

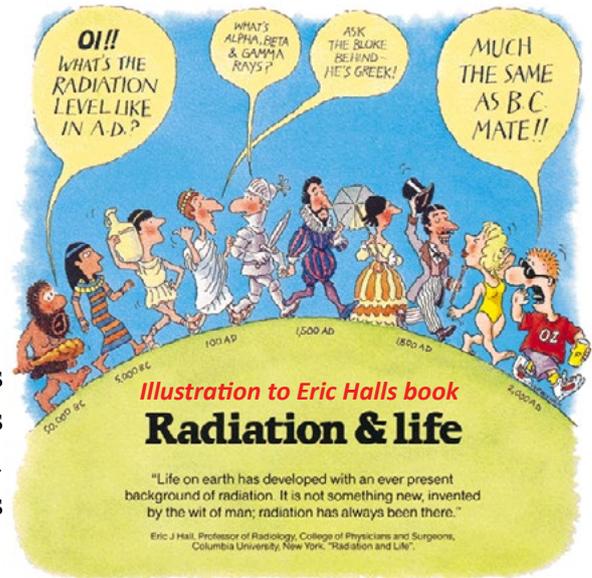
Chapter 2

What is Radioactivity?

Radioactive Elements

The atomic structure of most elements contains a nucleus that is stable. Under normal conditions, these elements remain unchanged indefinitely. They are not radioactive. Radioactive elements, in contrast, contain a nucleus that is **unstable**.

The unstable nucleus is actually in an excited state that can not be sustained indefinitely; it must relax, or *decay*, to a more stable configuration. Decay occurs spontaneously and transforms the nucleus from a high energy configuration to one that is lower in energy. This can only happen if the nucleus releases energy. The energy is emitted by the relaxing nucleus as radiation. All radioactive elements have unstable nuclei; that is what makes them radioactive.

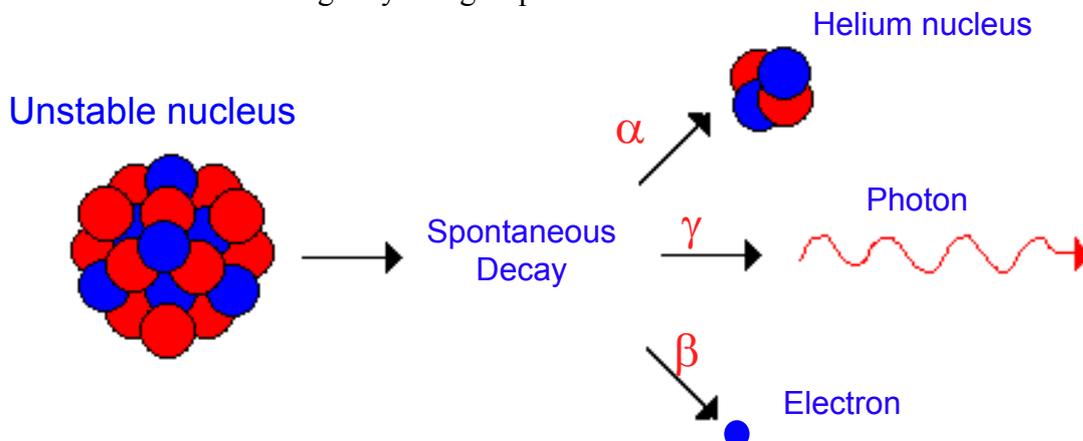


The Nature of Radiation

The energy emitted by an unstable nucleus comes packaged in very specific forms. In the years that followed the discovery of radioactivity, it was of great interest to determine the kind of radiation emitted from the different radioactive compounds. It was found that the radiations in general consisted of three types called: alpha (α), beta (β) and gamma (γ) radiations after the first three letters in the Greek alphabet (see figure below).

The radiation emitted transforms the element into a new element. The process is called a decay or a *disintegration*.

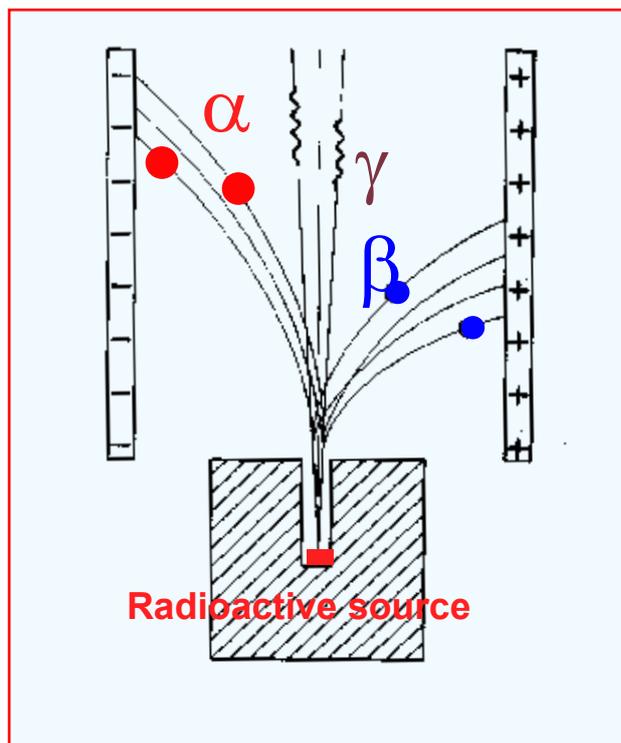
The research leading to the identification of the radiation emitted from the radioactive atoms is exciting and fundamental. We shall give you a glimpse of this work.



A radioactive atom possesses an unstable nucleus. This means that radioactive atoms will emit radiation sooner or later and by this convert into a more stable state. The types of radiation that may be emitted are called alpha (α), beta (β) and gamma (γ) radiation. Later we shall see some more exotic ways of disintegration.

Evidence for the three types of radiation comes from experiments in which the radiation from radioactive compounds passed through magnetic and/or electric fields. The illustration to the right demonstrates this point.

γ -rays passed through the field without disturbance, whereas the two other types were deflected from a straight line. This shows that γ -rays have no charge while α - and β -radiations consist of charged particles. The α -particles are positive whereas the β -particles, deflected in the opposite direction, are negative. We shall return to special sources where positive electrons (*positrons*) are emitted).



Some details on the nature of the radiation from radioactive sources

We shall give you some information about the radiation from the different radioactive nuclei. Such information is necessary in order to use radioactive sources in medicine and industry as well as for calculation of doses. All the details are gathered in the so called “*decay scheme*” for a radioactive isotope. Some examples will be given.

Alpha-radiation

Intensive research was going on in the years around 1900 to determine that the α -particle was the nucleus of helium. A radioactive source that emits α -particles is called an α -emitter. Many of the natural sources consisting of heavy elements, like radium and thorium are α -emitters (see illustration).

${}^{226}_{88}\text{Ra}$

Upper number = atomic weight
Lower number = atomic number

Radium – 226
Unstable

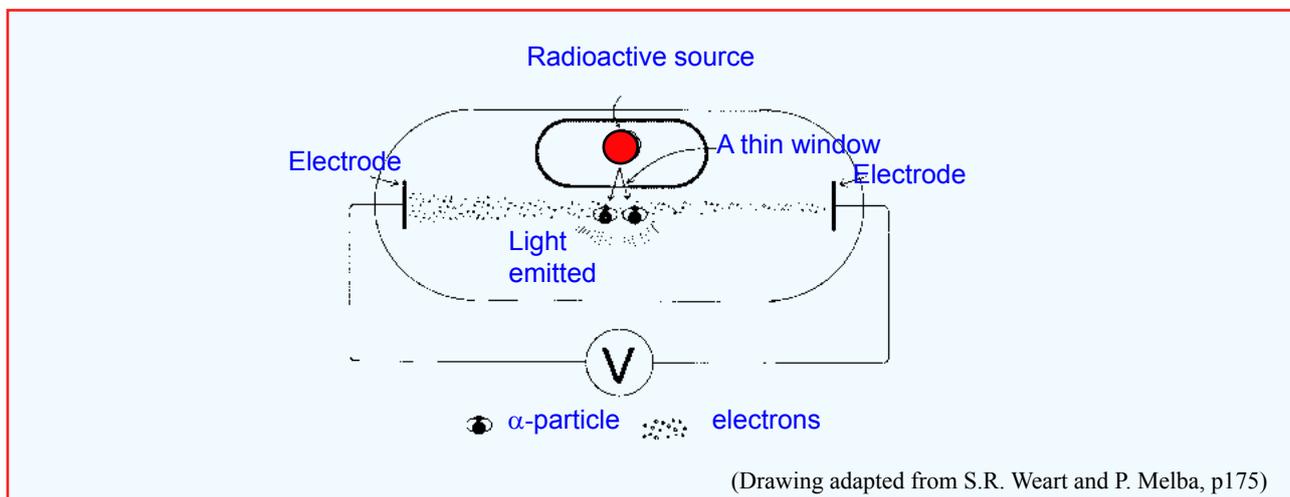
Radon – 222
Unstable

α -particle

Radium (atomic number 88) has an unstable nucleus weighing 226 atomic units. It decays by emitting an α -particle and becomes a new element **Radon**, written Rn-222 (atomic number 86) weighing 222 atomic units. Rn-222 is however, unstable and will in turn decay into polonium, Po-218.

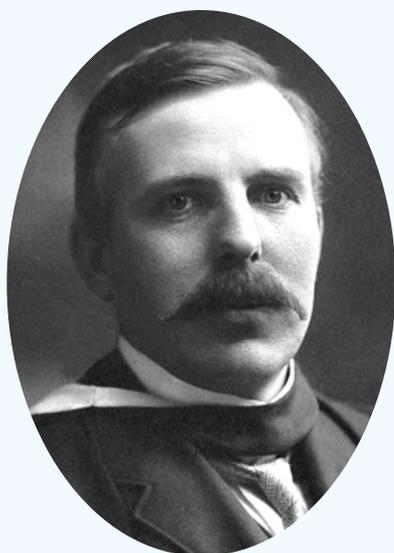
It was Ernest Rutherford (considered as the father of nuclear physics) that finally could conclude that the α -particle was the nucleus of the helium atom. We would like to share with you this elegant experiment from 1908.

Rutherford positioned one glass tube inside a second glass tube. The inner tube contained a radioactive source that emitted α -particles (figure below). The outer tube was evacuated and at each end there was an electrode. The α -particles passed through a thin window and entered the outer tube as a gas.



A drawing of Rutherford's experiment. α -particles from a radioactive source pass through a thin window into an evacuated glass tube. The α -particles "pick up" electrons and become ordinary helium atoms. The color of the emitted light confirmed that the glass tube became filled with helium.

When Rutherford turned on the high voltage between the electrodes, the tube emitted light at very specific wavelengths (specific colors). He compared wavelengths of this light with the wavelengths of light produced by a similar tube that he had filled with helium gas. The colors of the light were identical. Rutherford concluded that an α -particle is simply the nucleus of a helium atom and that when the α -particles reach the outermost tube they have picked up two electrons to become helium atoms.



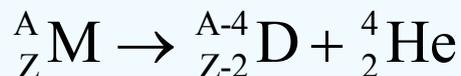
Ernest Rutherford
(1871 – 1937)

Ernest Rutherford was born in New Zealand. He was a research student at the Cavendish Laboratory in England and became professor at McGill University in Montreal in 1898. Rutherford returned to England in 1907 and was Professor of Physics in Manchester, and finally at the Cavendish laboratory in Cambridge. Rutherford introduced a new atom model after his well-known "gold foil experiment" in which he demonstrated that the atom has a tiny, massive nucleus.

For his magnificent work with radioactivity in these early years he was awarded the Nobel prize in chemistry in 1908.

Summary on α -particles

An α -particle is the nucleus of helium. It has a charge of +2 and a weight of 4 atomic mass units. The “mother” nucleus (M) is changed into a “daughter” nucleus (D) according to the following reaction:



A = atomic mass (the number of protons and neutrons).
Z = atomic number (the number of protons).

The emitted α -particles all have the same energy, or are distributed in a few mono-energetic groups. The energy is high – ranging from 1.5 MeV to about 11 MeV.

Almost all α -particle sources are found among the heavy elements and most of them are natural.

The daughter nucleus is very often unstable – and most often emits γ -radiation. We can notice that the γ -radiation comes from the unstable daughter nucleus.

Beta-radiation

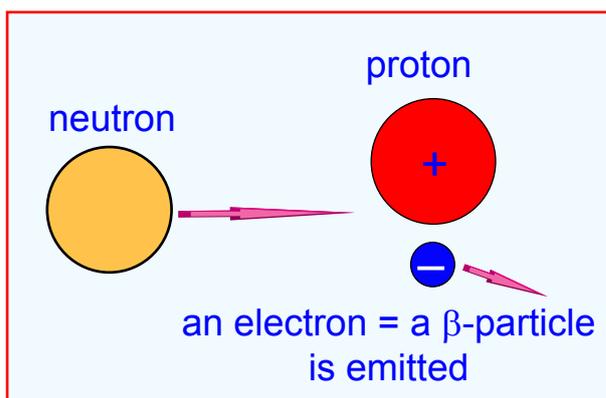
An unstable nucleus may attain a more stable configuration by emitting a β -particle. In this process a neutron in the nucleus is transformed into a proton and an electron (see illustration).

Due to the difference in mass, we can consider a neutron to be a proton + an electron + a small sub-atomic particle (the *neutrino*).

Both natural sources and artificial radioactive sources may be β -particle emitters. The energy of the emitted β -particle is usually much smaller than that of the α -particles.

Furthermore, the energy of the β -particles varies from one disintegration to another!

In fact β -particle emission involves a whole spectrum of energies. The reason for this situation is that together with the β -particle, a tiny neutral particle is emitted. This particle was named the “*neutrino*” by the Italian physicist Enrico Fermi. (The term neutrino means a “small neutral particle”). The β -particle emission is written:



The mass A is unchanged.

The proton number (Z) increases by one.

The kinetic energy of the β -particle and the neutrino combined is constant. The energy of the β -particle alone, varies from zero up to a maximum value – equal to the constant. The average energy of the β -particle is about 1/3 of this maximum energy.



The average β -particle energy : rule of thumb.

The β -particle energy for a source varies from zero up to a maximum value.

The average energy is approximately 1/3 of the maximum energy.

Proton changes into a neutron

In the case of β -decay, we described this reaction as a transformation of a neutron in the nucleus into a proton and an electron, which in turn was emitted. This may be a favorable reaction since the neutron mass is larger than the proton mass. The opposite reaction would be that a proton is transformed into a neutron. This process may take place via two different routes – electron capture and positron emission.

Electron capture

This is a decay process whereby an orbital electron (mainly a K-electron) is captured by the nucleus and together with a proton is transformed into a neutron. The nucleus with atomic number Z is transformed into a new one with atomic number $Z - 1$, whereas the mass is unchanged. This reaction is usually followed by γ -radiation, and some characteristic x-radiation (the orbital hole is filled by electrons from the outer orbital shells).

Electron capture was discovered in 1938 by Luiz Alvarez. Since then, electron capture seems to be a very common mode of decay for neutron-deficient nuclides. It is the only mode of decay when the energy difference between the parent atom and the daughter atom is less than $2m_e c^2$ (two electron masses or 1.022 MeV). If, however the energy is larger, another mode is possible – emission of a positively charged electron – the *positron*.

Positron decay

The existence of the antiparticle to the electron was suggested by Dirac in 1928. Four years later Carl D. Anderson observed a particle with the mass of the electron and with opposite charge in experiments with a cloud chamber and cosmic radiation. He named the particle as *positron* and he was awarded the Nobel prize for this discovery in 1936 – when he was only 31 years old.

As mentioned above, electron capture takes place when the energy between the parent and daughter atom is low (less than $2m_e c^2$). If the energy difference is higher, positron emission may take place. The emitted positron will meet an electron and a “*positronium atom*” will exist for a very short time. This atom disappears in an annihilation process – mainly forming two photons with energy 0.511 MeV flying off in opposite direction. We shall return to this in Chapter 9 in connection with the modern diagnostic technique PET (positron emission tomography).

What is an isotope ?

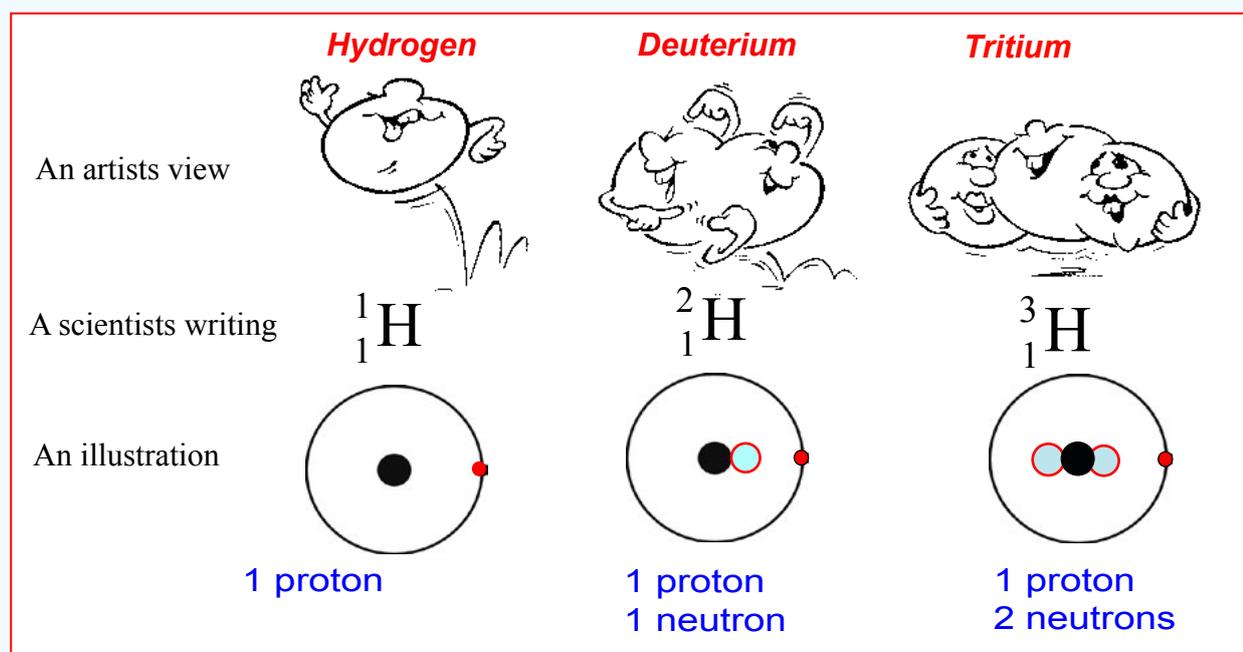
We have so far, several times, talked about isotopes – assuming that you know the definition. Some isotopes are unstable, and therefore radioactive, while others are stable, and thus non-radioactive. So – what is an isotope?

The nucleus of an atom consists of protons and neutrons (called nucleons). The number of protons determines the element and its chemical properties. The number of nucleons determines the atomic weight.

“Isotopes are atoms with the same number of protons, but with different numbers of neutrons.”

Isotopes are chemically equivalent, but have different atomic weights. All elements have several isotopes – some of them may even be unstable and thus radioactive.

An attempt to illustrate this is shown below for the most common of the elements, hydrogen which has three isotopes. They all have a nucleus with one proton. However, the number of neutrons are; zero, one and two.



Isotopes are written using the symbol for the element, such as H for hydrogen, O for oxygen, and U for uranium. Furthermore, the nucleon number (the sum of protons and neutrons) is used to separate the isotopes. For example the three hydrogen isotopes mentioned in this book are written; H-1, H-2 and H-3. You will often see the isotopes written as ${}^1\text{H}$, ${}^2\text{H}$ and ${}^3\text{H}$ – similarly for other isotopes.

Since the hydrogen isotopes are so well known, they have attained their own names. H-2 is called deuterium and H-3 is called tritium. The latter isotope is unstable – radioactive. When tritium disintegrates, it emits a β -particle with a maximum energy of 18.6 keV and an average energy of only 5.68 keV. The half-life is 12.3 years (see page 17).

In nature, 99.985 % of hydrogen is the H-1 isotope and 0.015 % is H-2. In ordinary water, only one out of 6500 atoms is deuterium. Ordinary water is H_2O , whereas heavy water is D_2O .

Heavy water – the Vemork sabotage during World war II

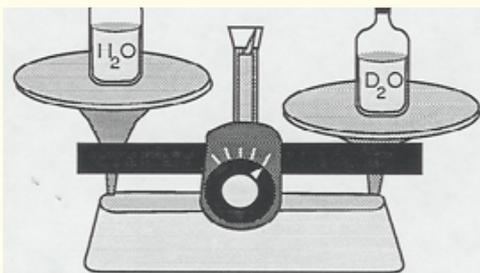
The molecular weight for H_2O is 18 (16 for oxygen and $1 + 1$ for the hydrogens). The molecular weight for D_2O is 20 since the mass for D is 2. Consequently heavy water – or pure D_2O , is weighing more than ordinary water (ratio 20/18 or 10/9).

In a fission reaction fast neutrons are emitted, which in turn can induce fission in other uranium atoms. In order to have a chain reaction going, the neutrons must be slowed down (see more about this in Chapter 14). Heavy water and graphite are suited for this purpose – and therefore heavy water was very important in World war II. Heavy water was made by electrolysis, and before the war the power station in Rjukan, Norway was the only commercial plant. Part of the story is the following.

In 1906 Norsk Hydro started the construction of Vemork power plant. The famous Rjukan waterfalls was closed and the water was instead directed in “pipelines” directly to the power station which was situated on a shelf above the valley (see picture). Heavy water was a by-product in the fertilizer production.

It became an important issue to stop the heavy water production and to hinder the Germans to get any heavy water. Several actions were initiated and carried out to attain this purpose.

The most famous sabotage took place in February 1943 when a small group of Norwegians, with the code name “Gunner-side”, crossed the ravine (see picture below) and climbed the steep hill – reached a railway track that led them in to the plant. They destroyed the plant with a loss of 500 liter D_2O .



Above is a picture of the Rjukan waterfalls. The waterfall is usually dry, but once every year it runs at a reduced capacity. This picture is from 2007.



To the left is a picture of the power plant Vemork. You see the pipelines down the mountain. Today the power station is turned into a museum.

Natural isotopes

We have 35 nuclides that have half-lives long enough to have survived from the formation of the Earth. They are the so-called *primordial isotopes*. Of these we mention Th-232, U-238 and K-40.

Potassium isotopes – K-40

Potassium is an example of an element that has radioactive isotopes. Potassium consists of 93.10 percent K-39, 6.88 percent K-41 and 0.0118 percent of the radioactive isotope K-40. The latter isotope is primordial with the very long half-life of 1.27 billion years.

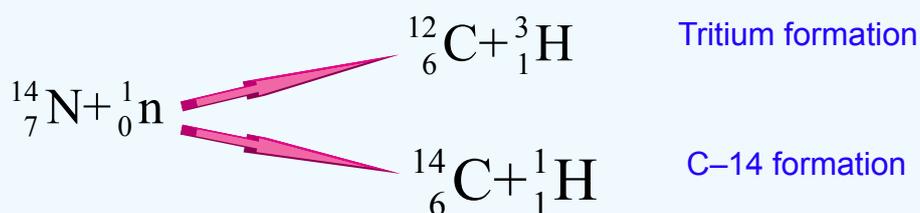
The Earth's crust contains a lot of potassium – and in spite of the small fraction of K-40, the radiation from this isotope is quite important. All living organisms contain some radioactive potassium. For example a human being contains, on average, about 60 Bq/kg body weight of K-40. We eat about 2.5 gram of potassium per day – implying that we each day eat about 70 becquerel of K-40.

Furthermore, we have a number of naturally occurring isotopes with shorter half-lives – which implies that they must be formed constantly. Two of the most famous natural isotopes are H-3 and C-14.

Tritium H-3. The tritium isotope H-3 is formed via nuclear processes in the atmosphere. When nitrogen is hit by neutrons both H-3 and C-14 can be formed (see the nuclear reactions below). These processes are going on continuously in the atmosphere and small amounts are always present. Both isotopes are radioactive (half-lives of 12.3 years and 5730 years) – and both are β -emitters.

The concentration of nitrogen in the atmosphere is constant – and if the flux of neutrons from the cosmic radiation is constant, it would be a steady state level of these isotopes.

During the years with nuclear bomb testing in the atmosphere the level of neutrons increased with the result that more tritium and C-14 was formed.



The Radioactive Series (families)

We stated above that a radioactive atom sooner or later will emit radiation in order to attain a more stable state. In some cases it turns out that the daughter nucleus is also unstable – and consequently will emit another particle. Thus, we have a whole series of radioactive atoms. Uranium is a typical example. The start point is the U-238 isotope – which decays through 14 steps and ends up as the stable lead isotope Pb-206. The whole series is shown in the figure below.

Type of radiation	Isotope	Half-life
α	Uranium-238	4.47 billion years
β	Thorium-234	24.1 days
β	Protactinium-234	1.17 minutes
α	Uranium-234	245,000 years
α	Thorium-230	77,000 years
α	Radium-226	1600 years
α	Radon-222	3.82 days
α	Polonium-218	3.05 minutes
β	Lead-214	26.8 minutes
β	Bismuth-214	19.8 minutes
α	Polonium-214	0.164 milliseconds
β	Lead-210	22.3 years
β	Bismuth-210	5.01 days
α	Polonium-210	138.4 days
	Lead-206	Stable

This part of the series is known as; "Radon and radon daughters"

Uranium-radium-series. The start of the series is U-238 and the end point is Pb-206. The first isotope has the longest half-life, 4.47 billion years. Radon and the radon decay products (the 5 isotopes marked red and placed between the two red horizontal lines), have rather short half-lives. Radon is a noble gas and may leak into houses. Its decay products may deposit on particles (dust) in the air and some may end up in our lungs – giving us a radiation dose. It should be mentioned that several of these isotopes emit γ -radiation. It is the γ -radiation that is responsible for the use of radium in radiation therapy. It can also be mentioned that it is the γ -radiation from Bi-214 that is used to observe Uranium.

A series of unstable atoms where one atom changes into another is called a *radioactive family* or simply a *radioactive series*. Altogether, 4 naturally occurring radioactive families have been on Earth. Two of them have almost disappeared (due to the short half-life of the longest lived element) and only the uranium-radium series and thorium-series are still active.

Half-life

A radioactive source consists of a large number of unstable atoms. For example, one gram of the iodine isotope I-131 consists of $4.6 \cdot 10^{21}$ atoms. All these atoms will sooner or later emit radiation, but these emissions do not take place simultaneously. It is a statistical process, with one atom decaying every now and then. When one half of the atoms have decayed the source has gone through what is called one “*half-life*”. After an additional half-life 1/4 of the atoms remain (a half of the half).

The Energy of the Radiation

In order to detect radioactivity and to evaluate the biological effect of the radiation it is important to have information about the energy as well as the type of radiation emitted. The unit used for energy is the *electron volt* (abbreviated eV).

By definition; *one electron volt is the energy attained by an electron when it is accelerated through a voltage gap of 1 volt.*

The product of voltage and the electron charge (given in Coulombs, C) gives the relation between electron Volt and a unit of energy, the joule:



James Prescott Joule
(1818 – 1889)

$$1 \text{ eV} = 1 \text{ V} \cdot 1.6 \cdot 10^{-19} \text{ C} = 1.6 \cdot 10^{-19} \text{ joule}$$

The electron volt is a very small unit. However, it is a convenient unit within this field when discussing x-rays and radioactivity.

The x-ray energy is determined by the voltage between the electrodes. The maximum energy emitted is simply the voltage multiplied with the electron charge – in the range from about 20 000 eV (20 keV) to 300 keV.

The energy released by a disintegration varies from a few thousand electron volts (keV) to approximately 11 million electron volts (MeV). The largest energy is usually taken by the α -particles. The β -particles carry an initial energy up to about 1 million eV (1 MeV), whereas γ -rays exhibit energies up to about 2 MeV.

How is a radioactive source described?

The intensity of the source depends on the number of atoms that disintegrate per second (i.e. the number of becquerels). This is also called the activity.

Other parameters are: *type of radiation, half-life, and energy of the radiation.*

All these parameters can be given by a **decay scheme**.

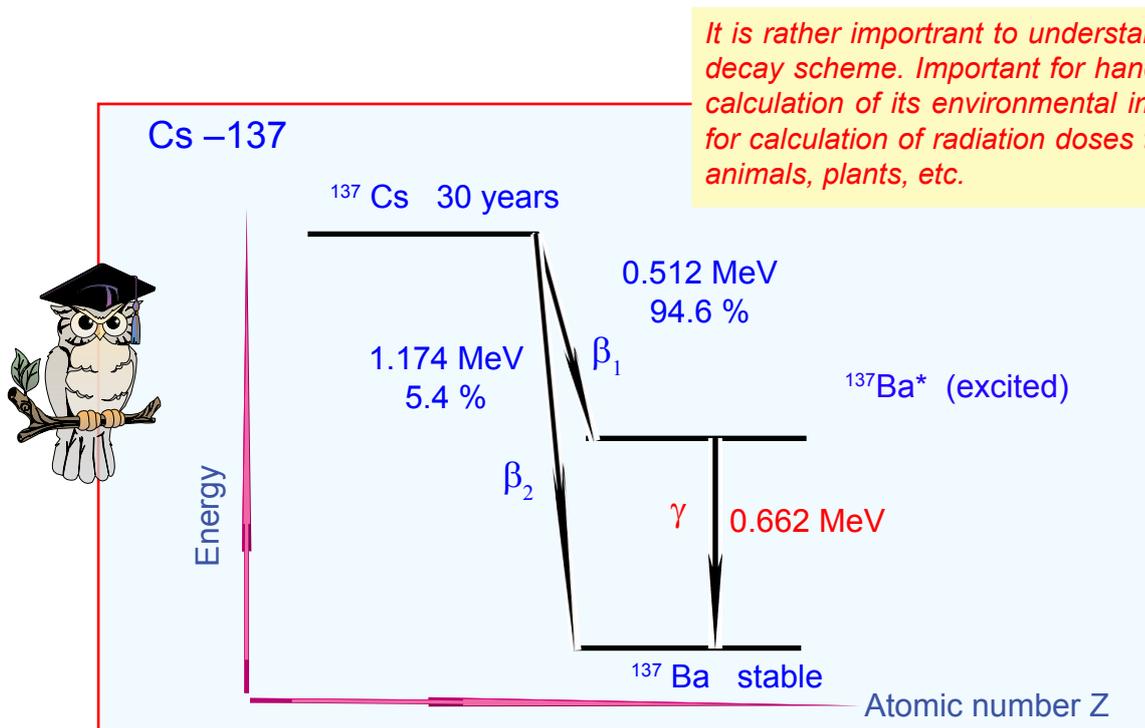
Decay scheme

A decay scheme is a way physicists use to convey information. The scheme tells us about the types of radiation emitted, the energy involved, half-life, etc. This type of information is valuable in order to find the way of detection – and it is necessary information with regard to calculations of radiation doses and risks.

We shall give a few examples – each isotope has its own decay scheme.

Decay scheme of Cs-137.

Cs-137 is an important radioactive isotope. Cesium has 19 isotopes – only Cs-133 is natural and stable. The isotope Cs-137 is formed as a waste product in a nuclear fission reactor. This isotope is consequently of environmental interest. We can mention that it is also used as a radiation source in cancer therapy. The decay scheme is given in the figure below.



The idea with this particular type of decay scheme is that both the horizontal and the vertical scale involve information. Thus, the atomic number is given along the horizontal line – increasing from left-to-right. Cs has the atomic number 55 and Ba is 56.

The vertical scale indicates the energies involved. Thus, the distance between the lines indicate the energy difference. The energy released by a disintegration is the maximum energy for the β -particle (it must be remembered that this particle is accompanied by a neutrino). In the case of γ -rays – they all have the value given in the scheme. In this case it is 0.662 MeV. The γ -rays is emitted from the excited daughter nucleus.

The decay scheme shows that Cs-137 is transformed into the stable barium isotope; Ba-137. This can take place via two different routes:

1. In 94.6 % of the disintegrations a β -particle is emitted with a maximum energy of 0.512 MeV followed immediately by a γ -ray with an energy of 0.662 MeV.
2. In 5.4 % of the disintegrations the stable barium isotope is reached directly by emitting only a β -particle, with a maximum energy of 1.174 MeV.

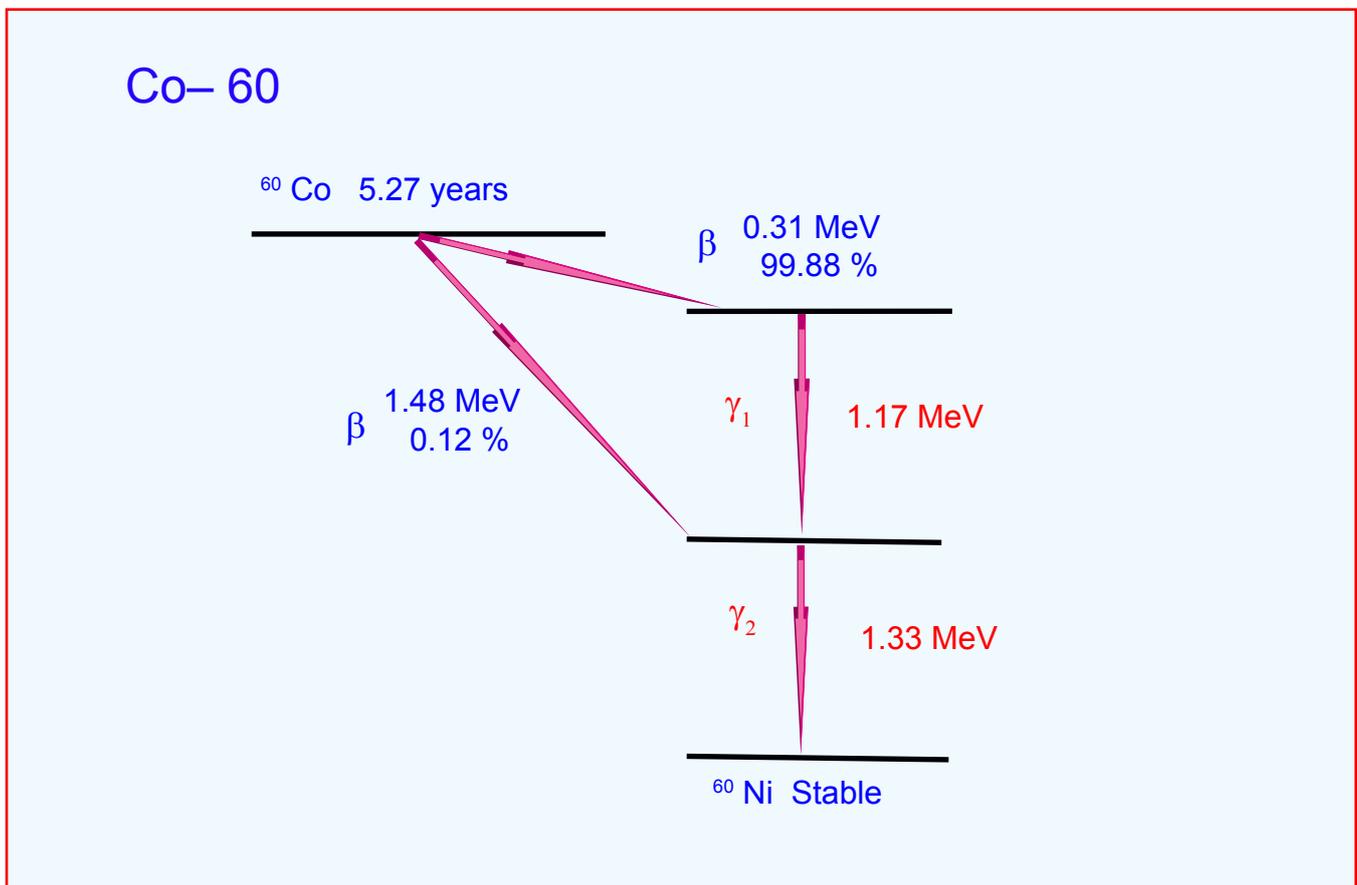
The decay scheme also shows that the half-life of Cs-137 is 30 years. In addition, one might guess that Cs-137 can be observed by measuring the emitted γ -rays. Gamma-rays are very *penetrating*, they have the same energy (0.662 MeV) and are easily detected and identified using a so called gamma-counter.

The decay scheme also include β -particle emission and the maximum energy is given. We know that the average β -energy is about 1/3 of the maximum energy.

Decay-scheme for Co-60

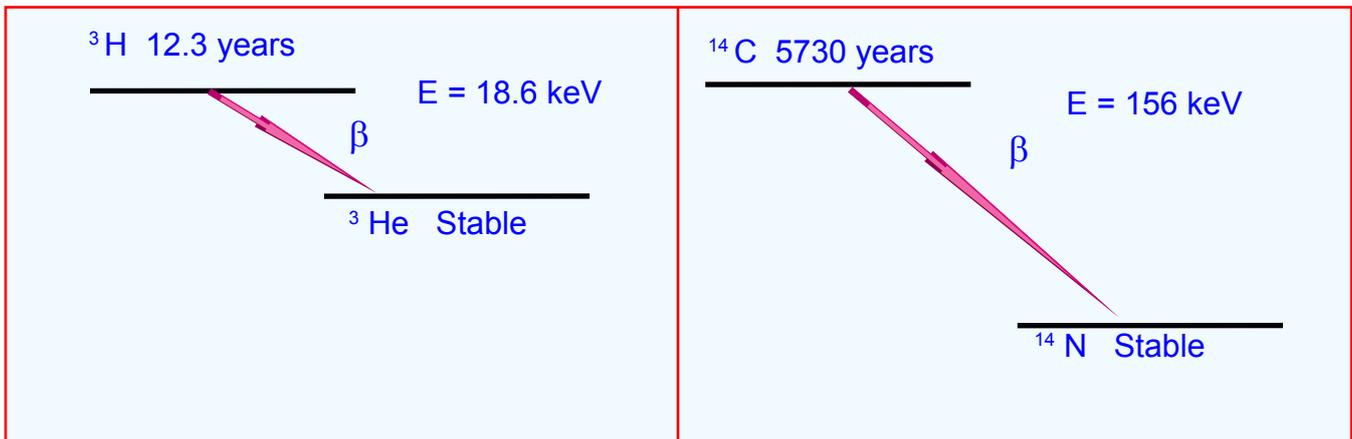
Cobalt has atomic number 27. Only the Co-59 isotope is stable, but we have more than 20 unstable isotopes of cobalt. Co-60 is made from Co-59 in a reactor by exposure to neutrons. Co-60 is used in radiation therapy, for sterilization of medical supplies, for radiation treatment of foods and for industrial radiography. The decay scheme is given below.

The half-life is 5.27 years. It decays by mainly (99.88 %) by emitting a β -particle – followed by the emission of two γ -ray photons with energy of 1.17 MeV and 1.33 MeV respectively.



Decay schemes for tritium H-3 and carbon C-14

We mentioned above that these two isotopes (H-3 and C-14) are formed in the atmosphere after neutron bombardment of nitrogen. They are both pure β -emitters with decay schemes shown below. Both isotopes are used in research; H-3 as a tracer in many biological experiments (for example thymine in DNA can be labelled), and C-14 is used for dating purposes.



As you can see the two isotopes have no γ -emission. Furthermore, the β -particle energy is low – for tritium very low since the maximum is 18.6 keV. Since these β -particles have a very short range, even in air, a number of problems occur with regard to measurements. In recent years several methods have been developed – in which the detector material is mixed into the sample. In an earlier period auto radiography (the sample was covered with a film) was used.

Due to the very low β -particle energy, these isotopes represent no hazard to humans when they are outside the body – and they yield a very small dose when they are inside the body.

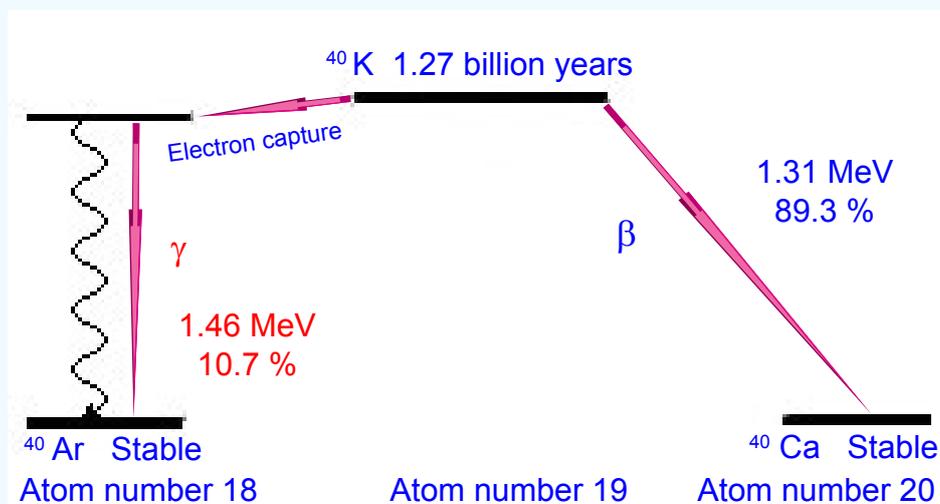
Decay scheme of K-40

The last example would be the decay scheme of the potassium isotope K-40 – mainly because it is different from the other examples. In this case we have to include a decay route via “*electron capture*”.

K-40 is a natural isotope since 0.0118 % of all potassium is K-40. It has a half-life of 1.27 billion years and have been with us all the time. Potassium makes up about 1.5% of the weight of the Earth’s crust and is the seventh most abundant element. This implies that you will find radioactive potassium everywhere – also in our bodies. We have earlier mentioned that we all have a level of K-40 of about 60 Bq/kg in our bodies. The content is higher for men compared to women – and seems to vary with the muscle mass – reaching the highest values when you are about 20 years.

The decay scheme is given in the figure on the next page.

K – 40



The decay of this isotope is somewhat special. Thus, in 89.3 % the decay is by the usual β -decay, with emission of an electron with a maximum energy of 1.31 MeV. For 10.7 % of the disintegrations the decay route is different. Here we have an electron capture and potassium is transferred to argon. This nucleus is in an excited state and emit γ -rays with an energy of 1.46 MeV. This mode of disintegration includes also some characteristic x-rays – because one of the orbital electrons is captured by the nucleus and leaves a hole that is filled with other electrons.

Summary – decay schemes

We have about 3400 radioactive isotopes. About 900 have half lives of more than 60 minutes. Furthermore, 339 are naturally occurring isotopes.

It can be mentioned that all elements above lead ($Z = 82$) are radioactive. In order to use and handle all the isotopes we must know quite a lot about how they are formed – the half-life, the particle emitted, the energy – in other words the **decay scheme**.

Some of the decay schemes are very complicated, like those including the radioactive series. We have for many years used radium for cancer treatment. In this case we are only interested in the γ -radiation from all the isotopes involved.

Throughout this book we are interested in radioactive isotopes connected to medicine, tracer technology as well as to the environment. Let us mention a few.

The radioactive series (Uran-radium series and Thorium-series) are important, both with regard to energy production, cancer-therapy and lung cancer formation from radon and daughters.

We are interested in the isotopes used within life sciences for tracer technology, as well as those used for medical purposes within diagnostic such as PET.

In Chapter 9 we are discussing PET and the use of $\text{Tc}(m)$

Some of the radioisotopes are present, some are made as surplus, and others are made artificially determined to distinct projects. All the time we must have knowledge about the decay scheme – in order to treat the isotopes in a safe way. We must know the half-life, the particle(s) emitted and their energy – this include also the daughter elements if they are not stable.

Artificial isotopes are made in reactors by (n, γ) reactions, some are made in cyclotrons and particle accelerators. Consequently, a lot of experimental equipment are involved both for production as well as for the detection of the radiation.

You can see more of the use of radioactive compounds in the address:

<http://www.frankswebpace.org.uk/ScienceAndMaths/physics/physicsGCSE/usesNuclear-Radiation.htm>

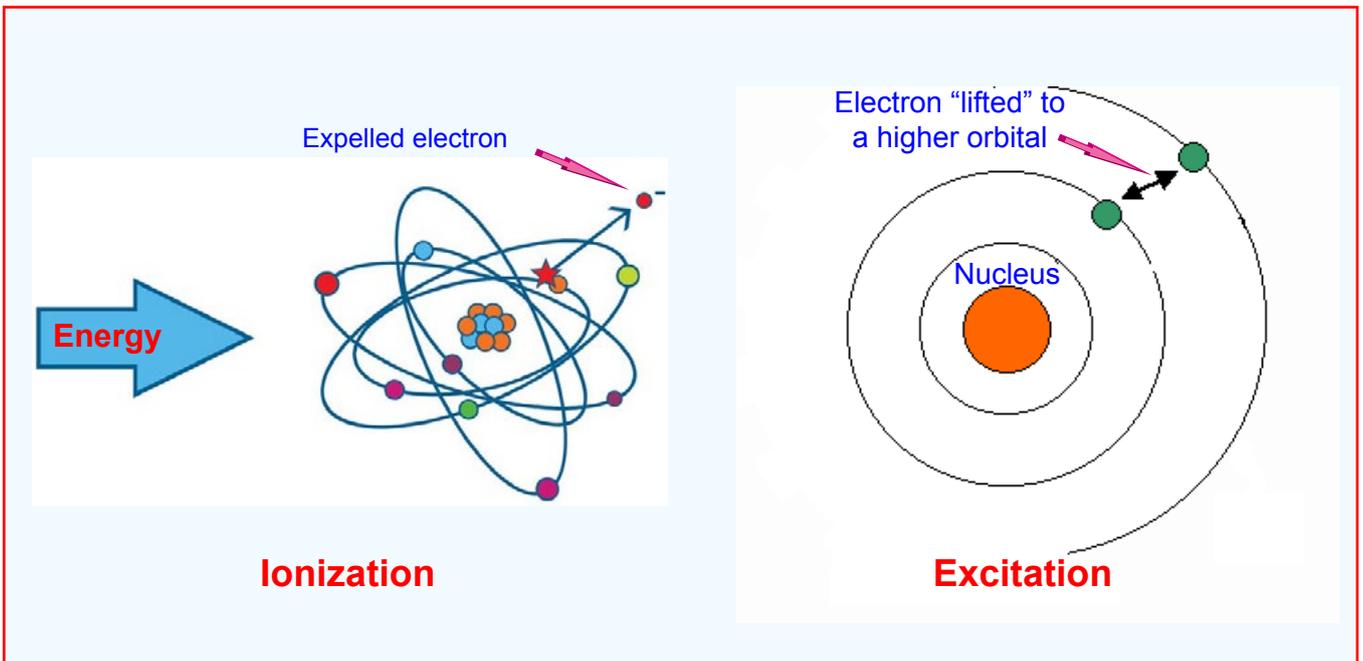
How radiation is absorbed in matter

When x-rays and radiation from radioactive sources hit matter it will collide with the constituent atoms and molecules with the result that ions and excited molecules are formed. The radiation itself will gradually loose energy and finally be stopped. The penetration depth vary considerably with the type of radiation and the type of material that is hit. Since we, in this book, is mainly engaged in living organisms, we will relate penetration depths to tissue – or simply water which is the major constituent of tissue.

The type of collision processes vary with the type of radiation. Thus, charged particles like α -particles and β -particles interact with electrons in the absorbing matter in so called Coulomb collisions – whereas x - and γ -rays take part in other types of reactions. The final result of all these reactions is, however the same. Ions and excited molecules are formed. Consequently, the radiation is known as “*ionizing radiation*”. The result can be illustrated as follows:



M is the molecule hit by radiation. The result may be either an ionization or an excitation. M^+ is a positively charged molecule (positive ion) and e^- is an electron that was knocked out of the molecule in the process. The expelled electron will loose energy in reaction with other molecules (it may even ionize some new molecules), and will finally end up on some molecule forming a negative ion. M^* is an excited atom or molecule. In this process not enough energy is available for ionization (see figure next page).



Absorption mechanisms for the different types of radiation

Alpha-radiation

The energy of an α -particle, when it is emitted by a nucleus, is usually a few MeV (this is very large compared to the energy attained by β -particles and γ -radiation). Some of the properties which are characteristic for the absorption of α -particles are:

1. The alpha-particles loses energy by Coulomb collisions. The particle-path, the track, is rather straight and the lost energy makes a core of ions, with δ -rays extending out of this core – like the branches of a tree. The larger the δ -ray energy the longer is the δ -tracks.
2. The number of ions formed in the core track is large and can be described by the so called Bethe formula (named after Hans Bethe, who introduced it in 1930). A “light version” of this formula is:

$$\frac{dE}{dx} \approx k \frac{z^2}{v^2}$$

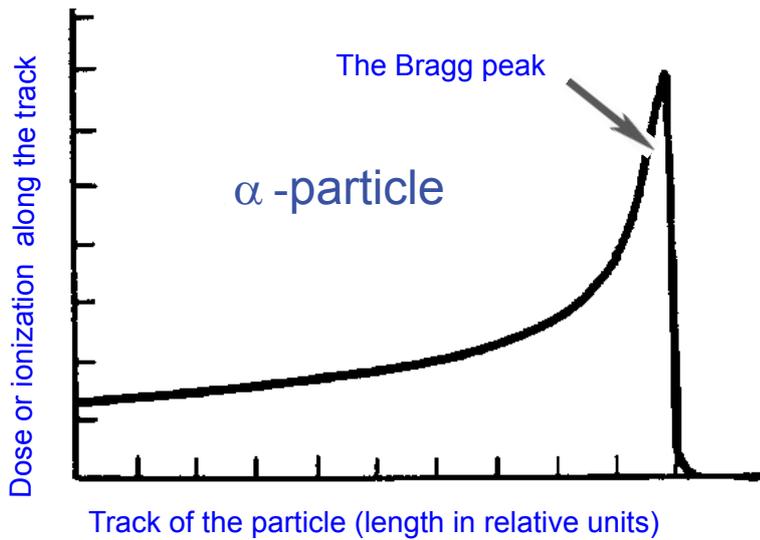
Hans Bethe
(1906 – 2005)



z is the charge of the moving particle, and v is the velocity.

The energy deposited per unit length of the track (dE/dx) is called the “**Linear Energy Transfer**” (abbreviated **LET**). Examples of LET-curves from heavy ions hitting a biological target are given on the next page.

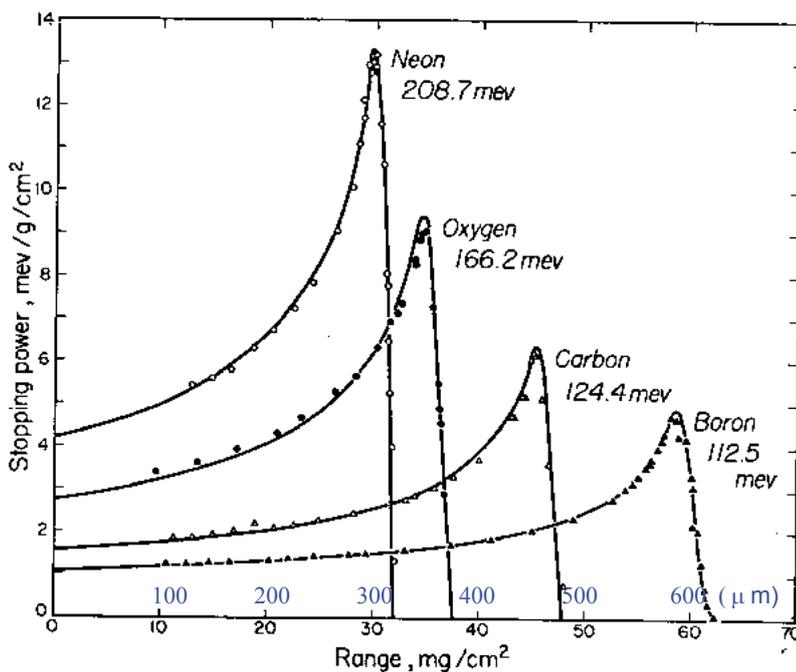
The **range** of an α -particle from a radioactive source is very short in tissue (water) and in air the range is only a few centimeters. Thus, a 10 MeV α -particle has a range in air of 10 cm and in tissue or water about 0.12 mm. The range for almost all α -particles from radioactive sources is shorter since the start energy of the α -particle is below 10 MeV. That implies that the range is only a few cell-diameters.



The Bethe formula describes the energy deposition along the track of the ionized particle. Since the velocity decreases towards the end of the track, the curve has a particular shape as shown in the figures to the left.

The peak in the absorption curve in the end is called the **Bragg peak**.

In the figure to the left is given the Bragg-curve for an α -particle. The range is determined by the start energy.



In the figure below we have given some Bragg curves for accelerated heavy ions. The start energy of the ions are given in the figure.

The ions were accelerated with the HILAC (Heavy Ion Linear Accelerator) in Berkeley around 1960. The max energy achieved was 10.4 MeV per nucleon. Thus C^{+6} -12 ions had an energy of about 124 MeV. The range in tissue is given in μm (above the abscissa). With this short range it was possible to irradiate enzymes, bacteria, virus and yeast cells.

Data above are from Tor Brustad in "Advances in Biological and Medical Physics. Volume VIII" 1962)

We would like to mention that with present days large accelerators it is possible to use heavy particle beams in cancer therapy. Thus, if we could land the "Bragg peak" on the tumor, the tumor dose would be much larger than the dose to the surrounding healthy tissue. This is the main goal of radiation therapy. In some of the hospitals around the world have already (2013) established this possibility.

We shall return to this issue in combination with heavy ion therapy in Chapter 10.

Beta particles

β -particles are stopped by collisions with electrons in materials in a process similar to the way α -particles are stopped. As a rule of thumb one can say that a β -particle with an energy of 1 MeV will have a range in water or soft tissue of 0.5 cm. The β -particles from Cs-137 have an average energy of 0.2 MeV. If these particles hit the skin, the penetration into the body would be less than 1 mm. However, if a sufficient number of these β -particles hit the skin, it will be burned.

Gamma-radiation

The energy of a γ -ray is given by the expression:

$$E = h\nu$$

where h is a fundamental constant, known as Planck's constant and ν is the frequency of the radiation. The radiation can be considered to consist of small energy packages called quanta or photons. The energy of the γ -photon, ranges from 0.1 to about 2 – 3 MeV.

We have seen that the γ -rays, following a disintegration from Cs-137 have an energy of 0.662 MeV, from the cobalt isotope Co-60 two quanta with energies of 1.17 and 1.33 MeV are emitted and from K-40 the γ -rays have the energy of 1.46 MeV.

Gamma-rays and x-rays are absorbed differently from α -particles. When γ -rays penetrate a material, the intensity of the radiation (I) decreases according to an exponential formula:

$$I(x) = I_0 \cdot e^{-\mu x}$$

where x is the depth in the material and μ is the absorption coefficient (μ describes how the radiation decreases per unit length for each type of material).

The absorption coefficient has **three** different components. This is because three processes are involved: **photoelectric effect**, **Compton scattering** (inelastic scattering) and **pair production**.

X- and γ -rays is absorbed by 3 processes:

1. Photoelectric effect (important for energies up to 100 keV).
2. Compton scattering (important in the energy range 0.1 – 20 MeV).
3. Pair production (takes place only for energies above 1.02 MeV).

All 3 processes varies with the electron density (that is the atomic number) of the absorbing material. This implies that x-ray pictures yield the electron density of an object.



Photoelectric effect

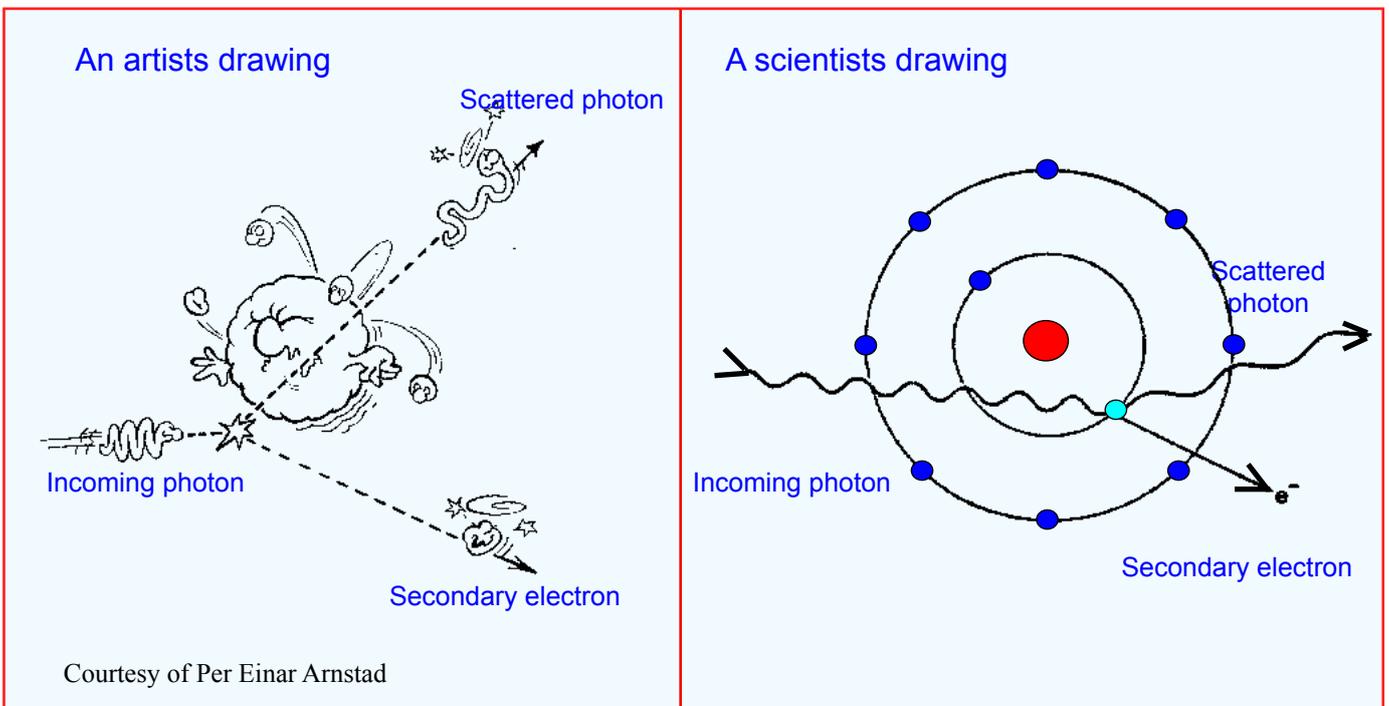
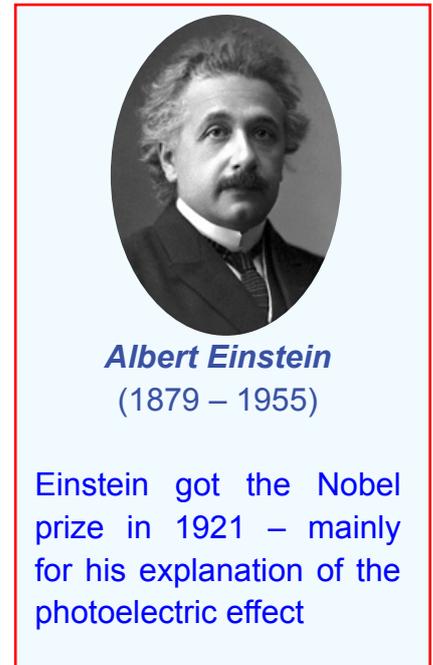
This is a process in which a photon interacts with a bound electron. The photon itself disappears, transferring all its energy to the electron and thereby imparting kinetic energy to the electron – which in turn can ionize other molecules.

This is the most important absorption process for radiation with an energy less than about 100 keV (which is the type of radiation used in medical diagnostics). The photoelectric effect varies dramatically with the electron density of the absorbing medium. Thus material that contains atoms with high atomic numbers, e.g., the calcium in bone, gives strong absorption due to the photoelectric effect. Furthermore, we make use of this effect when contrast media are introduced.

Compton scattering

This is a process in which a photon collides with a bound electron and where the photon energy is considerably greater than the electron binding energy. An attempt to visualize this is given by the artists drawing and the figure below.

After the interaction, the photon continues in a new direction with reduced energy and the electron attains enough energy to leave the atom. We call this electron a *secondary electron*. The Compton process is the most important absorption process for photons with energies from about 100 keV to approximately 20 MeV (the type of radiation mainly used for radiation therapy).



This is an illustration with the purpose to describe the Compton process. It all starts with the incoming high energy photon interacting with an electron. The result is that the photon is scattered and its energy is reduced. The electron involved in the interaction is ejected and becomes a "secondary electron" – which in turn can ionize along its own track.



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Arthur H. Compton
(1892 – 1962)

Arthur Compton was born in Ohio. He began to study X-ray scattering and in 1922, he found that X-ray wavelengths increase due to scattering by "free electrons". The scattered quanta have less energy than the quanta of the original ray. This discovery is known as the "Compton effect" – and gave him the Nobel prize in Physics for 1927.

During the war, Compton, along with Vannevar Bush and Ernest Lawrence started the Manhattan Project with the purpose to make an atomic bomb. At the university of Chicago, Compton had a facility with the cover name "Met Lab". Its objectives were to produce chain-reacting "piles" of uranium to convert uranium to plutonium. Furthermore to find ways to separate the plutonium from the uranium and to design a bomb.

In December 1942, underneath Chicago's Stagg Field, a team of Met Lab scientists, directed by Enrico Fermi, achieved a sustained chain reaction in the world's first nuclear reactor.

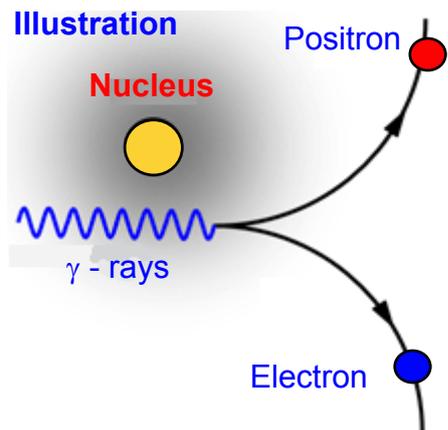
The Nobel Prize in Physics 1927

To Arthur Holly Compton
"for his discovery of the effect named after him"

Pair production

Pair production is a process in which the energy of the photon is used to produce a positron-electron pair. The photon energy must be above 1.02 MeV, the threshold energy for forming two electrons. The process takes place near the atomic nucleus and is the most significant absorption mechanism when the photon energy is above about 20 MeV.

Pair production is found in many experiments where high energy radiation interacts with matter. It was first observed by the British scientist Patrick Blackett in 1933 in some cloud chamber experiments with cosmic radiation. He found tracks like that in the illustration – where the electron and positron is deflected in opposite directions in an electric or magnetic field. Blackett was awarded the Nobel prize in Physics for his discoveries in 1948.

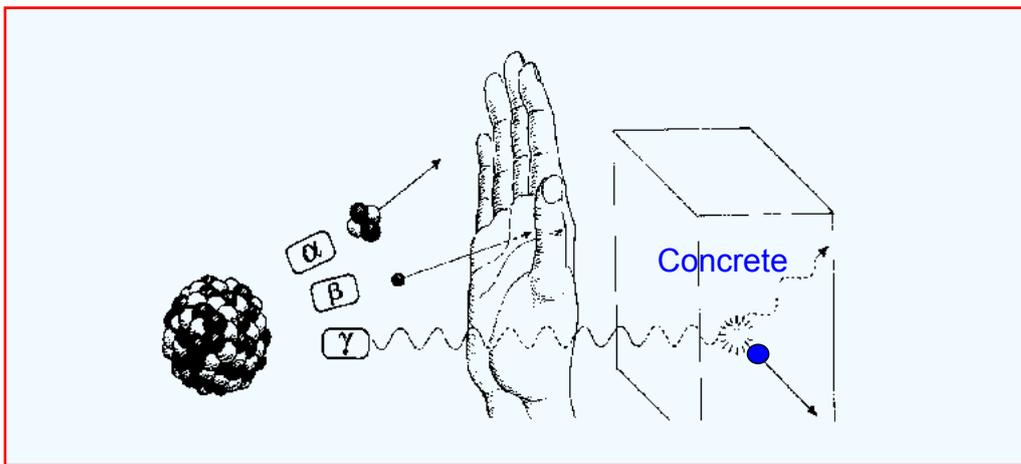


Patrick M.S. Blackett
(1897 – 1974)

The Penetration of Radiation

We have described the different absorption processes for the radiation from radioactive sources and x-ray machines. We can therefore get a picture of the penetration of the radiation in materials.

If we are using a gun, the penetration by the bullet depends on the energy of the bullet as well as the composition of the target. For example, a pellet from an air gun will be stopped by a few millimeters of wood, whereas a bullet from a high powered rifle will pass through many millimeters of steel. It is similar with ionizing radiation. There are large differences in penetrating ability depending on the type of radiation (α -, β - or γ -radiation). The illustration below gives you an idea about the penetration of the radiation from the radioactive sources.



Alpha particles from radioactive sources have a range of less than 10 cm in air. In condensed matter such as water or tissue the range is much shorter (the difference in range is approximately 1/1000, due to the difference in density) – usually less than 100 μm . This implies that α -particles will not even penetrate clothing. If α -particles only are emitted “*you can sit on the radioactive source*”. If, however, the source is inside the body, all the energy is deposited in the body and may give a large radiation dose.

A tragic example of this was the poisoning of Aleksandr Litvinenko in 2006 with Po-210. This isotope emits an α -particle with energy 5.3 MeV

Beta-particles with an energy of 1 MeV have a range in soft tissue of approximately 5 mm. The majority of β -particles have an energy far less than 1 MeV.

Consequently, almost all β -particles coming from sources in the environment are stopped by clothing.

Gamma-radiation has the ability to penetrate tissue and even concrete (see illustration above). For example, 50 % of the γ -rays from Cs-137, with energies of 0.662 MeV will penetrate a water layer of about 9 cm. We call this a **half-value layer**. Five half-value layers (less than 0.5 meter of water) will reduce the radiation by 97 percent. γ -radiation is easy to measure, whether the source is outside or inside the body. Consequently, isotopes emitting γ -radiation are used in medical diagnostic.

Summing up

X-rays and γ -rays will easily penetrate the human body. This property is utilized when x- and γ -rays are used for diagnostic purposes. α - and β -particles, on the other hand, lose their energy within a short distance and cannot penetrate the body. Because of these penetration properties, γ -radiation is easy to observe whereas α - and β -radiation are more difficult to detect. Special instruments are often needed in order to observe α - and β -rays. The following conclusions can be drawn:

- If a radioactive source is on the ground, such as in a rock, the α - and β -radiation will be stopped by air and clothes. Only γ -rays would penetrate into the body and deliver a radiation dose.
- When a radioactive source is **inside** the body, it is a different situation. α - and β -particles are completely absorbed within a short distance in the tissue, whereas only a certain fraction of the γ -radiation is absorbed. The rest of the γ -radiation escapes and can be observed with counters outside the body. Consequently, if you eat food containing radioactive compounds, they can be easily measured if γ -rays are emitted.

It is possible then to measure the radioactivity that is inside animals and humans which have eaten food containing Cs-137 due for example to fallout from nuclear tests or nuclear accidents. For adults, approximately 50 % of the γ -radiation escapes the body and the other half is absorbed by the body. Other important isotopes such as Sr-90 (strontium) and Pu-239 (plutonium) are very difficult to observe since they only emit β -particles and α -particles.



The start point for all biological effects of ionizing radiation is the **excited** and **ionized** molecules that are formed. These primary products are very reactive and have short life times in living systems – of the order nanoseconds or less.

Several ingenious methods and techniques have been explored to study the primary radiation products – and we shall explore some of them in this book. It has been found that the biological effect depends both on the distribution as well as the number of ions and excited molecules formed.