Applied Phisics Notes

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Collaboratori

Contents

Chapter 1

Introduction to applied physics

This course will be focused on applications of physics of the fundamental interactions. This applied physics branch uses radiation as a probe, and also as an instrument, to inspect and/or partially modify the object subjected to the study.
In the framework of medical applied physics, for instance, the studied object is a living patient: the radiation can cross the body (diagnostics) or also interact with it, as it happens in radiotherapies. The discussion will mainly revolve around: radiation which delivers a local energy release, such as β or α radiations, $\beta+$ radiations which are absorbed through annihilation and photon emission, and pure γ electromagnetic radiation.

For a more complete and organic introduction to applied physics and nuclear physics, please refer to [RP06] [Bai+], [Cla], [Corc], [Ber].

A brief review of the applications of nuclear and subnuclear physics that will be described in these lectures is presented, with particular emphasis on the physics principles behind the application considered.

1.1 Diagnostics

The term diagnostics refers to all the techniques and technologies used to extract information about an object of study.
Morphological diagnostics provides information about the object morphology (density, spot of anomalous masses,...). Examples of morphological diagnostics are the CT and the 2-dimensional radiography, which both exploit x-rays radiation.
Functional diagnostics embraces the analysis returning information also on the metabolic processes happening in a specific tissue. The PET and the SPECT analysis are an example of functional diagnostics, they exploits $\beta+$ annihilation with matter which produces photon pairs.
In functional diagnostics, the patient is given a radiopharmaceutical: the substance is usually created, on metabolic or receptor affinity basis, to be absorbed the most by the organ on which the analysis should be performed. Metabolic base absorption happens when some physical characteristics of the tissues in analysis are used to induce the assimilation: for instance, cellular membranes can be crossed only by particles smaller than a certain size.
The absorption based on receptors, instead, is based on the chemical properties of the receptors present on the tissue of interest. Specific radiopharmaceuticals, in fact,can mock the chemica features of a specific receptor site, linking the substance to the tissue and keeping the radiative source close to the region to be analyzed.

Examples:

- Single Photon Emission Computed Tomography (SPECT). It is performed using ^{131}I o ^{99m}Tc. Tecnetium is disposed by the kidneys relatively fast.It there decays, emitting di $E = 140keV$ γ rays. The position of the source of the emission is reconstructed through a technique called tomography, providing information about the organ metabolism.

- Positron Emission Tomography (PET): is tipically performed through ^{18}F, attached to sugar compound: sugar is absorbed mainly by the brain and cancerous masses. PET exams are useful to asses the size and growth status of a cancerous mass.
  The physics principle on which the PET exam is built is the decay of the fluorine isotope through ^{18}F in $\beta+$ radiation. The emitted positrons annihilate with the surrounding electrons in matter, through an in flight interaction or also forming a metastable state called positronium. In any case, the annihilation produces photons, mostly in pairs: the position of the photons source is computed through tomography, providing information on the power of absorbition of different organs and tissues in the body.

- Radio-Guided surgery. Exploits the same sugar absorption principles explained in PET for the enhancement of cancerous masses within an inspection/removal surgery. It is often used on lymph nodes, and the latest application are implementing $\beta-$ emitters for the tissue enhancement.

More on PET: [JP06] [BTVM05].
More on CT: [Nat01]
More on radiosurgery: [MGS06] [al99].

1.2 Radiotherapy

Radiotherapy is based on the destruction of the tumor reproduction mechanism, the cancer cell DNA. The DNA has to be broken in at least two points, or otherwise it will be able to pass the reproductive information on anyway.
Conventional radiotherapy is performed through irradiation with photons or electrons, and does not release enough energy in the tissues to properly break the DNA structure. It rather relies on the conspicous production of free radical which comes from the water molecules rupture within the tissues, as the radicals intoxicate the cancer cell and impair it. It can be thought as a local chemotherapy. In this framework, a discussion on the use of heavy ions in place of light or massless particles will be presented, as heavy ions release more energy and more locally, preserving healthy tissue and causing, in some cases, the necessary damage to the cancer cells DNA.

Radiometabolic therapies is based on the destruction of the tumor by the absorbtion of a radiopharmaceutical by the interested tissue. The emitter will release the radiation from within the mass itself.
Brachiterapy, on the other hand, consists in the creation of emitter enriched ointment, which emit electrons in the very superficial layers of the skin.

More on hadrotherapy: [Ros13] [Bra12] [Adr] [IAE] [Acc] [Lin]
More on brachiotherapy: [Wat]

1.3 Teragnostics

Teragnostics techniques are the one in which diagnostics and therapy are performed within the same treatment. It is performed with isotopes which emit $\beta-$ and γ, such as ^{177}Lu and ^{90}Y with ^{68}Ga. .

1.4 Cultural heritage - Ion Beam Analysis (IBA)

Cultural heritage hugely benefits from "diagnostics" techiques developed with nuclear and subnuclear physics. The analysis of the concentration of certain isotopes within an object, or the composition of its absorption spectrum can give information on:

- Age
- Superficial composition
- Whether the work is true or a false
- Corrosion
- Origin

The analysis that can be applied on cultural heritage are in the Ion Beam Analysis (IBA) group. The analised object is the target of ion beams (generally protons or α particles), and study the result of the interaction. Some IBA techniques are:

- Proton Induced X-rays Emission (PIXE): the object is exposed to a proton ion beam. The interaction results in emission of photons, in the x-rays spectrum.
- Rutherford Backscattering Spectroscopy (RBS): very useful for thin samples of heavy compounds. It consists in an analysis of the angular distribution of the particles scattering back from the target.
- Elastic Recoil Detection analysis (ERD): same as RBS, but for very light compounds.
- Proton Induced Gamma-rays Emission (PIGE): similar to PIXE. but does work better with light compounds. It results in an emission spectrum in the gamma region.

The X-Ray Fluorescence (XRF) is not based on ion beams "bombing": the sample is exposed to x-rays, and the fluorence radiation induced in the object is studies

More on applied physics for cultural heritage: [rev]

1.5 Carbon 14 dating

In nature, carbon exists in three isotopes: ^{12}C and ^{13}C, which are stable, and ^{14}C, which is radioactive, with $\tau = 8267y$. The mean^{14}C concentration in the Earth atmosphere is more or less a constant, thanks to the continuous flux of incoming cosmic rays.A secondary component of cosmic rays are, in fact, neutrons, which interacting with the stable isotopes of carbon produce ^{14}C. Therefore the number of carbon stable and radioactive isotopes is roughly constant, around 10^{-12}. When an organism is alive, the processes of photosynthesis, breathing and feeding maintain the carbon isotopes ratio constant whitin it as well. After the death of an organism, the radioactive isotope starts to decay, changing the radioactive to stable isotopes ratio. Studying the ratio of radioactive and stable isotopes it is possible to define when an organism lived.

1.6 Neutrons

The probability for an element to interact with x-rays is inversely proportional to the probability of its interaction with a neutron. Therefore the neutrons start to be useful when the X rays are not able to extract any information. Neutrons are absorbed immediately by water, making them extremely useful for tomographies in which we want to enhance the presence of water (motors)-

More on neutrons: [Corb] [Non]

Chapter 2

Natural Units

Nuclear and particle physics mathematical relations and expression can reach very high levels of complexity. For this reason, in this branch of science, units of measurements that do not belong to the SI are often used. Moreover, the full form expansion of fundamental constants can lead to very long and difficult to handle formulas. In this framework Natural Units, which underlie and contain the constants in their definition, can be defined and used. In quantum and relativistic mechanics it is convenient to set:

$$c = \hbar = 1 \tag{2.1}$$

The table 2.1 summarizes the values of these constants in the most common units of measurement. This values can be used as conversion factors between the SI and the Natural Units system. The units of measurement obtained in this way, together with the definition of the fine structure constant $\alpha_{em} = \frac{e^2}{4\pi\epsilon_0\hbar c} \sim \frac{1}{137}$ which, placed $c = \hbar = 1$ becomes $\alpha_{em} = \frac{e^2}{4\pi\epsilon_0}$, constitute the system of natural units.

The simplest method for converting quantities from natural units to an international system is to set:

$$Q_{SI} = Q_{UN} \cdot (\hbar c)^m \cdot c^n \tag{2.2}$$

Where Q_{UN} is any quantity expressed in the system of natural units, Q_{SI} is the same quantity expressed in SI and m and n are the specific powers that must be put to the terms $\hbar c$ and c so that

	Dimensions	Unit of Measure
$\hbar$	energy· time	$1,035 \cdot 10^{-34} J \cdot s$
		$6,5 \cdot 10^{-16} eV \cdot s$
		$6,5 \cdot 10^{-13} MeV \cdot ns$
c	position/time	$3,0 \cdot 10^{8} m/s$
		$300 km/s$
		30cm/ns
		$3,0 \cdot 10^{14} fm/ns$
$\hbar$ c	energy·position	$3,1 \cdot 10^{-26} J \cdot m$
		200MeV · fm

Table 2.1: Values of the constants $\hbar$ and c in the most common units of measurement

SI	UN
$\beta = \frac{v}{c}$	$\beta = v$
$E = \sqrt{p^2c^2 + m^2c^4}$	$E = \sqrt{p^2 + m^2}$
$p = m\beta\gamma c$	$p = m\beta\gamma$
$T = E - mc^2$	$T = E - m$
	$\beta = \frac{p}{E}$

Table 2.2: Comparison of relativistic kinematic equations in the two units systems

the dimensions of the quantity considered are coherent in both systems of units of measurement. We recommend using the values of the constants shown in bold in the 2.1 table.

2.1 Kinematics and Relativistic Dynamics

The natural unit system is particularly useful because it simplifies the equations of special relativity. A comparison of these equations in the international unit system and in the natural unit system is reported in Table 2.1. Since in restricted relativity the energy of a particle is linked to the mass m and to the impulse p by the formula $E^2 = m^2c^4 + p^2c^2$, measuring the masses in eV/c^2 and the impulses in eV/c all the formulas of relativistic kinematics are simplified, in the sense that the three quantities can be simply added, being c = 1.

2.1.1 Examples and Applications

An electron has momentum $p_{UN} = 1MeV/c$. What is its momentum expressed in the international system?

Recalling the conversion $1eV = 1.6 \cdot 10^{-19}J$ and the value of the speed of light $c = 3 \cdot 10^8 m/s$, we obtain:

$$p_{SI} = p_{UN} \cdot \frac{1,6 \cdot 10^{-19} \cdot 10^6}{3 \cdot 10^8} = 5 \cdot 10^{-22} kg \cdot m/s \tag{2.3}$$

What is the electrostatic energy of an electron at a distance $d = 0.5$ Å from a carbon nucleus, neglecting the shield produced by the other electrons?

Recalling the expression for the electrostatic potential energy for a system of two point charges we have

$$U = \frac{Ze^2}{4\pi\epsilon_0 d} = \frac{Z\alpha_{UN}}{d} \tag{2.4}$$

Where $\alpha_{UN} = \frac{e^2}{4\pi\epsilon_0} \sim \frac{1}{137}$ is called a constant of fine structure and is dimensionless: therefore it does not depend on the system of units of measurement chosen. By doing a dimensional analysis we now decide which powers of $\hbar c$ and c are to be used in the conversion.

On the left we have an energy, on the right the inverse of a length.

$$E = \frac{([\hbar c])^m \cdot [c]^n}{L} = (E \cdot L)^m \left(\frac{L}{T}\right)^n \cdot L^{-1} \tag{2.5}$$

From which we can deduce that necessarily $m = 1$ and $n = 0$. Or:

$$U = \frac{Z\alpha\hbar c}{d} = \frac{6 \cdot \frac{1}{137} \cdot 200MeV \cdot fm}{5 \cdot 10^4 fm} = 175eV \tag{2.6}$$

Where we use that 1Å$= 10^{-10}m$ e $1fm = 10^{-15}m$.
Further exercises:

- *What is the kinetic energy of a helium nucleus with impulse* $p = 50MeV/c$*?*
- *What is the radius of the orbit of a proton with kinetic energy* $T = 10MeV$ *immersed in a magnetic field of modulus* $B = 0.5T$*?*
- *What are the* β *and* $\beta\gamma$ *of an electron accelerated by* $1MV$*?*

Chapter 3

Radiation-Matter Interaction

This chapter describes the main mechanisms of interaction of different types of radiation with matter. The energy range of interest for applied physics reaches at most a few tens of MeV, The following discussion will therefore mainly deal with the models of particle interactions acting in this range.

3.1 Interaction Ions-Matter

Light ions such as H^+ (protons), He^{2+} (particles $alpha$) and C^{6+} mainly interact with the electrons in the matter on which they affect, by Coulumbian interaction.
When the ion exchanges more energy with the electron than the binding energy between electrons and the atomic nucleus, an ionization process is triggered.
In the following discussion the process will be described from a classical point of view. Since the energy of the ion is of the order of MeV while the electrons of matter have energies of the order sim eV, in the description of this interaction process it is possible to consider the electron as stationary. Furthermore, since the mass of the electrons is much lower than the one of the interacting ions, the reference system of the C.M. coincides with the latter and it is possible to consider it unperturbed during the interaction. In this framework, the ion will be stationary in the center of the system and will see the electrons moving towards itself with velocity $-v$ equal and opposite to the v of the ion. Let's consider an electron at a distance b from the trajectory of the incident particle; the variable b is defined as impact parameter for the interaction.

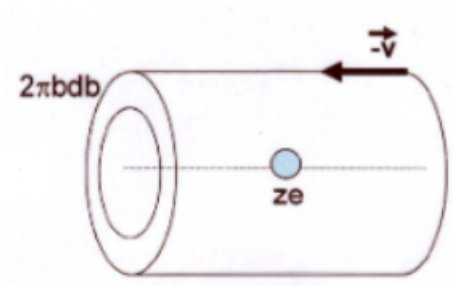

Figure 3.1: Application of the Gauss theorem in the ion reference system

The momentum transferred to the electron is given by the relation:

$$\Delta p_e = \int F dt = e \int E dt = \frac{e}{v} \int E \mathrm{d}x \tag{3.1}$$

where we can replace the total electric field $vecE$ with the only transverse component $vecE_{perp}$ as the longitudinal component is deleted due to symmetry.

To evaluate the integral one can consider the Gauss theorem applied to an imaginary cylinder of radius b around the ion:

$$\Phi(E) = 2\pi b \int E \mathrm{d}x = \frac{Ze}{\epsilon_0} \tag{3.2}$$

Where b is the base radius of the cylinder and represents the distance between the ion and the electron. From the previous equation we obtain:

$$\int E \mathrm{d}x = \frac{Ze}{2\pi b \epsilon_0} \tag{3.3}$$

Substituting in the expression for the variation of the electron momentum we get:

$$\Delta p_e = \frac{Ze^2}{2\pi\epsilon_0 v b} \tag{3.4}$$

From which we can calculate the total kinetic energy transferred from ion to electron:

$$\Delta K_{I,e} = \frac{\Delta p_e^2}{2m_e} = (\frac{Ze^2}{2\pi\epsilon_0 v b})^2 \frac{1}{2m_e} \tag{3.5}$$

Note: the impulse transfer is inversely proportional to the ion velocity! In fact, the slower it is, the more time it spends near the electron, transferring impulse to it.

The amount of transfer energy, or momentum, is computed in the previous formula for a single electron interaction, for a single impact parameter. We are working under the hypothesis $\Delta p << p$, meaning that the momentum loss for the ion is almost negligible for a single electron interaction. This caveat is extremely important, as it draws a difference with, for instance, photon interactions with matter, in which the photon either does not interact at all, or looses all its energy within a single interaction.

The hypothesis can be easily verified by computing the ratio between momentum loss and momentum for the ion:

$$\frac{\Delta P}{P} = \frac{Ze^2}{4\pi\epsilon 0} \cdot \frac{hc}{m_e c^2 \beta^2 b} = \frac{2z}{137} \cdot \frac{200\ MeV fm}{0.5\beta^2 b} \sim \frac{5.8z}{\beta^2 b} \tag{3.6}$$

Where in the last member of the equation 5.8 is a number collecting all the constant values. If we want to compute the amount of energy loss per unit of transverse length in the mean, we have to consider the effect of different interactions, with several electrons and at different impact parameters.

When the ion crosses a dx path within the mean, it encounters a number of electrons per unit of volume $dn_e = n_e 2\pi b\ dx\ db$, where $n_e = Z\frac{N_A}{A}\rho$, is the electron density in the material. The expression of the infinitesimal energy loss is therefore:

$$-dE = (\frac{Ze^2}{2\pi\epsilon_0 v b})^2 \frac{1}{2m_e} n_e 2\pi b db dx, \tag{3.7}$$

where we are underlining the energy *loss* by putting a minus sign in front of dE.
To compute dE/dx we now have to integrate on all the possible impact parameters: the operation in itself is trivial, as:

$$-dE/dx \propto \int_{b_{min}}^{b_{max}} \frac{1}{b} db. \tag{3.8}$$

What is less trivial is the definition of the integration extremes. These values can be retrieved by considering the minimum and maximum energies E_{min} and E_{max} that the ion can loose within the interaction.

$$E_{min} = (\frac{Ze^2}{2\pi\epsilon_0 v b_{min}})^2 \frac{1}{2m_e} \qquad E_{max} = (\frac{Ze^2}{2\pi\epsilon_0 v b_{max}})^2 \frac{1}{2m_e} \tag{3.9}$$

Different approaches are used in different texts to define these values. For the sakes of our discussion, we can naively take the mean bond energy for the outermost electrons in an atom of the mean for the e E_{min}, while E_{max} is the maximum energy transferable in an ion-electron interaction (non relativistic limit):

$$E_{min} = \bar{E}_{ionization} \qquad E_{max} = \frac{2m_e\gamma^2\beta^2c^2}{1 + 2\gamma m_e/M + (m_e/M)^2}. \tag{3.10}$$

Combining respectively the equations for E_{min} and E_{max} in 3.9 and 3.10, we obtain our integration extremes.
We finally cook up all of the expression in the final expression for the ion energy loss per unit of crossed path, which, in its classical limit, is known as **Bloch formula**:

$$-\frac{dE}{dx} = \pi N_A Z \rho r_e^2 c^2 \frac{z^2}{\beta^2} ln\left(\frac{m_e\gamma^2\beta^2c^2}{h\omega_e}\right). \tag{3.11}$$

Bibliografia: [LD]

3.2 Bethe-Bloch

The Bethe-Bloch formula describes the loss of energy per unit of space traveled for a massive charged particle that interacts via ionization in a material.

The only difference with the Bloch formula in Eq. 3.11 lies in the integration extremes for the impact parameters, as

$$E_{min} = \frac{E_{ionization}^2}{2m\gamma^2\beta^2} \qquad E_{max} = 2\nu_i, \tag{3.12}$$

are computed within the relativistic limit: E_{min} is the energy exchanged within the minimal transition time, while E_{max} is the maximum trasfer energy for a relativistic scattering process between the ion and the electron.

The Bethe-Bloch formula [1] is:

$$-\frac{dE}{dx} = 4\pi N_A \frac{Z\rho}{A} r_e^2 m_e c^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2}\right) \tag{3.13}$$

where

[1] https://userswww.pd.infn.it/ carlin/riv/Slides/parte1.pdf

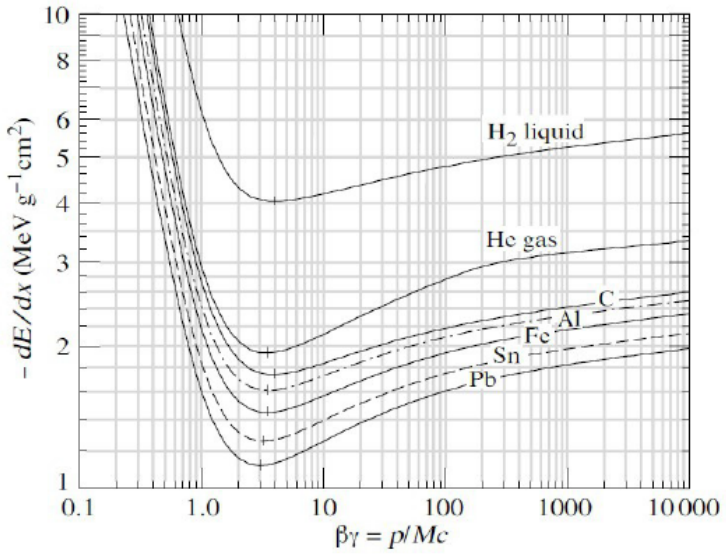

Figure 3.2: Graph of the Bethe-Bloch formula. We observe the first section of descent dominating the term $\frac{1}{\beta^2}$, the minimum at $\beta\gamma = 2m_0c^2$ and the following section of ascent.

- A is the target's atomic number;
- Z and z indicate the charge of the incident particle and the target respectively;
- ρ is the target density;
- m_e, r_e and e are the mass, the classical radius and the charge of the electron;
- I is the average ionization potential of the material;
- β is ratio v/c where v is the velocity of the bullet, γ can be calculated as $1/\sqrt{1-\beta^2}$;
- W_{max} is the maximum transferable kinetic energy in a collision;
- $\delta(\gamma)$ is a correction due to the polarization of the medium induced by the electric field of the incident particle which, by shielding the most distant electrons, reduces their contribution to energy loss;
- C is the *shell correction* and comes into play when the incident particle has a speed equal to or less than that of the orbiting electron.

In the range of energies of interest for these lectures, ($\beta\gamma < 2$) the function can be approximated in the formula $\frac{1}{\beta^2}$ so with the increase of the particle speed, the loss of energy it decreases quadratically. As we saw from the considerations in the previous paragraph, if the incident ion is slower, it will lose more energy for the same path. Beyond the type of material it is affecting, in general, for the unit order $\beta\gamma$ we have that $-\frac{1}{\rho}\frac{dE}{dx} \simeq 2MeVg^{-1}cm^2$.

3.3 Stopping Power e Linear Energy Transfer (LET)

In the previous paragraph we have seen that the trend of the Bethe-Bloch in the interval of our interest goes as $\frac{1}{\beta^2}$. That is, set an initial speed, a particle that passes through a certain material slows down until it stops. The lower the particle β value, the greater the particle energy loss per path unit $\frac{dE}{dx}$ in the mean. The size $\frac{dE}{dx}$ is called *Stopping Power*.
The path taken by a particle that crosses a material depends on the type of material crossed, the type of particle and its energy. The length traveled by the incident particle before losing all its energy is called the **Range**. It is possible to calculate the range of a particle of given initial energy K_0 knowing the trend of the stopping power:

$$R(E) = \int_0^{K_0} \left(\frac{dE}{dx}\right)^{-1} dK \tag{3.14}$$

The *Linear Energy Transfer* (LET) is often preferred to the *Stopping Power* in the framework of energy loss phenomena within biological tissues. Unlike the *stopping power*, the LET takes into account the energy lost only by the primary charged particles, leaving out the releases induced by the secondary particles produced as photons or δ *rays*, that is, very energetic electrons produced by ionization. In Medical Physics, LET is preferred to *stopping power* because it is directly related to DNA damage.

The first quantitative difference between the two variables is that the LET has a trend such as $\frac{1}{\beta^{2*0,82}}$: the reason for such an unusual power is due to the fact that the integration in energy is here limited in the region before the Bethe-Bloch minimum.
The LET is defined as

$$LET = \frac{L_0 Z^2}{(K/m)^{0,82}} \qquad L_0(water) = 0,12\frac{keV}{\mu m}, \tag{3.15}$$

where L_0 is a constant with the same dimension of the LET. The expression is proportional to the atomic number of the mean, and inversely proportional through the 0,82 exponent to the ratio of the kinetic energy of the particle and its mass.
The LET is an expression of the energy *absorbed* within the material, and it is therefore dependent on atomic number of the mean. This feature draws the main difference with the Stopping power, which is instead an expression of the *released* energy, and does not give any information on where, or how much energy, has been absorbed. The energy absorption in biological tissues translates in damage, or eventual destruction, of cells. It is then fundamental to know *where* and *how much* energy is released: in the treatment of, for instance, cancerous regions in the human body, we want to damage and eliminate the cancerous cells and meanwhile we would like to damage the least possible the surrounding healthy tissues.

It is possible to derive an expression for the range starting from the definition of LET [Ama01]:

$$R = \int_{K_0}^{0} \frac{dK}{-|\frac{dE}{dx}|} = \int_0^{K_0} \frac{dK}{LET} = \int_0^{K_0} \frac{dK(K/m)^{0,82}}{L_0 Z^2} \tag{3.16}$$

$$R(K) = R^* \frac{A}{Z^2}(K/m)^{1,82} \qquad R^* = 425cm \tag{3.17}$$

Note: these considerations apply to $K/m < 0.4$. In the case of protons this translates into $K < 400MeV$.

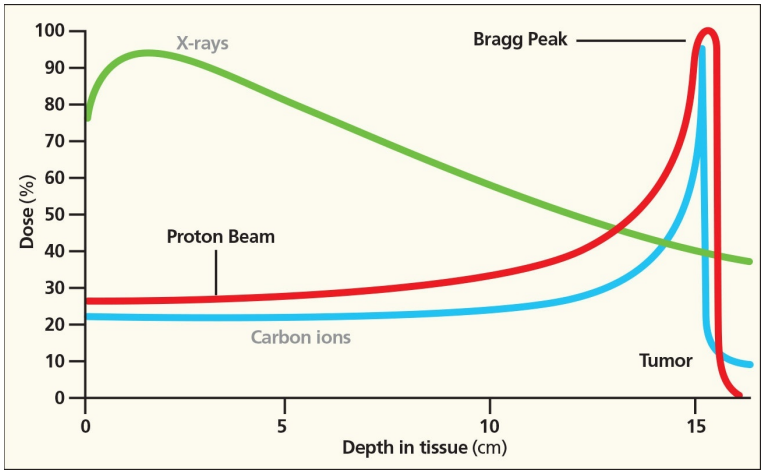

Figure 3.3: Relative dose as a function of the penetration for photons, protons and carbon. The graph is representative of the trend of LET (x) unless a constant. Image from scripps.org

This formula for R can be understood as a function of K. That is, it expresses the path that remains to the particle in question if it has kinetic energy K. I can also express the LET as a function of the remaining path of the particle: just invert the relationship between R and K and replace in the LET formula. You get:

$$LET(R) = L_0 Z^{1,1} A^{0,45} (R^*/R)^{0,45} \tag{3.18}$$

Now, considering that R is the remaining path to the particle and $x = R_0 - R$ and the real position, the previous equation is reformulated:

$$LET(x) = L_0 Z^{1,1} A^{0,45} (\frac{R^*}{R_0 - x})^{0,45} \tag{3.19}$$

First Exercitation

Graph the range as a function of kinetic energy and the LET as a function of the position for protons, alpha particles and carbon nuclei in water.

The analytical expression of LET (x) has an asymptote. In reality it is bypassed, because the beam of incident particles always has an uncertainty about its energy and its spatial distribution. Only a purely monochromatic beam would have an asymptotic course.

To destroy DNA from a cancer cell directly, the minimum LET (x) value must be $20eV/mm$. In therapies where the tumor is attacked through the creation of free radicals (as in the case of hadrontherapy), a lower LET value is sufficient.

The real plot of the trend of LET (x) is called *Bragg curve*. By comparing the Bragg curve of a proton with that of a carbon nucleus, the following considerations can be made:

- The Bragg peak of carbon ions is narrower than that of protons
- Carbon has a tail after the peak due to nuclear fragmentation processes. This means that there is an energy release in the tissues even at depths greater than that of the particle range

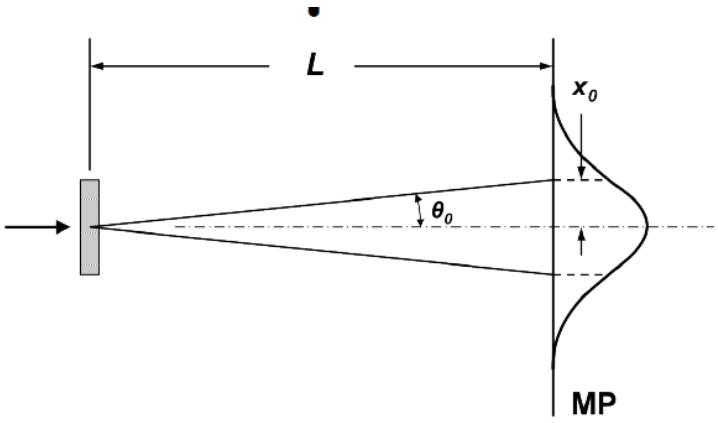

Figure 3.4: Representation of the effect of Multiple Scattering. The exit corner has a Gaussian distribution.

3.4 Multiple Scattering - Ion Nuclei

Up to now we have observed the case in which an ion interacts with the electrons of the material and there is an energy transfer by ionization. If, however, the ion interacts with the nucleus instead of an exchange of energy, there will be a change in momentum which results in a change in direction for the ion. It will be diverted in its path. Since a particle that passes through a medium is subject to multiple interactions, this phenomenon is called *Multiple Scattering*. The end result is that a perfectly collimated beam after passing through a quantity x of material will have a certain transverse dimension with Gaussian standard deviation distribution:

$$\sqrt{\sigma_\theta^2} = \frac{z}{\beta p}\sqrt{\frac{x}{X_0}} \tag{3.20}$$

Where X_0 is a constant of a material.

NB: Multiple scattering is the real reason for the smoothing of the asymptote of $LET(X)$. In fact, if a different final angle corresponds to different energies, this means that the range (projected on X) is different for each energy and therefore spreads around the maximum. Hence also the reason why carbon has a more defined maximum: it undergoes less multiple scattering.

Second Exercitation

- *Estimate CSDA (real range, not projected) and projected range in water for alpha and proton particles with kinetic energy between* 1 *and* 10 MeV.
- *Estimate the amount of Teflon, iron and lead needed to stop alpha particles and energy protons* 1, 5 *and* 10 MeV.

3.5 Electron-Matter Interactions

An electron that affects the target can basically interact in three ways. The first is by ionization like ions. In this case the Bethe-Bloch formula must be modified by introducing relativistic corrections:

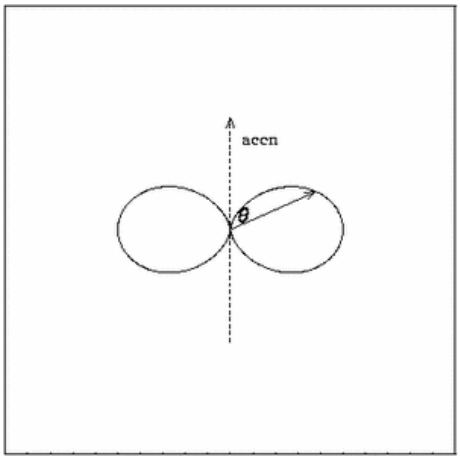

Figure 3.5: Trend of radiated energy as a function of the angle with the direction of motion.

$$-\frac{dE}{dx} = 0,306 N_A \frac{Z\rho}{A}\frac{1}{\beta^2}\ln(\frac{1,16 m_e c^2 \beta^2}{2I}) MeV/cm \qquad for \beta < 0,5 \tag{3.21}$$

$$-\frac{dE}{dx} = 0,153 N_A \frac{Z\rho}{A}\frac{1}{\beta^2}\ln(\frac{E(E+m_e c^2)^2\beta^2}{2I^2 m_e c^2}) MeV/cm \qquad for \beta \simeq 1 \tag{3.22}$$

If, on the other hand, the electron interacts with the nuclei of the material, multiple scattering can take place (with a much more intense effect than for the ions given the smaller mass of the electrons) or *Bremsstrahlung* (also called braking radiation). In fact, an electron that is deflected in its motion by a nucleus emits radiation. The power of the emission is given by:

$$W(\theta) = \frac{q^2 a^2 sin^2\theta}{4\pi\epsilon_0 c^3} \tag{3.23}$$

Where θ is the angle between the direction of motion of the electron and the direction of radiated radiation.

The effect on electron energy loss is given by the following equation:

$$-\frac{dE}{dx} = \frac{E}{X_0} \tag{3.24}$$

with solution:

$$E(x) = E(0)e^{-x/X_0} \tag{3.25}$$

where

$$X_0 \simeq \frac{A}{N_A Z^2 \rho}\frac{1}{4\alpha_{em} r_e^2 \ln(\frac{184}{Z^{1/3}})} \tag{3.26}$$

Furthermore, characteristic lines due to a second process can be added to the continuous spectrum produced by the braking radiation: the shell radiation K. This process occurs when the photon emitted by the braked electron ionizes the atoms of the target, striking not the valence electrons but those closest to the nucleus. When this happens, the external electrons can go down

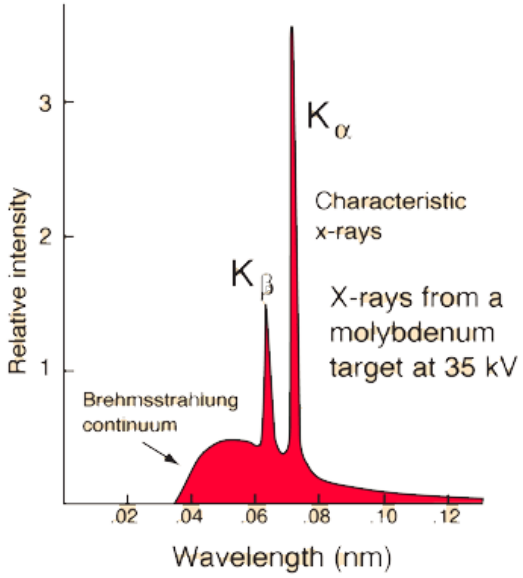

Figure 3.6: Spectrum of the resulting radiation, given by Brehmsstrahlung and shell radiation K.

to the levels closest to the nucleus by emitting X radiation. We speak of K_α when we indicate the radiation emitted by an electron passing from $n = 2$ to $n = 1$, while we talk about K_β when we want to indicate radiation emitted by an electron that drops from $n = 3$ to $n = 1$. This radiation is monochromatic, although it was originally generated by a continuous spectrum.

An example of total spectrum produced by the interaction of electrons is shown in the figure (3.6)

NB: for projectile electrons, the braking radiation dominates the ionization only if $E > \frac{800MeV}{Z}$. *In the human body* $Z \sim 6$ *therefore the braking radiation dominates as LET only if* $E > 133MeV$ *which is a very high value if we consider the energies involved in medical applications. So in our interests for electrons in patients, ionization always dominates.*

3.5.1 Electrons for medical therapies

When it comes to electrons usage in applied physics, we have to consider the relative effects of these three types of interaction we have discussed. In particular, we noticed that the behavior in energy loss for electrons in a material is not so far from what happens with heavy ions, at least until the trend reaches the plateau: in the relativistic region we expect in fact that the function resumes its increase.
A direct consequence of this analogous behavior is that we expect the electrons to have a range and a definite Bragg Peak in matter. In Figure

3.7 a schematic representation of the LET in electrons as a function of the material depth is shown in light blue. The LET does not show the characteristic shape of a Bragg peak, it instead looks like a somewhat "smoothed" step function. This behavior is due to the fact that electrons are heavily affected by multiple scattering, in such a way that the trajectory of the single particle almost curls up on itself. Therefore the actual depth on the electron in the material is very limited: an electron of $E = 0.5\ MeV$ has a mean travel path in a material of $2 - 3mm$. Analogously, an electron beam of mean energy $\bar{E} = 2\ MeV$ would release all its energy within a

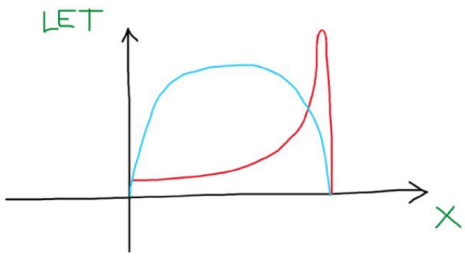

Figure 3.7: Comparison between the electrons(blue) and carbon ions(red) LET.

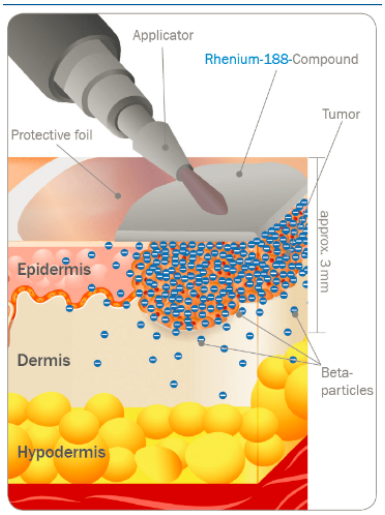

Figure 3.8: Representation of brachiotherapy.

material depth of 7 mm.
On the other hand, if we compute the LET as a function of the x along the trajectory of the electron, we will recover the expected Bragg Peak. The x coordinate along the electron trajectory is defined as CSDA, so when we want to visualize the electrons range and LET, we talk about **CSDA range** and CSDA LET.

This LET distribution is particularly interesting, as it can be useful to target cancerous tissue right adiacent to the radiative source. This feature is exploited in a therapy specific for skin tumors, called **brachitherapy** [Wat], in which an ointment enriched with ^{188}Re (electron emitter with a long lifetime $\sim 17\ h$) is applied on the region to treat, or electrons accelerated by a LINAC are sent directly on the skin lesion to treat. A schematic representation of how brachiteraphy works is represented in Figure 3.8.
Another very recent therapy is the Intra Operative Radiotherapy(IORT) [al99]: when it is possible, the tissue is exposed to radiation by exposing the organ, within a surgery, to a electron beam.In this way, only the targeted tissue is hit and damaged, while very little radiation reaches the healthy regions.

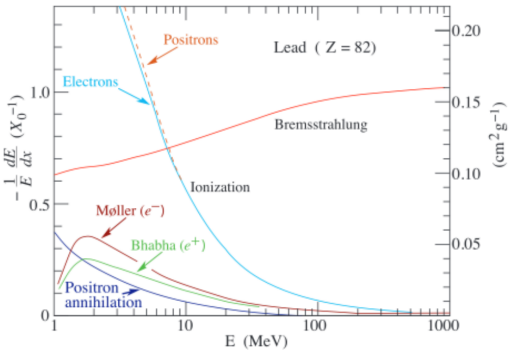

Figure 3.9: Relative energy loss of electron in matter,for different interactions, as a function of the electron energy.

3.5.2 Electrons for diagnostics

In Figure 3.9 the relative loss of energy (normalized to X_0) driven by different electron-matter interaction is presented. The ionization process dominates at low energy, and it shares with multiple scattering the inverse dependence from the energy of the electrons: for ionization, the slower the particle, the bigger the energy loss, for multiple scattering, the smaller the momentum, the bigger the trajectory deviation. The brehmsstrahlung radiation, on the other hand, leads to very small loss of energies with respect to ionization for energies in the $1-10$ range, as we can see in Figure 3.9, while it dominates for energies $E > 120\ MeV$. The medical therapies exploiting electrons act in this energy range: β-emitters produce electrons of $\mathcal{O}(MeV)$, while accelerated electrons such as the ones for IORT are of $\mathcal{O}(20MeV)$. Therefore brehmsstralhung interaction is completely neglected when dealing with electron-based treatments.

The brehmsstralhung emission is exploited in another field of applied medical physics, the diagnostics. In particular, the braking radiation is the phenomenon that produces the x-rays commonly used for visualization of structures within the body.
An x-ray tube is basically a source of braking radiation: a schematic representation of an x-ray tube is reported in Figure 3.10. A metal cathode is heaten up and emits electron by thermo-ionic

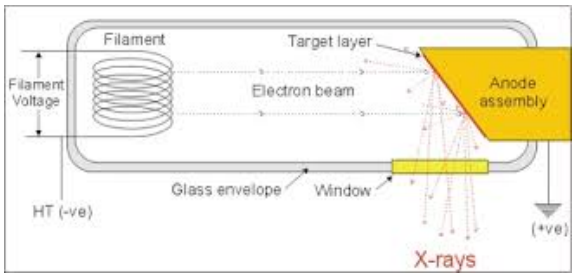

Figure 3.10: Representation of brachiotherapy.

effect; the electrons are accelerated towards an anode which is set to have a different in potential $\mathcal{O}(10-100kV)$ with respect to the cathode. The electrons then collide with the metal anode, interacting with matter. More or less the 1% of all the beam energy is emitted, most of it through brehmmsstrahlung, perpendicular to the acceleration of the electrons. Therefore, placing a window perpendicular to the beam direction and in correspondence of the anode, we can collect

Figure 3.11: Comparison of stopping power for different types of radiation in lead.

the x-ray radiation produced.

3.6 Photon-matter interactions

Unlike what happens with charged particles, in the interactions between photons and matter the probability that a quantum of light interacts with matter in a stretch of path dx is independent of the rest of the path. This probability dp is proportional to the width of the path crossed and therefore the relation holds:

$$\mathrm{d}p = \mu \mathrm{d}x \tag{3.27}$$

Where the proportionality coefficient μ is called the absorption coefficient, and depends on the type of material crossed, as well as on the energy of the incident photon. The number of photons that interact and are therefore absorbed in a stretch dx will then be given by the following relationship:

$$\mathrm{d}N(x) = -N(x)\mu \mathrm{d}x \tag{3.28}$$

With solution

$$N(x) = N(0)e^{-\mu x} \tag{3.29}$$

Where it has been considered that the intensity of a light beam is proportional to the number of photons that make up this beam. In general, a photon can interact with matter through different types of interaction, each with its own absorption coefficient. The term μ that appears is therefore the sum of several contributions:

$$\mu = \sum \mu_i \tag{3.30}$$

Now let's introduce the concept of *cross section*. In a classical schematization in which the incident beam encounters a series of obstacles that block part of this beam by passing the rest of it, the cross section represents the hindering surface constituted in our case by the molecules of the human body. The differential equation that defines it is the following:

$$\mathrm{d}\Phi(x) = -\sigma_b n_b \Phi(x) \mathrm{d}x \tag{3.31}$$

Where Φ is the flow of particles, σ_b is the cross section of the single element making up the target, n_b is the numerical density of elements with this cross section included in the target.

The solution of this differential equation is:

$$\Phi(x) = \Phi(0)e^{-\sigma_b n_b x} \tag{3.32}$$

By comparing the equations (3.29) and (3.32), different only for a multiplicative coefficient (the surface of the beam), we obtain the following relationship between absorption coefficient and cross section:

$$\mu = \sigma_b n_b \tag{3.33}$$

3.6.1 Photoelectric effect

The photoelectric effect consists in the absorption by the target atom of all the energy of the incident photon, leading to the ionization of an electron which will be emitted with energy:

$$E_{e^-} = E_\gamma - I \tag{3.34}$$

Where I is the ionization energy of the affected electron. This phenomenon is therefore a threshold effect: it occurs only if the energy of the photon is greater than that of ionization of the electron.

It is experimentally observed that the cross section of the photoelectric effect has the following trend depending on the target and the energy of the incident photon:

$$\sigma_{photo} \simeq Z^5 \alpha (\frac{m_e c^2}{E_\gamma})^n \tag{3.35}$$

Where Z is the atomic number of the target, α is the fine structure constant, n is 3.5 or 1 depending on whether the energy of the photon is less than or at rest of the electron much greater. Recalling the relationship between cross section and absorption coefficient, I can derive the expression:

$$\mu = n_b \sigma_b \tag{3.36}$$

$$\mu_{photo} \simeq \frac{\rho N_A}{A} Z^5 \alpha (\frac{m_e c^2}{E_\gamma})^n \tag{3.37}$$

3.6.2 Compton Effect

The Compton effect is the phenomenon in which a photon that undergoes elastic scattering with an electron undergoes a variation in wavelength (and therefore energy). In this process, unlike the photoelectric effect, its energy is not completely absorbed by the electron and the photon can undergo successive interactions. To describe the energy variation of the photon after the impact, we start from the imposition of the conservation of the total four-pulse:

$$\gamma^\mu = (E_\gamma, E_\gamma \hat{p_\gamma}) \qquad e^\mu = (m_e, \vec{0}) \qquad \gamma'^\mu = (E'_\gamma, E'_\gamma \hat{p'_\gamma}) \qquad e'^\mu = (E_e, \vec{p_e}) \tag{3.38}$$

$$e'^\mu = \gamma^\mu + e^\mu - \gamma'^\mu \tag{3.39}$$

$$m_e^2 = 0 + m_e^2 + 0 + 2\gamma^\mu e_\mu - 2\gamma^\mu \gamma'_\mu - 2\gamma'^\mu e_\mu = \tag{3.40}$$

$$= m_e^2 + 2m_e(E_\gamma - E'_\gamma) - 2(E_\gamma E'_\gamma - E_\gamma E'_\gamma cos\theta) = \tag{3.41}$$

$$m_e(E_\gamma - E'_\gamma) = E_\gamma E'_\gamma (1 - cos\theta) \tag{3.42}$$

$$\frac{1}{E'_\gamma} - \frac{1}{E_\gamma} = \frac{1 - cos\theta}{m_e} \tag{3.43}$$

Now explaining the final energy of the photon which is what interests us in this case we get

$$E'_\gamma = \frac{E_\gamma m_e}{m_e + E_\gamma (1 - cos\theta)} \tag{3.44}$$

From which it is observed that the range of energies that the photon takes is, for $\theta \in [0, \pi]$ $E'_\gamma \in [E_\gamma, \frac{E_\gamma m_e}{m_e + 2E_\gamma}]$

By simply requiring the conservation of the first coordinate of the four-pulse instead I can observe the range of energies taken by the electron:

$$E_\gamma + m_e = E'_\gamma + m_e + K'_e \qquad K'_e = E_\gamma - E'_\gamma \tag{3.45}$$

Then for the kinetic energy of the electron it can be said

$$K'_e \in [0, \frac{2E_\gamma^2}{m_e + 2E_\gamma}] \tag{3.46}$$

Experimentally to the Compton effect the following cross section is associated (non relativistic electrons):

$$\sigma_{Compton} \simeq \frac{8\pi}{3} r_e^2 \tag{3.47}$$

Where r_e is the classical electron radius.

From this we obtain the Compton absorption coefficient:

$$\mu_{Compton} \simeq \frac{\rho N_A}{A} Z \frac{8\pi}{3} r_e^2 \tag{3.48}$$

3.6.3 Pair production

When a photon has enough energy to produce a positron electron pair (equal to at least the sum of their masses equal to 1,022 MeV) it can create them as long as there is a nucleus nearby that balances the total quadrimpulse, which must remain zero in square norm like that of the photon. In the description of the phenomenon, the variation of kinetic energy of the nucleus is considered null, and the kinetic energy of electron and positron respectively is given by the following equality:

$$K_{e^{+/-}} = \frac{E_\gamma - 2m_e}{2} \tag{3.49}$$

The cross section of this phenomenon is:

$$\sigma_{pair-production} \simeq \frac{Z^2 \alpha^3}{(m_e c^2)^2} \tag{3.50}$$

Taking into account that $\mu = \sigma n$ and that $n = \frac{\rho N_A}{A}$:

$$\mu_{pp} = \frac{\rho N_A}{A} \frac{Z^2 \alpha^3}{(m_e c^2)^2} \tag{3.51}$$

Note that this absorption has a trend that goes like the square of the atomic number.

Third Exercitation

Estimate the quantities of lead, plastic ($C_5O_2H_8$, $rho = 1.2 g/cm^3$) and paraffin ($C_{31}H_{64}$, $\rho = 0.9 g/cm^3$) necessary to attenuate photons by a factor of 10^{-4} or to stop electrons and alpha particles of energies 0.1, 1 and 10 MeV.

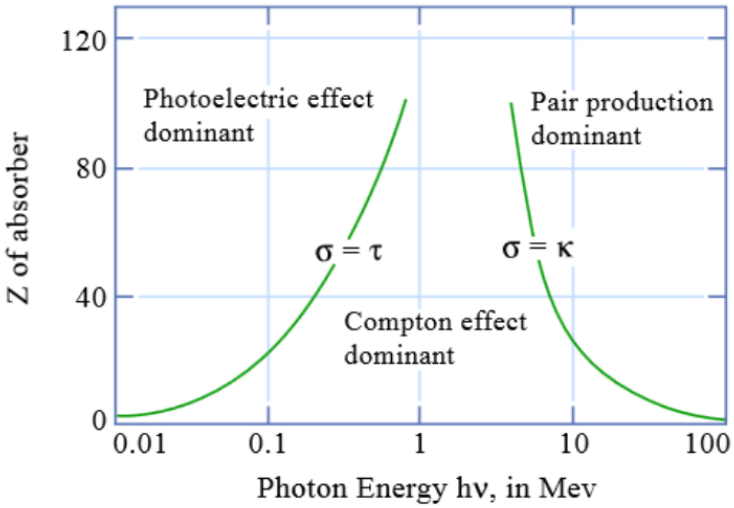

Figure 3.12: Dominance regions of the three modes of interaction of photons with matter, for different energies of photons and different atomic number of targets.

3.7 Positron-Matter interactions

The positron produced in a $\beta+$ decay interacts mainly by multiple scattering and ionization. Since the positron is an antimatter particle, along its path it will interact with one of the electrons of the medium, leading to annihilation:

itemize

With 20% probability it annihilates in flight with an electron producing two photons. By placing ourselves in the reference system of the electron that is hit, the relation $2m_e + K_e = E_{\gamma 1} + E_{\gamma 2}$ holds and the angle between the photons is less than 180°.

With 80% probability, after releasing all its energy into the medium, the positron begins to orbit around a free electron, forming the system e^+e^- called *positronium*. itemize

Let's analyze the possibility of positronium formation. It, depending on the total spin, forms the ortho-positronium or the para-positronium. Since the singlet state is only one while the triplet state is three, the formation of para-positronium (total spin: 1) is three times more likely than that of ortho-positronium (total spin: 0). In total for each positron produced by a $\beta+$ decay the probability of forming para-positronium is 64%. Para-positronium has an average life of $125ps$ and then decays in a pair of back-to-back photons, while ortho-positronium has an average life of $140ns$ and decays in three photons. The pair of photons emitted by the para-positronium is interesting because if detected it can give information to triangulate where the decay occurred. They are issued at 180° for momentum conservation. In addition, for energy conservation, the two photons are exactly $511keV$. PET is based on these principles, a diagnostic test that through the introduction of a metabolic radiopharmaceutical that decays $\beta+$ allows to obtain functional images through the reconstruction of the emission point of the back-to-back photons. The main limitation of PET is the fact that the positrons before forming positronium move in the body by multiple scattering and ionization, varying their position and therefore creating an uncertainty on the final measurement. Maximum resolution: $0.44mm$.

Insights and bibliography: [JP06] [BTVM05]

Chapter 4

Nuclear Decays

Radioactive decays indicate all those spontaneous processes during which an unstable nucleus transmutes into a more stable one with the emission of particles, which can be of different types and with different energies.

Nuclear decays are expressed with the notation:

$$X \longrightarrow Y + \sum_C A_C \tag{4.1}$$

where X is the parent nucleus that decays into the child nucleus Y by emitting several particles A_C. The constraint for a decay to be possible is given by the relationship:

$$m_x > m_y + \sum m_C \tag{4.2}$$

where m_x, m_y e m_C are the nuclear masses to be consider.
The exact equality, taking into account also the kinetic energies of the decay products T_y and T_c, is given by the relation $m_x = m_y + T_y + \sum(m_c + T_c)$, from which:

$$m_x - m_y - \sum m_c = T_y + \sum T_c = Q_{\text{value}} \tag{4.3}$$

The Q_{value} represents the maximum kinetic energy that can be assumed by the decay products in the reference system integral with the unstable atom. Given the relationship, it is noted that in a decay $Q > 0$.

4.1 The Atomic Nucleus

For light nuclei the stability is verified when $Z \sim N$ but with increasing atomic number the number of neutrons necessary to guarantee stability increases. The figure (4.1) represents the *Carta di Segrè* where the stability curve is compared with the straight line $Z = N$.

Two atoms are said:
itemize

Isotopes, if they have the same atomic number;

Isotons, if they have the same number of neutrons;

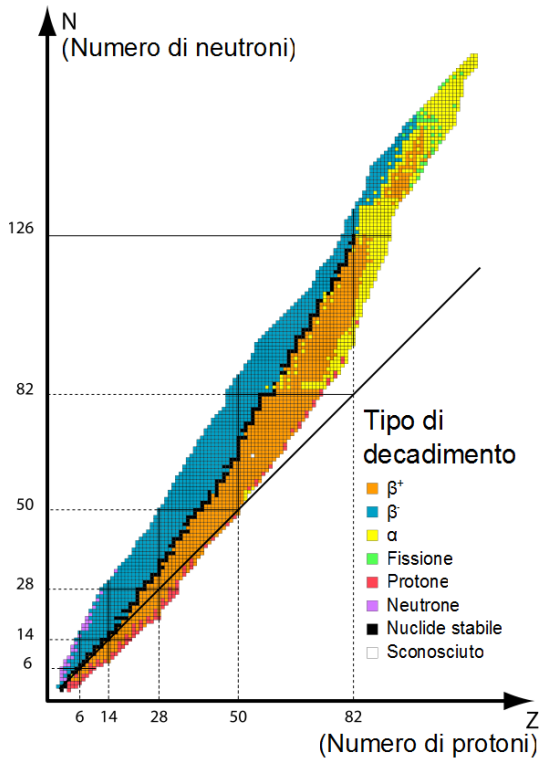

Figure 4.1: Stability curve of nuclei as a function of the number of protons and number of neutrons. The type of decay that each isotope tends to make outside the stability curve are also represented.

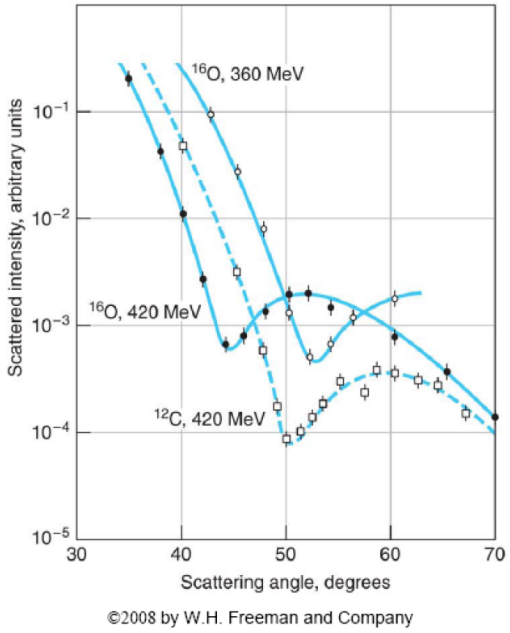

Figure 4.2: Trend of the scattering angle of electrons on oxygen and carbon nuclei.

Isobari, if they have the same mass number. itemize

Neutrons and protons are spin 1/2 *fermions*. They therefore organize themselves in the nucleus on energy levels in which they arrange themselves in opposite spins. When the number of neutrons and protons is even, each energy level is completely filled. When their number is odd, nuclear reactions are more likely in order to arrive at more stable energy levels. For example, by filling the energy levels of $^{12}_{5}B$ I have an extra neutron on a higher energy level than those filled by protons. This element in fact decays β in the $^{12}_{6}C$. To differentiate different isotopes, mass spectrometers are used, in which, taking advantage of the Lorenz force generated by a magnetic field, I observe the correlation between the radius of curvature and the mass of the isotope considered. To measure the nuclear beam, instead, we observe the diffraction pattern of the scattering of electrons on this nucleus. Graphing the intensity of the scattering as a function of the angle, I have the following relation for the first minimum point of the trend:

$$\sin\theta^* = 0.16\frac{hc}{pcR} \tag{4.4}$$

From which the radius can be derived.

The law that links nuclear ray and atomic mass is empirically defined:

$$R = 1,15A^{1/3}(fm) \tag{4.5}$$

Let us now consider nuclear density. It can be expressed as:

$$\rho = \frac{m}{\frac{4}{3}\pi R^3} = \frac{Am_p}{\frac{4}{3}\pi(1,15A^{1/3})^3} = \frac{m_p}{\frac{4}{3}\pi 1,15^3(fm^3)} = 10^{17}kg/m^3 \tag{4.6}$$

and is therefore in a first approximation independent of the element considered. The density

obtained is compatible with that of the white dwarfs, stars composed of nucleons compressed on each other analogously to an atomic nucleus.

In order to obtain the atomic mass with greater precision, we stop neglecting the difference in mass between neutrons and protons and we also consider the binding energy between nucleons, the *Binding Energy (B. E.)* in the nucleus. We then have that:

$$M(Z, A) = Z \times m_p + (A - Z) \times m_n - A \times B.E. \tag{4.7}$$

Fourth Experience

- *Graph the nuclear mass as a function of Z for* $A = 18$ *and* $A = 208$*. Compare the result with the decay time graph.*
- *Graph Sp (Z) and Sn (Z) for* $N = 9$*.*
- *Graph Sp (N) and Sn (N) for* $Z = 33$*.*

4.2 Important quantities

When a nucleus is unstable it has a certain probability per unit of time of decaying in a stable nucleus, called *radioactive constant* λ. By indicating with N the number of unstable nuclei, the average number of nuclei that decay in the unit of time is given by λN. This overall size is called *activity*. In the time between t and $t + dt$ the number of nuclei varies as follows:

$$\mathrm{d}N = -\lambda N \mathrm{d}t \tag{4.8}$$

Solving the differential equation we obtain

$$N(t) = N(0)e^{-\lambda t} \tag{4.9}$$

half-life is defined, that is the time at which the number of active nuclei is halved compared to the initial number, as:

$$\tau_{\frac{1}{2}} = \frac{\ln 2}{\lambda} \tag{4.10}$$

Recalling that the activity is defined as λN, multiplying the previous equation by λ I get the temporal trend of the activity:

$$A(t) = \lambda N(t) = A(0)e^{-\lambda t} \tag{4.11}$$

In the past, the unit of measurement of activity in the S.I was the emph Curie, corresponding to 37 billion disintegrations per second, indicated with Ci. It represents the activity of one gram of ^{226}Ra. Currently the unit of measurement has become the *Bequerel*, indicated with *Bq*, which corresponds to a disintegration per second. Sources commonly used in the laboratory have activities of the order of kBq. From the definitions of the units of measurement follows the change:

$$1\mathrm{Ci} = 3,7 \times 10^{10}\mathrm{Bq} \tag{4.12}$$

An unstable atom can decay into different channels, each with a different average life τ_i (and therefore a different radioactive constant λ_i).

The total radioactive constant is defined $\lambda_{tot} = \sum \lambda_i$. Branching fraction is introduced as $\mathrm{BR} = \frac{\lambda_i}{\lambda_{tot}}$.

Note: the activity does not take into account the type of phenomenon that is taking place and how many particles it generates. It represents the number of decays that occur, whatever they are and whatever number of particles they produce. To specifically count the number of a certain type of particles that are produced, we conventionally use Hz or CPS (Counts Per Second).

In applied physics and in particular in medical applications, other important quantities related to the activity are used:

- Specific Activity: $A_{sp} = \frac{\mathrm{d}A}{\mathrm{d}V}$
- Standard Uptake Value (SUV): $\mathrm{SUV} = \frac{A_{sp}(\mathrm{tumore})}{A(\mathrm{somministrata})}$ to make it dimensionless you do $\mathrm{SUV} = \frac{A_{sp}(\mathrm{tumore})}{A(\mathrm{somministrata})\times\rho} m_{\mathrm{paziente}}$
- Tumor Non-tumor Ratio (TNR): $\mathrm{TNR} = \frac{\mathrm{SUV(tumore)}}{\mathrm{SUV(limitrofo)}}$

Typically you search SUV ~ 5

4.3 Alpha Decay

decays are defined as those of the following form:

$$ {}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He \tag{4.13} $$

that is, they provide for the emission of a nucleus of ${}^{4}_{2}He$, commonly known as *alpha particle*. Since there are two reaction products, in the reference system of the decaying atom they are produced back to back with the same impulse for conservation of momentum. The following equality applies:

$$ Q = T_y + T_\alpha = \frac{p^2}{2m_y} + \frac{p^2}{2m_\alpha} = \frac{m_\alpha}{m_y}T_\alpha + T_\alpha \tag{4.14} $$

From which

$$ T_\alpha = \frac{Q}{1 + \frac{m_\alpha}{m_y}} \tag{4.15} $$

From which it is deduced that for decays of atoms with high A, in which also the decay product Y has high mass, I have $T_\alpha \simeq Q$.

Note: a decay can lead to the creation of a product that is not in its fundamental nuclear spin state (excited state), but decays in it by emitting γ rays

It is observed that there is a relationship between the average life of a certain radionuclide and the energy with which the particles α are emitted. This relationship is called *Geiger-Nuttall's law*:

$$ \log_{10}\tau = a + b\log(E) \tag{4.16} $$

where a and b are two empirical constants obtainable as fit parameters of the experimental data with the above relationship.

Note: ${}^{223}Ra$ is used to treat metastases in bones or prostate because it mimics calcium.

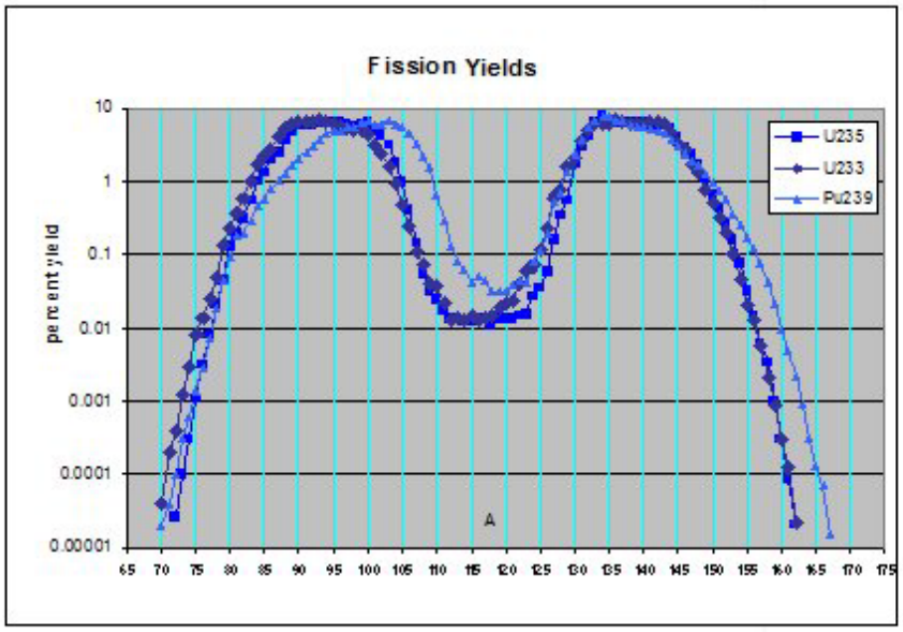

Figure 4.3: Probability distribution of the fission products of ^{235}U, ^{233}U and ^{239}Pu. It is observed that the production of two nuclei with similar mass is unlikely. Much more likely is the production of a heavy core and a light core.

4.4 Spontaneous fission

Spontaneous fission consists in the decay of a heavy nucleus into two lighter nuclei with probable neutron production. Due to the high potential barrier that must be overcome for the reaction to take place, the spontaneous fission process becomes possible only for very heavy nuclei. The lightest nucleus for which spontaneous fission is observed is ^{226}Ra, while this process occurs with a probability comparable to that of decay α in some uranium isotopes. Spontaneous fission branching ration becomes dominant only for $A > 260$. The fission products are normally far from the stability curve and in turn decay $\beta-$. The decay products produced by a spontaneous fission have a mass number *asymmetric*, that is they are preferably produced with a different A, as shown in the figure 4.3. The most likely value of difference in mass number between fission products is ~ 45.

4.5 Beta decay

Beta decays are isobaric transformations that occur by weak interaction and include the presence of an electron or positron. They are of three types:

$$\beta-: \quad n \longrightarrow p + e^- + \bar{\nu_e} \quad thatis, atomically \quad {}^A_Z X \longrightarrow {}^A_{Z+1} Y + e^- + \bar{\nu_e} \tag{4.17}$$

$$\beta+: \quad p \longrightarrow n + e^+ + \nu_e \quad thatis, atomically \quad {}^A_Z X \longrightarrow {}^A_{Z-1} Y + e^+ + \nu_e \tag{4.18}$$

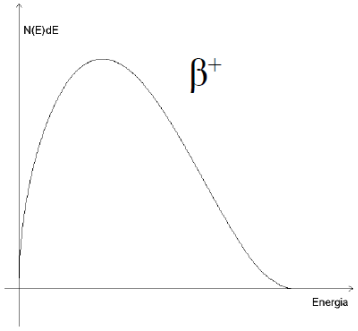

Figure 4.4: Distribution of positron energy produced in a $\beta+$ decay. The probability that it has zero energy is zero.

$$CE: \qquad p + e^- \longrightarrow n + \nu_e \quad thatis, atomically \quad {}^A_Z X + e^- \longrightarrow {}^A_{Z-1} Y + \nu_e \tag{4.19}$$

We observe that in all reactions the total mass number of the atom is conserved while its atomic number changes. Outside the atomic nucleus it is impossible for decays to occur $\beta+$ because the mass of the proton is less than that of the neutron. Instead the $\beta-$ reactions take place outside the nucleus with a very short decay time and lead to the production of free neutrons. We also observe that when electronic capture takes place within a nucleus, the electron participating in the reaction comes from one of the innermost electronic shells. Following the absorption of an internal electron, the electrons that populate the outermost shells tend to move towards the lower levels producing intense X radiation.

For the α decays, given the presence of a massive child nucleus and a lighter α particle, the Q_{value} of the decay was almost entirely converted into the kinetic energy of the α particle. In this case the kinetic energy with which a α is emitted depends on the type of decay, and is the same for all alpha produced by the same parent nucleus. The decays β instead, are decays in 3 bodies in which two *light* particles are produced: the neutrino and the electron / positron. In this case, as can be seen in the figures (4.4) and (4.5) the energy distributions with which electrons and positrons are produced are different because the percentage of Q_{value} is different converted into the kinetic energy of the detectable particle. The extreme point of the distribution of energies of the electrons in these two reactions is called End Point, and is given by the condition in which the Q_{value} is entirely converted into the kinetic energy of the electron / positron (and therefore the neutrino is produced stopped).

Indicating the atomic masses with M_* and the nuclear masses with m_*, in the decays β^- it is observed that

$$M_x = m_x + Zm_e \qquad M_y = m_y + (Z+1)m_e \tag{4.20}$$

$$Q_{\beta^-} = m_x - m_y - m_e \tag{4.21}$$

it is easy to observe that $M_x - M_y = m_x - m_y - m_e$. So we can say:

$$Q_{\beta^-} = M_x - M_y \tag{4.22}$$

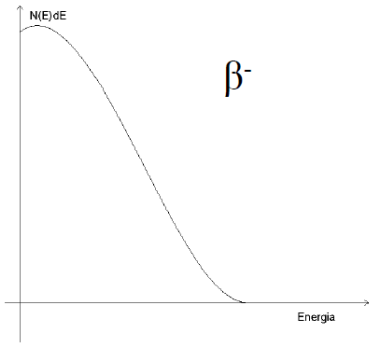

Figure 4.5: Distribution of the electron energy produced in a decay $\beta-$.

This also tells us that a necessary and sufficient condition for a β^- decay to occur is that the mass of the parent nucleus is greater than the mass of the child nucleus.

For the decay β^+ instead:

$$M_x = m_x + Zm_e \qquad M_y = m_y + (Z-1)m_e \tag{4.23}$$

$$Q_{\beta^+} = m_x - m_y - m_e \tag{4.24}$$

It is easily observed that $M_x - M_y = m_x - m_y + m_e = Q_{\beta^+} + 2m_e$. That is

$$Q_{\beta^+} = M_x - M_y - 2m_e \tag{4.25}$$

Then a necessary and sufficient condition for a decay to occur β^+ is that the difference in atomic masses between the parent nucleus and the child nucleus is at least twice the mass of the electron: $M_x - M_y > 2m_e$.

In nature, with the exception of the ^{40}K, there are no radionuclides that decay β^+. The numerous radionuclides β^+ commonly used for research or medical practice are artificially produced.

In the case of *Electronic Capture*, a nucleus can capture an electron from an atomic shell, transform a proton into a neutron and emit a neutrino with the following reaction:

$$^A_Z X + e^- \longrightarrow ^A_{Z-1} Y + \nu_e \tag{4.26}$$

Since the mass of Y is much larger than that of the neutrino, the latter is practically always emitted with the same energy. In this case the Q_{value} leads us to put the following constraint:

$$M_x + m_e > M_y \tag{4.27}$$

Then summarizing on an increasing energy scale the possible decays are as follows:

- Electronic Capture if $M_x - M_y > -m_e$
- β^- decay if $M_x - M_y > 0$
- β^+ dacay if $M_x - M_y > 2m_e$
- α decay if $M_x - M_y > m_\alpha$

Fifth experience

- *Find a list of isotopes of C, Na, F, P, Ga, I, Re, Lu, Y and Sr with dominant $\beta+$ and $\beta-$ decays with a half-life of between 1 minute and 10 days .*
- *For each isotope, write half-life, end point and range projected for energies that are equal to half the end-point.*

4.6 Gamma Emission

Nuclei produced by β decays can be in states other than the fundamental state. Child isotopes that are in an excited state will decay towards the ground state (i.e. go from a higher to a lower energy level) by emitting γ rays.
The transition can take place with a single jump and production of a single photon whose energy will be equal to the difference between the starting and arrival energy levels, or with more intermediate jumps and the production of a cascade of γ rays.
It is called gamma emission and not gamma decay as there is no correlation between the number of atoms that pass into the ground state and the number of photons emitted. The average life of these states is of the order of picosecond, little more than that of beta decays. However, there are some exceptions, the *metastable states*, characterized by a longer average life. A metastable radioisotope widely used in medical physics (especially for SPECT exams) is the ^{99m}Tc, produced by the beta- decay of ^{99}Mo, which has an average life of 6 hours. Gamma emission is in competition with another phenomenon that can occur in the presence of an excited nucleus: the *Internal Conversion*. This consists in the phenomenon whereby the excess energy of the nucleus is directly transferred to an electron which is ionized and takes on final energy:

$$E_{e^-} = E_{s.eccitato} - I \tag{4.28}$$

Note: For possible gamma decays with their probabilities consult this web site:

4.7 Secular balance

An interesting phenomenon occurs when a parent nucleus with average life time τ_f decays into a child nucleus with life time τ_d a fraction Φ of times. Recalling that we defined the activity as $A = \lambda N = \frac{N(0)}{\tau} and^{-t/\tau}$, it follows that the total number of child nuclei increases thanks to the decays of the parent nuclei and decreases due to its own decay:

$$\frac{dN_d}{dt} = -\Phi\frac{dN_f}{dt} - \frac{\partial N_d}{\partial t} = \Phi\frac{N_f}{\tau_f} - \frac{N_d}{\tau_d} \tag{4.29}$$

By integrating I get

$$N_d(t) = \frac{\Phi}{\frac{\tau_f}{\tau_d} - 1} N_f(0)(e^{-t/\tau_f} - e^{-t/\tau_d}) \tag{4.30}$$

Passing from Number of isotopes to activity dividing by τ_d we obtain:

$$A_d(t) = \frac{\Phi}{\frac{\tau_f}{\tau_d} - 1} A_f(0)\frac{\tau_f}{\tau_d}(e^{-t/\tau_f} - e^{-t/\tau_d}) = \frac{\Phi}{1 - \frac{\tau_d}{\tau_f}} A_f(0)(e^{-t/\tau_f} - e^{-t/\tau_d}) \tag{4.31}$$

Let us now analyze the borderline cases. If $\tau_d << t << \tau_f$, as in ^{99}Mo $\rightarrow^{99m}$ Tc, will have:

$$A_d(t) = \Phi A_f(t) \tag{4.32}$$

That is, the activity of the child nucleus will only be scaled by a certain factor compared to that of the father.

Indeed when I have $\tau_f \sim t << \tau_d$, as in ^{223}Ra, I obtain:

$$A_d(t) = \Phi \frac{\tau_f}{\tau_d} A_f(0)(e^{-t/\tau_f}) \tag{4.33}$$

Let's go back to the first case and see what happens if we extract the child nuclei after a time equal to the average life τ_d. Graphic.

Continuous technetium generators can be created with machinery containing Molybdate $^{99}MoO_4^{2-}$ and Pertecnato $^{99m}TcO_4^-$. Other examples are the natural families of ^{238}U, ^{232}Th and ^{235}U. The activities of a family are all linked together by Bateman's differential equations.

Let's look at an example: ^{90} $textSr$ $rightarrow^{90}$ $textY$ $rightarrow^{90}$ $textZr$. When I take a certain amount of Becquerel of ^{90} $textSr$ I am also taking the same yttrium activity for less than a factor Phi. Here we see the difference between installments and activities: taking 1 Bq of strontium I have 2 kHz of electron production, one from the decay of Strontium and one from the decay of Yttrium.

Sixth Experience

Find pairs of father-daughter nuclei where:

- *The daughter falls β con $\tau \sim 1 - 100hr$*
- *Il padre decade con $\tau \sim 100d - 10y$*

Chapter 5

Nuclear Reactions

A nuclear reaction is a type of transformation that affects the nucleus of an atom of a specific element, which is converted into another with a different atomic number, involving the so-called nuclear forces. The bombardment of the nucleus with suitably accelerated nucleons, photons or other nuclei generates various processes consisting of violent changes in the energy and momentum of the interacting particles and, in many cases, in the production of particles other than those that interacted. In order to have a nuclear reaction between charged particles, it is necessary to ensure adequate relative kinetic energy to overcome the incoming Coulombian barrier. In nuclear reactions, the nuclei of the reactants are different from the nuclei of the final products. They can be both isotopes (i.e. atoms with the same atomic number, but with different mass number) of the initial reagents, or completely different chemical elements. The minimum energy that a reagent must have for the occurrence of the reaction is at least equal to the barrier energy. During a nuclear reaction the mass number A (number of nucleons = protons + neutrons) and the atomic number Z (number of protons) are kept.
For example, the correct nomenclature requires that the reaction $\alpha + {}^{14}_{7}N \rightarrow p + {}^{17}_{8}O$ be indicated as ${}^{14}N(\alpha, p)^{17}O$. In general:

$$X + x \rightarrow Y + y \tag{5.1}$$

$$X(x + y)Y \tag{5.2}$$

Where X and x are respectively the initial nucleus and the projectile and Y and y are the fragments produced by the reaction. We can have a great variety of different situations, both in the final and in the initial state, in particular we can group nuclear reactions into:

- **Nuclear Photo-disintegration**: an extremely energetic photon interacts with an atomic nucleus causing its transition to an excited state and its immediate decay in two minor nuclei:

$$X(\gamma, \star)Y$$

- **Neutron or Proton Radioactive Capture**: a reaction in which an atomic nucleus and one or more nucleons collide and unite to form a heavier atomic nucleus. Energy and impulse are conserved through a γ emission:

$$X(n/p, \gamma)Y$$

- **Elastic Scattering**: the input and output channels are identical, no particles in the output channel are in an excited state, the kinetic energy of the system in the center of mass is conserved, instead its direction of propagation are different:

$$X(a,a)X$$

- **Inelastic Scattering**: in the output channel one or more products are in excited states and the kinetic energy of the projectile is not conserved:

$$X(a,a)X^{\star} \rightarrow X(a,a+\gamma)X$$

Unlike nuclear decays (Chapter 4) in nuclear reactions the Q-value can be $<$, $=$ or > 0. In particular, depending on the Q-value we can distinguish three types of reactions:

- $Q > 0$: exothermic or spontaneous reactions (e.g. fission, fusion). The kinetic energy of the final state is greater than the initial one. They can occur for any energy of the bullet.
- $Q = 0$: elastic reactions.
- $Q < 0$: endothermic reactions, kinetic energy of the bullet, which will be greater than that of the fragments, must be greater than a certain threshold.

In particular, in the case of a collision, such as that shown in Fig. 5.1, between the incident particle i and a fixed target b, with the production of n particles in the final state, the threshold energy of the reaction is defined as the kinetic energy K_i of the incident particle at which the particles of the final state are produced at rest in the center of mass system. In the system of the particle b, the threshold kinetic energy turns out to be:

$$T_i > \frac{(\sum_{f=1}^{n} m_f)^2 - (m_i + m_b)^2}{2m_b} \tag{5.3}$$

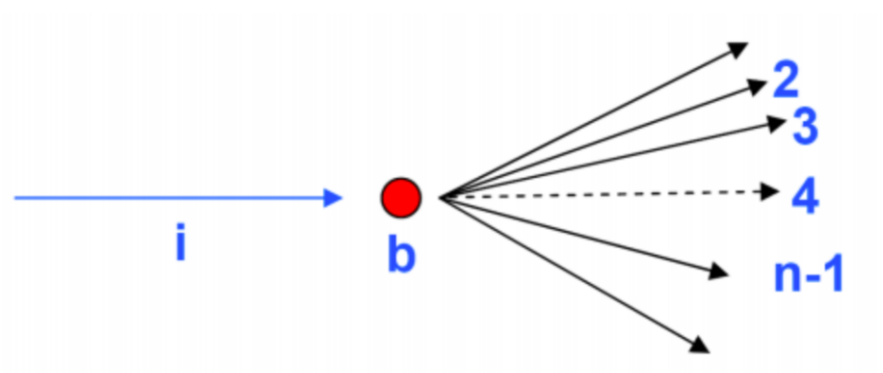

Figure 5.1: Collision of a particle i incident on a target b with production of n particles in the final state.

In the next paragraphs we will explore some types of nuclear reactions especially interesting for their applications.

5.1 Radioisotope production

Some stable substances can be made radioactive by nuclear reactions by bombarding a specific target with a proton beam. An immediate application of radioisotopes is their use in PET. In

fact for the occurence of a $beta^+$ decay it is necessary that the isotopes have an excess of protons. The nuclear reaction for the production of radioisotopes is governed by a complex mechanism and several models have been developed to describe it. In particular, according to Bohr's proposed nuclear model (1936), nuclear reactions occur in two different times. First the incident particle and the target nucleus form an intermediate state, the compound nucleus. In this phase there is the transfer of kinetic energy and the particle shares its energy with the nucleus. Due to statistical fluctuations, one or more nuclear particles can acquire an energy that allows them to leave this state. There is therefore a decay of the compound nucleus which has an average life of between 10 $^{-15}$ and 10 $^{-14}$ s. During this time the compound nucleus exists as a separate entity and the energy is distributed between the nucleons. In classical physics, a charge particle z can collide with the nucleus only if it has energy greater than the Coulombian barrier:

$$B = \frac{zZe^2}{r} \tag{5.4}$$

Where Z is the atomic number of the target nucleus, e the electron charge, r the nuclear beam. In quantum mechanics, however, due to the tunnel effect, even lower energies are possible. For example, in the reaction ^{18} O (p, n) ^{18}F, B corresponds to 3.8MeV and also for the other PET radioisotopes the values are similar (Tab. 5.1). After the particle has passed the Coulombian barrier there is another condition for a nuclear reaction to take place: the total energy must be greater than the mass of the products of the decay. Furthermore, the cross section for the reaction must be large enough to obtain a good performance. For PET isotopes the cross section is characterized by many peaks in the region of 10 to 20 MeV. For this reason the cyclotrons used to produce them work precisely in this energy range (Tab. 5.1). The mathematical model

Table 5.1: Reactions for the production of radioisotopes with relative Coulombian barrier (B) and energy.

ISOTOPES	REACTIONS	B ($unMeV$)	ENERGY ($unMeV$)
F_{18}	$^{18}O(p,n)^{18}F$	3.8	11-17
C_{11}	$^{14}N(p,\alpha)^{11}C$	3.1	11-17
N_{13}	$^{16}O(p,\alpha)^{13}N$	5.6	19
	$^{13}C(p,n)^{13}N$	5.6	11
O_{15}	$^{15}N(p,n)^{15}O$	2.6	11
	$^{14}N(d,2n)^{15}O$	2.6	6

that describes the trend of the activity of the substance produced is very similar to that of father and daughter nuclei seen in the chapter on nuclear decays. In particular, in order to estimate the production activity, it is necessary to take into consideration the decay during irradiation and the saturation effects, relevant already for bombing times of the average life order. Calling **P** the **production rate**, the number of irradiated N(t) atoms obey to the equation:

$$\frac{dN}{dt} = -\lambda N + P \tag{5.5}$$

Whose solution is:

$$N = \frac{P}{\lambda}(1 - e^{-\lambda t}) \tag{5.6}$$

which corresponds to an activity:

$$A = \lambda N = P(1 - e^{-\lambda t}) \tag{5.7}$$

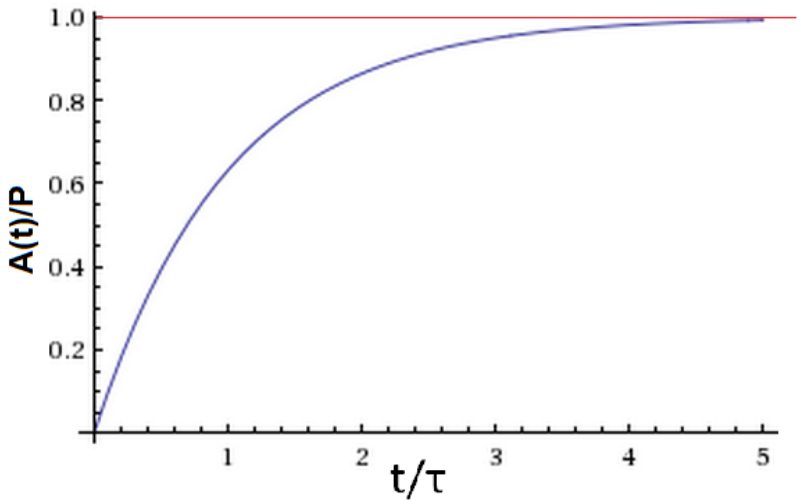

Figure 5.2: Activity of a radionuclide produced with a constant production rate.

Where the term $(1 - e^{\lambda t})$ is called *saturation factor*, $\lambda = \frac{1}{\tau}$ is the *decay constant* and τ the average life of the isotope. Fig. 5.2 shows the relationship between activity and production rate as a function of the relationship between time and average life. It can be seen that the production process begins to be inefficient already after an average life. With the passage of time saturation is reached, that is, the activity produced is at its maximum and the saturation term tends to 1. Therefore, since the production rate is equal to the decay rate, it is useless to continue with the bombing. The beam current used in the production of radioisotopes is directly connected to the cross section and the amount of activity required. These are limited by the maximum power the target can endure without being damaged. The cross section can be expressed as:

$$\sigma = \frac{P}{Inx} \tag{5.8}$$

where I is the beam current in μA, n the number of target nuclei for cm^3, x the thickness of the target in cm^2. By inverting the relation and expressing n as a function of the density of the material ρ (g/cm^3) we obtain the expression of the production rate as a function of the cross section:

$$P = \sigma \frac{I\rho x}{A \times 2.678 \times 10^{-10}} \tag{5.9}$$

Where A is the atomic mass of the target. Assuming a cross section of 100 mb, the typical value of the production of ^{18}F that is obtained is P = 9 $\frac{GBq}{\mu A}$. Cyclotrons can usually produce activities of the order of 100-200 GBq of ^{18}F in 60-90 minutes of irradiation at a total current beam of 50-80 μA. After the synthesis, this corresponds to about 50-100 GBq of FDG, enough for 2-4 PET centers an hour away from the production center, administering it to 10 patients for each center. The dose administered for each treatment is in fact 400-500 MBq, where Z is the atomic number of the target nucleus, e the electron charge, r the nuclear beam.

5.2 Fragmentation

Another reaction that can occur when a charged particle interacts with a target nucleus is the *nuclear fragmentation*. This process is of particular importance especially for the energies of interest in Particle Therapy. In fact, at the energies required for this therapy (several hundred MeV) the treatment is significantly influenced by nuclear fragmentation processes which cause an attenuation of the flow of the primary beam as the depth of penetration increases and lead to the emission of fragments with Z minor than the primary target or projectile. Based on the value of the impact parameter with respect to the radius of the interacting particles, it is possible to distinguish the collisions in *central* and *peripheral*. The first case occurs when the impact parameter is very small and therefore all nucleons, both of the target and of the projectile, can participate in the reaction creating a high multiplicity of fragments. As the impact parameter increases, peripheral collisions occur when the overlap between the projectile region and the one of the target is very small with a consequent incomplete fusion of the nuclei. As a result, few fragments are observed and above all with speeds approximately equal to those of the projectile, forward in the same beam direction.
The cross section is a function of the energy of the projectile and, while at high energies a partial fusion is much more likely, for energies in the Bragg peak region (e.g. particles with low energy at the end of their path) the probability of complete fusion reaches values of about 40-50 % depending on the mass of the bullet.

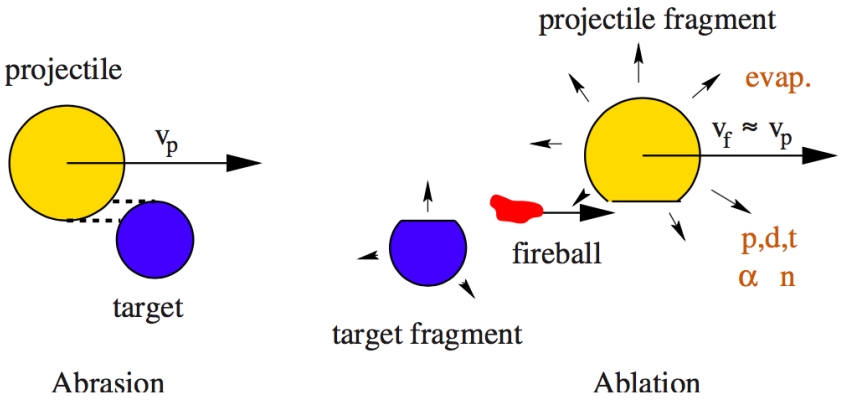

Figure 5.3: Abrasion-ablation model of peripheral collisions at high energies [**Serber:nuclear**].

Peripheral collisions occur in two passages that occur in two different time scales (*abrasion-ablation* model, Fig. 5.3); At first, with characteristic times of the order of $10^{-23}s$, the interaction transfers a certain amount of excitation energy to the target nucleus in the overlapping zone while the rest of the nucleus acts as spectator (Abrasion). At this stage, light particles are emitted. The bullet fragments follow the initial trajectory roughly keeping the same speed, while the target's recoil fragments move more slowly. Subsequently the system is thermalized and the remaining fragments of projectile and target de-energize by evaporation of neutrons, protons and light nuclei, fission or emission of gamma rays (Ablation). The characteristic time of emission of particles varies between $10^{-21}s$ and $10^{-16}s$ for excitation energies of 200 MeV and 10 MeV respectively.

When fragmentation occurs, whether it is from the projectile, the target or both particles, the total mass must be preserved as well as the total charge. A concern Particle Therapy, in proton beam treatments only the fragmentation of the target nuclei occurs, e.g. the evaporation of the

excited target following the collision with the consequent production of light particles. The speed of these fragments is very small and therefore their range does not exceed a few microns thus depositing the energy near the point where the collision occurs. In the case of particle beam with Z > 1, on the other hand, the fragmentation of the target contributes only a small part and that of the bullet is dominant. Most of the charged fragments, produced in the fragmentation of the incident beam, have a speed similar to that of the projectile but the particles are smaller in size. Considering that for particles with the same velocity the trend of the range goes as A/Z^2, the fragments ($Z_{framm} < Z_{proj}$) will deposit their energy at depth penetration beyond the Bragg peak of the projectile, creating a tail that is absent in the case of proton beams. This phenomenon is evident in Fig. 5.4 where the contribution of ionization due to the primary beam and to the secondary and tertiary fragments is represented. It can be seen that after the Bragg peak there is a tail due to this phenomenon.

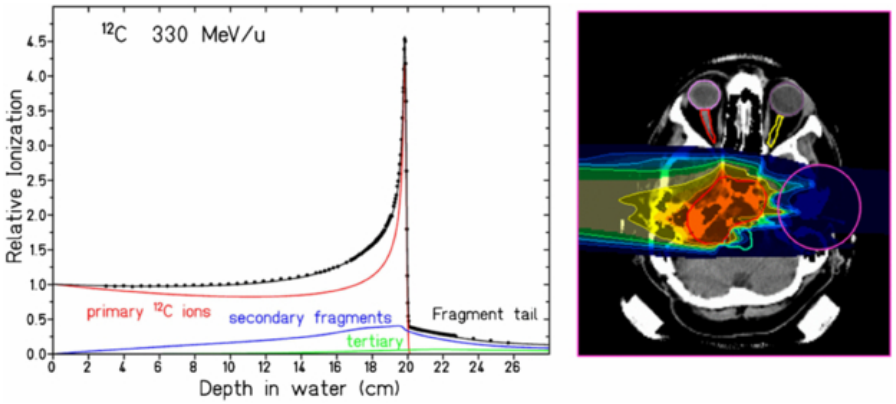

Figure 5.4: On the left the ionization in water of a carbon ion beam of 330 MeV / u. The black line indicates the total contribution while the red, blue and green lines highlight the contribution respectively of the primary beam, of the secondary and tertiary fragments produced by the fragmentation of the secondary ones. On the right the respective simulated dose on a patient's CT. The tail due to fragments is highlighted in purple.

5.3 Neutron Activation

Neutron activation is a process in which a neutron flux induces radioactivity in a material. In particular, it occurs when an atomic nucleus captures free neutrons, becoming heavier and entering in an excited state. The excited nuclei often decay immediately emitting gamma rays or beta, alpha, fission products and neutrons. These radioactive nuclei can have half-life ranging from small fractions of a second up to many years. Neutron activation can be used for analysis by neutron activation, which is one of the most sensitive and specific methods for searching for trace elements. It does not require the preparation of the sample or its solubilization and can therefore be applied to objects that must remain intact, such as works of art of great value. Even if the activation induces radioactivity in the object in question, its level will be typically low and its short half-life, therefore its effects soon disappear. In this sense, the neutron activation procedure is a non-destructive analysis method.

Chapter 6

Dosimetry

Dosimetry is a subject between physics and medicine that deals with the calculation and measurement of the dose absorbed by matter when subjected to both ionizing and non-ionizing radiation. This quantification is necessary for both accidental radiation exposure and for intentional radiation exposure for therapeutic purposes.
The damages that a radiation can cause concern in particular the DNA that contains the genetic instructions used for growth, development, functioning and cell reproduction. The cell diameter is $\sim 10 \div 100 \mu m$ while the distance between the two helices that make up the DNA is 2 nm and they are contained in the cellular nucleus whose diameter is $\sim 3 \mu m$ (Fig. 6.1).

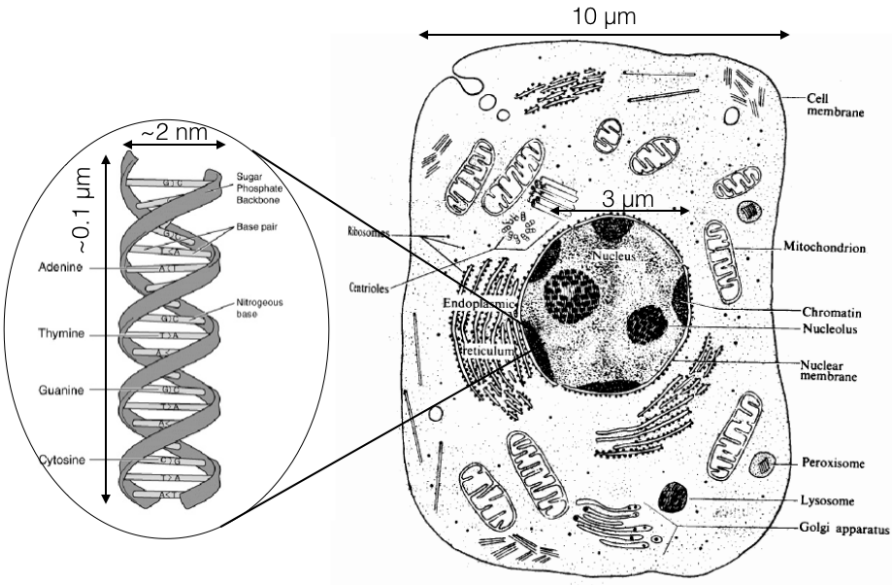

Figure 6.1: Representation of an animal cell. The dimensions of the nucleus and DNA are specified.

In Fig. 6.2 it is possible to see an example of DNA breakdown from photons interaction: when neutral radiation passes through the patient's body, it ionizes the cells, both healthy and

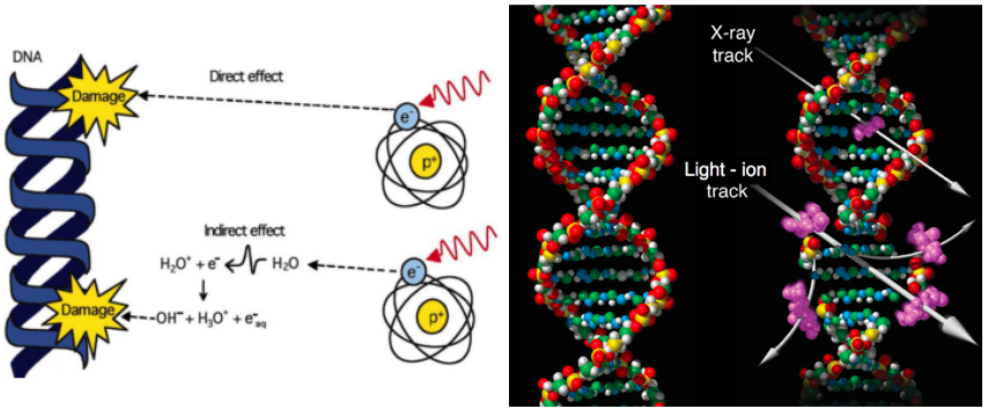

Figure 6.2: On the left a DNA helix broken by the direct action of an ionized electron due to the passage of a gamma radiation, and by the action of free radicals (OH) induced by an ionizing radiation of a photon in the cellular tissue. On the right an example of the difference in damage caused by photons and light ions.

cancer. The electrons produced can directly hit the DNA of the cell (direct damage), creating more efficient damage, or they can ionizing the water, which makes $\sim 80\%$ of the human body, producing free radicals (OH, O). These radicals are chemically very reactive and, although they have a very short life, they can reach the nuclei of cells and damage the DNA (indirect damage). Cells have an extremely elaborate repair system and if not properly damaged in both DNA helices they do not lead to cell death. The effects of radiation can be distinguished in stochastic or non-stochastic. Stochastic effects are those that occur with a certain probability and do not require a minimum exposure threshold to occur. Furthermore, these effects do not depend on the intensity of the radiation. The non-stochastic effects, on the other hand, are foreseeable and occur when the amount of radiation absorbed by the body exceeds a certain intensity level. The effects severity also depends on the intensity of the radiation.
Finally, radiation damage can be divided into somatic and genetic, depending on whether the affected cells are somatic or germ cells. The unit of measurement used to quantify the damage is the Dose and the ability to create irreparable damage depends on the LET of the incident beam and on the Relative Biological Effectiveness (R.B.E.).

6.1 Absorbed Dose LET

A quantity used in medical physics is the *absorbed dose*, defined as the average energy deposited by ionizing radiation (E) per unit of mass (m):

$$D = \frac{dE}{dm} \quad \left[1Gy = 1\frac{J}{Kg}\right] \tag{6.1}$$

where the unit of measurement used in the international unit system (SI) is *Gray*.
It is possible to calculate the quantity of dose released in a material of density ρ for a parallel particle beam with a flux F (dN particles crossing a dS surface) from the following formula:

$$D[Gy] = 1.6 \times 10^{-9} \times \frac{dE}{dx}\left[\frac{keV}{\mu m}\right] \times F[cm^{-2}] \times \frac{1}{\rho}\left[\frac{cm^3}{g}\right] \tag{6.2}$$

where $\frac{dE}{dx}$ is the *stopping power*, i.e. the energy loss per unit of length where the contributions of all types of interaction are included.
A dose-related quantity is the *Linear Energy Transfer* (**LET**) which describes energy transferred from an ionizing particle to the matter per unit of lenght. The LET depends only on the energy lost by the charged particles due to the electronic collisions:

$$LET_{\Delta} = \left(\frac{dE}{dx}\right)_{\Delta} \quad \left[\frac{keV}{\mu m}\right] \tag{6.3}$$

It only takes into account the energy deposited close to the particle track, excluding the more distant interactions due to secondary electrons with energy greater than Δ. In radiobiology, $\Delta = 100\ eV$, that is the limit introduced to exclude the *delta rays*, i.e. secondary electrons produced by the electrons released in the ionizations produced by the primary charged particles, which carry energy away from the original track. If the Δ is placed $= \infty$, this quantity includes all the particles contributions to the energy loss and therefore coincides with the stopping power.

6.2 Damage caused by ionization

There is a direct correlation between LET and DNA damage. Fig. 6.3 shows a LET comparison between photons, carbon ions and protons beams. In particular, the distance (indicated with d) between two adjacent ionizations is highlighted. The value of the LET depends on the velocity and the charge of the ionizing particle. Protons and other hadronic particles have a high LET because, thanks to their mass and their charge, they transfer energy more easily than photons which provided indirect ionization. In fact, in order to have a sufficient dose release to kill cancer cells, it is necessary to irradiate with a large number of photons. The photon interactions, classified as "*poorly ionizing*", are distributed randomly in the human tissues and therefore the ionization density for a typical treatment of a photon beam of $\sim 200\ nm$ can be considered homogeneous along their path in the patient. For hadrons, however, the distribution of the dose release varies visibly as the beam enters the body. The protons reach a distance between two adjacent ionizations of the order of 10 nm in the Bragg peak area. The carbon ions are called "*densely ionizing*", since along their trace the energy deposition events are extremely close starting from d $\sim 4\ nm$ when the beam enters the patient arriving up to $\sim 0.3\ nm$ in the Bragg peak. Considering that the distance between the two DNA helices is about 2 nm the probability of creating irreparable damage is very high.

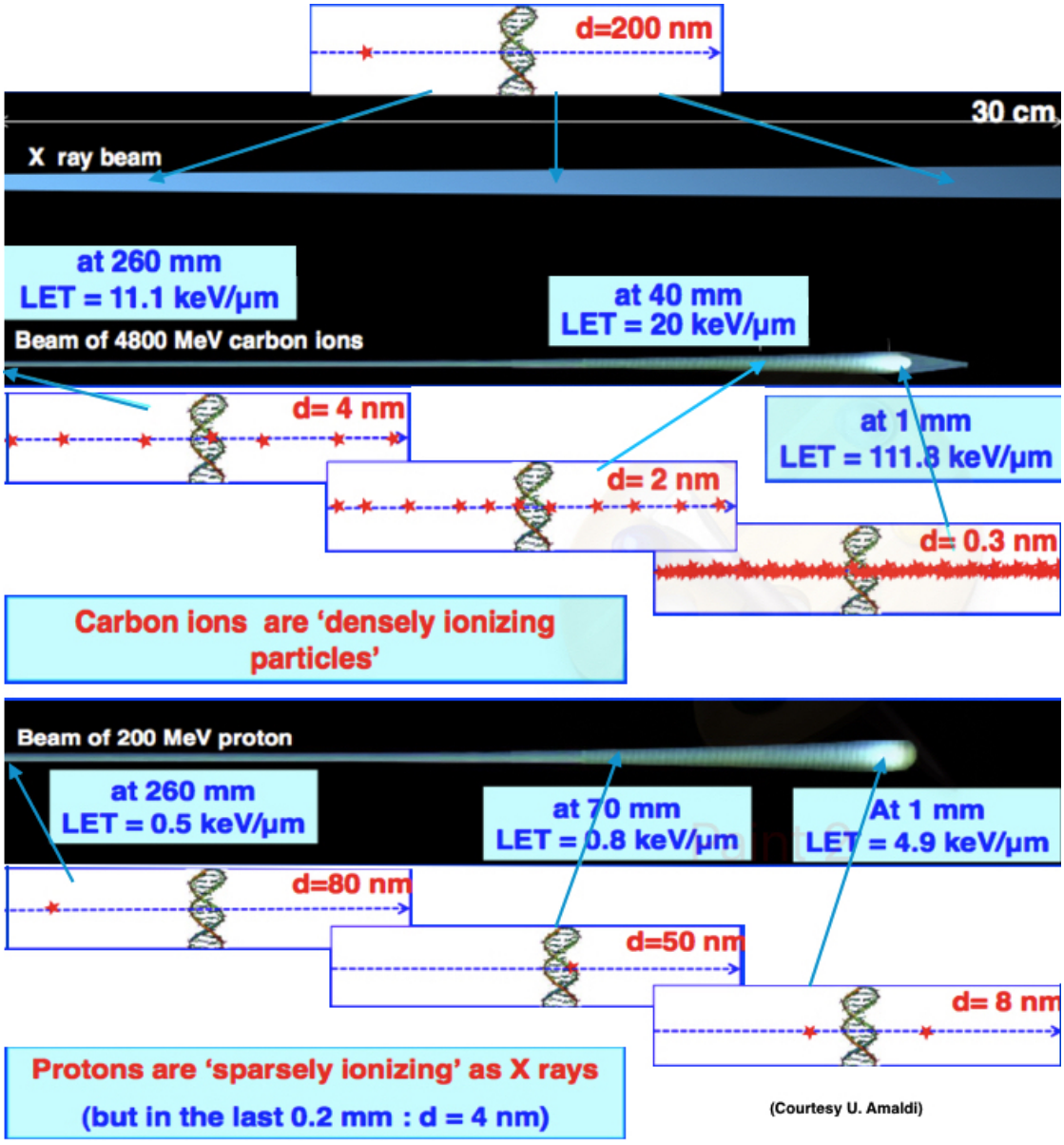

Figure 6.3: LET comparison of beams composed by X-rays (top), carbon ions (center) and protons (bottom); d indicates the average distance between two ionizations.

6.3 Relative Biological Effectiveness

The quantity used to calculate and predict the biological damage due to the incident radiation is the *Relative Biological Effectiveness* (**RBE**). The RBE is defined as the ratio between the D_x dose of a reference radiation (generally X-rays) needed to produce a certain biological effect and

the D_i dose of any other incident beam needed to produce the same effect:

$$RBE = \frac{D_x}{D_i} \tag{6.4}$$

To evaluate the RBE and to compare the biological effects from different radiations, the cell survival curves are used. The curves show the relationship between the fraction of cells that preserve reproductive integrity as function of the absorbed dose (Fig. 6.4). Biological effectiveness depends both on physical parameters (type of particle, dose and LET) and on the biological parameters of the body on which the treatment is carried out. The RBE is different considering different types of tissues or organs and can also varies within the tumor itself. Each type of radiation is characterized by its own survival curve with different RBE values compared to photons (RBE = 1.0). In Fig. 6.4 it is shown how the RBE values can be graphically determined for a specific type of radiation by setting a survival level.

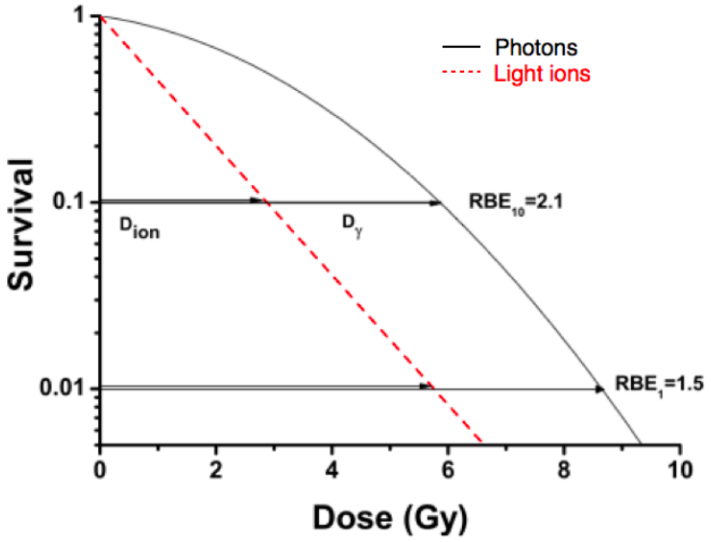

Figure 6.4: Cell survival curves for light ion radiation (red dotted line dotted) and photons (black solid line). In the curve the values of the RBE are expressed for the survival levels of 10% and 1%.

In a logarithmic representation, the relationship between the survival fraction and the dose for light ions is almost exponential. For photons there is an initial linear decrease followed by a "shoulder" for high dose values.
Using the quadratic linear model developed by E. Hall ("Radiobiology for the radiologist" 2000), the survival fraction of cells irradiated with a dose D is described by:

$$S(D) = \frac{N_{soprav}}{N_{seed}} = e^{-(\alpha D + \beta D^2)} \tag{6.5}$$

wherein α and β are two experimental parameters that measure the amount of lethal and sublethal damage respectively. Depending on the tissue and the type of tumor, these parameters characterize the initial slope of the survival curves, the trend of the curve instead is determined by the ratio $\frac{\alpha}{\beta}$.

6.4 Cellular Oxygenation

The presence of oxygen in a cellular tissue is able to enhance the radiation lethal effect through the formation of free radicals. Cells irradiated with low LET radiation in the presence of oxygen (air) are about three times more sensitive than the same cells irradiated under hypoxia condition (Fig. 6.5).
The parameter that was introduced to describe this enhancement is the **OER** (*Oxygen Enhancement Ratio*) defined as:

$$OER = \frac{D}{D_O} \tag{6.6}$$

where D is the dose necessary to produce a certain effect in the absence of O_2 and D_O is the dose necessary to produce the same effect at the pressure of 101.3 kPa of O_2.
Typical OER values vary between 1 (if the damage produced by radiation does not depend on the presence of oxygen) and 3 (if the damage produced by radiation is strongly affected by the presence of oxygen). The effect becomes negligible if high LET radiation is used for which cellular inactivation is not mediated by hydrogen or hydroxyl radicals but is directly due to the ionizations produced. For this reason, radiation of charged hadrons is the most effective for the treatment of poorly oxygenated tumors.

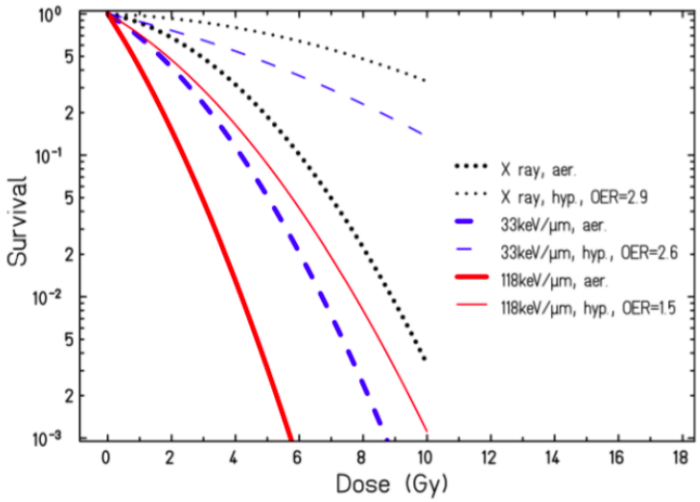

Figure 6.5: Survival curve of human kidney cells as a function of the dose of irradiated cells in the presence of O_2 (thicker line) and in conditions of severe hypoxia (thinner line) for different energies and therefore different LET. The influence of the oxygen level for carbon ions at 33 keV/μ m is shown in blue, at 118 keV/μ m in red. In black, however, it is possible to observe the variation for X-rays.

6.5 Exposure

The exposure is a quantity exclusively linked to neutral radiation (x-rays and γ rays). It is defined as the ratio between the charge ΔQ produced in a medium when all the electrons released by

photons in a mass volume Δm are completely stopped in the medium:

$$X = \frac{\Delta Q}{\Delta m} \tag{6.7}$$

The old unit of measurement used for the exposure is *Roentgen*:

$$1Roentgen = 2,58 \times 10^{-4} \frac{C}{kg} \tag{6.8}$$

In SI the unit that is used for exposure is $\frac{C}{Kg}$ but it is never really used.
There is an indirect way for exposure calculation. If $\mathrm{d}Q = \frac{eE_\gamma \mathrm{d}N}{w}$ where e is the electron charge, E_γ the energy of the incident neutral radiation, $\mathrm{d}N$ the number of accelerated charges and w is the average ionization energy (34 eV in air), and if the unit of mass is expressed as $\mathrm{d}m = \rho A \mathrm{d}x$, then:

$$X = \frac{1}{\rho}\frac{e}{w}\frac{E_\gamma \mathrm{d}N}{A\mathrm{d}x} = \frac{e\mu N E_\gamma}{w\rho A} = \frac{e\mu E_\gamma \phi}{w\rho} \tag{6.9}$$

where $\frac{N}{A} = \phi$ and $\frac{\mathrm{d}N}{\mathrm{d}x} = \mu N$.
Another udes quantity is the exposure rate, which is the derived over time of the exposure. In the specific case of point sources of γ rays the following law can be applied:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \Gamma \cdot \frac{A}{d^2} \tag{6.10}$$

Where Γ is a specific coefficient for each source, A is the activity of that source, d is the distance from that source. Comparing the expression of the dose for photons and exposure, we observe that:

$$X = \frac{e}{w}\frac{\mu}{\rho}E_\gamma \phi = \frac{e}{w}D \tag{6.11}$$

Now, knowing that $\frac{w_{air}}{e} = 8.74 \cdot 10^{-3}\ Gy/R$ we can calculate the dose in any material knowing the exposure to air of a certain radiation, remembering that $D_{air} = X_{air}\frac{w_{air}}{e}$ as follows:

$$D_m = D_{aria}\frac{(\mu/\rho)_m}{(\mu/\rho)_{aria}} = X\frac{w_{aria}}{e}\frac{(\mu/\rho)_m}{(\mu/\rho)_{aria}} \tag{6.12}$$

6.6 Other Dosimetric Quantities

A specific radiation can be more or less harmful to a certain tissue. In order to take these differences into account, the stochastic evaluation of the biological damage that the average dose of a specific radiation will do on a particular tissue can be expressed as the equivalent dose.

$$H = D \cdot Q \tag{6.13}$$

Where the proportionality factor Q is called Quality Factor, and depends on the type of incident radiation and its energy. The equivalent dose unit is the following:

$$1Sv = 1\frac{J}{kg} \tag{6.14}$$

It can be seen that Gy and Sv are analogous but are used respectively for the absorbed dose and the equivalent dose.

The *effective dose* is the sum of the equivalent doses absorbed by each tissue weighed with factors that represent the sensitivity of this tissue to the radiation in exam.

$$E = \sum H_T W_T \tag{6.15}$$

The parameters W_T are dimensionless, therefore the unit of measurement of the effective dose remains the Sievert.

The Kinetic Energy Release in the Medium (KERMA) is then defined as follows:

$$\text{KERMA} = \frac{\Delta E_k}{\Delta m} \tag{6.16}$$

This quantity is measured in Gray. It is the sum of the initial kinetic energy of all charged particles released by ionization of the particles or photons in a volume element of a specific material. Corresponds to the dose if ΔE_k is precisely the difference between energy entering and leaving a volume. This condition is called Charged Particle Equilibrium (CPE), and is microscopically verified if each particle that takes away some energy from the volume is immediately replaced by an identical particle that carries that same energy in the volume. In general, while the dose is the energy absorbed per volume unit, KERMA is the energy transferred by the original particle or photon in that same volume unit.

6.7 Dosimetry tools

The dosimeter is a device used to determine individual exposure to ionizing radiation. An ideal dosimeter must have the following properties:

- High accuracy and precision;
- Linear response over a wide range;
- Little dependence on dose and dose rate;
- Flat energy response;
- Independence from the direction of the incident radiation;
- High spatial resolution;
- Wide dynamic range.

Some dosimeter loses linearity between response and actual dose. This can happen by superlinearity or by saturation. The first case can also be useful having a software that expects superlinearity and uses it to increase the resolution of the tool.

An example of a dosimeter is the ionization chamber. It is usually cylindrical with the size of a pen, with external graphite armor and an internal one in aluminum. The electrical signal can be transformed into an Exposure value. It can also be with a well-size, to measure quantities related to point sources that are placed inside the well. This type of cameras has high sensitivity and can function actively.

Another type of detector is the Radiographic Film [FA], which consists of a metallic coating that emits electrons by photoelectric effect when it is crossed by radiation, which ionize the underlying AgBr emulsion. At this point the silver neutralizes without binding again with bromine. Silver is black, so what I observe when the film is subjected to radiation is gradual blackening. Finally, the film is illuminated and its opacity observed, estimated as follows:

$$\mathrm{OD} = \log_{10}\left(\frac{I}{I_0}\right) \tag{6.17}$$

Opacity is then a monotonous function of the exposure, and therefore it is possible to derive this latter magnitude.

A Radiochromic Film, on the other hand, is a film containing a tint that polymerizes when it is hit by radiation and therefore shows color after being hit (GafChromic).

Another type of dosimeters are those which are based on luminescence phenomena such as phosphorescence and fluorescence [Tld]. Through the positioning of impurities, intermediate metastable states are created in the decay of electrons excited by radiation, which therefore passing through these states emit visible light.

Finally there are the semiconductor detectors in which the incident ionizing radiation creates electron-hole pairs that generate a current inside the semiconductor.

As for the neutron dosimetry, materials are used that contain nuclei with a high cross section with neutrons, so that the reaction creates charged particles, which are then easily traceable.

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Chapter 7

Neutron Physics

The Neutron is a neutral charge baryon, with spin $\frac{1}{2}$, composed of quarks *udd* with mass $m_n = 1.67 \cdot 10{-}27$. In nature the neutron is a stable particle only within the atomic nucleus; as a free particle it decays with a $t_{1/2} = 899 \pm 2$ s in $n \to p + e^- + \bar{\nu}$ (*decay* β). Since neutron production and detection techniques are highly energy dependent, traditionally neutrons are classified according to their energy (E_n):

- *Ultra-cold Neutrons*: $E_n \simeq \mu eV$;
- *Cold Neutrons*: $E_n \simeq$ meV;
- *Thermal Neutrons*: $E_n \simeq 25$ meV;
- *Epithermal Neutrons*: 0.1 eV $\leq E_n \leq$ 100 keV;
- *Fast Neutrons*: 100 keV $\leq E_n \leq$ 10 MeV;
- *Ultra-Fast Neutrons*: 10 MeV $\leq E_n \leq$ 100 MeV;

7.1 Neutron Sources

7.1.1 Nuclear Fission

Epithermal and fast neutrons can be produced in large quantities through the process of *Nuclear Fission*. It can occur in a *spontaneous* or *induced* manner.

The energy distribution with which spontaneous fission occurs is as follows:

$$\frac{dN}{dE} = \sqrt{E} e^{-E/T} \tag{7.1}$$

An often used element that exploits this phenomenon is the ^{252}Cf. 1 μg of Californio produces 2.3 million of neutrons per second. The fission of some nuclei can also be artificially induced inside nuclear reactors by bombarding elements such as ^{235}U with thermal neutrons. The reaction is exothermic, so I don't have a projectile threshold energy to make it happen. Neutrons with thermal energies are used to maximize the cross section of interaction for triggering the fission process (Figura 7.1).

During the fission process, neutrons are produced in much shorter times than those produced by proton β decay. In the latter case, neutrons are called *delayed neutrons*. In large scale nuclear

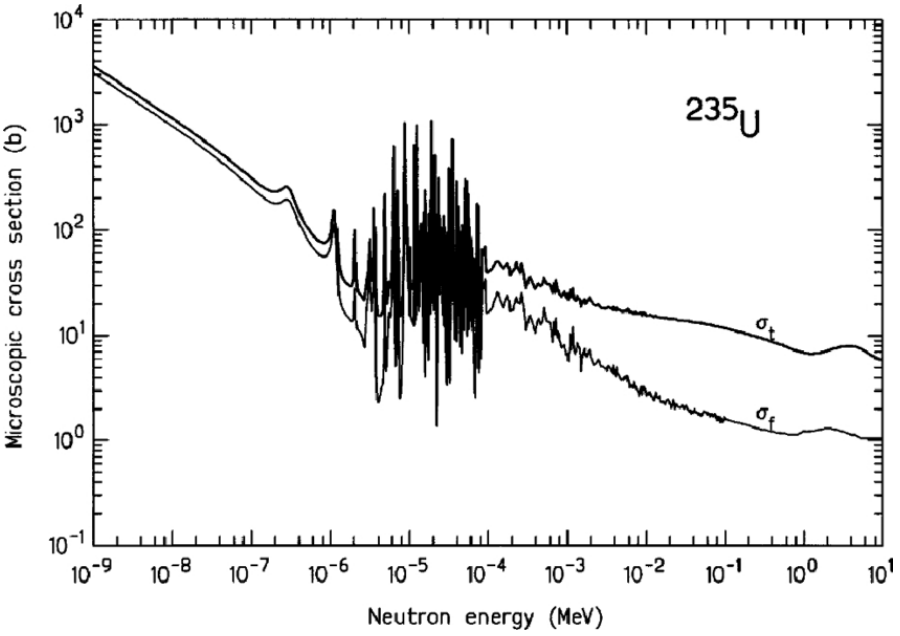

Figure 7.1: Cross section of the induced fission process of ^{235}U as a function of the neutron energy used to trigger the reaction

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reactors used as neutron sources there is a core of ^{235}U while the neutrons needed to induce the fission process are produced by a spontaneous fission isotope. The neutrons produced by the fission induced inside the core have energies that range from a few keV up to about ten MeV. To bring these neutrons to thermal energies (and therefore to trigger a cascade fission process) the energy of the neutrons is lowered by making them interact within a moderator (usually water). To bring a neutron from MeV energies to meV it takes about 30 collisions. Since it is not possible to guide neutrons by means of magnets as happens for charged particles inside the accelerators, in order to obtain a directional neutron beam there is a collimation system around the reactor. A beamline emerges from each hole in the collimator, which takes the beam to an experimental room. Generally fission is a continuous process, but it can be made pulsed by placing an intermittent screen in front of the core. The number of collisions that the neutron must make for its energy to go from E_0 to E_f is described by the equation:

$$\eta = \frac{1}{\xi} \ln \left[\frac{E_0}{E_f} \right] \tag{7.2}$$

Where η is the number of collisions needed, while ξ is defined as follows:

$$\xi = 1 + \frac{(A-1)^2}{2A} \ln \left(\frac{A-1}{A+1} \right) \tag{7.3}$$

with A representing the atomic weight of the element used as a moderator. The value of ξ increases for small A values. To minimize the number of collisions in the moderation process, it is therefore preferable to use light elements such as hydrogen.

7.1.2 Nuclear Fusion

Nuclear fusion is a very high Q reaction. An example is the following:

$$ {}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + n + Energy \qquad Q = 17\ MeV \tag{7.4} $$

The Q value is divided between the neutron, which will be emitted with energy of 14 MeV and the alpha particle which takes $sim3$ MeV.

Today we try to replicate the fusion through machines like the TOKAMAK. A specific deuterium ion plasma collimates through specific electromagnetic field configurations. Temperatures of 13.6, or thousands of degrees Kelvin, are required to obtain the plasma condition. Another method is the *inertial fusion*. It consists in the use of a triziate shell containing deuterium bombarded with very powerful lasers. The shell should therefore implode on deuterium causing fusion.

Through the fusion mechanism it is possible to produce neutron beams of some MeV. At the *Frascati Neutron Generator and Sources facility* (FNG) the fusion reaction is exploited

$$ {}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + n \tag{7.5} $$

to produce pulsed neutron beams ($1E11n/s$) of 2.5 MeV energy.

7.1.3 Accelerator Driven Neutron Production

Neutron beams can be produced by exploiting the interaction of accelerated particles with different types of targets. In particular, it is possible to exploit high energy photon or proton beams (*spallation*).

High energy photons are produced through the Brehmsstrahlung process of electrons produced and accelerated (up to some GeV) in a LINAC. Photons, by exciting the vibrational states of the atomic nuclei present in the target, can produce the emission of a neutron (the neutron has energy to overcome the strong interaction force that binds it to the nucleus). The energy of the neutron emitted depends on the binding energy of the nucleus.

Spallation is the process that consists in the production of neutrons through the collision of high energy protons (greater than 100 MeV) against a target of high Z material (usually Mercury, Tantalum, Lead or Tungsten). A spallation reaction produces a large number of neutrons (15-20 n per incident p). In addition, other protons are produced as fragments during interaction with the target's heavy nuclei, generating a cascade process. For this reason, spallation sources are currently used for the production of high intensity neutron beams. ISIS Neutron and Muon Source is an example of a spallation source, currently in operation at the Rutherford Appleton Laboratory (UK). The facility has the ability to provide high intensity sources of both neutrons and muons produced through a mechanism similar to that described in this paragraph.

7.2 Neutrons Detection

Being neutral particles, neutrons are generally detected indirectly by exploiting nuclear reactions that involve the emission of a charged particle (such as for example a p or a α). The devices used for neutron detection must therefore consist of two parts: a *target* where the neutron must interact by emitting some form of ionizing radiation and a *detector* tailored to the emitted radiation. The neutrons interactions mechanisms change as energy changes. It is therefore necessary to identify different detection techniques for different energy ranges in order to maximize efficiency and discriminate neutrons from γ radiations. The main detection techniques will be described below, separating the treatment for *slow neutrons* ($E_n < 0.5$ eV) and for *fast neutrons* ($E_n > 100$ keV).

7.2.1 Slow Neutron Detection

The identification of the reactions used to detect slow neutrons must take into account several factors:

- The cross section of the process must be large in order to have a high efficiency even for small devices;
- The target must contain the isotope to be activated in large quantities. This leads to choosing nuclei with considerable isotopic abundance;
- Neutron interaction reactions must have a high *Q-value* in order to discriminate the abundant photon background as much as possible.

The isotopes most satisfying these characteristics are the ^{10}B and the ^{6}Li. In some applications, the ^{3}He is also used which, however, compared to ^{10}B and ^{6}Li, has a higher cost and a smaller *Q-value*. Figure 7.2 shows the cross sections of interaction of neutrons with these isotopes.

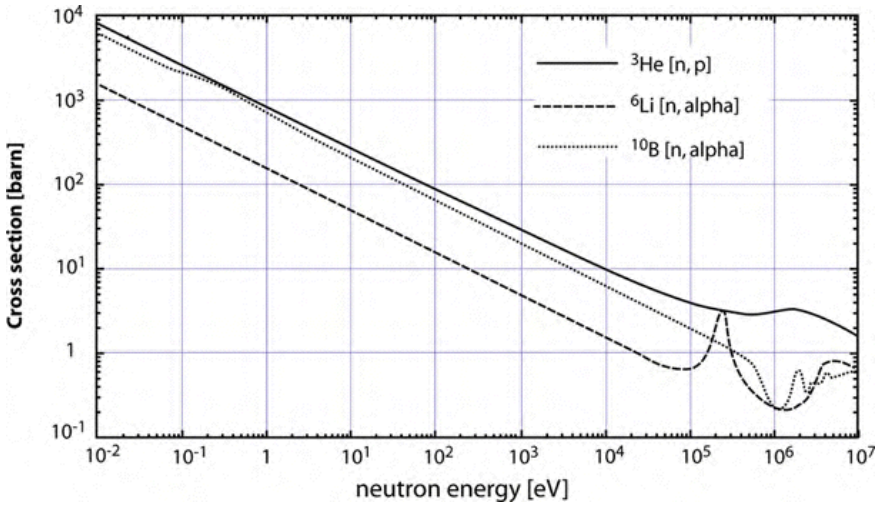

Figure 7.2: Trend of the cross section as a function of the energy of the processes $^{3}He(n,p)^{3}H$, $^{10}B(n,\alpha)^{7}Li$ and $^{6}Li(n,\alpha)^{3}H$ used for the detection of slow neutrons [**Tavernier**]

BF_3 Gas Counters

Detectors based on the activation of Boron nuclei are among the most used for the detection of slow neutrons. They are based on the following reaction:

$$^{10}_{9}B + n \rightarrow ^{7}_{3}Li + \alpha \tag{7.6}$$

where the lithium in the final state can be in both the ground state and in an excited state with *Q-vaue* of $2,792$ MeV and $2,310$ MeV respectively. The kinetic energies of the detected neutrons are negligible with respect to these values, making it impossible to reconstruct the kinetic energy of the particle. The most common detectors of this type are gas meters containing *boron trifloride* BF_3. The main feature of these devices is to provide excellent discrimination from the γ background. The photons in fact react mostly in the walls of the detector emitting e^- which

ionize the gas. Since the stopping power of the electrons is lower than the one of the α emitted by Boron, the signal they generate will be smaller and easily eliminated. The disadvantages include fast wear, typical of all gas detectors, which makes the BF_3 counters unsuitable for detecting high neutron fluxes.

Litium Scintillators

Unlike Boron, lithium, if activated by a neutron, emits a nucleus of tritium always in the fundamental state:

$$^{6}_{3}Li + n \rightarrow ^{3}_{1} H + \alpha. \tag{7.7}$$

Neglecting the neutron energy, the reaction will have a constant *Q-value* and energies $E_{^3H} = 2.73$ MeV and $E_\alpha = 2.05$ MeV fixed. Since it is not possible to obtain stable gases containing Lithium, the detectors that exploit this reaction are exclusively scintillators, in particular LiI(Eu) crystals (*Lithium iodide* doped with Europium). The use of such detectors is however disadvantaged due to the more difficult background discrimination due to the production of very similar signals for electrons and α.

7.2.2 Fast Neutron Detection

The techniques already described can also be used to detect fast neutrons. However, as the cross section of the neutrons decreases with increasing energy, devices such as BF_3 tubes or Lithium crystals will have low efficiency. The dominant interaction process at high energies is elastic scattering in which a neutron transfers part of its kinetic energy to a target nucleus. In particular, by exploiting targets of ^1H it is possible to maximize the exchange of energy. This mechanism reduces the energy of the incident neutron, making the devices typically used for slow neutrons efficient for the detection of fast neutrons. This process is called *moderation*. An example of detectors that exploit this technique are the *Bonner Spheres* (figure 7.3). The idea, proposed by Bramblett, Ewing and Bonner in 1960, is to exploit crystals of $LiI(Eu)$ coated with polyethylene spheres of different sizes within which the neutron is slowed down [**Bonner**].

By comparing the neutron flux revealed by each sphere it is possible to obtain a very accurate measurement of the energy spectrum. The B_i response of the *i-th* detector can be expressed as an integral of textit Fredholm:

$$B_i = \int_0^\infty N(E) R_i(E) dE \tag{7.8}$$

where $N(E)$ is the energy spectrum of the neutron field and R_i is the absolute response of the *i-th* detector as a function of the energy of the neutron. By applying numerical *unfolding* methods on the measurements obtained from the different spheres it is possible to obtain global information on the neutron spectrum. Although the Bonner spheres are the most used device for neutron spectroscopy, they are characterized by low efficiency, and do not allow to determine both the energy and direction of the single neutron. This problem is overcome by devices that exploit the detection of the recoil cores. Following the reaction, the recoiled nuclei will have a kinetic energy equal to the sum of the energy of the neutron and the *Q-value* of the reaction. In the case of fast neutrons where E_n is comparable or much greater than the *Q-value*, by measuring the energy of the reaction products it is possible to obtain the energy of the neutron by a simple subtraction of the value of *Q-value* known. This calculation is further simplified by exploiting the elastic scattering, so the *Q-value* is zero. As described in the 7.1 section, in order to release a large fraction of neutron energy, the material with which they interact must have a low atomic

Figure 7.3: Bonner Spheres

number A: for this reason, most devices that use this technique revelation are based on the use of plastic scintillators, cheap and rich in light materials such as H and C.

7.3 Use of Neutrons

One of the possible use is the analysis of the conformation of a crystal through Bragg diffraction. Neutrons are used in the process rather than other charged particles because they would lose energy immediately and could not penetrate deeply. More specific applications are:

- Small Angle Neutron Scattering (SANS): it is a study of neutron scattering figures against a given target that gives information on the shape and size of target materials.
- Neutron Activation Analysis (NAA): thermal neutrons are absorbed by the target which then decays. The process can take hours. The products are studied.
- Neutron Stimulated Emission Computed Tomography (NSECT): it makes use of more energetic neutrons to make the decays instantaneous, to do imaging directly.
- Chip Irradiation: it is the phenomenon whereby energy neutrons in cosmic rays can attack chips causing data loss or other problems. The bombardment of the chips with artificial energy neutrons serves to verify their correct shielding before they are used for planes or satellites.

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