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PHYSICAL AND HISTORICAL PRINCIPLES OF IONIZING RADIATIONS WITH THE FLIPPED CLASSROOM METHOD

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ABSTRACT. From the late 1800s to the present day, ionizing radiations played a very important role in fields regarding everyday life and research. In this work, we cover several physical and historical aspects from the EM waves to the particles. In particular, after a brief introduction of electromagnetism and EM spectrum, we talk about some ionizing radiations focusing on their detection and their natural and artificial sources. Furthermore, we show the importance and use of these kind of radiations for medical applications and their biological effects. Finally, we propose the deepening of one of the topics covered through the innovative teaching method of the "flipped classroom" in which the student prepares the lesson as a homework, and then in the classroom develop collaborative and debate activities on the topic previously studied in autonomy.

1. Electromagnetism and electromagnetic waves

Electromagnetism is the unified theory of electricity and magnetism involving the investigation of all phenomena related to the electromagnetic (EM) force, a type of fundamental physical interaction that exists between electrical charges and plays an essential role in constituting matter (Jackson 1998; Serway 2004; Shankar 2016; Griffiths 2017; Halliday *et al.* 2018). In fact, the majority of all forces affecting the interactions between atoms can be comprehended in terms of EM force acting between the electrically charged atomic nuclei and electrons of the atoms.

The EM force is carried by EM fields, and it is responsible for EM radiations (EMR) or *EM waves*, such as light.[1] An EM wave can travel through anything (i.e., air, a solid material or vacuum) transporting energy, and it does not need a medium to propagate or travel from one place to another (Jackson 1998; Serway 2004; Shankar 2016; Griffiths 2017; Kimura 2017; Vanderwerf 2017; Halliday *et al.* 2018). As showed in figure 1, EM waves have a "trough" (lowest point) and a "crest" (highest point), a precise propagation direction

[1] In general, the term "radiation" indicates the phenomenon by which energy is emitted from matter in the form of particles or electromagnetic waves, which propagate in the surrounding space, interacting or not interacting with things and people they find in their passage.

(specified by the grey arrow), that identifies the wave's central axis, and are composed of oscillating electric field $\vec{E}$ and magnetic field $\vec{B}$, indicated with a red continuous line and a blue dashed line, respectively. Note that the electric and magnetic fields of an EM wave are perpendicular to each other, and are also at right angles to the direction of the EM wave, forming a transverse wave.

An EM wave is characterized by its amplitude h, frequency ν and wavelength λ, and, consequently, its energy (Pavia *et al.* 2013; Shankar 2016; Kimura 2017; Halliday *et al.* 2018). The amplitude is defined as the vertical distance between the tip of a crest and the wave's propagation direction, and it is correlated with the brightness, or intensity, of the wave. The frequency and the wavelength represent the number of waves that form in a given length of time and the distance between two consecutive troughs or crests of a wave, respectively. These two latter quantities are related to each other by means of an inverse relationship. In dispersive media, the frequency is equal to the phase velocity v of the wave divided by the wavelength of the wave

$$\nu = \frac{v}{\lambda}, \tag{1}$$

instead, when the EM wave propagating in vacuum, we have

$$\nu = \frac{c}{\lambda}. \tag{2}$$

where c is the speed of light in vacuum ($c = 300 \times 10^6$ ms^{-1}) (Lipson 2011; Vanderwerf 2017; NIST 2018a). Equation 2 is really important because it states that all electromagnetic waves propagate through the vacuum at the same speed, which is precisely the speed of light c. In this frame, if the distance between the highest point of a wave ("crest") is large (i.e., the wavelength is long), then the frequency is low; if the distance is small (i.e., the wavelength is short), then, the frequency is high. Note that this fact obviously also applies to the lowest point of a wave. The wavelength λ is usually measured in nanometer (nm), whereas the frequency ν is reported in Hz (s^{-1}).

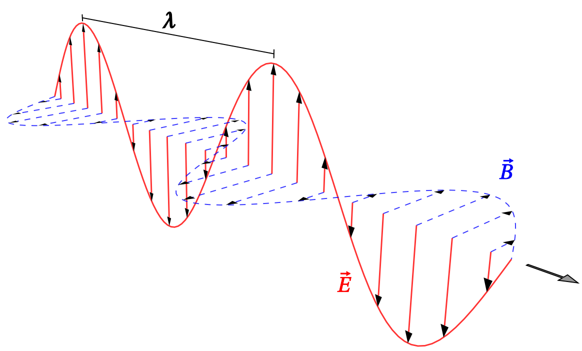

FIGURE 1. Representation of an EM wave. EM radiations are composed of oscillating electric field $\vec{E}$ (red continuous line) and magnetic field $\vec{B}$ (blue dashed line). They have a precise propagation direction (grey arrow), that identifies the wave's central axis. The wavelength λ indicates the distance between two consecutive "crest" (highest point) or "trough" (lowest point).

TABLE 1. Physical quantities

		units
wavelength	λ	nm
frequency	$\nu = \frac{c}{\lambda}$	Hz
photon energy	$E = h\nu = \frac{hc}{\lambda}$	J
wave number	$k \approx \lambda^{-1}$	cm^{-1}

Regarding energy, in classical physics, it is distributed in a wave along the direction of propagation (Poynting vector) and, uniformly, on the wavefront (Huygens-Fresnel principle). The energy that the wavefront can deliver to the electron, and the cross section between wavefront and energy, is very small. Therefore, it is expected that a lot of time pass before every single electron accumulates sufficient energy to exchange it, instead researchers saw that this kind of phenomena happened in very short times. Einstein, to explain experimental observations that did not agree with the wave model of light (primarily the properties of the black body[2] and the balance between matter and EMR), introduced the concept of *photon*(Hentschel 2018), a massless quasi-particle that possesses energy and momentum that can be associated with a wave (i.e., exhibit wave-particle duality[3]), in which the scientist thought that the energy was distributed in the single "packet" of energy and not in the entire wavefront. In quantum mechanics, so, photon is considered the quantum of the magnetic field including EM radiation (Vanderwerf 2017; Hentschel 2018). The photon's energy and momentum are determined only by its frequency (ν) or inversely, its wavelength (λ):

$$E = \hbar\omega = h\nu = \frac{hc}{\lambda}, \tag{3}$$

$$\vec{p} = \hbar\vec{k}, \tag{4}$$

where $\vec{k}$ is the wave vector (its module is the wave number $k = |\vec{k}| = 2\pi/\lambda$, typically expressed in cm^{-1}) $\omega = 2\pi\nu$ is the angular frequency, h and $\hbar = h/2\pi$ are the Planck constant and the reduced Planck constant, respectively. The Planck constant is a fundamental physical constant defined to have the value $h = 6.62607015 \times 10^{-34}$Js in SI units (NIST 2018b).

A summary of the main physical quantities that will be considered in this work are shown for convenience in table 1:

1.1. Generation of electromagnetic radiation and sources. Matter with temperature greater than absolute zero emits thermal radiation, i.e. EM wave originated by the thermal motion of particles. Generally speaking, EMR is produced when a charged particle, such as an electron, modifies its velocity (Cloude 1995; Bettini 2016). For example, in a phenomenon called bremsstrahlung process (Jackson 1998; Fritzsche and Phillips 2017; Kimura 2017), a charged particle emits EM radiation when it is suddenly decelerated being deflected by another charged particle or an atomic nucleus. The energy of the produced EM radiation derive from the charged particle and is lost by it. So, it is possible to state that in

[2]See section **5** fo further information.
[3]See section **8** fo further information.

every physical source of EMR (e.g, an atom, a lamp, a radio station or a star), accelerating charges are always present and, often, their motion is an oscillation (Cloude 1995; Bettini 2016). A typical example of this phenomenon is the oscillating charge or current in a radio antenna (Cloude 1995; Fritzsche and Phillips 2017) in which an EM wave is generated and can be collected by an analogous antenna tuned to that same frequency. The EM radiation in turn generates an oscillating motion of charge in the receiving antenna. Therefore, it is clear that any system which emits EM wave with a precise frequency can absorb radiation of the same frequency.

In this frame, one may classify the production of EM radiation into two groups: (i) processes or systems that originate EM waves with frequencies that cover a large and continuous spectrum, and (ii) those that radiate (and, as stated before, absorb) EM waves of discrete frequencies that are peculiar of specific systems. A naturally source as the Sun with its continuous spectrum is an example of the first, while a radio antenna tuned to one specific frequency is an evidence of the second category (Fritzsche and Phillips 2017). Simply, from what has just been said, we can consider another immediate distinction: natural and artificial EM wave sources (Vanderwerf 2017).

1.1.1. *Natural sources.* The universe is full of objects that emit EMR naturally(Vanderwerf 2017): just think of some entities that we can even observe continuously in everyday life. As already stated, the Sun is a star and one of the most important natural sources, being the major source of light for our planet allowing the sustainability of life on Earth. Every other star generates light too, but only a small or no amount of it reaches the Earth because of the huge distance. Certain other natural phenomena such as lightning and volcanic eruptions also radiate EM waves as light.

1.1.2. *Artificial sources.* Light can be produced artificially, and examples of artificial sources are common lamps, MASERs and LASERs (Lipson 2011; Bettini 2016; Vanderwerf 2017).

For what concerns lamps, essentially, we can group them in three categories: (i) incandescent sources (e.g., incandescent lamp), whose operating principle is based on heating objects to a high temperature that begin to emit light; (ii) luminescent sources (e.g., fluorescent lamp), in which light can be produced by accelerating charges in a luminescent material. for example, by passing current through the material; and (iii) gas discharge sources (e.g., Sodium lamp) that produce light by passing electricity through certain gases at a very low pressure.

An important consideration is that in macroscopic sources, like a lamp, we can found a huge amount of atoms, a fraction of which, once excited, are the microscopic sources of EM wave. However, even if the emitted radiation has essentially a single wavelength (it is *monochromatic*), its instantaneous phase varies in a chaotic way. These kind of sources are called thermal sources (Bettini 2016).

In contrast, LASERs and MASERs are suited to let all the atoms oscillating in phase between them in a process called stimulated emission, emitting coherent radiation (Chang 2005; Demtröder 2008; Bettini 2016; Ghosh 2018). The acronyms LASER and MASER stand for Light and Microwave Amplification by Stimulated Emission of Radiation, respectively, and today they are considered the main sources used in spectroscopy.

TABLE 2. Spectral range of pure colors in the visible region of EM spectrum

Color	Wavelength	Frequency
Violet	380-450 nm	680-790 THz
Blue	450-485 nm	620-680 THz
Cyan	485- 500 nm	600-620 THz
Green	500-565 nm	530-600 THz
Yellow	565-590 nm	510-530 THz
Orange	590-625 nm	480-510 THz
Red	625-720 nm	416-480 THz

1.2. Spectroscopy and electromagnetic spectrum. The term *spectroscopy* indicates a set of techniques that allow to experimentally study the absorption and emission of light by matter (Demtröder 2008; Pavia *et al.* 2013; Gauglitz 2014), allowing its characterization. Generally speaking, spectroscopy is considered the study of any interaction between matter and EMR with a radiative energy as a function of its wavelength or frequency, predominantly in the electromagnetic spectrum.

The *electromagnetic spectrum*, showed in figure 2, allows us to indicate different types of EM waves, classified according to their frequency or wavelength (Pavia *et al.* 2013; Fritzsche and Phillips 2017; Vanderwerf 2017; Halliday *et al.* 2018). The regions of the spectrum have precise denominations originating from the different ways of generating and/or observing EM radiations, including their effects on matter.

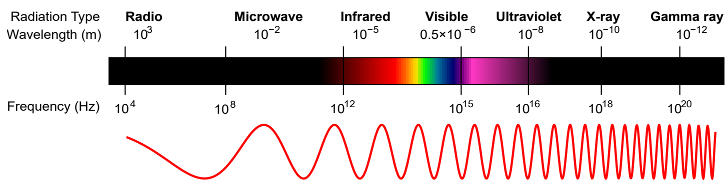

FIGURE 2. Diagram for the electromagnetic spectrum in which we reported frequencies and wavelengths.

Going into more details, we should start with probably the most important part of the EM spectrum: the visible region, that refers to EMR called *light*, "colored" EM waves that we can see with our eyes (Halliday *et al.* 2018). This region extends from around 400 nm (violet) to approximately 700 nm (red). Table 2 reports the spectral range of pure colors, that are EMRs containing only one wavelength (monochromatic light). Note that the indicated ranges are approximation because the spectrum is continuous, with no clear boundaries between one color and the next (Bruno and Svoronos 2005). The sources of lights are many, both natural and artificial, as already showed in subsection **1.1**, and are used for an even greater amount of experiments (UV-VIS Spectroscopy) and applications in fields ranging from medicine to horticulture (OSRAM GmbH 2020).

Anyway, the visible region of the EM spectrum makes up only a small part of the several types of radiation that exist. Indeed, to the left of the visible spectrum, we find the EM waves characterized by an energy that are lower in frequency (and thus longer in wavelength) than visible light. These types of energy include infrared (IR) rays (heat waves given off by thermal bodies), microwaves, and radio waves. This kind of radiations are often known as *non-Ionizing Radiations*, are not harmful and surround us constantly: indeed, their energy are very low because these EM waves have frequency so low, and thus they are not dangerous to our health.

IR has wavelengths that extend from the nominal red edge of the visible spectrum at around 700 nanometers to 1 millimeter. Referring to thermal radiation already seen previously (see **1.1**), EMR emitted by objects near room temperature is mostly infrared. Infrared radiation can be generated in different ways, such as laser, and it is used in several fields including industrial, scientific, military, law enforcement, and medical applications. For example, near infra-red (NIR) laser beam is used to perform optical trapping, imaging and Raman scattering, techniques that have been particularly successful in studying nanomaterials and a variety of biological systems in recent years (Vasi *et al.* 2011). Infrared Spectroscopy is the analysis of IR light interacting with a molecule and it measures the vibrations of atoms, allowing the determination of functional groups (Pavia *et al.* 2013; Mallamace *et al.* 2014).

Microwaves and radio waves are characterized by the shortest frequencies in the EM spectrum. Microwaves cover the region of wavelength from about 10 centimeters to one millimeter, are produced artificially, for example, with MASER, and are used in microwave ovens, industrial heating and medical diathermy, radar and to accelerate electrons and protons to very high energies in linear accelerators (Bettini 2016; Kimura 2017). Note that, unlike higher frequency EMR such as IR and light which are absorbed mainly at surfaces, microwaves can penetrate into materials and deposit their energy below the surface, an effect used to heat food in microwave ovens. When we have EM waves with wavelength equal or longer than 10 cm, we are in the part of the EM spectrum of radio waves. This kind of EMR is emitted and absorbed by antennas (as already seen in **1.1**) and is used in multiple ways and applications, from cell phones, GPS, and wireless networks, to watching TV (Bettini 2016; Kimura 2017). With the term radiofrequency (RF) EM radiation, we usually indicate the transfer of energy by radio waves. As stated before, RF EMR is non-ionizing radiation, and covers the range of frequencies between 3 kHz and 300 GHz. One example of application of this type of EMR is found in NMR spectroscopy in which RF waves, hitting the sample, allow promoting transitions between nuclear energy levels (Resonance) and studying physical chemistry properties of matter (Chang 2005; Pavia *et al.* 2013; Corsaro *et al.* 2016; Vasi *et al.* 2016).

On the right side of the visible region of the EM spectrum, as shown in figure 2, we have ultraviolet (UV) rays, X-rays, and gamma rays. Most of these types of radiation are recognized as *Ionizing Radiations* because they are harmful to living organisms, due to their extremely high frequencies (and thus, high energies, see equ. 3).

Ultraviolet (UV) is a form of EM wave with wavelength from 10 nm to 400 nm. UV radiation is naturally produced by the Sun, constituting about 10% of the total electromagnetic radiation output from it, and can be generated by means of electric arcs and particular sources, such as mercury-vapor lamps and excimer lasers (Kimura 2017). In contrast to long-λ UV rays carrying out not enough energy to ionize atoms, short-wavelength UV light damages DNA and sterilizes surfaces with which it comes into contact.

X-rays have a wavelength ranging from 10 pm to 10 nm and can be divided, essentially, in two groups, depending on the energy range to which they belong: (i) hard, and (ii) soft X-rays. Hard X-rays carried high energies (above 5-10 keV) and are characterized by an high penetrating ability. For this reasons, they are commonly used to acquire images inside an object as often happens in medicine and for security screening. A method to produce hard X-rays is to use X-ray tubes in which, firing upon a target, e.g. tungsten, with high-energy electrons originates X-rays via a bremsstrahlung process, already described in **1.1**. Instead, soft X-rays have less energy than hard X-rays and consequently they do not penetrate materials as easily, being absorbed in air. Anyway, this property allows soft x-rays to be used as probe for molecules, such as DNA, without damaging them, unlike hard X-rays. Essentially, this kind of radiation can be produced using the same setup of hard X-rays, i.e. X-ray tube, changing the applied voltage and installing an input beryllium window.

γ-rays are characterized by the shortest wavelength (less than the size of an atom) of the EM spectrum being one of the most energetic forms of EM radiation. γ-rays are originated in nuclear reactions, such as in unstable nuclei (radionuclides), and sub-nuclear nuclei, e.g., in the annihilation of particle-antiparticle pairs or decay of elementary particles. Furthermore, gamma rays are produced by very high-energy electrons in several astronomical processes.

Later, we will talk more about this type of radiations, about their properties, generation and applications.

2. Production and measurement of ionization in a gas

The ability of a particle to produce ionization in a gas has very important consequences, especially because this has allowed the development of detectors suitable for investigating the characteristics of incident radiation. When an ionizing particle passes through a volume of gas, it is able to create positive ion-electron pairs, if it has sufficient energy; this energy is linked to the first ionization potential, which for gases it takes on average values between 10 eV and 25 eV. However, the particles lose energy due to various interaction processes in which gas does not ionize, for example excitation processes. For this reason, a quantity W is defined which represents the energy that on average an incident particle must possess in order to create an ionic pair. The value depends on the gas present in the detector and on average $W \approx$35 eV is obtained. Taking as an example an α particle, which carries energy between the values of 4 and 9 MeV, within a gas, it will potentially be able to produce more than 100000 ionic pairs. The ionization produced can be measured using appropriate devices: gas detectors.

A gas detector can be schematized as a hollow cylindrical container (see Figure 3), inside which a gas resides at a certain pressure p. To make the measurement more accurate, the cylinder surfaces must be made of a material capable of protecting from environmental radiation, so that this does not contribute to the creation of ionization, thus dirtying that produced by the radiation on which you want to investigate. In fact, for the entrance of the particles, is provided a small "window" in mylar, a radiation transparent material, having a density similar to that of polyethylene. Once the particles enter the detector through the mylar window they are able to ionize in the gas volume. By imagining that a large number of ionic pairs are produced, therefore electrons and respective positive ions, it is possible to collect them through the help of an electric field, in this way the negatively charged particles will move towards the anode and, consequently, those positively charged , will move towards the cathode. The most convenient way to apply the electric field is to place a filiform anode axially to the cylinder and make the cathode coincide with the lateral surface of the cylinder itself. In this way, the charged particles will be collected and it will be possible to obtain information on the amount of ionization produced by measuring current values, using an external ammeter.

It must be specify that, since positive ions tend to attract electrons, therefore to recombine by forming electrically neutral atoms again, it is necessary the charges reach the collection system before the phenomenon of recombination occurs; for this reason the value of the potential difference applied to the electrodes plays a fundamental role. Furthermore, as the voltage applied to the electrodes varies, five regions can be distinguished related to a different operating regime (showed in Figure 3). As you can imagine, with a zero potential difference, therefore in the absence of an electric field, no current is measured.

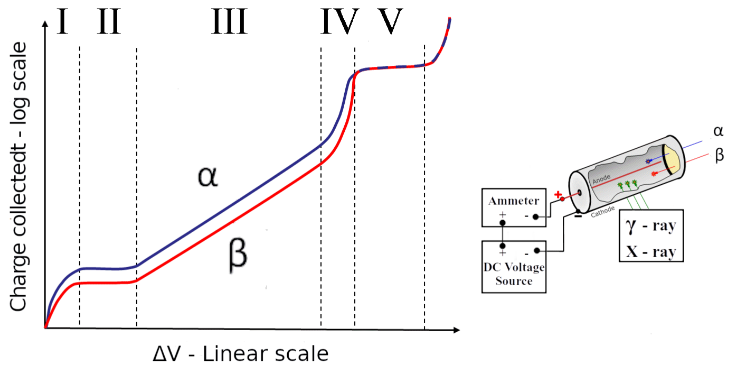

FIGURE 3. Gas detector features. On the left there is the graph that shows the trend of the collected charges as a function of the applied voltage. Regions that behave differently can be distinguished: Recombination region [I], Ionization chamber region [II], proportional counter region [III], limited proportional region[IV], Geiger-Mueller region [V]. On the right a working diagram of a gas detector, it is highlighted how gamma particles are more penetrating and can be able to cross the walls (modified from Power (2020)).

By applying the difference in potential, we are in a region where the number of ionic pairs collected increases proportionally to the value of the voltage, as more intense electric fields are able to collect gradually more and more distant couples from the electrodes, that in lower voltage conditions manage to recombine before reaching the electrode.

The following region is characterized by a plateau and is called *ionization chamber* region; under these conditions the voltage is high enough to attract all the ionic pairs produced by winning the recombination process.

By increasing the voltage again, you exit the constant curve section and collect a number of electron-ion pairs greater than those formed by the incident radiation; this is because the difference in potential applied, not only manages to guarantee the collection of all the couples created, but is also able to accelerate the couples created and provide them with enough energy to allow them to produce further ionization within the gas which results in other pairs created and collected, consequently measured in the form of output current. The detectors that work in this regime are called *proportional counters*; in this case the number of couples collected is proportional to the number of couples created. This type of detector finds several fields of application, for example, if you want to quantify the ionization produced by a relatively weak radiation, using this type of device, it is possible to display a more defined and intense signal, correlating it to that produced by the radiation using the ratios of proportionality.

With a further increase in voltage one enters the area called *limited proportional* region, here the voltage accelerates the particles even more, but a certain relation of proportionality is maintained between incident radiation and collected torques, amplitude still increase but non in a linear fashion.

The last region, the one characterized by very high voltages, is that of the *Geiger-Mueller counters*. In this case, the intense electric fields manage to trigger an avalanche ionization. Even starting from a single pair created by radiation it is possible to ionize all the gas molecules through the avalanche multiplication process. This type of detectors fail to provide a response related to the amount of ionization produced by the radiation, they are useful, however, because they manage to establish the presence or absence of radiation (Knoll 2010; Kratz and Lieser 2013).

3. X-ray discovery

A sensational discovery in the field of ionizing particles was that of X-rays, dated 8 November 1895, by the German physicist W. C. Röntgen. The discovery took place in a laboratory of the University of Würzburg, of which the studious was the director. The scientist, at the end of October of the same year, devoted himself to experiments on cathode rays, starting from the results obtained by scientists such as P. von Lenard and H.R. Hertz linked to discharge phenomena in vacuum tubes.

It should be noted that the experiments, even during the day, were carried out in conditions of total darkness because the scientist was color blind. The apparatus was initially formed by the device used to generate the voltage, a Ruhmkorff inductor, produced by Reiniger, Gebbert-Schall Company, now kept at the Deutsche Museum in Munich, connected to the two electrodes placed in the vacuum tube of Hittord-Crookes. Furthermore, before attempting new experiments, Röntgen wanted to attempt to replicate the experiments of Hertz and Lenard; he therefore used, in the initial stages, the Gaede tube and, like Lenard himself, a sheet of black paper and a screen of barium platinocyanide, on which the cathode rays coming from a single window could be observed, on which it was usual lay small thicknesses of metal (usually aluminum), to demonstrate the properties of electrons to pass through some materials. The German physicist tried to modify the experiment using the aforementioned Hittord-Crookes tube and making various attempts by covering the tube with different thicknesses of black paper; at one point, on the evening of November 8, 1895, he noticed a faint light on the fluorescent screen. He then tried to interpose his own hand, noting with surprise that the image of his bones appeared on the screen with a halo around attributable to the tissues of his fingers. Subsequent tests involved other types of materials but only lead was able to block the phenomenon. Then, again, photographic plates were used, in an attempt to fix the amazing results of the experimental tests on film. One day, then, the scientist put his wife's hand between the vacuum tube and the photographic plate and, after an exposure of about 15 minutes, he obtained an incredible and famous result still today: the first radiography in history; it showed Mrs. Röntgen's hand (see Figure 4), in which the bones and fingers were clearly visible, complete with a wedding ring (Underwood 1945; Glasser 1993; Busacchi 2015).

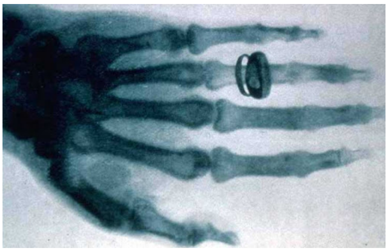

FIGURE 4. Röentgen's wife hand after X-ray exposure.

4. X-rays: Characteristics and Applications

X-rays means the portion of the spectrum of electromagnetic radiation having a wavelength between 1 picometer and 10 nanometers; these are very energetic radiation, and for this reason, they are also classified as ionizing radiation. X-rays can be produced through two processes:

- Bremsstrahlung (braking radiation);
- Fluorescence (interaction with K-shell electron causes the production of characteristic radiation).

In both cases, a vacuum tube with electrodes placed to which a potential difference is applied is used (schematic showed in Figure 5). In addition, a filament capable of emitting electrons by thermionic effect is placed in the tube, these are accelerated by the potential difference and hit the anode. The negatively charged electrons are attracted by the nuclei of the material that makes up the anode, this causes a sharp deviation of the electron's trajectory which gets rid of an important amount of its kinetic energy by emitting a photon of wavelength typical of the X radiation, this is called Bremsstrahlung effect. The photons generated by this process give rise to continuous spectra with maxima centered around certain values. The trend of the spectrum is a function of the potential difference applied inside the tube and can be predicted by the following equations:

$$hc = e\Delta V \tag{5}$$

$$\lambda_{peak} = \frac{hc}{e\Delta V} = \frac{1238nm}{e\Delta V} \tag{6}$$

h is Planck constant, c the speed of light in vacuum, e the electron charge and ΔV the potential difference.

The fluorescence emission occurs, however, when the accelerated electron, affecting the anode, manages to expel an electron belonging to the shell K, the anode is usually composed of heavy metals with a high atomic number. The electrons of the subsequent shells, M or L, fill the vacancy by getting rid of excess energy by emitting a X photon of frequency and typical wavelength, associated with the difference in energy between the shells. For this reason the spectra related to this phenomenon have a continuous background, corresponding to the braking radiation, called the Bremsstrahlung background, and two very pronounced peaks corresponding to the energies of the photons emitted by fluorescence (Figure 6); they are called K_α and K_β, due respectively to the transition with lower difference in energy between the levels (transition from L to K - K_α peak) and to the one with major energy difference (transition from M to K - K_β peak). These peaks position can be calculated by:

$$\nu = A(Z - b)^2 \tag{7}$$

ν is the peak-frequency, Z the atomic number of target atom (usually tungsten or molybdenum) and b, A and b constants (Massey and Burhop 1952; Merzbacher and Lewis 1958; Beutel *et al.* 2000).

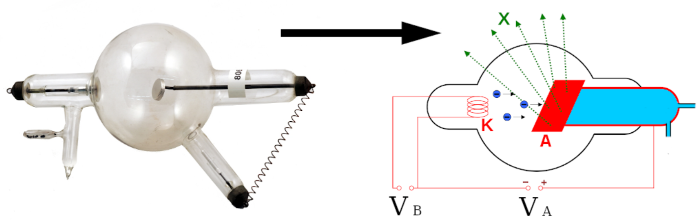

FIGURE 5. On the left a X-ray vacuum tube; on the right, the diagram of a vacuum tube for X-ray production.

There are many applications related to the use of X-rays, for example in scientific research it is possible to use them for X-Ray Diffraction experiments (XRD), to characterize the crystal lattices, or in X-Ray Fluorescence (XRF) to characterize the elements that make up a material (MacDonald 2017; Castorina and Caccamo 2019).

Another example of very common applications known to all are those concerning the field of medicine. Again there are several applications, especially related to medical imaging. These are both applications for diagnostic and navigation purposes, or rather, X-ray imaging is used to monitor the patient's region undergoing treatment. X-ray medical imaging includes widely used techniques such as Radiography, Mammography and Computed Tomography (CT).

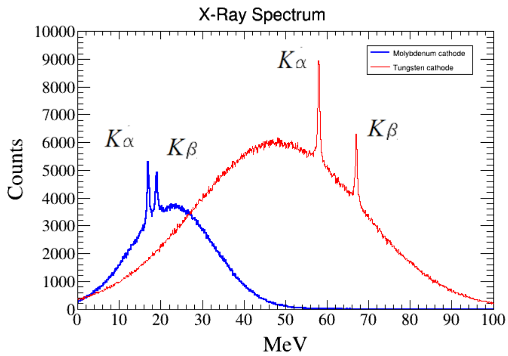

FIGURE 6. Difference between the characteristic x-ray peaks of molybdenum and tungsten. W: K_α = 58 keV, K_β = 67 keV; Mo: K_α = 17keV e K_β = 19 keV. Given the different energies involved, it is usually convenient to use the tungsten anode for radiography and the molybdenum anode for mammography.

In the case of X-ray, the patient is interposed between the source and the photographic plate (like Mrs' Röntgen hand), even if, thanks to new technologies, today the photographic plate is often replaced by detectors which make it possible to acquire images on a PC and processed with special software; this allows not only to reduce the costs of the plates but, above all, to obtain better images with the administration of lower doses. In this diagnostic technique, information is drawn from a single patient exposure to radiation (Beutel *et al.* 2000).

CT instead allows you to reconstruct and map, even three-dimensionally, regions of the patient's body following the processing of multiple slices relating to different sections of the patient. This technique allows a more complete and precise imaging than that obtained by simple radiography; however, it requires administration of a dose about 32 times higher than that deriving from an X-ray (Beutel *et al.* 2000; Scannicchio 2013).

5. Black-body radiation

Black-body radiation has been studied extensively by many physicists and scholars, especially between the second half of the 1800s and the early 1900s; has led to amazing results, of fundamental importance for the development of quantum mechanics and modern physics. The term black body was coined by Gustave Kirchhoff in 1860 (Kirchhoff 1860a), is still used today, and is based on the principle that a body, in thermodynamic equilibrium with its environment, is opaque at all the frequencies of electromagnetic radiation that are perfectly absorbed by it; consequently it appears, in fact, "black". This process, based on the principle of energy conservation, is followed by an irradiation towards the outside by the black body. However, this is an idealization, as there is no ideal black body. The black body radiation generates a continuous spectrum of a typical bell shape bearing asymmetries and a more or less pronounced peak based on the temperature of the emitter body (Figure 7), on which the emission is solely dependent, for this reason it is also called thermal radiation. Thermal radiation sources are considered: the sun, stars in general and incandescent lamps, but also radiators and stoves; the differences between the spectra and the effects produced are all explained by thermodynamic considerations (Chandrasekhar 1950; Goody and Yung 1989; Giancoli 2000; Incropera *et al.* 2006). The intensity of the radiation can be obtained from Stefan-Boltzmann's law:

$$I = \sigma T^4 \tag{8}$$

In this equation T is the temperature in Kelvin and σ is the Stefan-Boltzmann's constant and is worth $5.670374419 \cdot 10^{-8}$ $\mathrm{Wm^{-2}K^{-4}}$. [4]

The wavelength at which the maximum emission intensity occurs through the Wien's law can also be obtained:

$$\lambda_{max} = \frac{b}{T} \tag{9}$$

T is still the black body temperature and b is called *Wien's displacement* constant and worth $2.897771955 \cdot 10^{-3}$ mK.[5] The Wien's law allows, for example, to explain why the radiation from the sun appears to be of a different color than that from a star or, again, why the radiation produced by a tungsten lamp is visible while that caused by a stove does not is: simply by applying the Wien's law to the stove it will be seen that, based on its temperature, the emission peak will correspond to a wavelength located in the infrared region, therefore invisible to the human eye. With the latter consideration, it can also be explained why infrared sensor cameras allow night surveillance; they are sensitive to infrared radiation produced by the heat of the human body (Kirchhoff 1860b; Hermann 1971).

Many theories, however, do not find any experimental evidence, such as that of Rayleigh-Jeans which predicted the *"ultraviolet catastrophe"*, according to which, the emission had to tend to infinity with increasing frequency. Furthermore, this theory provided that X and γ radiation emissions were expected for a body at room temperature and that the body itself had to store a great deal of energy to increase its temperature by one degree centigrade. It was not easy to correctly interpret the black body spectrum, but, as already stated in Section **1**, Einstein, following Planck's hypothesis of photons and quanta, supposed that energy could be expressed in the form of equation 3.

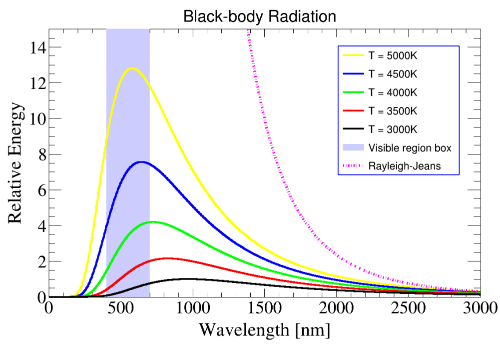

FIGURE 7. Black-body spectrum at different T.

[4]"2018 CODATA Value: Stefan-Boltzmann constant". The NIST Reference on Constants, Units, and Uncertainty. NIST. 20 May 2019. Retrieved 2019-05-20.

[5]"2018 CODATA Value: Wien wavelength displacement law constant". The NIST Reference on Constants, Units, and Uncertainty. NIST. 20 May 2019. Retrieved 2019-05-20

This was an extraordinary result that gave away to the greatest scientific discoveries from the early twentieth century to today (Planck 1914; Feynman *et al.* 1963; Cohen-Tannoudji *et al.* 1977; Kuhn 1978; Walker 2008).

6. Photoelectric effect

Another very important result of Physics of the last century is the discovery of the photoelectric effect. For the correct interpretation of this phenomenon Albert Einstein was awarded the Nobel Prize in 1921. The first studies on the photoelectric effect date back to 1887 and were performed by Hertz, who was carrying out experiments on cathode rays and discharges produced by charged conductors triggered by sparks. The studious noted that the phenomenon was favored if an ultraviolet light beam affected the electrodes. At the same time, Ebert and Wiedemann also noticed that the negative charges came from the negative electrode and were more easily released if the light tended gradually towards the frequencies corresponding to ultraviolet radiation (Hallwachs 1887; Hertz 1887) The term *"photoelectric"* however derives from an Italian, Augusto Righi. He used the term for the first time in 1888, when during his experiments, he noticed that a sheet of conductive material had a positive charge after being irradiated with ultraviolet light (Righi 1887). On the authorship of the term he also had to debate with Hallwachs, who in the same experimented with the same type noting a real production of electricity. For some time the effect was called the Hertz-Hallwachs effect. A few years later, in 1900, Philipp von Lenard carried out the experiment that bears his own name. During the experiment, a current was measured when the light of appropriate frequency (ultraviolet), hit the cathode, causing the expulsion of a certain number of electrons. The effect was more pronounced, therefore a greater current was measured, as the frequency increased. It was also noted that, for certain frequency values, the emission of electrons did not take place; that is, there was a threshold below which the effect did not occur (Thomson 1899; Lenard 1902; Wheaton 1978).

Einstein's interpretation came in 1905 and, like all the great innovative theories, caused a sensation and was not immediately accepted; eminent scientists in the field of electromagnetism such as Lorentz, Millikan and Planck were also skeptical. Planck even considered, for quite some time, his own photon hypothesis, a mathematical artifice devoid of experimental findings. Einstein's hypothesis was soon accepted universally, also thanks to Millikan's experiments which gave clear experimental confirmation (Einstein 1905; Millikan 1916; Gliozzi 2005). The photoelectric effect, ultimately, provides that an incident photon, on a metallic material, can interact with one of the electrons, usually of the external shell, therefore more weakly linked to the atom, giving it all its energy (Figure 8a). The energy transferred from the photon is partly spent to free the electron from the atom to which it is linked, while the remaining is purchased by the electron in the form of kinetic energy. The energy with which the electron is linked to the atom is typical for each material and is called the *work function* or *extraction potential*, for metal materials it is worth on average a few eV. The relative equation is:

$$E_e = h\nu - \Phi_s \tag{10}$$

where E_e is the energy of the photoelectron, ν the frequency of the incident photon and Φ_s the work function of the electron in the shell. It is clear that the photoelectric effect can occur if and only if the energy of the incident photon is greater than the energy with which the affected electron is linked to the atom. By combining the Planck relation with the previous equation, the dependence of the process on the frequency can be explained and an activation threshold can be defined:

$$E_e = h\nu - h\nu_0 \tag{11}$$

If $\nu < \nu_0$ the photoelectric effect does not occur.

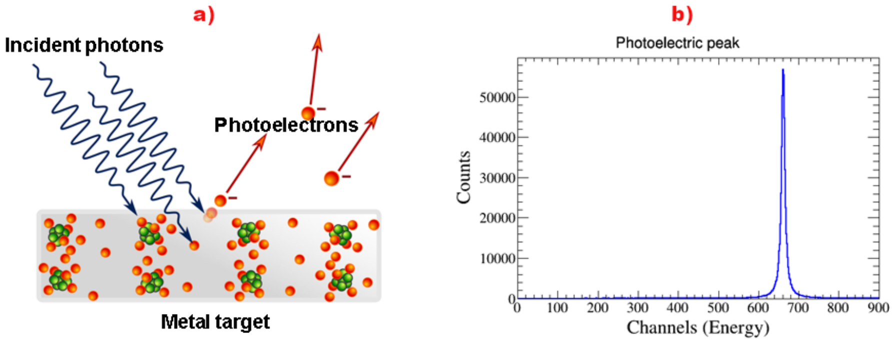

FIGURE 8. Left: Einstein's interpretation of the photoelectric effect. Right: typical spectral component due to photoelectric effect.

One of the experimental applications in which the photoelectric effect is particularly important concerns nuclear physics. In fact, during an analysis in which we try to determine the energy of the photons emitted by a source of gamma rays, the peak produced by the photoelectric effect in the spectrum is the only one from which we can obtain information about the amount of energy of the incident photon. This is because, in this type of analysis, the released electrons are revealed; consequently those to which the photon has transferred all its energy by photoelectric effect generate a peak with energy equal to that of the incident radiation (Figure 8b). It should also be noted that the energy that we reveal from the electron is less than that of the incident photon of a few eVs that were spent to free the electron from the atom. However, since gamma radiation is very energetic, they generally have energy of the order of MeV, these small deficiencies can be overlooked (Knoll 2010).

7. Compton effect

Another mechanism of interaction of photons with matter is represented by the Compton Effect, discovered by Arthur Compton himself in 1922. This effect is very important, especially because it highlights the particle nature of light. The experiments carried out by the scientist consisted in sending X-rays with a wavelength λ = 0.0709 nm on graphite targets and energy gamma rays between 0.5 and 3.5 MeV and displaying the particles on screens after interaction. Much of the incident radiation did not interact, generating photons of wavelength equal to the incident output, however, there was also a diffuse component at angles from to 0 to π relative to photons deflected and deteriorated in frequency and energy (Compton 1922, 1926).

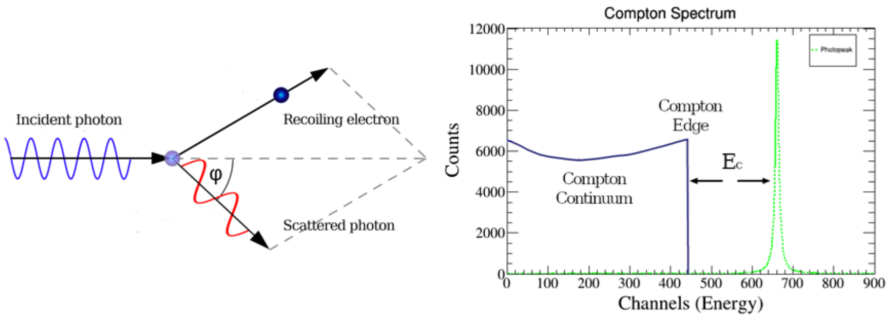

FIGURE 9. Compton scattering diagram (left) and spectrum (right).

The experiment can be schematized as in the Figure 9: an incident photon that colliding an electron gives it part of its energy, releasing it with a direction that forms a θ angle with the incident direction of the photon, while the same photon is deflected by an ψ angle degrading into energy. It has been shown that the photon transfers the maximum amount of energy to the electron when it is deflected by π, therefore in the case of back-scattering, while it gives very little energy when it is deflected at very small angles, close to 0. The photon, despite being massless, has momentum and, given that it is a very fast particle (c in a vacuum), it is necessary to take into account the relativistic effects in the calculations. Taking advantage of the principles of conservation of energy and momentum:

$$E_k = h\nu - h\nu' \qquad (12)$$

The energy of the scattered photon will be:

$$h\nu' = \frac{h\nu}{1 + h\nu/(m_0 c^2)(1 - cos\theta)} \qquad (13)$$

E_k is the kinetic energy of the scattered electron, ν and ν' the frequency of the incident and scattered photons, m_0 the resting mass of the electron, θ the scattering angle of the photon.

The photons that interact according to this process generate a continuous energy spectrum; in a multichannel analysis the events characterized by scattering at large angles $\approx \pi$ will be displayed in the higher energy channels, while those at smaller angles gradually in the lower energy channels. Remembering that photons can give rise to different interaction processes, such as the photoelectric effect, the spectrum will be formed by multiple contributions. The one due to the Compton Effect is called *Compton continuum* and, as already mentioned, it goes from energies close to zero to higher energies corresponding to the back scattering of the incident photon, the latter part is called *Compton edge*. It is possible to see that the part placed at higher energies is indicated by the name *Compton Edge* and is energizing separated from an amount equal to the energy carried by the backscattering photon from the point marked with $h\nu$, where the events due to the photoelectric would be located; here photons transfer all their energy in the material (Knoll 2010).

8. General characteristics of the photon, wave and corpuscular dualism for radiation

One of the most difficult questions that physicists of the past centuries have tried to answer was certainly: is light a particle or a wave? Before reaching the universally accepted theory of the dual nature of light, several quarrels were triggered. One of the first was the one between Newton and Huygens, around the end of the 17th century. The famous Isaac Newton was a great supporter of light as a corpuscle, in agreement with the same Galilean mechanics which predicted that phenomena such as reflection derive from elastic impacts between a surface reflective and the *"corpuscles of light"*. This theory was also confirmed by the simple observation with the naked eye of phenomena such as the shadow generated by an opaque medium interposed between a light source and a screen; in this case, the corpuscle light was intercepted by an obstacle because it was unable to cross it. On the contrary, Christiaan Huygens was a strong supporter of the wave theory; this was able to explain phenomena such as refraction and dispersion and birefringence, a phenomenon much studied by the Dutch scientist (Huygens 1690). As the years progressed, numerous experiments were carried out and many theories were developed by eminent figures of the world physics panorama. Among the most important results, especially for the wave theory, it is necessary to place Young's experiment of 1801 and the formulation of Maxwell's Equations, in the second half of the nineteenth century. Young's experiment, also known as the double slit, showed that, by passing the light coming from the same source through two parallel slits, in front of which a screen was placed, on this a diffraction figure was formed due to the effects of interference between the light coming from the two slits. From the resolution of Maxwell's equations it was possible to note that the light radiation was a wave generated by electromagnetic fields and that the part of radiation visible to the naked eye represented only a small part of the whole spectrum (Maxwell 1873). Even in the early twentieth century, very different opinions were expressed on the behavior of electromagnetic radiation. Einstein and Compton, with the interpretation of the photoelectric effects and Compton described above, made the quotation of the photon grow as a quanta of light and corpuscle, which colliding the electrons transmits energy to it; Max Born himself, in 1926, affirmed that quantum interpretations should be based on the existence of microscopic particles with which Ψ wave functions were associated but which were pure mathematical instruments, whose $|\Psi|^2$, was able to describe the probability density of finding a particle in a region of space. On the contrary, Schröedinger argued the correctness of his method which provided for the analysis of microphysical phenomena through wave interpretation (Born 1926; Scröedinger 1926, 1952; Feynman 1988; Baierlein 1992; Introzzi 2010). All the examples cited are shown to be valid but never occur simultaneously. This leads directly to the *"complementarity principle"* due to Niels Bohr, dating back to 1927; according to Bohr, each quantum system must have at least one pair of properties that describe it but these cannot be known simultaneously, information on one completely destroys information on the other. In the same year Davisson and Germer experimentally demonstrated De Broglie's hypothesis dating back to 1924. The two physicists conducted an experiment in which they obtained a diffraction figure by incising an electron beam of appropriate energy on a nickel crystal; they also noticed that the pattern relating to the energies of the electrons sent, was similar to that obtained by replacing the electrons with X-rays. In accordance with Bohr's principle and De Broglie's hypothesis, it was concluded that light presents itself under a dual wave and corpuscular aspect and these cannot be observed simultaneously and also that the particles show wave behavior following the relations of De Broglie:

$$p = \frac{h\nu}{c} = \frac{h}{\lambda}; \quad \Longrightarrow \quad \lambda = \frac{h}{p} \tag{14}$$

λ is call De Broglie's wavelenght, p is the momentum. This hypothesis also allows a wavelength to be associated with each particle (Thomson and Reid 1927; Bohr 1928; De Broglie 1928).

Even today we try to understand when electromagnetic radiation "chooses" to show one or the other nature. Pauli, for example, attributed the cause to the experimental apparatus (Pauli 1950). In this regard, interferometry experiments are still carried out today, even with a single photon. A laser beam is focused on a beam splitter that splits it and conveys it into two arms having different optical paths. The two secondary beams are then brought together; the light here, if a second semi-reflective mirror is present, behaves as a wave, otherwise as a particle. An attempt was made to radically change the parameters of the experiment but no differences were noted, the photon behavior cannot be predetermined. An experiment based on the application of the Wheeler interferometer over long distances was carried out at the *"Matera Laser Ranging Observatory"*. A pulse of light was sent into space and reflected to the Earth by a satellite at 3500 km was able to generate a phase shift, the revelation took place only in the terminal part of the return journey to Earth. The results confirmed that, even when performing experiments with very large distances compared to those of common instruments used in the laboratory, the results do not change, it is not possible to determine when the photon chooses to be a wave or a particle (Vedovato *et al.* 2017).

9. Radioactivity

9.1. From cathode rays to radioactivity. One of the most important issues of physics at the end of the 19th century regards the nature of cathode rays that went from the cathode to the anode causing fluorescence in tubes with rarefied gases (Bagatti *et al.* 2017). In 1896, a year after Roengten's discovery of X-rays, Becquerel (Figure 10a) decided to understand the relationship between X-rays and fluorescent studying the behavior of some uranium mineral crystals that exhibited the phenomenon of fluorescence. Becquerel's studies are closely related to those of his father on the phosphorescence properties of materials which, for this purpose, had also designed special tools (Becquerel 1896a,b; Sekiya and Yamasaki 2015). The experiments consisted of exposing small thicknesses of uranium – potassium double sulfate crystal $K(UO)SO_4 + H_2O$ to the sun which, subsequently, were wrapped in a black cloth opaque to visible radiation and placed near a photographic plate which was then impressed by a component that he called *"Invisible radiation emitted by a phosphorescent substance"*. Completely by accident on a cloudy day, the scientist interrupted the experiment due to the absence of sun and placed the minerals in a drawer in which there were also photographic plates, against all odds he found these impressed (Figure 10b). He repeated the experiments with other materials and concluded that the one called *"unknown radiation"* (or "Becquerel rays") was typical of uranium salts (Hashimoto 1996; Shimizu 1996; Nishio 1997; Yamasaki 2012). It was the physicist Ernest Rutherford who discovered that the

Becquerel rays were actually made up of different types of radiation. In fact, Rutherford identified the α (alpha) and β (beta) rays, to which the γ (gamma) rays were added (already introduced in paragraph **1.2**) (Ostinelli 1996). It soon became clear that it was not uranium compounds that emitted radiation, but the uranium atoms themselves, which in fact exhibit this characteristic when we found them in the elementary state and when they are mixed with other elements in compounds.

At that time, Marie Curie (Figure 10c) decided to deepen Becquerel's discoveries through careful experimental work on some samples of uranium minerals (Bagatti *et al.* 2017). She realized that, in some cases, the radiation emitted by minerals was much greater than expected on the basis of the uranium content and therefore assumed the existence of other radioactive elements. It was indirect evidence that there was an element still unknown from the very high *radioactivity* (as the phenomenon was called by the Curie itself). With the help of her husband, Marie Curie announced in 1898 that she had discovered a new element, which she proposed to call Polonium in honor of her homeland. The ascertained presence of Polonius, however, could not fully explain the radioactivity of the pitchblende, a radioactive mineral containing uranium, this led the Curie spouses to discover a second unknown element: Radio. This, for the same mass, is a million times more radioactive than Uranium. The experiments were conducted on very large quantities of pitchblende, about 10 tons, from which small quantities of the new elements were extracted; this confirms the great radioactivity of the latter. The Curie spouses, together with Becquerel, were awarded the Nobel Prize in 1903 for the discovery of natural radioactivity. In 1911 Marie Curie also won the Nobel Prize in Chemistry for the discovery of Radio and Polonium (Pasachoff 1997; Oba 1998; Ogilvie 2004; Caballero 2016). Becquerel (Bq) and Curie (Ci) are still the units of measurement for the activity of a radioactive substance and correspond to 1 Bq = 1 dps and 1 Ci = $3.7 \cdot 10^{10}$ dps (dps = disintegrations per second). The value of Ci corresponds to the activity of the Radio. Today the use of the Becquerel is preferred.

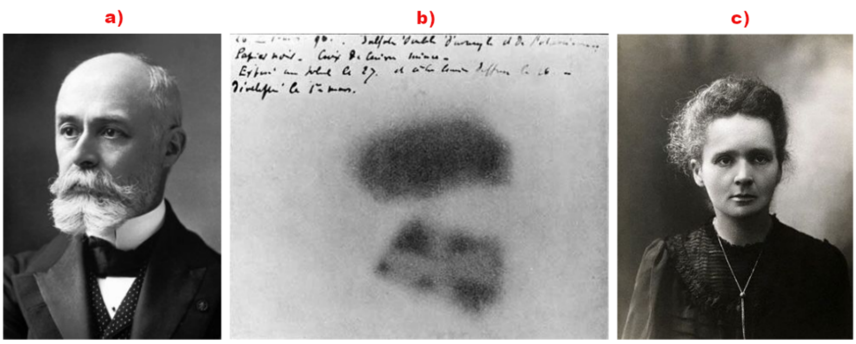

FIGURE 10. A. H. Becquerel on the left, in the center the plate with the first signs of radioactivity and, on the right, Marie Curie.

Note that Marie Curie's contribution to the study of radioactivity was mainly experimental, but the discovery of radioactivity was also a theoretical problem because physicists wondered why some substances spontaneously transform themselves emitting energy and what was the origin of this phenomenon. In 1900 Marie Curie announced that there was a very close link between β rays and cathode rays, which in 1897 Thomson had shown to be made up of negative particles, electrons (Bagatti *et al.* 2017). In consideration of what had been found, it was deduced that electrons are constituents of all atoms. When Marie Curie began to deepen research on the strange phenomenon discovered by Becquerel, however, the nuclear structure of the atom was not yet known and therefore it was not known that the β rays come from the nucleus. The scientific results of Marie Curie, her husband and Becquerel cannot be read separately from the contributions of numerous other scientists their contemporaries with whom they themselves exchanged opinions and reports of experiments: among the many it is important to remember Ernest Rutherford, who was the first to describe the phenomenon of radioactive decay and transmutation, that is, the transformation of one element into another through a nuclear reaction (Ostinelli 1996).

9.2. Identification of α, β and γ particles. As stated before, physicists Pierre and Marie Curie identified many distinct types of particles that result from radioactive processes (decays) as reported in figure 11 (Ostinelli 1996; Braibant *et al.* 2012). The three distinct types of radiation have been indicated with α, β and γ and can be separated by a magnetic field, since the alpha positive particles bend in one direction, the beta negative particles in the opposite direction and the electrically neutral gamma rays do not bend at all.

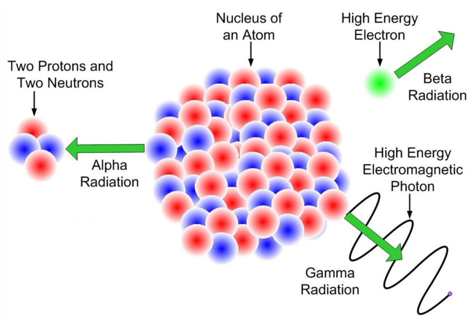

FIGURE 11. Radioactive decay and generation of α, β and γ particles.

Alpha particles (helium nuclei) are a highly ionizing form of corpuscular radiation, with a low penetrating power. Due to their electric charge, alpha rays interact strongly with matter and therefore can travel only a few centimeters in the air. These particles (although very ionizing) cannot exceed layers of matter greater than a sheet of paper. They can be absorbed by the outermost layers of human skin and so are generally not life-threatening unless the source that emits them is inhaled or ingested. In this case, the damage would instead be greater than that caused by any other type of ionizing radiation, and if the dosage was high enough, all the typical symptoms of radiation poisoning would appear.

Beta radiation (very fast electrons) is a form of ionizing radiation emitted by some types of radioactive nuclei (such as cobalt-60). This type of radiation takes the form of high energy electrons or positrons, expelled by an atomic nucleus. The interaction of beta particles with matter generally has a radius of action ten times greater, and an ionizing power equal to one tenth of the interaction of alpha particles. They are completely blocked by a few millimeters of aluminum.

Gamma-rays (high energy photons) have already been prefaced in paragraph **1.2** as a form of EM radiation produced by radioactivity or other nuclear or subatomic processes. They are more penetrating than both alpha and beta radiations, but are less ionizing. Although gamma rays are less ionizing than alpha and beta, thicker screens are needed to protect humans. Gamma rays produce effects similar to those of X-rays such as burns, forms of cancer and genetic mutations.

10. Ionizing radiations

As can be guessed from what has been said so far in this paper, we can made a first distinction between different type of radiations depending on the effects they cause on the matter with which they interact. On this basis, in fact, we consider (i) ionizing radiation, and/or (ii) non-ionizing radiation.

Non-ionizing radiation is any type of EM radiation that does not carry enough energy to ionize atoms, that is, to completely remove an electron from an atom. Instead of producing charged ions through matter, electromagnetic radiation has enough energy only to excite the movement of an electron to a higher energy state.

Ionizing radiation, instead, is endowed with a highly penetrating power, which allows them to ionize matter, that is, to be able to separate the electrons from the atoms they encounter in their path (Prise 2011; Organization 2016; Djezzar 2018). As a result, atoms lose their neutrality (which consists in having an equal number of protons and electrons) and charge electrically. As reported in paragraph **1.2**, gamma rays, X-rays and the high frequency portion of the ultraviolet of the electromagnetic spectrum are ionizing, while the lowest part of the UV region of the electromagnetic spectrum, and also the lowest part of the spectrum under UV rays, including visible light (including almost all types of laser light), infrared, microwaves and radio waves are all considered non-ionizing radiation. The most common ionizing subatomic particles include alpha particles, beta particles and neutrons. Almost all products of radioactive decay are ionizing because the energy of radioactive decay is generally much higher than that required for ionizing. Other ionizing subatomic particles that exist naturally are muons, mesons, positrons, and other particles that make up the secondary cosmic rays, which are produced after the primary cosmic rays interact with the Earth's atmosphere.

However, when we talk about ionizing radiation it is important to make another distinction between directly and indirectly ionizing particles (Ostinelli 1996; Knoll 2010). Directly ionizing particles are considered those particles with electric charge, which ionize the atoms of the medium when they pass through the medium itself. In this case, ionic pairs will be formed consisting of a free electron and a positive ionInstead, indirectly ionizing particles are considered that particles without electric charge that they impact the atoms of the medium transferring their energy when they enter inside the material medium. In this way, medium's particles begin to move ionizing other particles inside the material medium. Examples of indirectly ionizing particles are neutrons, X-rays and gamma photons.

When a particle goes to cross a material medium, it gives energy to the medium itself and, so, its initial energy decreases. The loss of energy of the particle E_p as a function of the thickness crossed x is called Stopping Power S:

$$S = \frac{dE_p}{dx}. \tag{15}$$

Figure 12 shows the stopping power of alpha particles in air. This curve is known as the *Bragg curve* (Knoll 2010). Initially the particle enters in the material medium and then begins to lose its energy by colliding with the atoms of the medium. As it loses energy, it slows down having an higher probability to interact with the medium's molecules. In fact, we see that the curve begins to rise due to the particle' slowing down, reaching the maximum value when the particles stops and, then, we see that the curve quickly drops to zero.

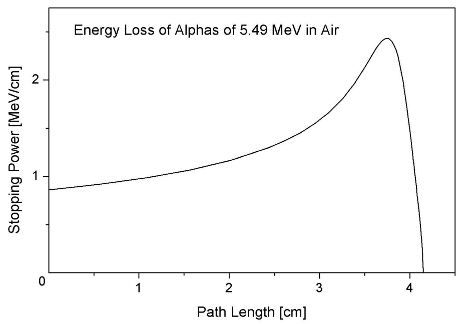

FIGURE 12. Bragg curve. The trend of stopping power of alpha particles of 5.49 MeV in air.

10.1. Biological effects. Man is one of the living creatures most sensitive to the harmful effects caused by ionizing radiation making him one of the weakest links in the natural biological chain (Ostinelli 1996; Organization 2016). In other words, protecting human health, the natural environment is guarded. The effects and damage caused by radiation on an organism are measured by means of the *equivalent dose*, expressed in Sievert, where 1 Sv corresponds to $1\text{m}^2/1\text{s}^2$. Compared to the *absorbed dose*, which measures the amount of energy absorbed by a mass unit of a material (whatever: inert or biological), indicated in Gray (1 Gy = $1\text{m}^2/1\text{s}^2$), the equivalent dose quantifies instead the biological effects of radiation on the organism: different types of radiation can in fact be more or less harmful to the organism.

The mechanism by which these damages occur in man (and, generally, in living organisms) is extremely complex. However, it can be considered that damage already occurs after a time interval between 10^{-18} seconds and 1 second, from the interaction of ionizing radiation with body tissues, as modifications of molecular structures. This harm is followed by the intervention of specific recovery processes in a span of between 10^{-5} seconds (chemical mechanisms) and hours or days (biochemical functioning). However, when these mechanisms fail, the damage is not repaired and its effects are manifested through the following chain of events:

- molecular damage (DNA, RNA, enzymes);
- subcellular damage (chromosomes, nucleus, membrane);
- cell damage (inhibition of subdivision, cell death, carcinogenesis),
- damage to organs or tissues (destruction of systems);
- damage to the organism (death, shortening of life);
- damage to the population (modification of genetic characteristics).

10.1.1. *Somatic and genetic damage.* The “final" damage received by a human being can be divided into: somatic and genetic damage (Ostinelli 1996). Somatic damage occur directly at the expense of the irradiated individual and can be divided into stochastic and deterministic effects. When the irradiated individual is subject to a probability of suffering late damage (neoplasms or leukemia) directly proportional to the effective dose received, we are in presence of *stochastic effects*, suggesting that forms of radio-induced cancer may originate from the damage received from a single cell. Despite the immune defenses, there is a small probability that this cellular damage, due to synergies with other agents not necessarily associated with radiation, could lead to the emergence of harmful effects. It can be reasonably asserted that, for exposures below about 0.1 Sv, only stochastic effects can appear. Instead, *deterministic effects* (or “tissue damage") occur in the individual irradiated above a given irradiation threshold, in the order of 0.5 Gray, but still dependent on the irradiated tissue, and have a typical cause-effect relationship between the amount of the dose received and the severity of the damage, which can therefore be substantially related to the number of damaged cells. Instead, *genetic damage* concern the progeny of the irradiated individual and it is believed that they can manifest themselves up to the second (or fourth) generation, following the damage suffered by the germ cells, mainly taking the form of malformations and anomalies of the offspring, and others yet. They are considered stochastic effects.

The main manifestations of both general and local harmful effects, both stochastic and deterministic, produced on man by ionizing radiation can be summarized as follows:

- Surface effects (skin damage and erythema);
- general effects on the whole body (hematopoietic organs) and generalized shortening of life span;
- induction of tumors;
- various effects, such as cataracts or reduced fertility;
- genetic effects.

Obviously excluding the genetic effects, all the remaining damages can be counted among the somatic ones.

10.1.2. *The effects of ionizing radiation.* Ionizing radiation cause several types of effects on organisms (Butturini and Butturini 1989; Organization 2016; Djezzar 2018). At a cellular level, radiation determines complex physical-biological phenomena, which cause the formation of free radicals (unstable and highly reactive molecules that, when in excess, can also seriously damage the cells of our body) and, directly or through the latter, modification of the structure of organic molecules. The biological effect of ionizing radiation and free radicals is mainly due to damage on enzyme systems, membrane structures and nucleic acids (subcellular damage). The main damages (cell death and mutagenesis) are related to the action on DNA. The changes found after exposure to radiation are the breakdown of one or both alpha helices, the alteration of individual bases and abnormal bonds between the helices or with the surface histones. The probability that alterations at the subcellular level occur depends on the characteristics of the irradiation (total dose, time and mode of exposure) and on cellular factors (moment of the mitotic cycle, activity of the repair systems, oxygen tension, temperature). Based on these variables, the type and degree of subcellular damage leads to three possible consequences: the cell can die (lethal damage), the cell manages to repair the damage and returns to normal (sublethal damage), or the cell does not die, but mutations of the genetic patrimony remain which can lead to neoplastic transformation or metabolic anomalies (genetic damage). The dose is the main determinant of the severity of damage. Very high doses ($>$ 1500 rad) of radiation lead to cell death in a short time, by coagulation of proteins, membrane lysis, etc. At intermediate doses (200-1500), cell death depends mainly on damage to nucleic acids: the cells or die in a few days, as the transcription of DNA and the synthesis of proteins are so altered that the resulting deficits are incompatible with cellular life, or die during the subsequent mitosis (or undergo few pathological mitoses) whereby the lysis follows at variable intervals according to the dose and the half-life of the cells. Low doses, below the threshold limit determined by the characteristics of the individual cells, can lead to permanent or transient gene alterations that underlie respectively the transformation phenomena or paradoxical reactions such as the induction of DNA duplication and transcription. The effect of the total dose is modulated by time and exposure mode.

10.2. A beneficial application: radiation therapy. Ionizing radiation is used in different areas, including in medicine for radiation therapy (Corvò *et al.* 2008; Prise 2011; Marcus 2020). Radiation therapy is a proven effective treatment used in the treatment of tumors. It can be used alone, or in combination with other treatments such as chemotherapy, immunotherapy or surgery. Radiation therapy uses ionizing radiation beams or ionizing particle beams to damage the genetic material (DNA) of malignant cells. Genetic material is essential for cell replication and tumor growth; therefore, when this is damaged, the cancer cells are no longer able to reproduce and face cell death. The purpose of radiotherapy treatment (curative, adjuvant, palliative, etc.) depends on the type of tumor, its stage, its position and the patient's condition.

Radiation therapy consists in directing radiation or ionizing particles towards the tumor mass, in order to kill the diseased cells that constitute it. The ionizing radiations used in radiotherapy are high energy X-rays and gamma-rays. The former are produced by specific instruments called linear accelerators for radiotherapy, while the latter are emitted by radioactive isotopes. Particle beams can consist of protons, neutrons or positive ions. These radiations or particles, when they hit the cell, interfere both with the genetic material, causing direct damage, and with the water inside it, causing indirect damage. In fact, as a result of the interaction of radiation with water, free radicals are generated which are capable of damaging the molecules that make up DNA. Healthy cells have defense mechanisms that can repair any damage to their DNA, while, in cancer cells, these mechanisms are less efficient, therefore DNA damage is more easily lethal. In addition to affecting the tumor mass, lymph nodes can also be affected; this intervention is desirable when the lymph nodes are clinically involved in the pathology, or if a malignant spread of the tumor through the lymphatic circle (metastasis) is feared. Of course, attempts are made to target only diseased cells but, unfortunately, portions of healthy cells can also be irradiated. Radiation therapy can be administered in two ways:

- external (or transcutaneous, or external beam) radiotherapy is so called because the source of rays is positioned outside the body;
- internal radiation therapy is so called radiotherapy administered from within the body. This can happen in various ways: by means of tiny radioactive metal probes that are positioned directly inside the tumor or very close to it (brachytherapy), or through a radioactive liquid to be drunk or injected into a vein, which is specifically captured from cancer cells.

The radiotherapy treatment is customized for each patient, depending on the type of tumor, its size, location in the body, and the patient's condition. In this regard, an important use of ionizing radiation in medicine is hadron therapy. Hadronic therapy is a form of external beam radiation therapy that uses proton, neutron or positive ion beams to treat tumors. This therapy takes advantage of the Bragg curve previously described, in order to concentrate the effect of light ion beams on the treated tumor and at the same time minimize the effect on healthy surrounding tissue as it exceeds this peak the dose drops to zero (in the case of protons) or almost zero (in the case of heavy ions). The advantage is in the lower deposit of energy in the healthy tissue surrounding the targeted one, saving it from unnecessary damage.

11. The flipped classroom method

This paper wants to try to renew and overturn the classical learning based on the explanation in class of the arguments by the teacher and on the study of the students later through the use of the "flipped classroom" method (Istituto Nazionale Documentazione Innovazione Ricerca Educativa (I.N.D.I.R.E.) 2018). This method is intended to make the lesson an homework, where it is possible to make an extensive use of videos and other digital resources, as content to be studied, while the time in the classroom is used for collaborative activities, such as debates and workshops. In this frame, the teacher does not take on the role of leading actor, he rather becomes a sort of facilitator, the director of the didactic action.

The reasons for using this method are several (Istituto Nazionale Documentazione Innovazione Ricerca Educativa (I.N.D.I.R.E.) 2018):

- To allow the improvement of educational interactions in the classroom, thus optimizing time at school.
- To put the student at the center of the learning process by providing him with tools that allow him to deepen the topics, thus generating a richer and more stimulating context. Students are not only actively involved in the educational path and aware of the objectives, but also participate in the evaluation.
- To promote the development of students' digital skills, their autonomy and ability to work with others, thus preparing them better for the world of work than traditional teaching.

- Because the student is the protagonist of activities oriented to problem solving and "learning by doing" and interpreter as well as author of his own knowledge.

To best develop this new method, it is important to start from an initial phase in which students can make use of material provided by a teacher or already existing in the network; this can obviously be a video or somehow accredited scientific sites or documents to familiarize you with the topic of the lesson (Agenda Digitale 2018). This is precisely what we propose with this paper, where we have provided the basic notions on radiations and radioactivity, and the harmful effects they have, also giving some examples on their use in the therapeutic field. About that, we have mentioned, in subsection **10.2**, the importance of radiation for the treatment of tumors through hadron therapy and we want to propose to students who will read this article to go deeper into how these radiations can be used in the context of Oncological Radiotherapy, starting from the basic topics reported. This technique requires a high level of knowledge of modern technologies and the use of extremely complex and sophisticated equipment to locate the tumor. Furthermore, it is critical to know how high doses of ionizing radiation can be generated to cover the target volume sparing healthy tissues.

In this way, we expect even the most insecure students can provide rich topics during the lesson becoming an interactive seminar where the teacher will lead the discussion on the basis of the material collected and used previously by the students, in order to generate new knowledge together (Agenda Digitale 2018). Furthermore, we propose to open discussion groups, with the participation of the teacher himself, whose functions are to support students in their study, removing any doubts that may arise in the reading of classic textbooks, and obviously to answer questions on the discussed topic. The method of "flipped classroom" is essentially a reversal method of the traditional school one: what was done in class and at home is overturned. The methodology that inspires it is collaborative learning that enhances collaboration within a group of students who work together, each with a specific but interdependent role, in the realization of a shared project (Agenda Digitale 2018).

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