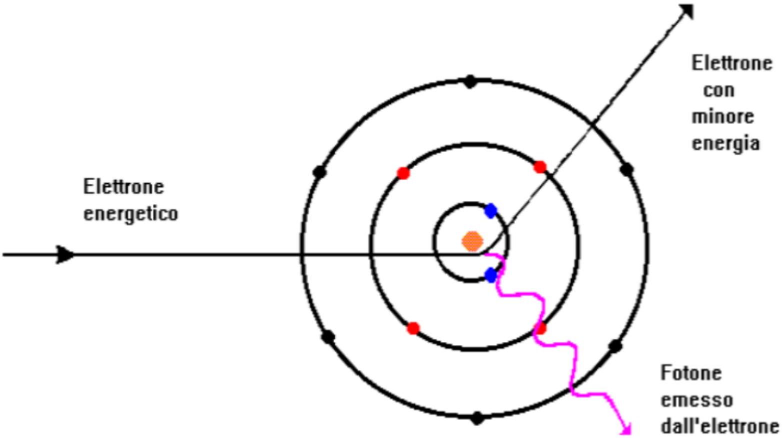
Bremsstrahlung X rays

- Electrons can also lose energy due to the acceleration to which they are subjected
- therefore generate electromagnetic waves whose frequency essentially depends on the amount of braking
- therefore on the variation of the kinetic energy of the electron.

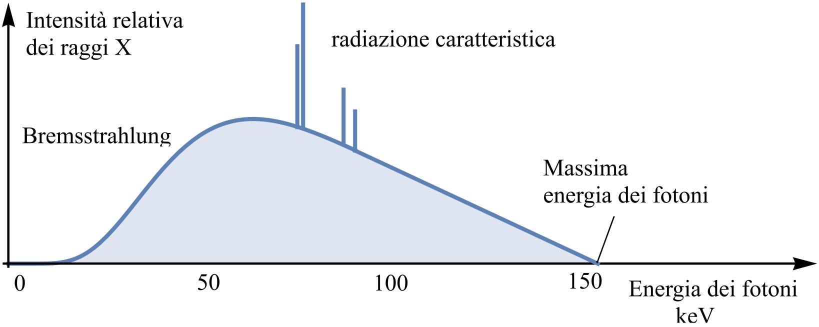
$$h\nu = \Delta E_C$$

- During this process, the electron can lose all or most of its energy.
- The continuous component of the X-ray spectrum is explained by this effect, so that the electrons lose different amounts of energy in order to generate photons with all the energies included in a certain interval.

Braking X-rays production (Bremsstrahlung).



X ray spectrum



- Note the continuous component (due to braking radiation) and the discrete component (the peaks that make up the characteristic radiation).
- The spectrum ends at a value that is equal to the potential accelerating energy.

radiation interaction

Radiation matter interaction

- The decay products of radioactive isotopes can interact with matter in various ways and can be classified into three groups:
  - heavy particles (neutrons, protons and α particles)
  - electrons and positrons ($\beta^+ and \beta^-$)
  - and γ rays
- In general these particles tend to penetrate into matter and not to 'bounce' or be reflected like photons of lower energy, reaching different depths and producing effects that depend on the type of interaction.

Radiation matter interaction - heavy particles

- In the case of heavy particles, these tend to release energy within the matter a well defined path (*range*)
- if it is made to engrave a bundle of heavy particles with the same energy on a sample of material, we have a progressive loss of energy practically the same for all the particles of the beam, so that they stop after passing through the same thickness.
- For example, the path of the α particles of 5.30 MeV (emitted by Polonium) in the air is about 3.84 cm, as they yield energy as a result of electron strikes of the atoms of the material traversed .
- Often the bumped electrons receive enough energy to be ripped from the atom of belonging thus creating an "ionized" atom (therefore also the heavy particles belong to the category of “ionizing radiations”).

Radiation matter interaction - adrons

- Moreover, a peculiar characteristic of heavy particles is that during the path inside the matter they do not release energy gradually, progressively decelerating due to the collisions until they stop
- but they stop giving almost the totality of their initial energy to a depth. well defined, which depends on the characteristics of the material crossed and the initial conditions of the ionizing particle.
- This property makes heavy particles, (*adrons*, as protons and neutrons), particularly suitable for radiotherapy, since it is possible to center the released energy, and therefore the damage to the tumor tissue, in a very well defined.

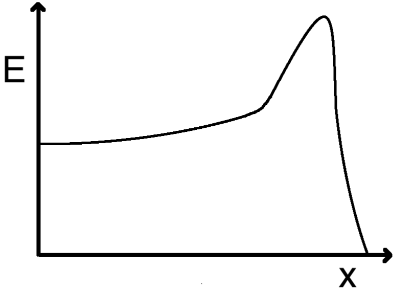
Radiation matter interaction - β particles

- Even the leptons (electrons and positrons) lose energy by ionization through a material, but having relatively small mass undergo, during the shocks, strong accelerations that cause further loss of energy in the form of electromagnetic waves (Bremsstrahlung).
- The latter effect becomes all the more important the greater the electron energy, and causes a more gradual energy release during the crossing.

Radiation matter interaction - α and β energy distribution

- Furthermore, while the α particles emitted by a given radionuclide all have the same energy, the β rays may have different energies in a certain range, due to the emission process that generates them.
- Therefore we can associate a single value of energy to the α particles emitted by a radioactive sample, while in the case of electrons we will have a different path depending on the possible energy values.

Bragg's peak



- Schematic representation of the energy distribution released to the material crossed by a hadron according to the depth reached.
- At the bottom we can see the peak of Bragg, where most of the initial energy is released.

Photons interactions

- Electromagnetic radiation (X-ray and γ) can interact with matter according to different mechanisms.
- They can induce ionizations in the material crossed, but unlike hadrons and leptons, we can not talk about the path
- this is because during the interactions with the surrounding matter the photons are absorbed and generated by various mechanisms, which can change their number, direction and power.

Photons interactions

- An X-ray beam that impinges on a material sample progressively decreases its intensity as it penetrates into the material.
- If I_0 is the beam intensity at the sample input, at a depth of x the intensity decreases exponentially:

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

- where μ depends on the nature of the material and the frequency of the incident photons and takes the name of "absorption coefficient" (or linear attenuation).

Photons interactions

- The coefficient μ grows with the atomic number of the absorbent material and decreases with the energy of the incident photon.
- More energetic photons, or as they say more 'hard', tend to penetrate deeper.
- The mechanisms of interaction of photons with matter are substantially of three types:
  - Rayleigh scattering (elastic collision, non ionizing)
  - Photoelectric effect
  - Compton effect
  - Pair production

Ionizing photons interactions

- **The photoelectric effect** consists in a collision of the photon with a bound electron, which receives sufficient energy to free itself from the atomic bond.
- The incident photon is absorbed by the impact, but its effect continues through the liberated electrons, which in turn they can hit other atoms and cause ionization and photon generation (called secondary photons).
- **Compton effect** in addition to the released electron there is a direct generation of a second photon (also this part of the secondary beam) with energy and direction different from the initial one.

Photons interactions

- **Production of pairs** if the energy of the initial photon is sufficient we can have a purely quantum and relativistic phenomenon: the energy of the photon transforms into a couple formed by a particle and its respective antiparticle.
- These particles are very unstable, and interacting with the surrounding matter generate other photons with energies and directions different from the initial one.
- **The sum of these phenomena** produces the stochastic behavior of an incident X or γ photon beam, which tends to spread over a large area of the material traversed.
- Although they are therefore less controllable, the X radiation is widely used in radiation therapy to bombard cancerous tissues in order to cause their necrosis, for their ease of generation and control.

Dosimetry

Biological effects of radiation

- When we talk about biological effects of radiation, we are implicitly referring to the radiations that can induce ionizations in the material both directly and indirectly.
- These include both true radiation, such as X-ray, γ and ultraviolet (UV), and α, β, protons and neutrons.
- The charged particles such as α , β and protons cause direct ionizations due to electrostatic forces
- therefore, when they go through matter they can interact with atomic electrons ionizing the atoms involved

Biological effects of radiation

- so they can induce substantial damage, especially in biological materials.
- The non-charged particles and the photons can ionize the matter by Compton or photoelectric effect and can also induce cascade ionization.
- Even in non-biological matter, ionizing radiation, especially if intense, can cause considerable damage, such as fragility in metals (cosmic radiation).

Somatic and hereditary effects

- The biological effects of ionizing radiation are manifold: they are classified by their size, by their probability of future, and by their precocity or lateness.
- These effects can be divided into:
    - somatic, if they are dependent on somatic cells (with effect on the organism that has received irradiation)
    - hereditary, if they influence the genome of the reproductive cells (and therefore with effect on the offspring of the organism affected by the radiation)

Somatic effects

The somatic effects can in turn be divided into:

- **deterministic**: immediate, generally linked to acute exposures, with a deterministically dependent effect on the received dose
- **stochastic**: late, with latencies even of tens of years, in which the effect depends in a probabilistic way on the received dose, and potentially also in a nonlinear way (hypersensitivity to low doses).

Somatic effects

- The effects can manifest themselves at the tissue, cellular and molecular levels.
- Their appearance is linked to the ionization of molecules and the breaking of covalent bonds as the energies involved are in these ranges.
- Ionizing radiation, especially X-rays, has a clear mutagenic effect, which in the past has been used to produce animal and plant mutants, mainly in the fly *Drosophila* and on maize.
- The biological damages induced by ionizing radiations are above all indirect effects, caused not so much by the radiations in themselves, but mainly by the free radicals that they produce by action on the water molecules of the cells and the tissues.
- Free radicals can damage the cell at the protein or DNA

DNA damage

- DNA damage is much more dangerous, since any alteration of DNA can affect a gene and therefore the protein encoded by that gene.
- Can therefore form mutated proteins with altered functional properties that can inhibit or even zero certain cellular functions causing cell death (lethal necrotic effect).
- On the contrary, if the cell survives the damage but in a mutated form, its subsequent proliferation may give rise to cancerous manifestations (carcinogenic effect)
- if it is a reproductive cells it can produce mutations in the progeny (mutagenic or teratogenic effect).

Radiotherapy

- Ionizing radiations are widely used, as well as for diagnostic investigations, in treatment protocols for the treatment of tumors as they have the ability to selectively kill cancer cells at certain doses.
- This property is based on the so-called *oxygen effect*.
- Cancer cells are characterized by a higher metabolic activity, linked to their increase in proliferation activity compared to healthy cells, which requires a greater supply of oxygen to maintain.
- The presence of oxygen inside the irradiated tissues has the ability to increase the effectiveness of ionizing radiations, since the production of free radicals (for example of the type HO_2) is greatly amplified
- so that the cells have the same irradiation tumors receive more damage than healthy cells.

Dosimetry of ionizing radiation

- The measurement of the radiation dose absorbed by a sample is of fundamental importance for evaluating its effects.
- The SI measure of activity is Bequerel (Bq):

$$1Bq = 1\text{decay per second}$$

- The unit of absorbed dose in S. I. is Gray (Gy):
- **One Gray corresponds to the $1\ J$ of energy deposit for Kg of matter: $1\ Gy = 1\ J/Kg$.**

Dosimetry of ionizing radiation

- The absorbed dose depends on several factors, such as the properties of the radiation and the nature of the material.
- For example, the bones absorb more X-radiation than soft tissues, and this causes the bones to “see” bones in ordinary x-rays
- as the X radiations tend to cross the biological matter, rather than being reflected as the light waves in the visible, what changes is the attenuation by the various tissues, so we have a sort of “negative” image of what is irradiated.

Relative Biological Effect (RBE)

- Gray does not take into account the effects on biological matter, as it does not consider the different different radiations.
- Different radiations produce different biological effects, even at the same dose, due to the different mechanisms with which the radiation interacts with the cells and the tissues releasing energy.
- is linked to how clustered the ionization events are per unit of energy

Radiation	RBE
γ	1
e^+/e^-	1
p^+	5-10
n^0	5-22
nuclei	20

RBE coefficients for some types of radiation.

Effective dose

- The different effect is quantified by the *effective dose*, which is measured in Sievert (Sv)
- linked to Gray by the Relative Biological Efficiency coefficient (RBE), different (empirically determined) for each type of radiation.

$$1\text{Sv} = 1Gy \times RBE$$

Effective dose

- As an example to understand the order of magnitude of these units of measurement, on average we receive from the surrounding environment about 2.4 mSv per year, the so-called background radiation.
- the effect at the same dose may also vary by a factor of 20, which should be taken into account when using different radiation for radiation therapy plans, or to assess the potential effect of nuclear accidents in to which different types of radiation are emitted.
- Another factor not to be overlooked, especially in the field of radiation protection, concerns the ability to shield the different radiations.

Radiation shielding

- The radiations from massive particles (protons and α), which as we have seen are potentially the most damaging on biological tissues, because of their nature they are also the easiest to shield
- for example, a thickness of just a few millimeters is sufficient with most materials (or about half a meter of air) to be completely shielded from α or electron particles.
- As for electromagnetic radiation, given the exponential behavior and the “transparency” of many materials to them, it is very difficult to obtain a complete shielding, except with thick barriers and very heavy materials (such as lead).
- A similar argument applies to neutrons (emitted for example in nuclear fission processes) that being neutral are hardly shielded, tending to easily cross the various materials.