

# Chapter 1

## FUNDAMENTAL CONCEPTS

The phenomenon named “X-rays” by their discoverer, the physicist Wilhelm Conrad Röntgen, was the beginning of the what are today the fields of Diagnostic Radiology and Radiation Oncology. On November 8, 1895 Röntgen observed that electrons (then called cathode rays) accelerated through an evacuated tube generated rays which penetrated a light-tight enclosure and caused a barium platinocyanide screen to fluoresce. He spent the next weeks thoroughly investigating this phenomenon and published his first of three papers about it on December 28, 1895. Early in his investigations, he exposed a photographic plate to X-rays and found that different materials stop X-rays in different ways. His photograph of his wife’s hand showed the bones and soft tissue as well as her ring had different degrees of permeability.<sup>1</sup> Although other investigators had observed X-rays, it was Röntgen who understood the full implications of their use and worked to exploit their potential for the good of humanity.

The discovery of X-rays was followed closely in 1896 by the confirmation of natural radioactivity by Antoine Henri Becquerel and the isolation of the radium by Marie Sklodowska Curie and her husband, Pierre Curie<sup>2</sup>. In the early part of the twentieth century, it was not at first recognized that either X-rays or radioactivity could be harmful as well as beneficial. This was first explicated carefully in the 1930’s and the study of biological effects of ionizing radiation was undertaken in several countries. Both the consequences of the low (and at that time, not so low) amounts of radiation received by radiologists and others in their daily work, as well as the natural background radiation to which we are all exposed was extensively investigated.

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1. Wilhelm Conrad Röntgen (1845-1923) refused to take out patents on his discovery so that the world might have it. At the time of his discovery, Röntgen was professor of physics at the University of Würzburg, Germany. He was awarded an honorary Doctorate of Medicine by Würzburg. He contributed his Nobel Prize (1901) money to the University of Würzburg. He was made Professor of Physics at the University of Munich in 1900 where he remained for the rest of his life. The old unit of exposure, roentgen, was named for him.

2. (Antoine) Henri Becquerel (1852-1908), a French physicist, discovered gamma-ray photons in 1896. Madame Marie Sklodowska Curie (1867-1934), working in France, though of Polish birth, and her husband Pierre Curie (1850-1906), isolated radioactive nuclei, significantly, radium. Becquerel and the Curies received the Nobel Prize in physics in 1903 for their work in radioactivity. Marie Curie also received the Nobel Prize in chemistry in 1911 for her work with radioactivity. The old, curie, and new unit, becquerel, of radioactivity, are named after these scientists who did pioneering work in the field of radioactivity.

Since then, the United Nations Scientific Committee on the Effects of Atomic Radiation<sup>3</sup> (UNSCEAR) has stated that medical use of radiation is the largest single source of man-made radiation exposure to the world population and that this source is increasing, both because more high dose procedures such as computed tomography (CT) are being used and because the use of diagnostic and therapeutic radiological procedures increases as more countries join the developing world. Medical use includes diagnostic radiology, radiotherapy, nuclear medicine, and interventional radiology. Additionally, radiation exposure occurs as a result of various occupations. Industries such as materials testing and nuclear power, as well as research which uses radiation or radioactive substances may be a source of exposure to workers. Radiation exposure to higher than natural levels of cosmic radiation is also experienced by airline passengers and crews and by astronauts.

The United States Food and Drug Administration (FDA) estimates that at least 130 million Americans have one or more diagnostic X-ray or nuclear medicine examinations annually. The FDA contends that these examinations account for more than 90% of the total man made radiation exposure to the U.S. population. While medical procedures account for only 15% of the total radiation exposure experienced by mankind, care should be taken to reduce it to as low a level as possible. The International Commission on Radiological Protection (ICRP) has emphasized [ICRP, 1982]

“the importance of including adequate training on radiation protection in the general education and training of individuals entering the medical and associated professions, since all those who enter these professions may be involved in prescribing procedures involving exposure to ionizing radiation. More thorough training in radiation protection is required by those planning to enter the field of radiology and by scientists and technicians assisting in the medical uses of radiation.”

The United States National Council on Radiation Protection and Measurements (NCRP) showed that public radiation exposure from nuclear power plants is indistinguishable from background radiation [NCRP, 1987]. This report also states that occupational radiation exposure (less than 0.3%) coupled with radiation exposure from nuclear fallout (less than 0.3%), the nuclear fuel cycle (less than 0.1%) and other miscellaneous sources (0.1%) comprise less than 1% of the total radiation exposure to the population. Nevertheless, training should be extended to all individuals working with radiation, so that the exposure each one experiences may be kept **as low as possible**.

## 1.1 Need for Radiation Protection

One aim of radiation protection is to encourage and enable the radiation worker to limit his/her exposure to potentially harmful radiation. A second and equally important aim is to limit unnecessary exposure of others (e.g., patients and the general public) which might result from poor working habits.

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3. See bibliography at end for references quoted in this and each succeeding chapter.

Various forms of radiation have always been present in mankind's natural environment. This radiation is known as background radiation and is generally divided into two categories: 1) radiation from specific forms of chemical elements that exist naturally in the earth's crust, the human body, and in materials about us; 2) radiation carried to the earth from outside the earth's atmosphere, commonly referred to as cosmic radiation.

In the twentieth century mankind learned how to produce radiation from various sources, and its uses have consistently increased. For example, we now use radiation techniques to produce nuclear energy for power, to sterilize both food and equipment (such as surgical and medical supplies), to produce new chemical polymers, to detect faults and flaws in metal castings and welds, and to aid research in areas such as medicine, biology, and material science. The most devastating use we have found for radiation is, of course, nuclear weapons, while the most widespread application of radiation has been in the field of medicine both for diagnosis and radiation oncology.

As is well-known, early radiation workers, such as technologists, radiologists, surgeons, and physicists, suffered severe radiation injury because they did *not* appreciate the extent to which radiation can cause injury. Many studies have been undertaken to further our understanding of the biologic effects of radiation and to establish acceptable limits of effective/equivalent dose (see Chapter 4 for specific details and examples). Some limited legislation has been enacted with this in mind, and regulatory bodies and licensing mechanisms have been established to set limits for radiation exposure as well as to delineate requirements for training programs for radiation workers. Their aim is to produce a uniformity of accepted practice in working with radiation.

The two general classifications of radiation are ionizing<sup>4</sup> and nonionizing. Ionizing radiation is capable of ionizing an atom. Ionization occurs when one of the orbital electrons of an atom has been completely removed. The residual atom, which is positively charged, is called a positive ion, or cation; the freed electron is known as a negative ion, or anion.

Radiation which creates ions that are then capable of disrupting life processes is known as ionizing radiation. In contrast, nonionizing radiation, such as ultraviolet and microwave radiation, lacks the ability to create ions. Nevertheless, nonionizing radiation can adversely affect human health. This book, however, is limited to a discussion of protection from ionizing radiation.

## 1.2 Ionizing Radiation and Injury

Transfer of energy to the human body may be beneficial, as is the case with food, or injurious, as is the case with a speeding bullet. Ionizing radiation always transfers energy to any material with which it interacts. The energy it deposits in living tissue causes disruption of the atomic structure, and when the atoms thus affected are essential for normal functioning a cell can be permanently damaged or killed. When ionizing radiation imparts

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4. See Glossary for definition of this term and of many others.

energy to living tissue, damage is done: the larger the amount of energy deposited, the more extensive is the damage. Sometimes, for example, in radiation treatment for cancer, this damage can be *both* beneficial and injurious; it kills the tumorous cells, but it may also kill healthy cells. It is the transferring or depositing of energy in living tissue that is significant in the production of injury by ionizing radiation. As a result all measurements and calculations to evaluate the hazard from ionizing radiation have, as their initial object, the determination of the energy imparted by this radiation to the region of interest.

It has been epidemiologically demonstrated that biological damage is produced by ionizing radiation. Since there is no practical alternative, the ICRP strongly recommends that the relationship between radiation exposure and biological effect be treated cumulatively. An extensive study of the effects of low level irradiation over relatively long periods of time was commissioned by the United States National Research Council and carried out by the United States National Academy of Sciences. A committee was appointed to study the Biological Effects of Ionizing Radiation (BEIR). The results of the latest committee, BEIR VII, were published in 2006.

Three schools of thought exist regarding the effects of low levels of radiation exposure. In the first BEIR report, a linear hypotheses was proposed, meaning that the effect was exactly proportional to the amount of exposure (curve A in Figure 1.1). Later, some researchers felt that a low-limit cutoff for harmful effects may exist (curve B of the same figure). This cutoff is known as the threshold effect. Most recently, some research groups have suggested that effects at low levels of radiation exposure may be more severe than those at higher values (curve C). This controversy is difficult to settle. The BEIR III committee report presents arguments for and against each of the alternatives, the BEIR V committee report continues the discussion, and the BEIR VII report concludes that there is no biological evidence to support rejecting the linear, no threshold model.

Because the body cannot sense exposure to radiation directly, except at levels that are invariably lethal, it cannot provide a defense. Hence, it is important to be able to anticipate radiation problems through calculation and analysis. It is equally important to properly use those radiation instruments designed to monitor the emissions from radiation sources.

## 1.3 The Structure of Matter

Atoms are composed of a dense nucleus which has a radius of about  $10^{-14}$  m ( $10^{-12}$  cm) with electrons orbiting about the nucleus at fixed energy levels resulting in an overall atomic radius of about  $10^{-10}$  m ( $10^{-8}$  cm). Hence the atom is mostly empty space. Atoms differ from one another in the number and arrangement of their basic constituents: the nucleus is composed of protons (which have a unit positive charge, i.e.,  $1.6 \cdot 10^{-19}$  C), and neutrons (which have no charge); electrons (which have a unit negative charge) form the remaining atomic component. It is the number of protons in the nucleus which determines the chemical element and the number of electrons which determines the chemical

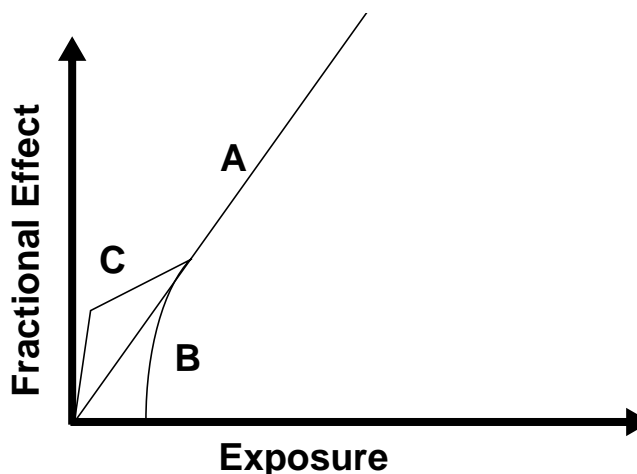


Figure 1.1: Relationship between radiation effects and exposure: Curve A represents the original linear relationship hypothesis. Curve B shows the possible cutoff of effects at low exposure levels (threshold effect). Curve C shows the possible enhancement of these effects at low exposure levels.

properties of an atom. When an atom is electrically neutral, the number of electrons is equal to the number of protons. The number of protons in the nucleus is symbolized by “Z” (the atomic number) and the sum of the number of protons plus the number of the neutron neutrons is symbolized by “A” (the atomic weight or mass). However, if one sums the mass of the protons ( $1.6726 \cdot 10^{-27}$  kg), neutrons ( $1.6747 \cdot 10^{-27}$  kg), and electrons ( $9.1091 \cdot 10^{-31}$  kg), note that this is about 1/1800 the mass of the proton or neutron) composing an atom, the sum would be slightly more than the actual weight of the atom. This difference in mass is termed the “mass defect” and represents the binding energy of the nucleus. One often measures the atomic mass in terms of atomic mass units (AMU). One AMU is 931.2 MeV and is equivalent to 1/12 of the atomic mass of  $^{12}\text{C}$ .

### 1.3.1 Atomic Electrons

Electrons are bound to the atomic nucleus by the Coulomb force (unlike charges attract, like charges repulse; the magnitude of the force is proportional to the amount of charge and inversely proportional to the square of the distance between the charges). Hence, electrons closer to the nucleus are more tightly bound to it, experiencing a larger force. Equally, the more protons in a nucleus, the more tightly the electrons closest to it are bound. The electrons in the atom normally occupy fixed energy levels usually referred to as “shells”. The first allowed shell is the “K” shell, which can contain two electrons. The next is the “L” shell which can contain eight electrons, the next is the “M” shell which can contain eighteen electrons, etc. However, there can be no more than eight electrons in an unfilled outer shell of an atom and so it happens that after an element contains enough protons in the nucleus to require more than eight electrons in the “M” shell, but not a full eighteen, the electrons start to fill the next available shell (in this case the “N” shell, until eight is reached, etc.) This gives chemical elements, such as metals (which are commonly called “transition elements”), their particular properties.

When electrons are in their stable configuration with respect to the nucleus, they have associated with them an energy known as the “binding energy”. This is the energy necessary to remove the electron entirely from the atom and is known as the “ionization” energy. An electron can also be “excited” into a higher energy state. When this happens, the electron usually returns promptly to its normal energy state, radiating the excess energy in the form of electromagnetic energy or a photon. (Recall that all electromagnetic energy travels with the speed of light, i.e.,  $3 \cdot 10^8$  m/s, and is governed by the equation  $\nu\lambda = c$ . Electromagnetic waves transport energy from one place to another, and this energy travels, or is transported by, the waves in packets or bundles termed quanta. These energy packets give electromagnetic waves their particle-like characteristics. The particle which characterizes an electromagnetic wave is called a “quantum” or “photon”.)

When an electron is removed from an inner shell, an electron from an outer shell generally takes its place and radiates the difference in energy between the two shells in the form of a high energy photon. Since the energies involved are absolutely characteristic of the nuclear configuration of the atom, these photons are known as “characteristic X-rays” or “characteristic X-ray photons”. An alternative process to the expulsion of a characteristic X-ray, is for a second atomic electron to be expelled. This electron is known as an “Auger” electron and it should be noted that now the atom has become doubly ionized. Note that electrons continue to fill in “lower” (i.e., closer to the nucleus) energy states until the missing electrons (or “holes”) are in the “valence” or outermost occupied shell. Figure 1.2 shows a schematic representation of an atom, with an “M” to “K” transition accompanied by production of a characteristic X-ray. (Note: an Auger electron could have been produced instead of the characteristic X-ray.)

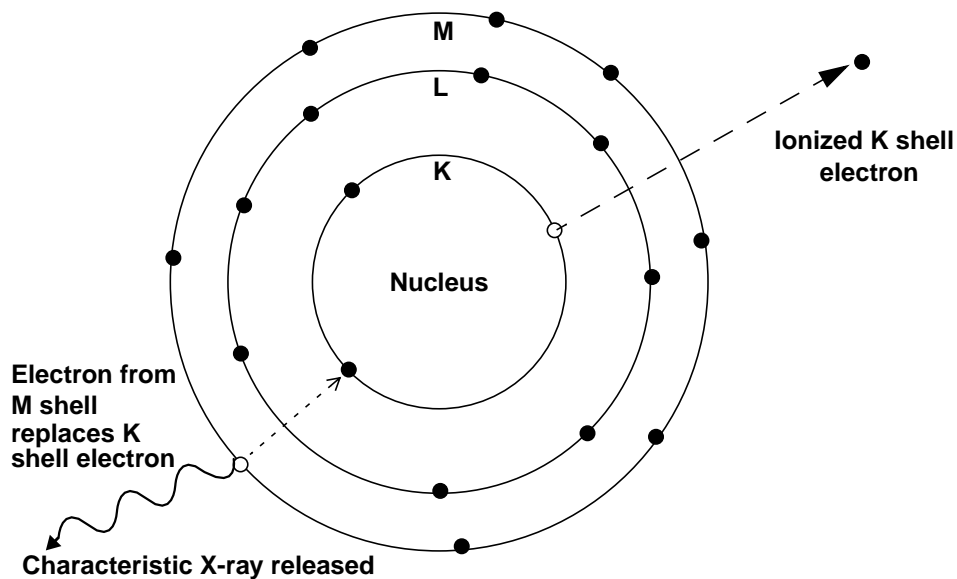


Figure 1.2: A schematic representation of atomic energy levels. Note that there are only eight electrons in the “M” shell. An electron has been removed from the “K” shell and an “M” shell electron fills in the vacancy and releases a characteristic X-ray.

## 1.3.2 The Nucleus

The nucleus contains protons (which all have a positive charge) and neutrons in a very small volume. Since like charges repel, the nucleus must be held together by a force greater than the Coulomb force. This force is known as the “strong” force and its exact nature is not yet well understood. One model of the nucleus postulates that the protons and neutrons exist in “shells” similar to electron shells. If one examines the periodic table, one finds that the number of neutrons increases disproportionately to the number of protons in the nucleus, thus suggesting that the neutrons help to keep the nucleus together as the proton number increases. However, after a certain number of protons, no nucleus is stable, i.e., all nuclei spontaneously undergo transitions such as nuclear fission, or far more frequently, radioactive decay (this will be discussed in detail in the next section).

If the number of protons in the nucleus is odd, the nucleus has a property known as nuclear magnetic resonance. Similar properties result if the number of neutrons is odd. If both are odd, these properties are magnified. However, if both are even, these magnetic properties do not exist. The nuclear constituents are known as “nucleons” and different nuclei are referred to as “nuclides”. Nuclides which are related in various ways are referred to by various names as shown in Table 1.1.

Table 1.1: Nuclear Nomenclature

Name	Atomic Number - Z	Neutron Number - N	Atomic Mass Number - A
isotope	same	different	different
isotone	different	same	different
isobar	different	different	same
isomer	same	same	same

From the table it is evident that isomers differ from each other only in energy. This leads us to the idea that the nucleus itself has distinct and fixed energy levels associated with it which are absolutely characteristic of the nuclide. When a nuclide is in one of its excited states, it usually returns to the ground state with the expulsion of one or more gamma-ray ( $\gamma$ -ray) photons. The energy of these photons reflects the difference in energy between the allowed energy states of the nuclide. If an excited nuclide does not return to its normal ground state in a measurable ( $\sim 10^{-11}$  s) period of time, it is said to be in a metastable state. Some nuclides, like  $^{99m}\text{Tc}$ , remain in these metastable states for hours. As in the case of atomic electrons, an alternative process to the production of a gamma-ray photon is the production of an electron, in this case known as an “internal conversion electron”.

The only difference between a gamma-ray photon and a characteristic X-ray photon is in their origin - the first results from a nuclear interaction and the second from an atomic interaction involving inner shell electrons. It is also important to understand that photons in the energy range denoted by these names are capable of ionizing atomic electrons. Interactions which involve outer shell, or valence electrons, usually result in photons having energies in the visible light region that are not capable of ionizing atomic electrons.

It was Albert Einstein who developed the equation relating the mass of a particle to energy, or the energy of a wave, to its mass equivalent. The equation is  $E = mc^2$  where “c” is the velocity of light as mentioned above. This equation can be used to find the energy equivalent for the mass of a stationary (i.e., non-moving) electron: 0.511 MeV (see Glossary). Hence we can use the terms “mass” and “energy” interchangeably.

## 1.4 Radioactive or Nuclear Decay

Nuclides which undergo natural or induced transformation or decay of the atomic nucleus are said to be radioactive. A nuclide undergoes decay by one or more of the decay modes known as alpha, beta, and gamma or isomeric decay.

### 1.4.1 Alpha Decay

The first radioactive decay method is known as “alpha decay”. When a nuclide expels an alpha particle (this particle consists of two protons and two neutrons) the energy of the particle is characteristic of the nuclide from which it came. Since the original or “parent” nuclide has lost two protons, the “daughter” or “offspring” nuclide is a different chemical element. The Z number has been reduced by two and also the neutron number, hence the A number of the new nuclide differs from that of the original nuclide by four. Since it is rare that the daughter nuclide is produced in its ground or lowest energy state, alpha decay is generally accompanied by gamma-ray emission and internal conversion electrons.

### 1.4.2 Beta Decay

The next method by which a nuclide may undergo radioactive decay, is known as beta decay. This type of decay mechanism comes in three varieties known as beta minus ( $\beta^-$ ) or negatron decay, beta plus ( $\beta^+$ ) or positron decay, and electron capture.

In negatron decay, a neutron in the nucleus decays into a proton (which remains in the nucleus) and an ordinary electron which is expelled from the nucleus. However, to obey all the conservation laws, vis., energy, angular and linear momentum, and lepton number (see Glossary), a second particle, known as an anti-neutrino, is also expelled from the nucleus. Hence:



The total available energy (the difference in mass defect between the parent and daughter nuclides among other things) is shared between the electron and anti-neutrino in a random manner, so that the total energy for the decay is fixed ( $E_{\beta\max}$ ), but the specific energy that a particular beta minus particle possesses is random until the maximum is reached.

However, the average energy of the beta minus particle is  $\frac{1}{3} E_{\beta\max}$  (see Figure 1.3).

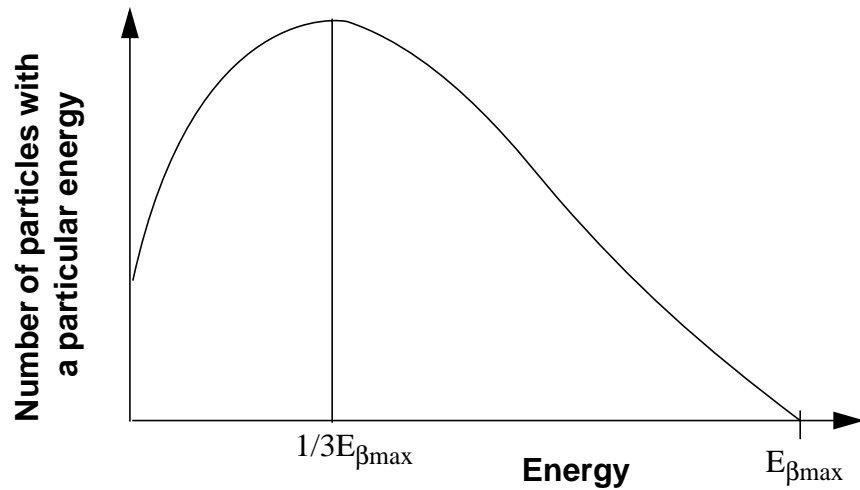


Figure 1.3: Energy spectrum of  $\beta$  particles. There is a maximum energy associated with any particular decaying nuclide, however, the total energy available is shared between the  $\beta$  particle and the (anti-)neutrino.

Since the daughter nuclide has a  $Z$  number which is one greater than the parent nuclide ( $A$  remains the same), it is a different chemical element.

In positron decay, a proton in the nucleus decays into a neutron (which remains in the nucleus) and a positive electron or positron along with a (real, not anti-) neutrino (for the same reasons as before) are expelled from the nucleus. Hence:



Again the total energy available is divided between the positron and the neutrino, so the energy of the positron is not fixed. There is a maximum and average energy as defined previously (see Figure 1.3). In this case, the neutron mass is greater than the proton mass, so energy must be put into the system in order for the decay to occur. Thus the difference in mass defect between the parent and daughter nuclide must be at least 1.02 MeV for positron decay to occur.

An alternative to positron decay is electron capture. In this decay mode, an orbital electron is captured by the nucleus and combined with a proton to form a neutron. Only a neutrino is expelled from the nucleus. However, since an orbital electron is captured, this mode of decay is always accompanied by characteristic X-rays and Auger electrons. This mode of decay can always occur and in fact when positron decay is energetically possible, it is always accompanied by electron capture. In both positron decay and electron capture, the  $Z$  number of the daughter nuclide is reduced by one from the parent nuclide, so these are always different chemical elements. (The  $A$  numbers remain the same.) In all three modes of beta decay, the daughter nuclide is almost always produced in an excited nuclear state. Hence, beta decay is almost always accompanied by gamma-ray photons and internal conversion electrons.

### 1.4.3 Gamma or Isomeric Decay

The last radioactive decay method is known as “gamma decay”. When a nuclide exists in an excited state, it returns to the ground state by expelling one or more gamma-ray photons. The energy of the gamma ray photons are characteristic of the nuclide from which they came. As mentioned previously, an alternative to the expulsion of a gamma-ray photon is an internal conversion electron. Since the original or “parent” nuclide has not lost any nucleons from the nucleus it is not a different chemical element. Since it is rare that the daughter nuclide in either alpha or beta decay is produced in its ground or lowest energy state, these decay methods are generally accompanied by the emission of gamma-ray photons and internal conversion electrons.

Each time a radionuclide undergoes a transformation or decay, a new nuclide is produced and is usually accompanied by other decay product(s). These decay products are usually, but not always, an alpha or and/or a photon. The rate at which radionuclides in a given sample undergo transformation, and, consequently, the rate of emission of the decay product(s), is directly proportional to the number of radioactive nuclides contained therein. Thus as the number of radioactive nuclides in the sample or source decreases because of the radioactive decay taking place, the rate of emission of the decay product(s) also decreases. The rate of nuclear transformation or decay is known as the activity of the source. This leads to an exponential decay curve, as shown in Figure 1.4. The time it takes for the activity to decrease to one half of its initial value is known as the half-life of the radionuclide. This will be more fully discussed in Chapter 11.

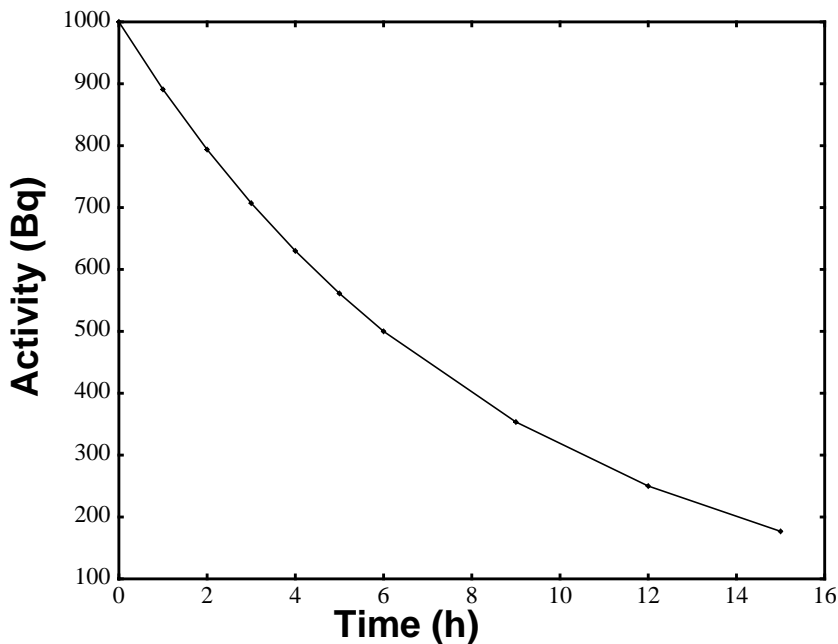


Figure 1.4: Exponential decay curve showing the natural rate of decay of  $^{99m}\text{Tc}$ .

Every chemical element has associated with it an atom that has a fixed number of protons in its nucleus and the same number of electrons orbiting about the nucleus. However, the number of neutrons present in the nucleus may vary (and often does). One example is oxygen. The most common form of naturally occurring oxygen, which has eight protons and eight neutrons in the nucleus, also has stable isotopic forms which have nine or ten neutrons in the nucleus. At the same time, oxygen has another form (seven neutrons in the nucleus,  $^{15}_8\text{O}$ ) which decays spontaneously, emitting a positive electron, or positron. When this nuclide decays, either by emitting excess energy in the form of a photon or by emitting a particle, or both, the nuclide is referred to as a radionuclide and is said to be radioactive. For example, most organic substances contain a very slowly decaying form of carbon (carbon-14,  $^{14}_6\text{C}$ ). Due to this slow decay the ratio of  $^{14}\text{C}$  to  $^{12}\text{C}$  is used for dating organic materials.

Some radionuclides exist in nature; common examples are uranium-238 ( $^{238}\text{U}$ ) and potassium-40 ( $^{40}\text{K}$ ). Other radioactive nuclides are produced in special machines. For example, tellurium-124 ( $^{124}\text{Te}$ ) can be used as the target material in a cyclotron. When this nuclide absorbs a high-energy proton produced in the cyclotron, it forms iodine-123 ( $^{123}\text{I}$ ) plus two neutrons.  $^{123}\text{I}$  then decays spontaneously emitting photons and electrons. The various radioactive decay processes are too extensive to be discussed here [Lederer, 1978].

In the SI system of units (see Appendix A) the unit of radioactivity is the becquerel (Bq). It is equal to one (disintegration, or decay) per second. In the former system of measurement, the unit of radioactivity was the curie (Ci), defined as  $3.7 \cdot 10^{10}$  (disintegrations) per second which represents the amount of activity in one gram of radium-226. Since the curie represents a very large number of disintegrations, it was common to express activities in units of mCi (one thousandth of a curie), or  $\mu\text{Ci}$  (one millionth of a curie). Note that 1 Ci is 37 GBq, 1 mCi is 37 MBq, and 1  $\mu\text{Ci}$  is 37 kBq. Appendix A gives an overview of the history of unit standardization and its current status.

## 1.5 Direct and Indirect Ionization

Ionizing radiation consists of charged particles, which are capable of ionizing directly, and/or of particles that, though uncharged, are capable of producing charged particles through a secondary mechanism. Electrically charged particles with sufficient kinetic energy (energy of motion) to produce ionization by collision are called directly ionizing particles. Uncharged particles, which produce ionization only through secondary mechanisms, are known as indirectly ionizing particles.

### 1.5.1 General Interaction Mechanisms

An atom can be ionized in several ways. The method involving ionizing radiation usually occurs as follows: An electrically charged particle, which has sufficient energy (by virtue of its motion) to release an electron from its orbit, undergoes an inelastic collision with an

orbital electron, transferring to it energy at least equal to that of the binding energy of that electron. This transferred energy enables the release of the electron from its orbit. Rarely does the initial charged particle, except in the case of fission fragments, interact with the atomic nucleus.

In general, charged particles are divided into three categories: 1) light particles such as electrons, positrons, and mu mesons, 2) heavy particles such as protons, pi mesons, and alpha particles, and 3) very heavy nuclear fission fragments. In the case of the first two categories, a charged particle, when it passes through matter, interacts mainly with atomic electrons. Charged particles that are light, like electrons undergo interactions within matter that are similar in the nature to two ping-pong balls colliding. Thus the path of light-charged particles through matter is not straight. Figure 1.5 is an attempt to illustrate this. As the incoming particle travels through matter, it loses energy, slows down and, therefore, the distance it travels between collisions is shorter. The incoming light particle transfers some of its energy to an atomic electron, thus giving it energy. Since both particles are approximately the same size, both have their direction of motion changed at least by a small amount. When the particle has slowed down sufficiently, it is trapped in orbit by an atomic nucleus. The ionization which light-charged particles produce is more concentrated toward the end of the path than toward the beginning. If the interacting material has a high atomic number, or if the energy of the charged particle is low, the probability that the light particle would be deflected from its path by more than  $90^\circ$  is increased.

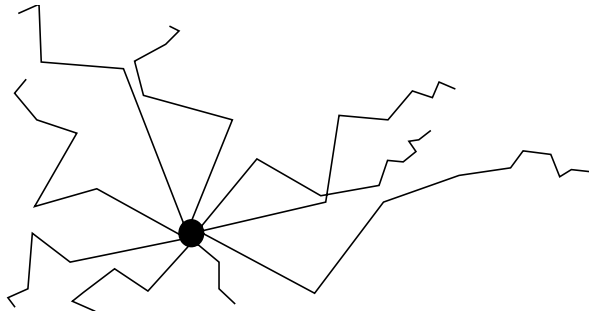


Figure 1.5: Tortuous paths that might be expected from a source of charged particles which are light, such as electrons, when they interact with matter.

However, in the case of a heavy-charged particle, the interaction with the atomic electron, which occurs in the form of collision, can be thought of more in terms of a bowling ball interacting with a ping-pong ball. The bowling ball transfers some of its energy to the ping-pong ball, but it is not noticeably slowed down or deflected from its path. The ping-pong ball on the other hand, because it has a small mass, usually moves quite rapidly away from the interaction site. After the collision, the heavy-charged particle has lost some energy, so the distance it travels before interacting again is shortened. This process, of course, repeats itself. Eventually, the heavy-charged particle has lost so much energy that it moves a very short distance between interactions, hence the volume of the matter surrounding the particle at this point is very heavily ionized. When a stable particle, such as a proton, has lost all or most of its energy, it gathers enough electrons around it to

neutralize its charge and effectively stops. If one were to picture the amount of ionization that occurs along the path of such a particle, one would find that it is very sparse at first, gradually increases, and finally, becomes quite intense. The charged particle travels in a relatively straight line, and the distance it travels in an absorbing material is a function of its original energy when it enters the material as well as the electron density (i.e., the number of electrons per unit volume) of the material. Figure 1.6 is an illustration of the manner in which a charged particle which is heavy, typically loses energy. For example, protons having an energy of 5 MeV are all stopped by 0.4 m of air, whereas those protons having energies of 10 MeV require 1.0 m of air measured at 15°C and standard pressure (one atmosphere or 101.3 kPa) before stopping.

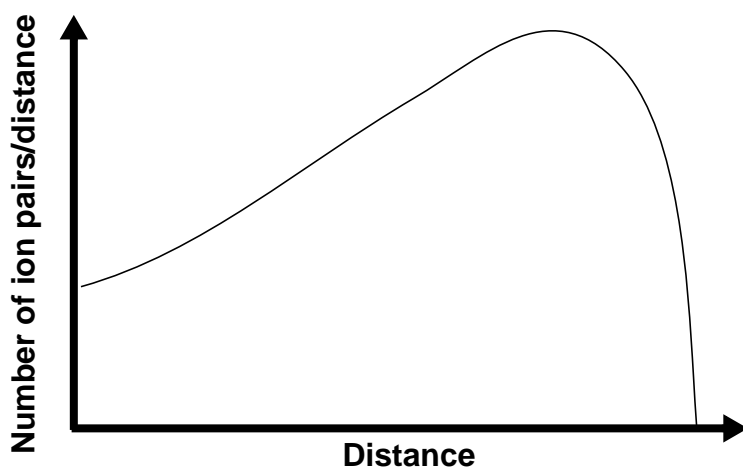


Figure 1.6: The specific energy lost by the interaction of a beam of charged particles which are heavy as it passes through matter. All particles are assumed to have the same initial energy.

Fission fragments, which are produced as a result of neutron-induced or spontaneous fission of heavy nuclei, contain nuclides of mass numbers from approximately seventy-two to one hundred sixty and start out having a positive charge of twenty to twenty-two. The initial energy possessed by fission fragments is also high, 65 to 97 MeV. The interaction of a fission fragment differs from that of other heavy-charged particles in two important aspects. First, it interacts not only with atomic electrons, but to a significant extent, with the atomic nucleus as well. Secondly, it continuously picks up electrons that reduce the original charge. A fission fragment, therefore, ionizes more heavily toward the point of its origin, and the amount of ionization it causes actually decreases as the particle loses energy in the absorbing material. Calculation of how far a fission product travels through a particular absorbing material is complicated. However, most fission fragments are stopped by 0.03 m of air at 15°C and standard pressure. Note that this is ten times less than the distance traveled in air by a 5 MeV proton. Hence, fission fragments are completely stopped very close to their point of origin.

## 1.5.2 Linear Energy Transfer

Both the ICRP and the International Commission on Radiation Units and Measurements (ICRU) have recommended that the effectiveness of a given radiation in damaging tissue be evaluated from its linear energy transfer (LET) for the requirements of radiation protection. The LET of a charged particle in a medium is defined as the average amount of energy locally imparted to the absorbing material by a charged particle of specified energy in traversing a suitably small (ideally infinitesimal) distance within the absorbing material [ICRU, 1970]. It is defined as an average value because the amount of energy imparted by a charged particle to an absorbing material, even over a very small distance may change especially near the end of its path, and also because secondary particles produced by indirectly ionizing radiation, such as photons or neutrons, are not all of the same energy.

LET is a term used extensively when the effect of ionizing radiation on biological material is being considered and its exact meaning and value is thoroughly discussed in the radiation biology literature, see for example, [Pizzarello and Witcofski, 1975]. For our purposes we will simply categorize charged particles as “high” and “low” LET particles in accordance with the general usage of ICRP, ICRU, and NCRP. Since heavy-charged particles lose all their energy in a relatively short path length, they are known as high-LET particles. Light charged particles, like electrons, experience many changes in path direction and lose their energy over a relatively long distance (the ionization produced is dispersed over a longer path or track length). Hence these particles are known as low-LET particles. As for indirectly ionizing particles, photons interacting with matter generally produce light-charged particles and so are low-LET particles, whereas neutrons usually produce heavy charged particles and fission fragments and so are high-LET particles.

## 1.6 Interaction of Directly Ionizing Particles

Of all the directly ionizing particles, alpha particles and electrons are the most commonly encountered by radiation workers. Radionuclides which produce alpha particles are common in the earth’s crust, are frequently used in home smoke detectors, and have been used in the field of radiation oncology. Electrons are commonly produced by the radionuclides used in diagnosis and therapy, are generated by X-ray oncology equipment, and often result from the use of collimation in diagnostic radiology.

### 1.6.1 Alpha Particles

The only natural source of alpha particles is nuclear decay. Because the alpha particle contains two neutrons and two protons, it has a mass of four units, which makes it a heavy particle. Because it contains two protons, the alpha particle has a positive charge of two times that of the electron, hence the alpha particle is highly interactive. The effect of its large mass and double charge makes an alpha particle highly interactive in the vicinity

in which it is produced; hence it never penetrates far into any material. A thin sheet of paper is usually sufficient to stop all but the most energetic alpha particles. When alpha particles travel through a material, they lose energy by collision with atomic electrons and cause ionization to occur. Their large mass and charge result in a path that is, in general, straight and not very long. The maximum distance that is necessary to stop all alpha particles is known as the range. Figure 1.7 illustrates the range of a thin source of alpha particles in tissue of less than 0.04 mm. initially having all the same energy. The mean range is that distance from the source in which the number of alpha particles detected has decreased to one half of the original number detected. As is true of any heavy-charged particle, alpha particles all travel nearly, but not precisely, the same distance in a given medium before coming to rest. This variation in travel distance toward path end is known as straggling and is due to the probabilistic nature of the collisions between alpha particles (and other heavy-charged particles) and atomic electrons. To assess the range of alpha particles, it should be noted that 5 MeV alpha particles are all stopped by 35 mm of air at 15 °C and standard pressure and have a range determined by the distance at which one half of the original number are detected. As is true of any heavy-charged particle, alpha particles all travel nearly, but not precisely, the same distance in a given medium before coming to rest. This variation in travel distance toward path end is known as straggling and is due to the probabilistic nature of the collisions between alpha particles (and other heavy-charged particles) and atomic electrons.

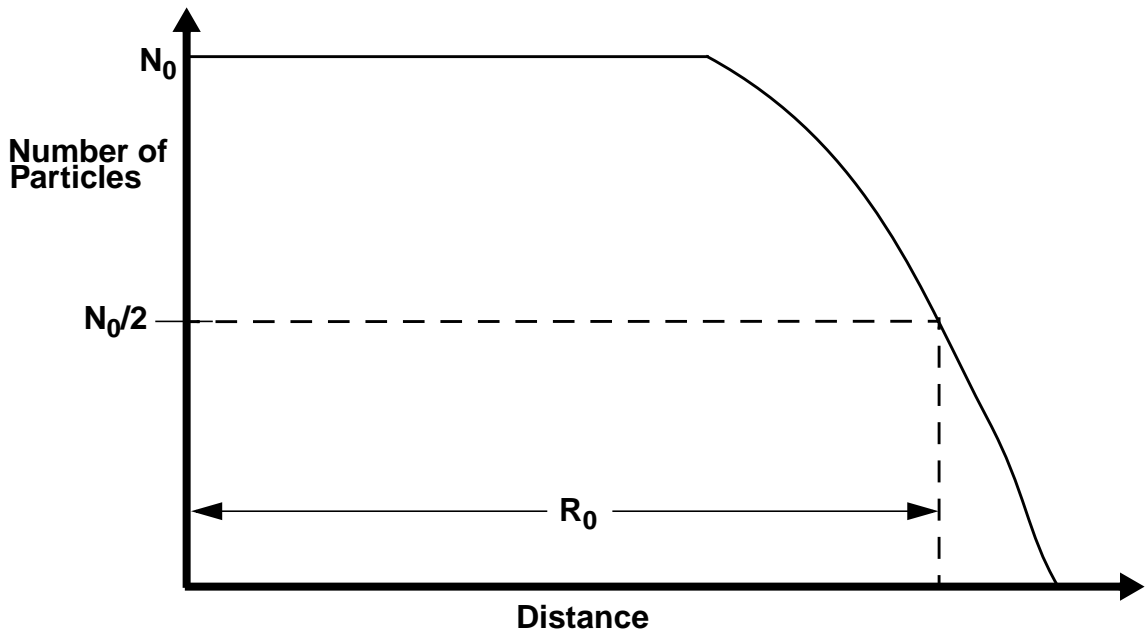


Figure 1.7: Range of alpha particles in matter.  $N$  is the number of alpha particles detected at any distance in the material.  $N_0$  is the initial number of alpha particles detected. When  $N_0$  has fallen to half its original value ( $N_0/2$ ) the depth of penetration into the absorbing material at that point is known as the mean range ( $R_0$ ).

## 1.6.2 Electrons

The major sources of electrons are 1) nuclear particle (neutron) decay, in which case the resulting electrons are known as (negative) beta particles or negatrons; 2) nuclear de-excitation, in which electrons, known as internal conversion electrons, may be expelled instead of gamma-ray photons; 3) atomic de-excitation, in which electrons, known as Auger electrons, may be expelled instead of characteristic X-ray photons; and 4) the end product in a material's attenuation of photons having energies in the visible-light region and above (see discussion of photon interactions with matter below). In the case of beta decay and most photon interactions (the photoelectric interaction case is a notable exception) the electrons do not have a specific energy when they are produced so, in general, one is dealing simultaneously with a number of electron energies limited by some maximum energy value. Electrons are very light particles, and have a negative charge.

Because of its light mass and single charge, an electron is not as interactive as an alpha particle and, therefore, has a much longer range in matter. Also, electrons tend to travel through matter in tortuous paths rather than in straight lines. In addition to losing energy by collision with atomic electrons, another mechanism by which electrons can lose energy (in the presence of a nucleus) is a braking action known as bremsstrahlung. Whenever a charged particle undergoes a change in direction or magnitude of its motion, it emits energy in the form of a photon. This change is proportional to the nuclear charge  $Z$ , which causes it, divided by the mass of the particle experiencing the change. An electron, because of its small mass can, in the presence of a nucleus, experience a large variation in its motion. Since the amount of change of motion is inversely related to the particle's mass, bremsstrahlung does not become important for heavy-charged particles until energies of billions of electron volts (GeV) are reached. Whenever bremsstrahlung occurs, the resulting photon produces charged particles (mostly electrons) by the methods described in the next section.

The amount of energy lost by bremsstrahlung, relative to that lost by collision, is generally very small in materials that have a low atomic number such as air and tissue. For high energy electrons interacting with high atomic number materials, however, the amount of energy lost can be considerable. For example, for 9 MeV electrons interacting with lead, the two mechanisms (direct collision and bremsstrahlung) contribute equally to the electron's loss of energy. This becomes important in shielding considerations. The ratio of energy loss by these mechanisms is approximately equal to:

$$\frac{\text{Energy lost by bremsstrahlung}}{\text{Energy lost by collision}} \sim \frac{E \cdot Z}{700 \text{ MeV}} \quad (1.3)$$

where  $E$  is the electron energy in MeV and  $Z$  is the atomic number of the material with which it is interacting.

The range of electrons in matter is a function of both the maximum energy of the electrons and the density of the material through which the electrons are traveling. Density, symbolized by the greek letter  $\rho$ , is defined as mass per unit volume of material. It is possible to obtain a relationship between the range  $R$  of electrons in a particular material

and the density  $\rho$  of that material. In fact the range of an electron in a material times the density is equal to a constant number  $k$ . In mathematical form:

$$R \cdot \rho = k \quad (1.4)$$

The quality  $k$  is often termed the density thickness. Certain physical properties including density thickness, of some commonly produced electrons are given in Table 1.2 Use of Eq. (1.4) is illustrated in the following example.

### Example 1.1

Calculate the minimum thickness of aluminum necessary to stop all the electrons from a phosphorus-32 ( $^{32}\text{P}$ ) source. From Table 1.2, the maximum electron (beta particle) energy is 1.71 MeV and the density thickness of these electrons in unit density material is  $8.0 \text{ kg} \cdot \text{m}^{-2}$ . The density of aluminum is  $2.7 \cdot 10^3 \text{ kg} \cdot \text{m}^{-3}$ . Using Eq. (1.4):

$$R \cdot 2.7 \cdot 10^3 \text{ kg} \cdot \text{m}^{-3} = 8.0 \text{ kg} \cdot \text{m}^{-2}$$

Solving for  $R$ :

$$R = \frac{8.0 \text{ kg} \cdot \text{m}^{-2}}{2.7 \cdot 10^3 \text{ kg} \cdot \text{m}^{-3}} = 2.96 \cdot 10^{-3} \text{ m} \sim 3 \cdot 10^{-3} \text{ m} = 3 \text{ mm}$$

From the above example we see that in this case a few millimeters of aluminum is sufficient to stop even the most energetic electrons produced by such a radioactive source.

Table 1.2: Selected Physical Properties of Commonly used Electron Sources.

Source	$^3\text{H}$	$^{14}\text{C}$	$^{35}\text{S}$	$^{32}\text{P}$
Maximum electron energy (MeV)	0.018	0.154	0.167	1.71
Average electron energy (MeV)	0.006	0.05	0.049	0.70
Density thickness ( $k$ ) in unit-density material ( $\text{kg} \cdot \text{m}^{-2}$ )	0.0052	0.29	0.32	8.0
Fraction transmitted through dead layer of skin (0.07 mm)	0.0	0.11	0.16	0.95

## 1.7 Interaction of Indirectly Ionizing Particles

Of all the indirectly ionizing, i.e., uncharged, particles, photons and neutrons are the most commonly encountered by radiation workers. Neutrons are included here because they are finding application in radiation oncology and are also of great concern to many industrial based physicists, engineers, and technologists.

## 1.7.1 Photons

The concept of electromagnetic radiation embraces a large class of physical phenomena: radio and television waves, microwaves, visible light, ultraviolet, X- and gamma ray photons. Although ultraviolet photons are sometimes encountered by radiation workers, X- and gamma-ray photons are the only types of photons that are of interest in the context of this book. Consequently, the photon energy range considered is between 10 and 50000 keV (0.01 to 50 MeV). It is important to keep in mind that the difference between X- and gamma-ray photons is in origin, not energy. The term X-ray photons is applied to those photons produced by interactions involving inner-shell atomic electrons or by bremsstrahlung. On the other hand, the term gamma-ray photon is applied when photons are the result of interactions involving the atomic nucleus. Because of the amount of energy associated with them, X- and gamma-ray photons interact with matter in special ways. An understanding of each of these interactions is helpful in realizing why X- and gamma-ray photons are potentially harmful, how they are detected in radiation protection work, and why the particular methods used to protect against them are effective. In this book we are concerned only with the three most common interactions of photons with matter.

The first method by which X- and gamma-ray photons interact with matter is known as the photoelectric effect (Figure 1.8). In this type of interaction a photon has a particle-particle collision with an atomic electron, and the photon transfers all of its energy to the electron. If that energy is sufficient to release the electron from its atomic orbit, the atom is ionized. The energy of the electron is equal to the total energy of the photon minus the binding energy of the released electron. The freed electron interacts in the manner described in Section 1.6.2.

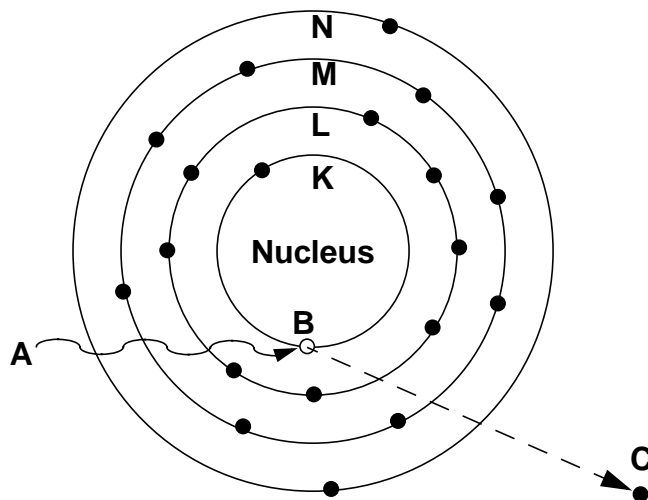


Figure 1.8: The Photoelectric Effect: The incoming photon A has energy equal to or greater than an electron B in the K shell. All the energy of photon is transferred to the electron releasing the electron C from the atom. The released electron has energy equal to that of the photon minus the binding energy of the K shell.

A second method by which X- and gamma-ray photons interact with matter is known as the Compton effect (Figure 1.9). In this type of interaction a photon collides with an atomic electron. This time, however, it transfers to the electron only part of its energy. The rest of the original photon's energy is radiated as a lower-energy photon. Usually, this secondary photon travels in a different direction from the one creating it. This action is referred to as scattering. It is possible for the lower-energy Compton photon to undergo either a photoelectric or a further Compton interaction. In the case of a Compton interaction, the electron is viewed as "free", i.e., the binding energy of the electron in its atomic orbit is insignificant when considered relative to that of the interacting photon. The energy of the original photon is divided between the electron and the secondary photon according to a complex but fixed set of rules. The electron released by the original Compton interaction, and any further electrons released, interact as previously described.

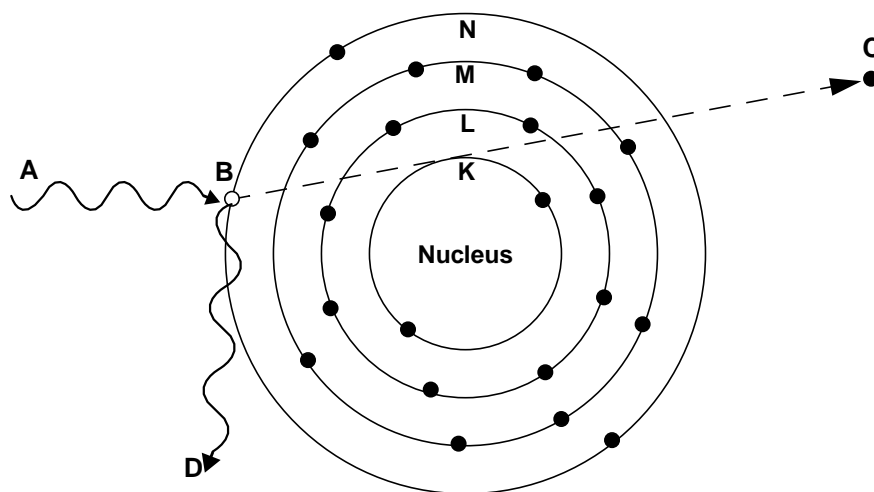


Figure 1.9: The Compton Effect: The incoming photon A has an energy much greater than the binding energy of the electron B. When the photon interacts with the electron B, it transfers only some of its energy to the electron. The energy transferred to the electron C releases it from the atom. The remainder of the photon's energy is re-radiated as a photon D of lower energy.

The third method by which X- and gamma-ray photons interact with matter is known as pair production (Figure 1.10). In this type of interaction the photon, in the presence of a nucleus, disappears, changing all its energy into matter in the form of an electron and a positive electron, known as a positron. In order for this interaction to occur, the photon must have an energy of at least 1.02 MeV, i.e., an energy at least equal to the rest mass (see Glossary) of the two particles produced. The total energy of the photon is shared equally between the two particles, giving them mass and (perhaps) energy. The electron then interacts as before. The positron loses its extra energy, if any, by ionization. When the positron has lost all its energy, it unites with an electron and the two particles disappear, or annihilate. Two characteristic annihilation photons are produced (see Figure 1.10). These annihilation photons move away from each in opposite directions at almost exactly  $180^\circ$ , and have the same energy (0.511 MeV). These photons then interact with matter by either the photoelectric or Compton effect.

Although photons do undergo other types of interactions with matter, at the photon energies encountered by most radiation workers, the three interactions just discussed are the most important ones. Which type of interaction a photon will undergo is determined by two factors: the energy of the photon and the material it is traversing. In general, photons of lower energy (less than 100 keV) are more likely to interact through the photoelectric effect; photons of intermediate energy (above 100 keV) through the Compton effect. Pair production is not possible until photon energies of 1.02 MeV or greater are reached. Photons with energy at or above 7 MeV, can interact directly with the atomic nucleus by a process known as photodisintegration which frequently results in the production of neutrons. This often happens when very high energy particle accelerators are used for medical (usually radiation oncology) or other purposes (such as high energy physics research). The specific energy range of each interaction is also determined by the properties of the material through which the photon is traveling. For example, pair production becomes dominant in lead for photon energies in the range of 4 to 5 MeV, whereas, for tissue, photon energies of 20 MeV must be reached. Figure 8.5 (Chapter 8) illustrates how the probability (known technically as the interaction cross-section) of the three major photon interactions changes in lead as a function of photon energy. Whenever a beam of photons traverses a material, some of the photons interact with the material and are lost from the beam. This process is referred to as *attenuation*. To attenuate a photon beam simply means removing some of the photons from it by interactions between the photons and the material. When a photoelectric interaction occurs, all of the photon's energy is absorbed or attenuated out of the beam. When a Compton interaction occurs, some of the photon's energy is absorbed out of the beam and the rest is scattered from the beam in the form of the secondary photon produced. In pair production, the photon's energy is absorbed or attenuated out of the beam. Photons can also be attenuated out of the beam by coherent or Rayleigh scattering, in which case no energy is transferred to the material, the photon simply changes its direction of motion.

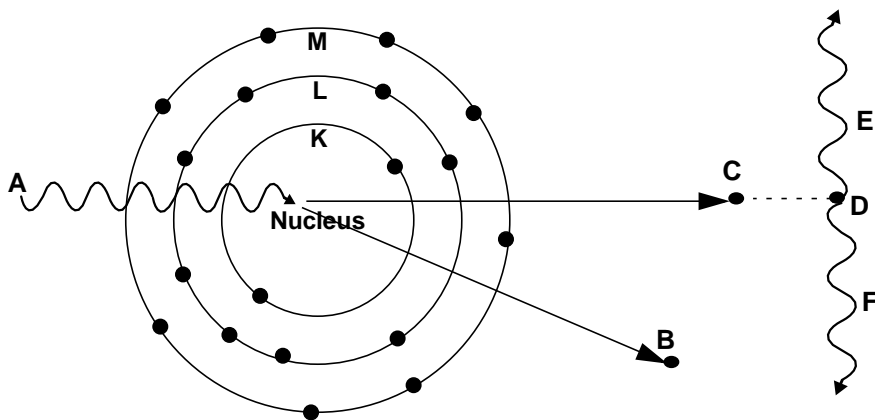
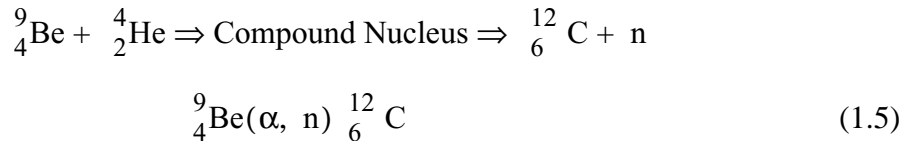


Figure 1.10: Pair Production: A photon A of energy equal to or greater than 1.02 MeV disintegrates, in the presence of a nucleus, into an electron B and a positron C. The positron loses energy by ionization until it finds an electron D and annihilates, producing two characteristic annihilation photons E and F. Note that the annihilation photons travel in directions almost exactly opposite to each other.

## 1.7.2 Neutrons

Neutrons have a mass comparable to that of a proton, but they are uncharged (i.e., electrically neutral). Hence the behavior of neutrons in matter is quite different from that of either charged particles or photons.

Neutrons are primarily produced in photodisintegration, as an end product in a nuclear interaction, or in a nuclear fission event. As an example of a nuclear interaction consider that of polonium (Po) with beryllium (Be). Polonium emits an alpha particle that enters the nucleus of the beryllium atom and remains there for a very short time, forming what is known as a compound nucleus. After a time interval of about  $10^{-20}$  to  $10^{-12}$  s, a neutron having an energy of about 14 MeV is emitted. Symbolically this reaction looks like:



The second form of Eq. (1.5) uses the notation  $(\alpha, n)$ , generically written as  $(A, B)$ . In this notation A denotes the incoming particle, an alpha particle symbolized by  $\alpha$  in the case of Eq. (1.5), and B denotes the outgoing particle, a neutron symbolized by  $n$  in the present case. Figure 1.11 illustrates a nuclear interaction. Notice that beryllium is a very low atomic number element.

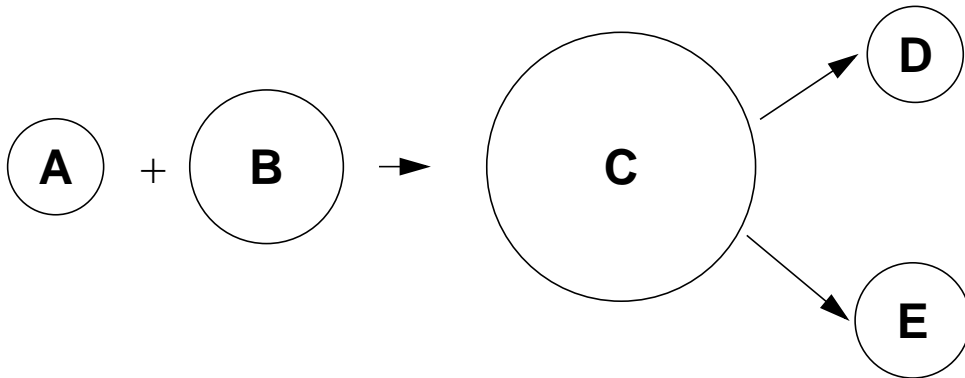
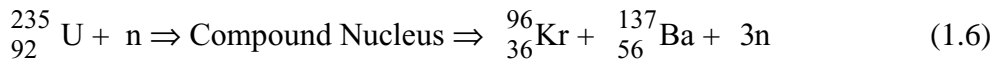


Figure 1.11: A neutron A interacts with a nucleus B, and forms a compound nucleus C. A short time later,  $10^{-12}$  s or less, particle D is expelled and a residual nucleus E is left.

Based on the amount of energy they have, neutrons are generally divided into two categories known as fast and thermal. Since fast is a very large energy range (i.e., everything above 0.025 eV at room temperature), neutrons with energies below 0.5 eV are sometimes called slow neutrons (see Glossary). The energy 0.5 eV is used because neutrons with energies below this are readily absorbed by cadmium and neutrons with energies above this value are not.

A fission event occurs when a very heavy nucleus breaks into two large nuclear fragments. Fission can occur spontaneously, although such events are rare, or it can be triggered by a (usually) very low-energy (known as thermal) neutron (about 0.025 eV at room

temperature) entering the nucleus of a very high atomic number element like  ${}_{92}^{235}\text{U}$  and forming a compound nucleus, which after a short time, breaks into two large nuclear fragments. Whenever fission occurs, one or more neutrons are produced and usually a large amount of energy as well. These neutrons generally have a high energy and are known as fast neutrons. The exact nuclear fragments into which the nucleus disintegrates is largely a probabilistic outcome. An example is:



Notice that in Eq. (1.6), three neutrons are produced and that the two fission fragments produced are quite disparate in mass number. In any fission event there is always a “light” fission fragment ( ${}_{92}^{96}\text{Kr}$ ) and a “heavy” fission fragment ( ${}_{56}^{137}\text{Ba}$ ) produced. Fission is most probable for  ${}^{235}\text{U}$ ,  ${}^{239}\text{Pu}$ , and  ${}^{233}\text{U}$  for thermal neutrons. However, some nuclei such as  ${}^{238}\text{U}$  will absorb fast neutrons and fission, but the probability of this happening is very small. Usually when  ${}^{238}\text{U}$  absorbs a neutron, it becomes  ${}^{239}\text{U}$ , which decays via beta minus decay to  ${}^{239}\text{Np}$ , which in turn decays by release of another beta minus decay to  ${}^{239}\text{Pu}$ .

Neutrons interact with matter in a variety of ways. All of these involve interaction with the atomic nucleus, however, and not the atomic electrons. We shall briefly describe each of the most commonly encountered.

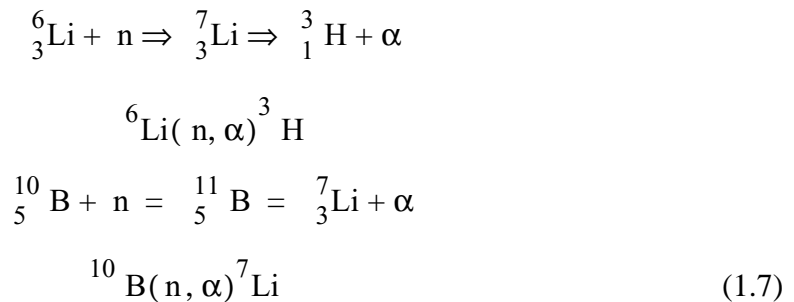
Elastic scattering is that process in which the initial kinetic energy of the neutron is shared with the atomic nucleus. The nucleus is not left in an excited state. The smaller the mass of the interacting nucleus, the greater is the fraction of the neutron’s energy transferred to that nucleus. This is, therefore, a very good method for slowing down neutrons. Materials employed for this purpose are known as moderators. Hydrogen is the most efficient moderator because a neutron can lose up to all of its energy in a single collision; therefore, hydrogen-rich materials such as water and paraffin are often used as moderators. Other good moderating materials are heavy water (water in which deuterium atoms,  ${}^2_1\text{H}$  have been substituted for some of the hydrogen atoms,  ${}^1_1\text{H}$ ), beryllium, and carbon.

In the process of inelastic scattering, possible only for fast neutrons, the atomic nucleus is left in one of its excited states. In most instances, the nucleus quickly radiates this excitation energy in the form of a gamma-ray photon. This photon production is an important consideration when designing neutron shielding, but it is an unwanted complication in detecting neutrons. When the incident neutron energy is 10 MeV or higher, it is possible for a second neutron to be radiated by the nucleus. Thus in inelastic scattering

we generally have (n,n $\gamma$ ) which signifies a neutron before the interaction and a neutron plus a photon afterwards. Or, the interaction may be described as (n,n) or (n,2n) with no photon produced and the nucleus remaining in a metastable excited state.

The most common interaction of neutrons with matter is simple capture. This consists of neutrons being captured by a nucleus and the subsequent production of a gamma-ray photon that usually has energies of several MeV. Thermal neutrons induce this reaction (n, $\gamma$ ) in nearly all nuclei. There is also a high probability for this to occur in some nuclei at particular neutron energies above the thermal range; this is known as “resonance” capture. Cadmium has a very high probability of interacting by simple capture (n, $\gamma$ ) with neutrons having energies up to 0.5 eV. Cadmium, therefore, is useful for detecting and classifying neutron energies and is used quite extensively as a material in control rods in a nuclear reactor or pile, (a machine in which controlled nuclear fission take place) but, because of the production of photons, cadmium is not so useful as a shielding material.

Often when neutrons are absorbed by atomic nuclei, charged particles are ejected instead of, or in addition to, gamma-ray photons. This interaction is most probable in the case of a light atomic nucleus and a fast neutron. There are important exceptions to this rule; in certain cases alpha particles are produced by thermal neutrons. Examples are:



The boron interaction above, with the subsequent detection of the produced alpha particle, is a favored method for identifying thermal neutrons. In addition, because of the production of an alpha particle, boron is used in neutron therapy for certain types of brain tumors. This type of therapy has had mixed success and is also hampered by the need to have a source of thermal neutrons present. This usually implies that the neutron therapy facility must have nuclear (fission) reactor on the premises.

The fission interaction takes place only with heavy atomic nuclei. The neutron is absorbed and the resulting compound nucleus splits into two fission fragments and one or more neutrons as previously described.

Finally, the capture by a nucleus of neutrons having energies of 100 MeV or higher, may cause the emission, known as a shower, of many different types of particles.

## 1.8 Review Questions

1. What accounts for more than 90% of the total man-made radiation exposure to the world population?
2. Is radiation from nuclear power plants distinguishable from background radiation?
3. What percentage of the total radiation exposure is attributable to occupational radiation exposure?
4. Is there a need for training for persons would regularly work with sources of ionizing radiation? State the reason(s) for your answer.
5. What are the two major categories of natural background radiation?
6. What are the constituents of the nuclear atom.
7. What are the three basic forms of radioactive decay? How do the three forms of beta decay differ?
8. Describe the process of ionization.
9. What are the major types of ionizing radiation?
10. To what process is internal conversion is an alternative process?
11. What is the difference between a 600 keV X-ray photon and 600 keV gamma ray photon?
12. Assuming that the transition energy is high enough, to what process is electron capture an alternative?
13. For which radioactive decay mode does the mass number (A) change?
14. Of what three categories or types of particles does directly ionizing radiation consist? Describe the manner in which each category interacts with matter.
15. What are the major indirectly ionizing particles?
16. Define the term linear energy transfer (LET).
17. What is the meaning of the term “mean range” for alpha particles?
18. What is the meaning of the term “range” applied to electrons?
19. What is “bremsstrahlung”? Briefly describe this mechanism for an electron.
20. What are the three most common ways in which photons interact with matter?
21. Into what two categories (based on energy) are neutrons divided?
22. Neutrons usually interact with matter by forming a compound nucleus. Describe what this is.

23. What is the meaning of the term radioactivity? What is the meaning of the term half-life?
24. What is the SI unit of radioactivity? How is it defined?

## 1.9 Problems

1. Consider an atom in which the binding energy of the "K" shell electrons is 30 keV and the binding energy of the "M" shell electrons is 0.7 keV. An electron with a kinetic energy of 25.3 keV is found to have been ejected from the "M" shell of this atom. The ejection was caused by Auger electron emission following an "L" to "K" transition. What is the binding energy of the "L" shell electrons?
2.  $^{224}\text{Ra}$  spontaneously decays via one of two alpha particles which have energies of  $\alpha_1 = 5.7837$  and  $\alpha_2 = 5.5427$  respectively. The resultant nuclide  $^{220}\text{Rn}$  is produced directly in its ground state when  $\alpha_1$  occurs. There is direct isomeric transition of  $^{220}\text{Rn}$  to its ground state when  $^{224}\text{Ra}$  decays into  $\alpha_2$ . What is the energy of this isomeric state? What is energy of the gamma-ray photon that is released?
3.  $^{22}\text{Na}$  spontaneously decays alternatively via electron capture and two possible positron emissions into  $^{22}\text{Ne}$ . One positron has a maximum energy of 1.8210 MeV and other of 0.5460 MeV. The higher energy positron results in  $^{22}\text{Ne}$  being produced in the ground state of the nucleus. Emission of the lower energy positron results in  $^{22}\text{Ne}$  being produced in the one excited state of the nucleus. What is the difference in energy between the two nuclear states of  $^{22}\text{Ne}$ ? What is the energy of the isomeric (gamma-ray photon) transition? What must be the minimum energy mass defect difference between  $^{22}\text{Na}$  and  $^{22}\text{Ne}$  for positron emission to occur? When the positron is not emitted with the maximum energy possible, what happens to the remaining energy?
4. What is the ratio of energy lost through radiation in the form of bremsstrahlung to energy lost by collision when an electron traveling through aluminum has decreased its energy to 7 MeV? What if the electron were in the lead?
5. What is the range of beta particles emitted by  $^{14}\text{C}$  traveling through aluminum?
6. What is the range of beta particles emitted by  $^{32}\text{P}$  traveling through lead?
7. An 80 keV photon undergoes a photoelectric interaction releasing a K shell electron from a tungsten absorber. The binding energy of an electron in the K shell of tungsten is almost 70 keV. What will be the kinetic energy of the released electron? Suppose the energy of the incoming photon had been 60 keV. Would photoelectric interaction with the K shell electron have been possible? Suppose

three or four photons, each of energy 60 keV were to bombard the K shell electron of tungsten, would an electron be released?

8. A 200 keV photon undergoes a Compton interaction in tissue. If the secondary photon has an energy equivalent of 150 keV, how much energy was transferred to the electron?
9. A 2 MeV photon undergoes pair production, dividing its excess energy equally between the produced electron and positron. What is the kinetic energy of the electron?
10. In a fission reaction,  ${}_{92}^{235}\text{U}$  decays into  ${}_{53}^{131}\text{I}$ . What is the other fission product which is produced? How many neutrons are released?