Radioactive Materials Handling Guide

A Study Guide for the RAM Test

July 2004

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Chapter 1

Notation

To classify different kinds of atoms, it is useful to introduce some notational definitions. The number of protons in an atom is called the **atomic number** and is denoted by Z. Atoms with the same Z are all of the same **element**. For example, an atom with six protons is carbon, abbreviated C, and an atom with 79 protons is gold, abbreviated Ag. To a large extent, the chemical properties of an atom are determined by Z.

An atom by itself is electrically neutral, so it will have an equal number of electrons and protons. Certain reactions can cause electrons to be added or removed from the atom so that there are greater or fewer electrons than protons. In this case the atom is called an **ion**.

The number of neutrons in an atom, denoted by N, may vary for atoms of the same element. Atoms that have the same Z but different N are said to be **isotopes** of that element. For example, naturally occurring nitrogen comes in two forms, one with seven neutrons, the other with eight. Each isotope has a certain **natural abundance**, the percentage of that element that appears as a particular isotope. A tank of nitrogen gas will be made up of 99.63% seven-neutron nitrogen and 0.37% eight-neutron nitrogen.

Finally, the **mass number** A of an atom is the sum of N and Z. An atom of given N and Z is called a **nuclide**, and is typically referred to by its elemental name and mass number. Note that this completely characterizes the nuclide. For example, consider sodium-24. All sodium atoms have 11 protons, so therefore sodium-24 has $24 - 11 = 13$ neutrons.

It is common to abbreviate the name of a nuclide using its standard elemental abbreviation and A, so sodium-24 and $^{24}\mathrm{Na}$ are interchangeable. On rare occasions, a text will use the redundant notation

$$^{A}_{Z}\mathrm{X}_{N} \tag{1.1}$$

where X is the elemental abbreviation. Sodium-24 would be notated as $^{24}_{11}\mathrm{Na}_{13}$.

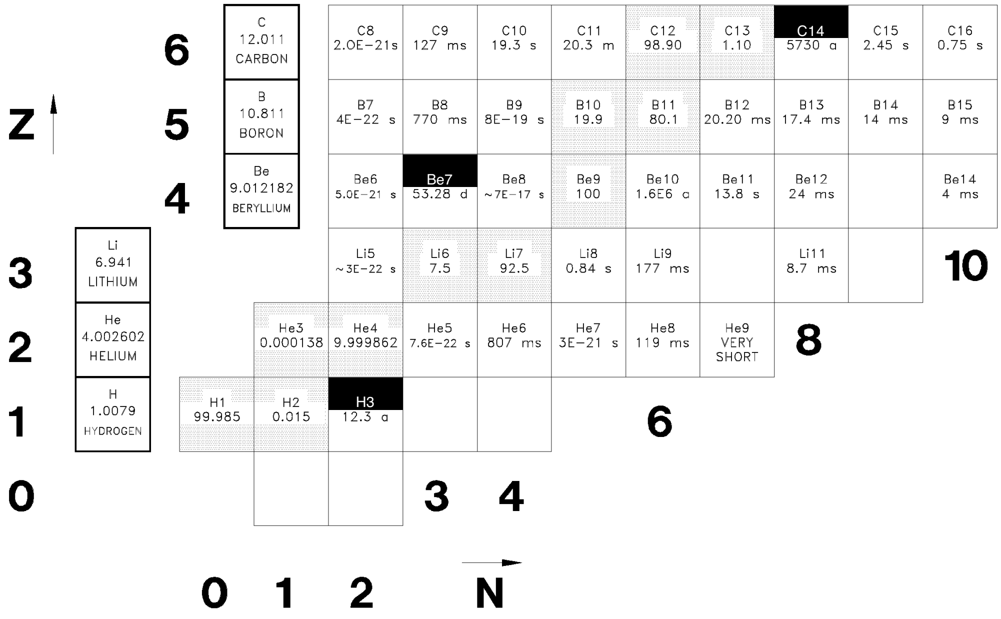

Figure 1.1: A sample chart of the nuclides showing the first six elements. See the text for further explanation.

1.1 Chart of the Nuclides

A tabulated chart called the *Chart of the Nuclides* lists all the known stable and unstable nuclides and pertinent information about each one. Figure 1.1 shows a small portion of a typical chart. This chart plots a box for each individual nuclide, with the number of protons Z on the vertical axis and the number of neutrons N on the horizontal axis.

The completely gray squares indicate stable isotopes; the number below each nuclide name is the percent abundance of that isotope. Those in white squares are **artificially radioactive**, meaning that they do not occur naturally but are produced by humans. Naturally occuring radioative nuclides are indicated by a black box along the top, like ^{14}C . The number below the nuclide name is the **half-life** of the nuclide: the average time it takes for half of the nuclei in a sample to decay away.

Located in the box on the far left of each row is general information about the element. The box contains the name of the element, its chemical symbol, and the average atomic weight of the naturally occurring isotopes.

A more detailed chart will have additional information about each nuclide's radioactive properties. A typical block for a stable nuclide is shown in the top half of figure 1.2. Most of the quantities listed are properties of the nuclide that are useful when irradiating it. These will be defined in later chapters.

An example of an unstable nuclide block is shown in the bottom half of figure 1.2. Information about the modes of decay and their characteristic energies are listed.

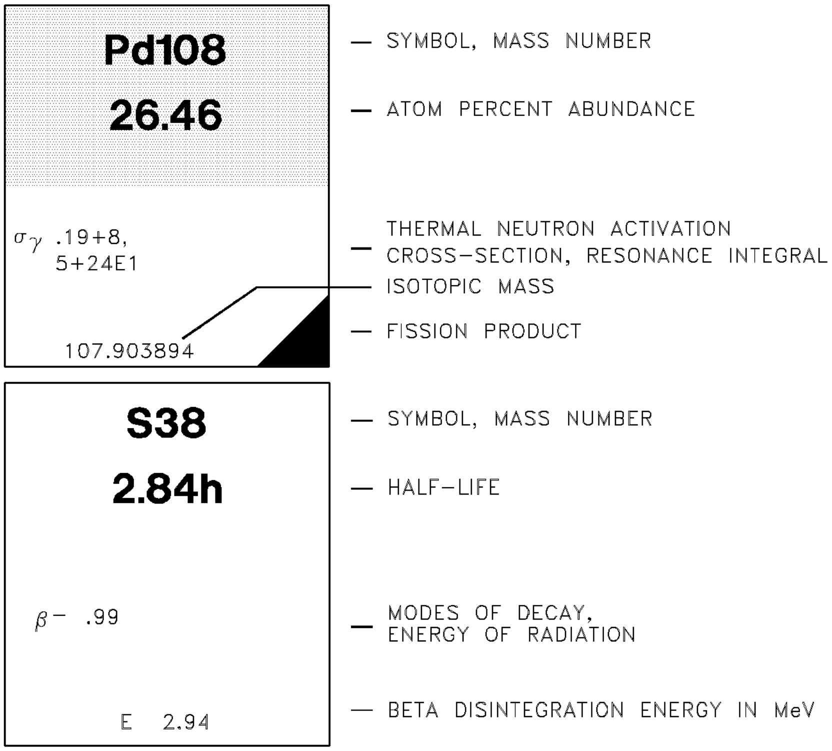

Figure 1.2: Nuclide information blocks for (top) a stable nuclide and (bottom) an unstable nuclide. Much of the data listed will be defined in later chapters.

A full chart of the nuclides will have a gray band where all the stable isotopes are located. This can be useful for predicting how a certain radioactive nuclide will decay.

If we were to shrink a chart of the nuclides down so that each box became a point, the result might look like figure 1.3. Each point on the graph represents a stable nuclide. The "line of stability" is a best-fit line through the stable nuclides. Nuclides near this line have nuclei with an appropriate ratio of neutrons to protons for the size of the nucleus. As is evident from the graph, heavy stable nuclei have a slightly higher neutron-proton ratio than light stable nuclei. Nuclei with a mass number, A, less than 20 tend to be stable when $N = Z$; nuclei with mass numbers greater than 200 tend to be stable when $N = 1.5 \times Z$; nuclei in between vary in proportion. At larger mass numbers more neutrons are required to hold the nucleus together with the strong force, to overcome the longer-range electrostatic repulsion between the protons.

Radioactive nuclides will tend to decay so that they get closer to this line. For example, those to the right of the line will undergo β^- decay to reduce their neutron-proton ratios. Likewise, nuclei to the left will use β^+ decay or electron capture to increase their neutron-proton ratios. Nuclides that are just too heavy to be stable will emit alpha particles to reduce their weight. These are only general rules for predicting decay and for understanding why nuclides undergo different types of

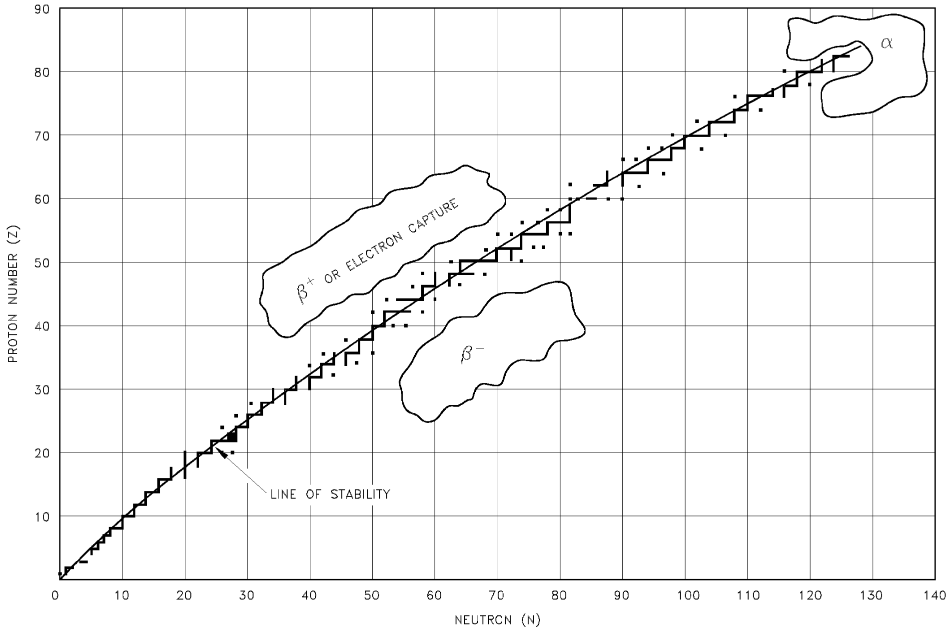

Figure 1.3: Predicting the mode decay from the neutron-proton ratio.

decay. There are exceptions to these rules, particularly in the region of heavy nuclei. If in doubt, check the information box for a particular nuclide.

Once an unstable atom decays, the resulting atom is not always stable, so it will also decay, following a list of decays known as a **decay series**. An example is the decay of uranium-238, known as the **uranium series**, shown schematically in figure 1.4. Uranium is a very long-lived nuclide, and found in relatively high concentrations in the soil. The decay products in this series are responsible for much of the background radiation present today.

One way to help cement in the mind the different modes of decay is to follow different decay series on the chart of the nuclides (they are usually marked on the chart) and note which modes of decay go which direction on the chart, and how each mode affects A and Z. Decay processes will be discussed in the next chapter.

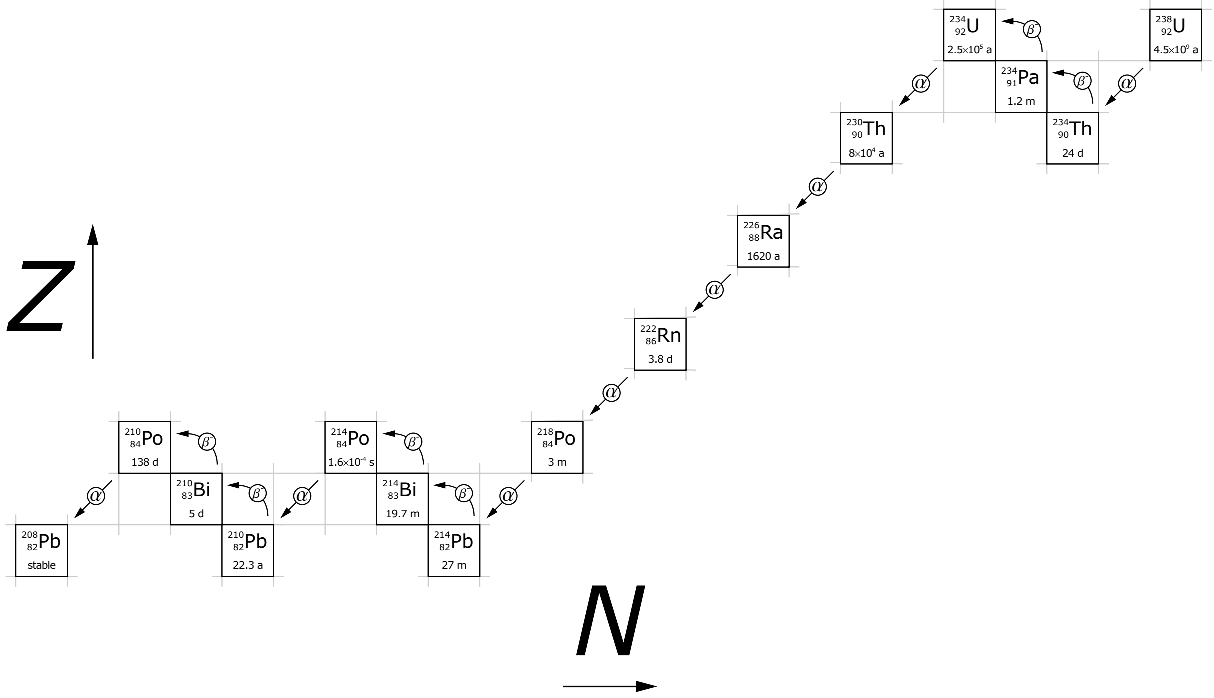

Figure 1.4: The uranium decay series.

Chapter 2

Radiation Basics

2.1 Radioactive Decay

So far, our discussions have focused mainly on stable atoms, but the heart of nuclear science lies in the study of atoms that are **radioactive**. Radioactive atoms have unstable nuclei that decay by emitting photons or particles (often both) to reach a more stable state. How an atom becomes radioactive will be addressed in later chapters, but for now we will concentrate on the various ways a nucleus can decay.

Alpha decay

Very heavy nuclei will tend to emit **alpha** (α) **particles** to become more stable. These particles are identical to a helium nucleus, that is, two protons and two neutrons. So, the result of alpha decay is that mass number is reduced by four, and atomic number by two. A commonly used alpha source is plutonium-239:

$$^{239}\mathrm{Pu} \rightarrow {}^{235}\mathrm{U} + \alpha$$

Kicking out an alpha particle carries away a certain amount of binding energy, so a particular nuclide will emit alpha particles of characteristic energy.

Beta decay

Beta (β) **decay** is a mechanism by which a nucleus can gain stability by converting a neutron to a proton or vice versa. Nuclides produced in a reactor usually undergo β^- decay, in which a neutron in the nucleus decays into a proton, an electron, and an **antineutrino**. The latter two are promptly ejected from the nucleus. An antineutrino is an extremely tiny uncharged fundamental particle. Its purpose will be discussed shortly. After β^- decay, the mass number of the nucleus remains unchanged, but its atomic number has increased by one. An example of a useful beta emitter is carbon-14:

$$^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + \beta^- + \bar{\nu}$$

The electron is commonly referred to as a β^- particle for historical reasons, and to indicate that it originated in the nucleus. The symbol ν is the Greek letter "nu," used to suggest neutrino; the overbar specifies that it is an *anti*neutrino. Each type of fundamental particle has a companion antiparticle that is almost identical; the primary difference between them is that they are oppositely charged. In the case of the uncharged neutrino, the differences are more subtle, but not relevant here. A charged particle and its antiparticle can come together and **annihilate** each other and release energy in the form of photons.

A more common example is the antiparticle of the electron, the **positron**. It has the same mass of an electron, but carries positive charge. There is an analogous form of beta decay, β^+ decay, where a proton absorbs energy from the nucleus and transforms into a neutron. This process creates a positron and a **neutrino** that are then ejected from the nucleus.

Neutrinos are not of much importance in reactor applications since they very rarely interact with matter: the average neutrino could pass through 2.5 light years of lead before being noticed. However, they are of high theoretical importance. Unlike most other forms of radiation, beta particles are emitted with a continuous spectrum of energies. When beta decay was first studied, only the electron could be detected. This did not make sense because the parent neutron carried a definite amount of energy, so the electron energy should not vary. In 1930, Wolfgang Pauli proposed the existence of the neutrino (named by Enrico Fermi a few years later) that shared the available energy with the electron. More than 20 years later, neutrinos were first detected using a research reactor near Savannah River, confirming Pauli's hypothesis.

Returning to practical matters, an example of β^+ emitter is copper-64:

$$^{64}\mathrm{Cu} \rightarrow {}^{64}\mathrm{Ni} + \beta^+ + \nu$$

Electron Capture

A nucleus must have enough excess energy to convert a proton into a neutron to undergo beta decay. If it does not have the energy, it can create the same effect via **electron capture**. The nucleus takes an electron from an inner orbit, and uses its energy to make the conversion. Nothing is radiated directly as a result of electron capture, but an outer electron will usually come down to replace the captured one, and in the process release characteristic X-rays. Some nuclides can only undergo either electron capture or beta decay, but in many cases the two are competing processes. For example, copper-64 can also decay by

$$^{64}\mathrm{Cu} + e^- \rightarrow {}^{64}\mathrm{Ni} + \nu$$

Gamma emission

Gamma (γ) radiation is very high energy electromagnetic radiation that originates in the nucleus. Like electron orbits, the nucleus has discrete energy states depending on the configuration of the nucleus. The mechanism is a bit more complicated, but the result is the same: when an excited nucleus relaxes to a lower energy state, it emits a photon of a characteristic energy, and keeps the atomic number and number of neutrons unchanged. This process may repeat several times before the nucleus reaches stability. So, a particular radioactive isotope may emit several characteristic gamma energies.

For many excited nuclear states, the transition to a lower energy level is almost instantaneous. However, some excited states have measurable lifetimes; atoms in these states are said to be **isomers** or **metastable** states of the ground state atom. Isomers will have different properties from their stable cousins due to their higher energy. The letter m is added to the notation for isomeric states. A transition from an isomeric state to a lower energy state is known as an **isomeric transition**.

A nucleus is often left in an excited state after particle (alpha or beta) decay, so gamma radiation will follow. For example, consider the decay of ^{16}N:

$$\begin{aligned} {}^{16}\mathrm{N} \rightarrow {}^{16}\mathrm{O}^{\star} + \beta^- + \bar{\nu} \\ {}^{16}\mathrm{O}^{\star} \rightarrow {}^{16}\mathrm{O} + \gamma \end{aligned}$$

The asterisk above ^{16}O indicates that it is an isomer of ground state oxygen. This intermediate state is not normally shown in the equation unless it has a long half-life such as ^{99m}Tc.

Internal Conversion

Instead of releasing a gamma to reach its ground state, an excited nucleus may directly transfer the necessary energy to an electron in an inner orbit around the nucleus. This will cause the electron to be ejected from the nucleus, and leave the atom in an excited orbital state. Then, another electron will make an orbital transition to take the missing electron's place, and emit a characteristic X-ray. This process is called **internal conversion**.

2.2 Activity

There is no way to predict when a particular nucleus of a radioactive sample will decay; the process is random. However, the average behavior of a large number of nuclei can be predicted accurately with statistical methods. There is a certain probability that in a given time interval a certain fraction of a sample of nuclei will decay. This probability per unit time that a nuclide will decay is known as the **decay constant** for that nuclide, notated λ. It has units of inverse time (e.g., 1/sec). The decay constant is the same for all atoms of a particular nuclide.

To consider a particular sample of atoms, another term is introduced: **activity**. The activity A of a sample is simply λN, where N is the number of nuclei in the sample. The activity of a sample is the number of nuclei that disintegrate per unit time. The SI unit for activity is the **becquerel** (Bq), equal to one disintegration per second (dps). In the United States it is more common to still see the old unit, the **curie** (Ci), which is based on the activity of one gram of ^{226}Ra. One curie is equal to 3.7×10^{10} Bq, which is actually a very large amount of activity. In most applications activity is measured in microcuries (μCi), equal to 10^{-6} curies.

As a sample decays, its activity will decrease since there are fewer nuclei available to disintegrate, and λ stays constant. In fact, the activity of a sample decays exponentially:

$$A = A_0 e^{-\lambda t} \tag{2.1}$$

where A_0 is the initial activity, and A is the activity after time t. The derivation of this equation involves some calculus and is not available in this manual.

With this equation we can write the **half-life** of the nuclide in terms of the decay constant. To that end, we can rearrange (2.1) as follows

$$\begin{aligned} \frac{A}{A_0} &= e^{-\lambda t} \\ \implies \ln\left(\frac{A}{A_0}\right) &= -\lambda t \end{aligned}$$

We want the original activity to be reduced by half, so we can write

$$\begin{aligned} \ln(1/2) &= -\lambda t_{1/2} \\ \implies t_{1/2} &= -\frac{\ln(1/2)}{\lambda} \\ t_{1/2} &= \frac{\ln 2}{\lambda} \end{aligned}$$

The numerical value of $\ln 2$ is about 0.693.

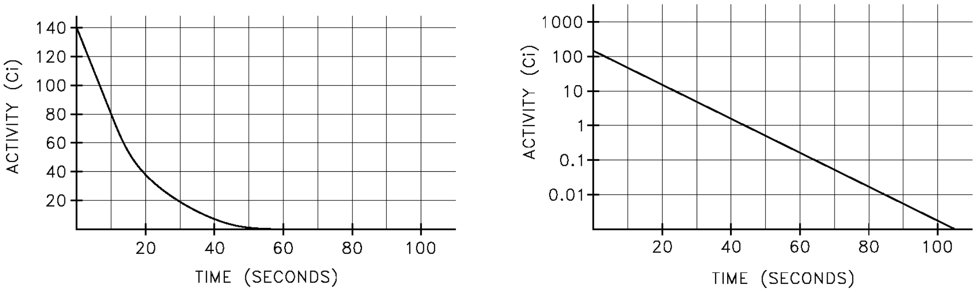

Figure 2.1: Two radioactive decay plots: (left) a linear plot and (right) a semilog plot.

To experimentally determine the half-life of a nuclide, we can measure the activity of a sample over time and plot the data on a graph. Two radioactive decay plots are shown in figure 2.1. The left plot is a normal linear plot showing the exponential activity vs. time curve. On the right is a **semilog plot**, where the horizontal axis is linear, but each tick on the vertical axis represents an increase by a factor ten, but there is equal space between ticks. On this grid, the logarithm of activity is plotted vs. time. Recalling equation (2.1), this results in the plot of a line:

$$\begin{aligned}\log A &= \log(A_0 e^{-\lambda t}) \\ &= \log(A_0) + \log(e^{-\lambda t}) \\ &= \log(A_0) + (\log e)(-\lambda)\, t\end{aligned}$$

This is a linear function of time, with slope $(\log e)(-\lambda)$. So, by creating such a plot from experimental results, we can calculate the decay constant and half-life of a nuclide.

Chapter 3

Interactions

3.1 Charged Particle Interactions with Matter

When charged particles interact with matter, the coulombic force dominates the interactions. Negatively charged particles are attracted to the nucleus and repulsed by the orbital electrons. Conversely, positively charged particles are attracted to the orbital electrons and repulsed by the nucleus. In this section, charged particle interactions that rely on classical mechanics are discussed along with those interactions which depend on quantum mechanics. There are two fundamental ways that charged particles interact with matter using classical mechanics: ionization and excitation. Ionization occurs when a charged particle passes an atom closely enough for its electric field to remove an orbital electron and create an ion pair. Excitation occurs when the charged particle excites an orbital electron into a higher energy level, and the excited electron releases its energy by emitting an X-ray when it returns to its normal energy level.

The interaction of charged particles, namely β^-, β^+, and α, is measured quantitatively in terms of the **range** of the particle — how far the average particle penetrates into a given material. Range is dependent on a number of factors including the density of the material the particle is traveling through and the atomic number of the atoms in the material. The unit for range is distance (cm or m) but can also be listed in mg/cm^2 because that takes into account the density of the material the particle is traveling through. The mg/cm^2 unit is simply the product of the range and the density, and by using this unit, it is possible to compare the ranges of a particle in different media in a way that is independent of the density of the media. For example in figure 3.1, we see that a gold shield is 30 times more effective than a hydrogen shield for 1 MeV alpha particles.

Alpha Particle Interactions with Matter

Alpha particles are the most massive particles resulting from simple decay processes and have a charge of +2. Because of this, an alpha particle is very effective in causing ionization of nearby atoms and subsequently capturing two electrons that it needs to become electrically neutral. Alpha particles interact strongly with charged

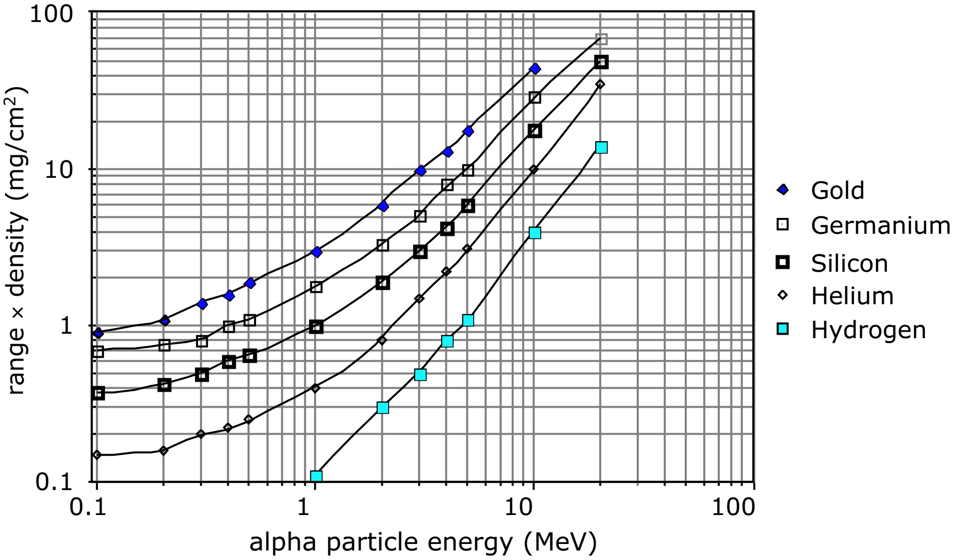

Figure 3.1: Range of α Particles in Common Media.

particles near them and have short ranges.

Beta Particle Interactions with Matter

Compared to alpha particles, beta particles have a much lower mass and charge, and as a result, their range through matter is longer than that of alpha particles. While alpha particles move in straight lines, the less massive beta particle is more strongly deflected by the atoms that it passes. This causes the path of a beta particle to be very complex and complicates the calculation of the range. This effect is called **straggling**. Because **beta particles** can be emitted with a spectrum of energies, it is difficult to list the range of a beta particle from a particular radionuclide through an absorbing material. To compensate for this problem, the maximum range of the beta particle is reported. The maximum range is the range of the beta particle emitted with the maximum possible beta energy. Figure 3.3 shows the maximum range of beta particles through several common materials.

Positrons interact with materials in the same manner as electrons except that the coulombic force is in the opposite direction, i.e., positrons are attracted to the orbital electrons and repulsed by the nuclei, and the positron annihilates with an electron at the end of its range. Pair annihilation produces two 511 keV photons. The secondary gamma radiation caused by a positron beam has an enormous range compared to that of the original positron, which creates shielding difficulties.

Bremsstrahlung

Translated from German, **bremsstrahlung** means braking radiation. When a beta passes a nucleus, it is attracted by the coulombic force and slows down. To conserve

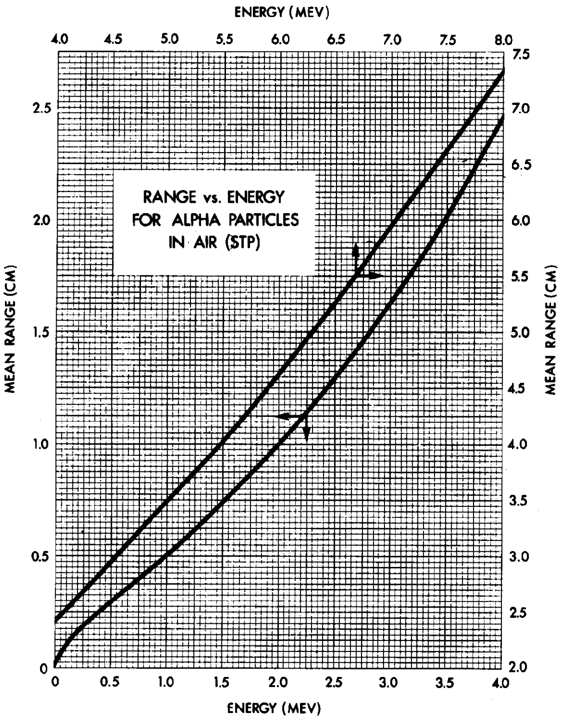

Figure 3.2: Range of α Particles in Air.

energy, a photon must be given off. Figure 3.4 illustrates bremsstrahlung.

The intensity of bremsstrahlung radiation is proportional to the charge of the electron and the charge of the absorbing material, and inversely proportional to the square of the mass of the particle. Technically, alpha particles can also cause bremsstrahlung, but it is $3,371,000$ times less likely than an electron. To decrease the intensity of bremsstrahlung radiation, beta emitters should be shielded with low Z material. Shielding a high-energy beta emitter with lead could create more bremsstrahlung radiation outside the shield than the source emitted unshielded.

Čerenkov Radiation

One reaction that produces visible radiation is **Čerenkov radiation**—a blue halo surrounding certain highly radioactive objects in a transparent medium. General relativity states that it is impossible for a particle to travel faster than light in a vacuum; however, light slows down by passing through transparent media such as water. Čerenkov radiation occurs when an electron moves faster than the speed of light in some medium.

As the electron travels through the medium, it polarizes the medium, exciting the molecules in that medium. The excited states decay, emiting photons. Only when the speed of the electron through the medium exceeds that of the propagation of light through the medium do those emitted photons constructively interfere with one

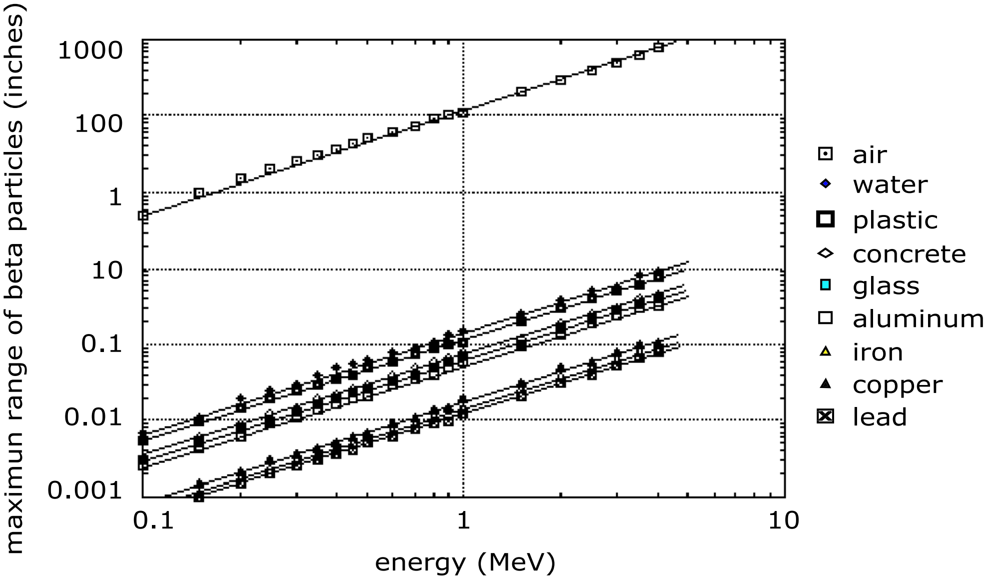

Figure 3.3: Range of β Particles in Air.

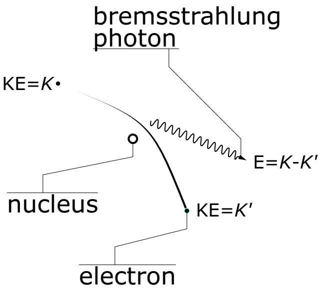

Figure 3.4: Bremsstrahlung, or braking radiation.

another, making visible Čerenkov radiation. At lower electron speeds, the photons will destructively interfere, and no Čerenkov radiation will be observed.

3.2 Photon Interactions with Matter

Photoelectric Effect

Several effects occur in quantum situations that are counterintuitive. One is the **photoelectric effect**; for explaning this effect Einstein won the Nobel Prize. When a beam of photons of sufficient energy strikes a metal, it liberates electrons from the surface of the metal. If an appropriate circuit is set up around the metal, this can be seen as an induced voltage. The number of photoelectrons ejected from the surface of some material with atomic number Z is proportional to the cube of the Z and inversely proportional to the cube of the energy of the incedent gamma ray,

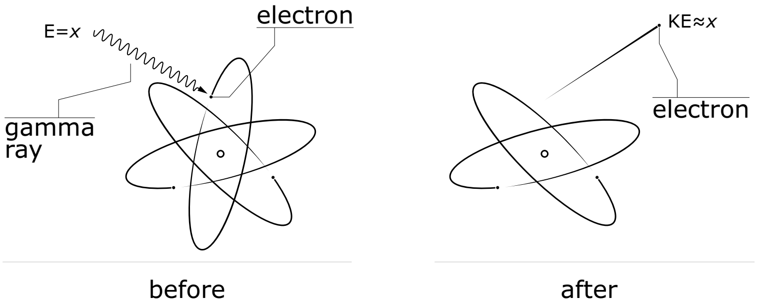

Figure 3.5: Photoelectric Effect.

so:

$$PE \propto \frac{Z^3}{E^3}$$

Classical mechanics would predict that the voltage, which is related to the energy of the electrons ejected from the surface of the metal, should be a function of the intensity of the light incident on the surface of the metal. However, it was found that this voltage is actually dependent on the frequency of the light, and that there is a frequency threshold for each type of metal below which no electrons were ejected. The photoelectric effect happens best with tightly bound electrons, so it is the K-shell electrons that are usually ejected in a photoelectric interaction. The K-shell is the electron shell closest to the nucleus. Electrons in outer shells are less likely to undergo a photoelectric interaction, and free electrons do not participate in the photoelectric interaction at all. Through quantum mechanics and conservation of energy, we know that the kinetic energy of the electron can be concisely stated as:

$$KE = h\nu - W$$

h is Planck's constant, ν is the frequency of the incident light, and W is the work function — the minimum threshold energy of the metal. From this, we can deduce that light is quantized — it occurs in bundles of energy $nh\nu$ where n is an integer and that a certain amount of energy is needed to eject each electron from the metal.

The probability per gram of some material of the photoelectric effect occurring is proportional to the cube of the atomic number and inversely proportional to the cube of the photon energy. If the medium is a chemical compound, the effective atomic number is used. Because the probability is inversely proportional with the cube of the energy, the photoelectric effect is much more likely to occur with lower energy photons.

Compton and Rayleigh Scattering

Compton scattering is the elastic scattering of a photon by an electron; it is an indication of the "particle" nature of light. Unlike the photoelectric effect where all of the energy of the incoming photon is absorbed, a lower-energy Compton photon is produced along with the free electron.

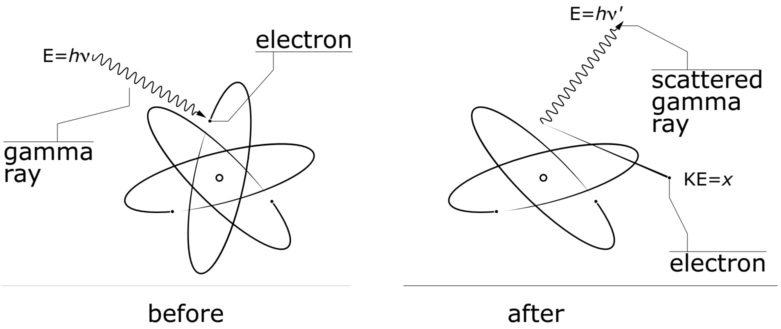

Figure 3.6: Compton Scattering.

The probability per gram of some material for Compton scattering is independent of Z, but it decreases with increasing photon energy. Compton scattering came as a surprise to physicists because it differs from the classical model for photon scattering of electrons: **Rayleigh scattering**. In the classical model, light is treated as a wave. The incident light wave is absorbed by the atom and excites an orbital electron. The excited electron then emits a photon of exactly the same frequency when it falls back into its ground state. The end effect is that the photon has the same amount of energy, but its direction may be changed.

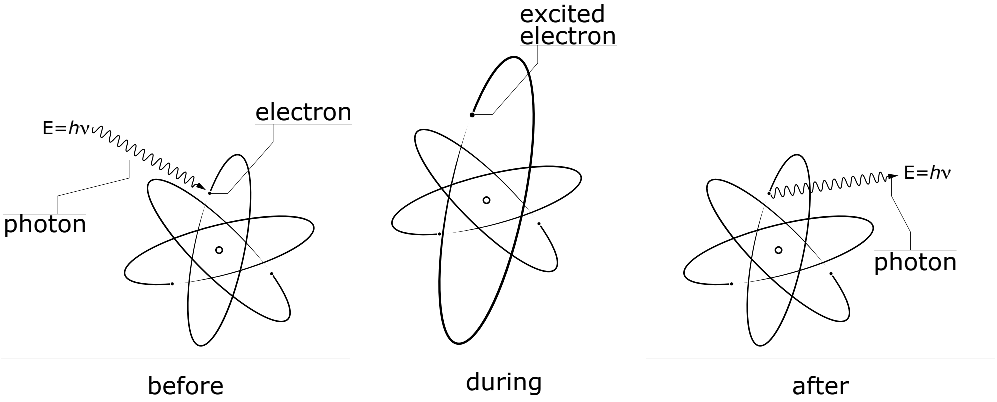

Figure 3.7: Rayleigh Scattering.

Rayleigh scattering is the microscopic process that occurs in most macroscopically observable situations. When you look in the mirror your reflected image has the same color shirt on that you do. If Compton scattering occurred in the visible light region, you might look in the mirror when wearing a blue shirt and find that your image was wearing a yellow shirt — provided, of course, that you looked at the correct angle.

Pair Production and Pair Annihilation

One interesting photon interaction is a process known as **pair production**. A photon of particularly high energy may be converted into an electron-positron pair. This usually takes place near the nucleus of an atom. Stated symbolically:

$$\gamma \rightarrow e^- + e^+$$

Note that charge is conserved through this process, and momentum is conserved through emitting the electron-positron pair in opposite directions. In order to conserve energy, the photon must have sufficient energy to make up the rest mass of an electron-positron pair (2×511 keV), and any excess energy will become the kinetic energy of the electron and positron. Theoretically, similar processes could produce heavier particles; e.g., a sufficiently energetic γ could create a proton-antiproton pair.

The inverse of pair production is **pair annihilation**. This occurs when a particle and its antiparticle meet each other. Typically, this means that whan an electron and positron meet each other, all their mass is converted to energy.

To conserve energy, the two emitted photons must carry away the rest mass of the electron-positron pair. Because of this, the annihilation photons will each have 511 keV of energy, and they will be emitted in opposite directions to conserve momentum. Charge is conserved as well.

The process may also occur for a proton-antiproton pair or any other particle-antiparticle pair. While all antiparticles have the opposite charge of their respective particles, it does not follow that any two particles of opposite charge can annihilate each other. Only the specific antiparticle can annihilate any given particle, although any two particles of opposite charge attract each other. The probability that electron-positron pair production will occur is proportional to the atomic number and increases with the energy of the photon above the threshold energy of 1.022 MeV. Because of these factors, pair production is most likely for high-energy photons. It should be noted that pair production is always accompanied by pair annihilation because the positron emitted from pair production will quickly lose its kinetic energy and pair annihilate.

Combining the Photon Interaction Effects

Because the different photon interaction methods vary with photon energy, a graph can be produced that shows the total probability of photon interaction while passing through matter. There are photon energies where two or three of the interaction methods may be possible, and the total interaction probability is the sum of the possible methods. Figure 3.8 shows the total probability of photon interaction with lead.

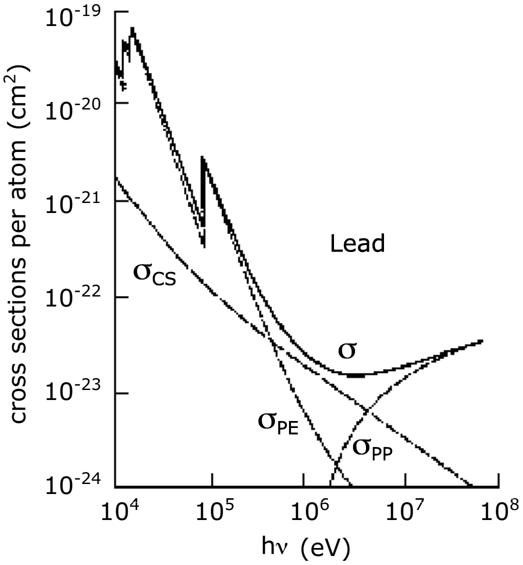

Figure 3.8: Cross Sections of Photon Interactions with Matter.

On this chart, the cross section is the probability of interaction and is represented by σ; the cross sections for photoelectric effect, Compton scattering, and pair production are σ_{PE}, σ_{CS}, and σ_{PP}, respectively. Similar charts can be generated for other elements.

3.3 Shielding

Well-designed shields can absorb particles and thus reduce the dose of people working nearby; shields may also be used to protect experiments from interference by background radiation. Since the various particles encountered in a nuclear research facility have different interactions with matter, their shielding requirements are specific to the type of particle. Under most circumstances, only gamma shielding and neutron shielding are considered because alpha and beta particles have comparatively small ranges in most material. In special circumstances, extra precautions are taken against beta radiation.

Alpha Shielding

Alpha particles have such short ranges that they are stopped by almost anything: a sheet of paper or a rubber glove. Even the water that covers the lens of the eye will block virtually all alpha particles. The dead outer layer of human skin will stop alpha particles up to 7.5 MeV.

Nuclide	Average Energy (MeV)	Range in H_2O (cm)
^{35}S	0.049	0.032
^{14}C	0.050	0.029
^{45}Ca	0.077	0.06
^{32}P	0.70	0.8
^{90}Sr+^{90}Y	0.93	1.1

Table 3.1: Properties of Common β Emitters.

Beta Shielding

Most beta particles are stopped by a 1 cm thickness of unit density material, e.g., water, plastic, or tissue. Common beta shields are wood or plastic. When materials with high atomic number are used, the radiation hazard can be increased by bremsstrahlung (§3.1) or backscattering (§3.3). Lead should not be used to shield beta particles.

Experimenters often wear plastic goggles or glasses to protect their eyes from beta radiation, and samples are typically placed in a wooden sample holder.

Gamma and X-ray Shielding

For a monoenergetic beam of photons passing through a shield of thickness x, the change in the intensity I of the beam is given by:

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

I_0 is the original intensity and μ is the linear attenuation coefficient of the shielding material.

The linear absorption coefficient, μ, has units of cm^{-1} and is dependent on the energy of the particle as well as the shielding material.

This equation only applies to monoenergetic photons. If the radiation source has photons with a range of energies, the situation is more complicated. Lower energy photons will be attenuated more quickly, leaving only higher energy photons going through. This is called **hardening**. The average energy of the photons has been shifted to a higher value since they can penetrate farther.

Attenuation does not include the secondary radiation created by interactions such as Compton scattering or pair production, so the actual number of particles successfully penetrating the shield is higher than predicted by the linear absorption equation. The secondary radiation will not have the same energy as the primary radiation.

Backscattering

One non-absorbing attenuation process is known as backscattering. Any particle can undergo backscattering, even photons. The mechanism and yield of the backscattering for different kinds of particles is worth noting, however. For electromagnetic radiation, some of the incident photons undergo Compton scattering through 180°, producing a new photon with frequency ν' given by:

$$\nu' = \frac{\nu}{\left(1 + \dfrac{2h\nu}{m_e c^2}\right)}$$

where ν is the frequency of the initial gamma and $m_e c^2$ is the energy equivalent of the rest mass of an electron.

Backscattering is also significant for β^- particles since they have low mass and are easily deflected by nuclei. The fraction of electrons backscattering off different materials is shown in figure 3.9.

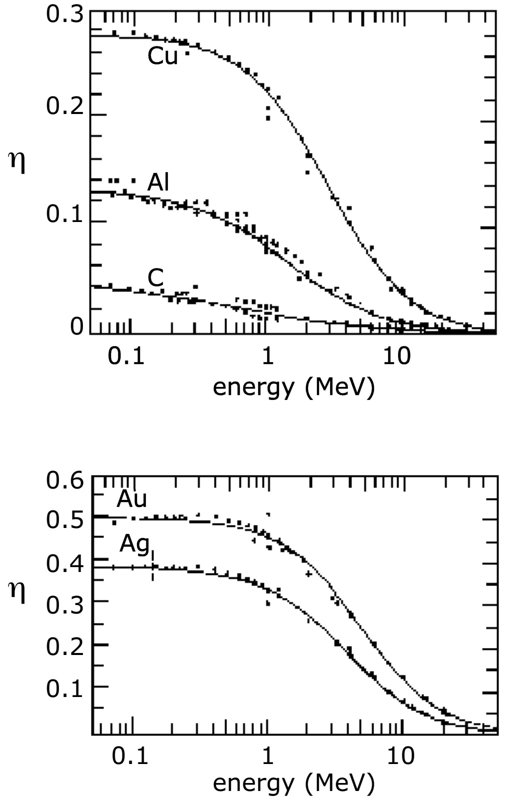

Figure 3.9: Backscattering of Electrons in Different Media.

The phenomenon of backscattering is very important in spectrometers since the scattered radiation is likely to rebound from the detection chamber walls and arrive at the detector with a lower energy. It is also important from a health physics perspective. Backscattering tends to increase the dose rate to someone standing between a source and a shield, because the radiation can travel from the source, through the person, and be backscattered off the shield to pass through the person again.

Buildup

Significant amounts of secondary radiation may increase the dose rate on the other side of a shield in a way not predicted by the attenuation equation. This is due to Compton scattering and pair production, which will eliminate the original photon but produce other photons not taken into account by the equation. This increase in the amount of radiation is called **buildup**, and the attenuation equation can be corrected using a buildup factor:

$$I = I_0 \; B(x, E_\gamma) \, e^{-\mu x}$$

The buildup factor, $B\left(x, E_\gamma\right)$, is a complex function of thickness and incident gamma energy. Some health physics reference books list tables of buildup factors for shielding materials.

Chapter 4

Radiation Detectors

4.1 Characteristics of the Gas-Filled Chamber

Because people cannot detect ionizing radiation with their five senses, all detection of radioactivity relies on artificial instruments. The simplest, most generic type of detection instrument is the gas-filled chamber, shown in figure 4.1.

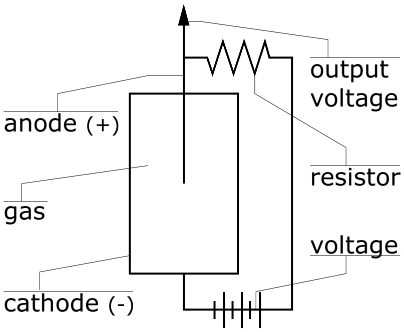

Figure 4.1: A typical gas-filled detector, the most generic radiation detector.

The fill-gas is usually an easily ionized substance such as nitrogen or a noble gas. The wall of the tube carries a negative charge and the inner wire carries a positive charge. When radiation is incident on the detector, electrons produced from the ionization of gas in the tube are attracted to the inner wire, and the remaining positive ions are attracted to the outside of the tube. This causes current to flow, changing the output, which is then sent to a meter.

The detector responds differently depending on the initial voltage across the tube. The plot of detector effect vs. voltage for different forms of radiation appears in figure 4.2.

At zero volts, the electrons produced by any kind of incident radiation are not attracted to the cathode or anode because there is no voltage difference, so the ion pairs recombine. As the voltage increases in this **recombination** region, more electrons become attracted to the anode (the positively charged central wire) and fewer recombine until the voltage difference is high enough to attract all the electrons to

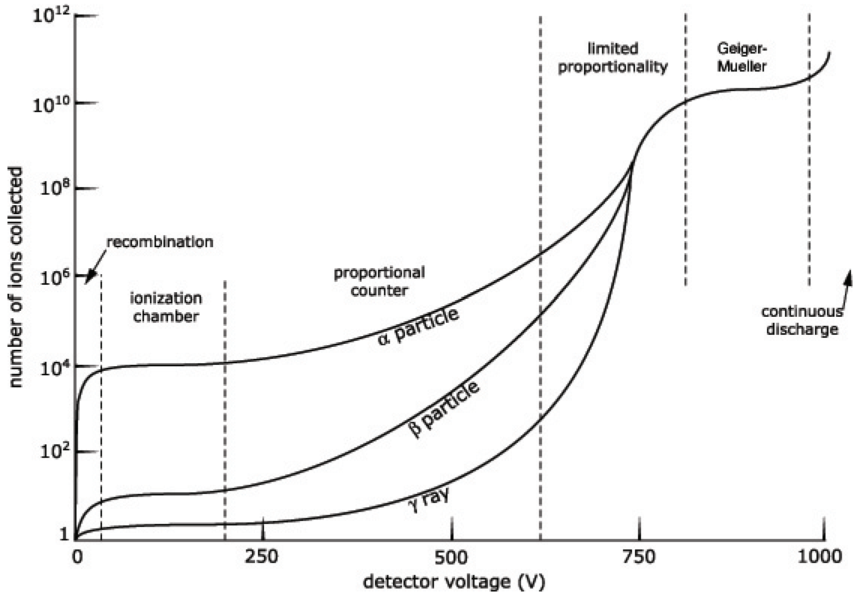

Figure 4.2: Voltage Plateau Curve. The number of ions collected by the detector increases as a function of voltage applied to the detector. Features of this curve are useful for different detection applications.

the wire. This starts the **ion chamber** region, where small increases in voltage do not significantly alter the amount of response, since no more free electrons exist to be attracted to the anode; all the ion pairs produced by the radiation are collected. Increasing the voltage above this region, however, does cause more free electrons to come into existence. The electrons liberated by the radiation incident on the detector are accelerated to the point that they are able to ionize some of the gas inside the detector; the number of additional electrons liberated increases as the voltage increases. This is called secondary ionization. In this region the number of additional electrons liberated is proportional to the number of ion pairs produced by the incident radiation, hence the name **proportional region**. In the ion chamber region and the proportional region, as shown in figure 4.2, different kinds of radiation produce different responses at a given detector voltage. This difference comes not from any qualitative difference between the forms of incident radiation, but rather a quantitative one. Alpha particles typically carry more energy than betas or gammas. Betas and gammas, in turn, can have energies over a wide range, so the lines representing beta and gamma irradiation on the graph actually represent only a typical energy of incident radiation. If a gamma ray entered this hypothetical detector with more energy than a given beta, the response from the gamma would be greater for a given voltage. Note that the vertical scale is logarithmic.

Increasing the voltage beyond the proportional region enters the region of limited proportionality, in which the detector reaction increases with increasing voltage, but non-linearly—no detectors operate in this region. Note that near the end of the region of limited proportionality the detector reactions to alpha, beta, and gamma radiation converge. This means the incident radiation produces the same number of ions in the chamber no matter how much energy it carries, because the entire tube is discharged by the secondary ionization produced by the large voltage across the tube. In the **Geiger-Mueller** region, the entire tube is discharged by secondary ionizations regardless of the incident radiation. Finally, in the **continuous discharge** region, the voltage is high enough to strip electrons off the gas without any incident radiation. This not only provides no useful information about incident radiation, it can also destroy the detector.

We will now discuss the three regions where detectors normally operate: Geiger-Mueller, Proportional, and Ion Chamber, starting at the higher voltages and moving down.

4.2 Geiger-Mueller Counters

Geiger-Mueller counters, commonly referred to as GM tubes or GM counters, are designed to operate in the eponymous region of the detector curve. A Geiger counter simply counts the number of radiation interactions that take place in the gas-filled chamber. Any radiation regardless of energy will create the same size pulse. Although many GM counters have displays reading in mR/hr, they are in fact measuring counts per minute (cpm). The mR/hr scale only has meaning for the type and energy of the radiation that was used to calibrate the instrument. In an environment where many different types and energies of radiation may be encountered, such as the reactor, the mR/hr scale cannot be used to measure the dose rate from a radiation field. If the dose needs to be known, an ion chamber should be used instead.

In the **GM** region, the voltage difference between the anode and cathode is sufficiently high that any ionizing radiation creates an **avalanche** of ions. All types of radiation of sufficiently high energy produce the same effect on the detector, making it impossible to differentiate between alpha, beta, or gamma radiation.

The operation of a GM can best be explained in terms of its design.

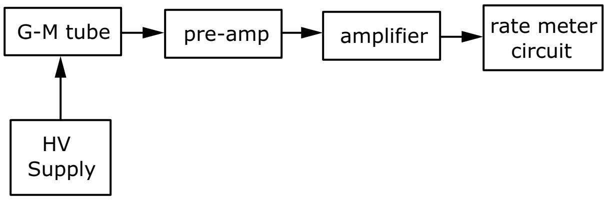

Figure 4.3: Schematic of a Geiger-Mueller Counter.

The voltage supply provides a potential difference across the gas-filled portion of the detector. Radiation enters the chamber and ionizes the gas, which produces secondary ionizations, and the tube discharges producing a current pulse. The preamplifier amplifies this pulse. A ”preamp,” as it is commonly called, must be in close proximity to the detector, as its job is to amplify the signal before much noise is introduced by the detector electronics and cables. The pulse is then sent to an amplifier, where it is boosted to a strength that is usable by the rate meter circuitry. The rate meter then converts the number of pulses produced by the detector into a readout like the deflection of a needle on a meter face or an audible click.

An exception to the rule that GM counters cannot measure dose is the **energy compensated GM**. This type of detector has a tin or lead covering that is designed to attenuate incoming photons penetrating the covering at a rate that is proportional to the energy of those photons. For example, it will detect 100 keV gammas with 10% of the efficiency that it detects 1000 keV gammas. Thus, the number of counts registered by the detector is proportional to the energy of the gammas, so it can be calibrated to display dose.

One very strong drawback to GM detectors is the large amount of time between the first ionization and when the meter regains the ability to register another ionization. This characteristic is known as **dead time**, and a second pulse entering during this time cannot cause a second avalanche of ionizations to occur. Dead time in a GM is typically about 300 microseconds, and is immediately followed by another lag known as **recovery time**. This second period is the time during which new pulses are registered as part of the same event; that is, the amplitude of the pulse produced by the second incident particle is too small to be registered on the detector but is sufficiently large to cause further ionization, so that a second dead time lag occurs. If the GM tube is presented with many ionizations close together in time, it will cease to register any of them, making the meter stop clicking, and the meter face will read zero cpm. This process is known as **swamping**, and because of it GM detectors must never be used to measure large radiation fields.

In less extreme cases, where the ionizing particles are incident on the GM at a sufficiently slow rate that the meter is not swamped, but still fast enough that some events are not fully registered, a correction formula can be used, so that the actual number of incident particles per unit time can be detected:

$$R = \frac{R_{obs}}{1 - R_{obs}T}$$

where the variables are:

$$\begin{aligned} R &= \text{the count rate incident on the detector (cps)} \\ R_{obs} &= \text{the count rate measured by the detector (cps)} \\ T &= \text{the dead time of the detector (s)} \end{aligned}$$

Example 4.1 A GM is reading 100 cpm and has a dead time T of 300 μs. What is the percent difference between the observed and incident count rates? What is the difference for the same detector if the observed count rate is 1000 cpm? 2000 cpm?

Solution.

$$
\begin{aligned}
R &= \frac{R_{obs}}{1 - R_{obs}T} \\
\frac{R_{obs}}{R} &= 1 - R_{obs}T \\
&= (1 - \frac{100}{60} \times 0.0003) = 99.95\% \\
&= (1 - \frac{1000}{60} \times 0.0003) = 99.5\% \\
&= (1 - \frac{2000}{60} \times 0.0003) = 99\%
\end{aligned}
$$

□

4.3 Proportional Counters

In a proportional counter, the voltage is lower than in a GM tube. It is low enough that the incident ionizing radiation does not fully discharge the tube, so radiation with different ionizing potentials produce different sized pulses. Also, proportional counters do not swamp like GM counters. A schematic of a typical proportional counter is as shown in figure 4.4.

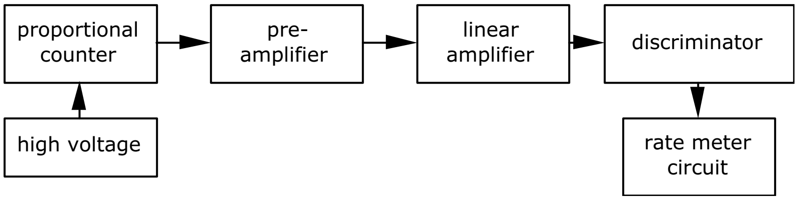

Figure 4.4: Schematic of a Proportional Counter.

The high voltage maintains the electric field between the anode and cathode so that incident radiation causes a pulse of current to flow. The signal is then sent through a pre-amplifier and an amplifier, and then a discriminator. The discriminator decides whether or not a pulse is big enough to be registered; if it is, the pulse is passed to the rate meter circuit. Proportional counters are more sensitive than ion chambers but can still differentiate between various types of radiation, making them well suited for specialized instrumentation used to detect low levels of highly ionizing radiation, such as alpha particles, discriminating out the other forms of radiation.

4.4 Ionization Chambers

The last important type of gas-filled chamber is the ionization chamber, commonly called an ion chamber, or IC. Unlike the GM tube, ion chambers directly measure the amount of energy deposited within the gas-filled chamber; as a result, the reading is in rad per hour rather than counts per minute. Ion chambers are also not subject to the swamping effects like GM counters. This makes the ion chamber essential for health physics to determine the amount of radiation to which personnel are exposed. The design of a typical ion chamber is shown in figure 4.5.

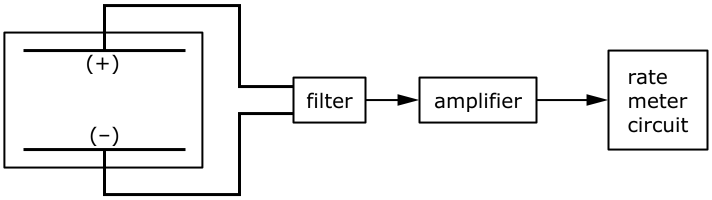

Figure 4.5: Schematic of an ionization chamber.

As a fill-gas, ion chambers usually have a hydrocarbon, such as propane or an argon-hydrocarbon mixture. In figure 4.5, the anode and cathode shown are parallel plates, to underscore that an ion chamber is like a capacitor. The relation between the voltage, V, across the plates and charge, Q, between them is given by:

$$Q = CV$$

where C is the capacitance of the chamber.

As with other chambers, the free electrons are attracted to the anode and the positive ions are attracted to the cathode. This causes a current to flow, which is amplified and displayed by the attached electronics. Each radiation particle that enters the ion chamber ionizes some of the gas atoms in the chamber. The voltage applied across the chamber is high enough to accelerate the electrons freed by the ionizations, but low enough so that the accelerating electrons and ions do not cause any secondary ionizations in the chamber. So, the number of ion-pairs produced by the incident radiation is directly proportional to the energy of that radiation. The number of ion-pairs is related to the incident energy by the formula

$$P_I = E/W$$

where E is the energy of the particle and W is the average energy needed to produce an ion pair; W is approximately 30—40 eV for most gasses.

Since the number of ion pairs produced is proportional to the energy of the incident radiation, and since the radiation dose is measured as energy deposited per unit mass, the ion chamber can directly measure dose. Radiation that deposits more energy will produce a larger signal. If it is desired to differentiate the dose due to different types of radiation, a shield can be used to eliminate the weaker radiation.

Example 4.2 An ion chamber reads a radiation source as 100 rad per hour. When an aluminum shield is placed between the ion chamber and the radiation source, the reading drops to 10 rad/hour. What are the gamma and beta dose rates?

Solution. With the shield in place, only gammas are measured, so the gamma dose rate is 10 rad/hour. Without the shield, both gamma and beta are measured, so the beta dose rate must be 90 rad/hour. ☐

4.5 Scintillation Detectors

The ionization of atoms in a gas-filled chamber is only one mode of radiation detection. Another common kind of detector takes advantage of a physical property of some materials known as luminescence, the absorption of a particle and release of an equivalent amount of energy as light. If this process takes more than 10^{-8} seconds, it is known as phosphorescence. Most scintillation detectors measure the light produced by a phosphorescent reaction.

The schematic of a typical **scintillation detector** is as shown in figure 4.6.

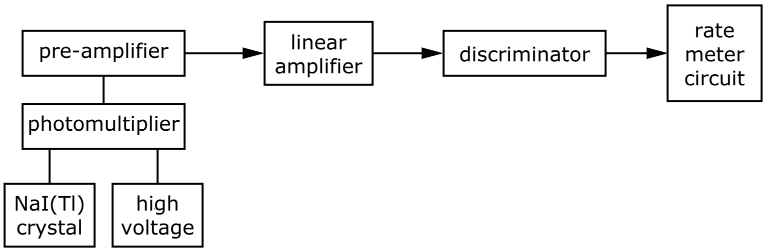

Figure 4.6: Schematic of a Scintillation counter.

The first component of the system is the crystal used to produce the light; the most common type is sodium iodide, an inorganic crystal. We speak of scintillation in inorganic crystals in the parlance of solid-state physics, so the next few paragraphs will serve as an introduction to solid-state physics using sodium iodide as an example.

The basic electronic structure of a solid is characterized by its band structure. Single atoms have discrete atomic orbitals, molecules have more complex molecular orbitals, and extended solids have bands. Just as electrons can move between atomic orbitals if enough energy is supplied or taken from the system, electrons can move between the bands in a solid if similar energy requirements are met.

A pure solid, such as NaI, has two bands: the valence band and the conduction band. When an electron only has sufficient energy to reside in the valence band, it is bound to an atom. If an electron is given an amount of energy greater than the energy difference between the top of the valence band and the bottom of the conduction band, the electron severs its bonds with all the other atoms and becomes delocalized—it is no longer fixed to a particular region in the crystal. It then resides in the conduction band, and it is these conduction electrons that are capable of contributing to a current through the material. In a metal, no energy needs to be supplied to the electrons to promote them to the conduction band, so metals conduct all the time. In an insulator, the band gap is ridiculously large, so that very few electrons can make the promotion. Semiconductors have a reasonably sized band gap, and this gives them their unique and useful properties.

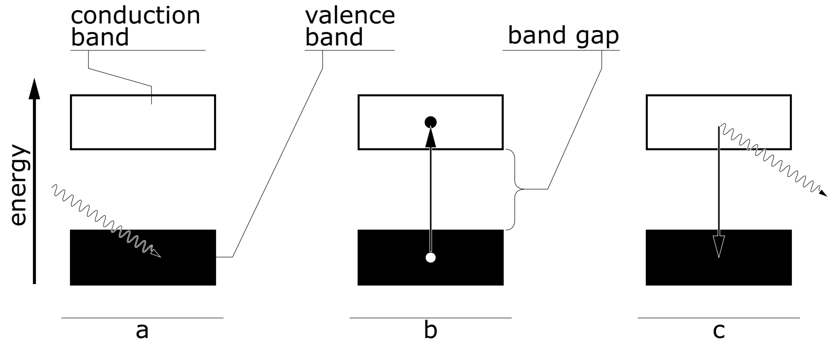

Figure 4.7: Illustration of how the population of a band in a semiconductor changes. in (a) energy is deposited. In (b) an electron is promoted. In (c) an excited state decays by photon emission.

When a gamma ray enters a NaI crystal, it imparts energy to some of the electrons through ionization, as shown in figure 4.7a. These electrons are promoted to the conduction band and are free to move about the crystal as in figure 4.7b. This leaves a tiny region of positive charge, called a hole, which behaves like a positively charged electron. You can think of this ”hole” as sort of an air bubble that forms in the sea of electrons in the crystal. Now, if the crystal is pure, this excited state, with the electron in the conduction band and the hole in the valence band, will decay by emitting a photon, shown in figure 4.7c. That photon is of an energy equal to the band gap. The photon can then either be reabsorbed by the crystal to create another electron-hole pair, or it can escape the crystal, in which case the energy is lost. The continual excitation and decay is not terribly useful to the application of radiation detection. What we want is some material that will absorb the gamma ray, and then produce some number of smaller photons that can be collected elsewhere. So, we add a little bit of thallium to the sodium iodide crystal, which is represented as NaI(Tl). The electronic structure of the thallium atom is very different from that of the sodium iodide matrix. Regions of the crystal that contain a thallium atom have a more complex band structure than the bulk of the crystal. These regions are called active sites. When an electron hole pair is formed, the hole migrates through the crystal until it comes upon a thallium atom. The hole comes to rest in the thallium atom, ionizing it. The original electron from the hole creation also migrates through the crystal, and is drawn to the now positively charged thallium atom. The electron must undergo several electronic transitions to reach the ground state on that thallium atom, as shown in figure 4.8, and each of these transitions emits a photon that is not of sufficient energy to promote an electron in the NaI crystal. The crystal matrix is transparent to these photons, and they can be easily collected.

Organic crystals are sometimes used in the place of NaI, particularly for beta counting. Anthracene and stilbene are commonly used organic crystals. The chief

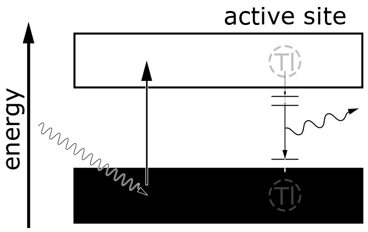

Figure 4.8: Band structure of an active site in NaI(Tl).

difference between how scintillation is accomplished in organic and inorganic crystals is that in organic crystals the incident radiation produces an electronic excitation in the scintillator, whereas in inorganic crystals the incident radiation produces ionizations. In both cases, the number of these excited states is proportional to the energy of the radiation, and the excited states decay with the emission of visible light.

The light that is produced by the scintillator is converted into an electronic signal by a **photomultiplier**.

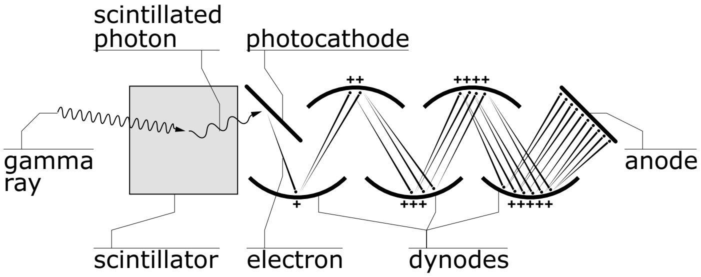

Figure 4.9: Photomultiplier tube.

When light is incident on the **photocathode**, electrons are ejected from its surface via the photoelectric effect. Since the actual number of electrons produced is relatively small, this small current must be amplified; this is accomplished by a series of increasingly positively charged dynodes. Dynodes are electrodes that provide secondary emission. When an electron lands on one of the dynodes, it ejects several electrons from its surface. The ejected electrons are then accelerated to the next dynode, where even more electrons are ejected. In this manner, a large output current can be produced from a small light pulse from the scintillator. The voltage required to operate a photomultiplier is very large, typically 1300 volts. A linear amplifier, discriminator, and rate meter circuit operate on the output of the photomultiplier tube as described previously in this chapter.

Unfortunately, crystal scintillators are not suitable for detecting the low energy beta particles produced by tritium and carbon-14, both frequently used in biological experiments, since the beta particles have such low energies that they are stopped by virtually anything other than air. Similarly, these devices cannot detect alpha particles.

Liquid scintillation detectors are similar to the scintillation detectors just described in that they also use photo-multiplier tubes to measure the light produced in a fluorescent reaction (scintillation is fluorescence due to radiation). Instead of a solid crystal of NaI, liquid scintillation detectors use organic liquids to produce light. Often the radioactive source is dissolved in to the scintillating liquid. This immersion liquid allows scintillation detectors to have an extremely high efficiency and allows them to be able to detect the low-energy betas and alphas which crystalline scintillation detectors cannot. Since samples are dissolved into the detector, attenuation by detector windows and beta back-scattering are eliminated.

Fluorescence in organic substances occurs when there is a transition in energy of a single molecule, whereas fluorescence in inorganic crystals is a property of the crystalline lattice. This property of organics allows them to fluoresce in any physical state (solid, liquid, etc.). An organic molecule will jump to a higher energy level when it interacts with a radioactive substance.

The detector's cocktail will contain a solvent to dissolve the source and solute, the scintillating liquid, an emulsifier to ensure proper mixing and uniform suspension of the source particles, and a wave-lengthening solute. Possible solvents are tolulene, dioaxane, and a series of new biodegradable and non-toxic solutes. Anthracene is a common scintillating solute.

As stated earlier, by construction the efficiency of liquid scintillation detectors is very high. Radiationless de-excitation of a molecule lowers the efficiency of the detector. This is known as quenching. There are two main forms of quenching. Optical quenching occurs when something in the solute absorbs some of the light before it leaves the solution. Chemical quenching occurs when atoms de-excite by a method other than releasing light (such as releasing heat). Interactions between the solutes can lead to chemical quenching. Impurities such as oxygen can lead to optical quenching.

If absorption and emission occur at the same wavelength, the scintillator's released photons would be easily reabsorbed. If this occurred in the scintillating cocktail, it would greatly decrease the efficiency of the detector. Fortunately it does not happen very often. This is because when a molecule moves to an excited state, it most commonly moves to a higher vibrational state in the excited state and decays without emitting radiation to the base excited state. The photon is emitted as the molecule moves from the base excited singlet state to the ground state.

The most common arrangement for the detector is the liquid solution between two photocathode tubes. For a light pulse to be an accepted count, it has to register on both tubes in a short and pre-determined time. This helps to eliminate background radiation counts. The electronics used to analyze the flashes are the same as the crystalline scintillation detectors.

4.6 Personal Radiation Monitors

Personal Ion Chambers

Many kinds of personal dosimeters exist; the electrometer is one of the oldest and simplest designs. An electrometer is commonly called a **personal ion chamber**, or a **PIC** for short. Its design is based on the gold-leaf electroscope. In an electroscope, a piece of gold leaf is folded in half and suspended from a wire. The gold is charged, and the like charges on the surface of the leaf open it up, much like a book. Ionization of the air in the electroscope allows charge to leak off the gold leaf, and the two halves fold back together. Similarly, a PIC has a quartz fiber that is displaced electrostatically like the gold leaves. Incident radiation ionizes the air in the PIC, and the ions neutralize some of the charge on the fiber, so the fiber moves back toward its uncharged position. The movement of the fiber can be seen through the built-in microscope, which has marks calibrated to measure the dose received. The dosimeter can be recharged via the charging assembly.

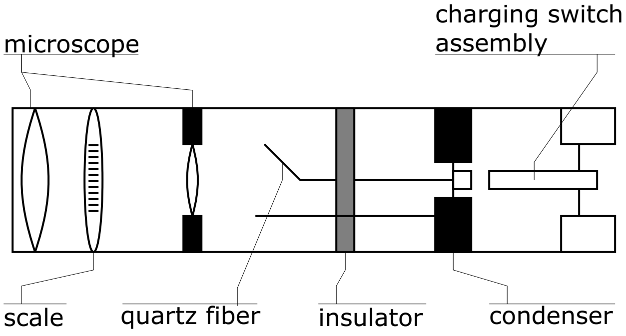

Figure 4.10: Personal Ionization Chamber.

The PIC has the advantage that it gives an instantaneous reading of accumulated dose and does not need special processing. However, the electrometer is very sensitive to static electricity, so an act as simple as wearing the PIC against a wool sweater can cause a false reading. It is also sensitive to heat, and dropping the dosimeter can cause the fiber to move, creating yet another opportunity for error. The PICs are not very accurate for measuring dosage; typical accuracy is ±20%.

Electronic Personal Dosimetry

Another popular type of personal dosimeters is the **electronic personal dosimetry** (**EPD**). The EPD is basically a small energy compensated GM detector with a digital display. In addition to the dose received, it can also display the dose rate and can be designed to alarm at a preset dose or dose rate. The EPD is not particularly sensitive to static or temperature, but it can be affected by electromagnetic radiation such as given off by two-way radios or high voltage equipment. EPDs are typically accurate to ±10%.

Thermoluminescent Dosimeters

As discussed above, incident radiation can raise an electron to a higher energy level in a crystal where it can be trapped in an active site. Only a small amount of energy is required to allow an electron trapped in an active site to return to the ground state. In many crystals the ambient thermal energy is enough to allow this transition. In some crystals, however, the thermal energy at room temperature is not enough. So, when electrons are promoted, they become trapped at the active site, storing the energy of the transition until enough energy is supplied to the crystal to allow for that transition. So, when a material like this is irradiated, lots of electrons are promoted to the active sites and stored there. Later, the crystal can be heated and the photons from the decay of those excited states can be collected. The number of photons produced is proportional to the total amount of energy deposited in the crystal by the gamma rays. In this manner, the total dose to the crystal can be measured. Such a crystal is called a **thermoluminescent dosimeter** (**TLD**).

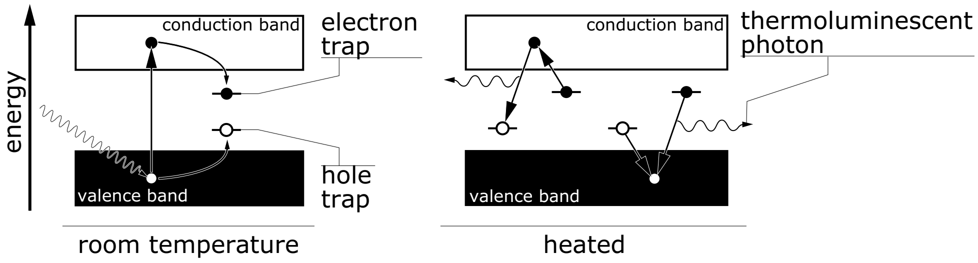

Figure 4.11: Thermoluminescence mechanism.

A principle advantage of TLDs is their linear calibration curve.

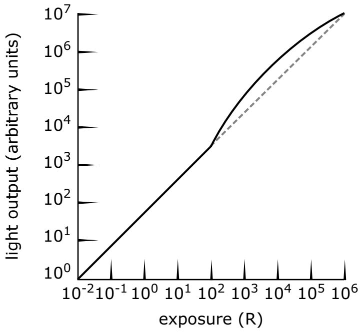

Figure 4.12: Thermoluminescent response curve.

The supralinear region of the curve occurs above 1000 R, which is twice the LD_{50} level and virtually never needs to be measured in dosimetry applications. TLDs have a very wide response range, so high and low doses can be measured by the same kind of crystal. TLDs also have the advantage of being able to be reused; after the crystal has been heated to a certain temperature and the photon emission recorded, it can be further heated, liberating all the electrons and "erasing" the record of exposure. This further heating of the crystal is called annealing.

The TLD crystal is made from a semiconductor material; LiF is one of the most common. This substance is especially useful because it has an atomic number very close to that of tissue, and thus tends to respond the same way that tissue does to radiation. LiF can be isotopically enriched in various ways so that certain particles are excluded from measurement; lithium-7 is insensitive to neutrons and lithium-6 is insensitive to fast neutrons and most low mass particles. Other common TLD crystals are $CaSO_4$ and CaF_2. Activators often used to dope TLDs include manganese, magnesium, and dysprosium.

Optically Stimulated Luminescence

A recent improvement on the TLD is the **optically stimulated luminescence** (**OSL**). OSL crystals are made of aluminum oxide and work via the same mechanism as the TLD, except that it is read by stimulating the detector with light instead of heat. A laser light stimulates the aluminum oxide after use, causing it to become luminescent in proportion to the amount of radiation exposure. Only a few of the electrons are released, so the OSL can be read again; it is a permanent record. Thus, OSLs are not reissued.

In addition to the ability to reanalyze to confirm the radiation dose measurement, OSLs have a large dynamic measurement range and increased sensitivity. Whereas TLDs do not normally indicate doses below 10 mrem, OSLs can register a dose as low as 1 mrem.

4.7 Other Detectors

Film Badges

Another common dosimeter is the film badge. Essentially, when black and white film is exposed to ionizing radiation, the silver bromide crystals receive enough energy to reduce into free silver. This forms a small image, often called the latent image, on the film, which is amplified during the development process and is seen as dark spots on the film. Generally, the darkness of the film is proportional to the amount of radiation to which it has been exposed.

An important consideration in reading film badges is that the film's sensitivity, i.e., how much it darkens for a given amount of exposure, is dependent on the energy of the incident radiation. Basically, the film over-responds to photons with energy less than 400 keV. This problem can be overcome by filtering the film, that is, encasing it in a material capable of absorbing low energy photons, usually a metal. These are known as low-Z filters because metals with low atomic numbers (Z) are used. Sometimes, in order to determine the dose from various types of radiation, other filters are placed over small portions of the film so that the dose rate due to several kinds of radiation can be determined.

Spectrometers

Spectrometers are a very important detector application for sample analysis. Spectrometers operate on the principle that radioactive samples emit gamma and beta particles of particular energies; thus, by finding the energies of particles emitted by the radioisotope, its content can be determined. Thus, **spectrometers** can be used to find either the content of samples or, if the concentrations of isotopes in the sample are known, the flux of the reactor during the experiment. Spectrometers rely on the detectors described above; their electronics are far more complex and will not be discussed in this manual.

Chapter 5

Health Physics

This chapter discusses radiation units, sources of ionizing radiation, how radiation affects living cells, the effects of radiation on humans, how to minimize the risks from radiation, and federal limits on radiation dose. Generally, these topics are called Health Physics. This discussion is limited to ionizing radiation, i.e., radiation with enough energy to remove electrons from neutral atoms.

5.1 Radioactive Material and Contamination

Some of the terms in the field of Health Physics are used with less precision in common speech and especially in the media. These terms need to be used precisely by radiation workers to avoid confusion. These terms are also defined in chapter 7.

Radiation is energy in transit in the form of high-speed particles and electromagnetic waves. The forms of radiation most commonly encountered are alpha, beta, gamma, and X-rays. At nuclear reactors neutron radiation is also present, and at accelerator facilities high-speed charged particles such as protons are present. Radiation is the actual particles or waves traveling through space or material.

Radioactivity is the spontaneous transformation of an unstable atom. When an atom undergoes radioactive decay, it usually emits one or more forms of radiation. Typical radioactive material produced in a nuclear reactor has too many neutrons and will emit a negative beta particle to balance its neutron and proton configuration, and the newly produced element normally emits one or more gamma rays and an X-ray. Some light elements often emit a beta particle without emitting a gamma ray. Elements heavier than bismuth will often emit an alpha particle and the newly produced element normally emits an X-ray. Many other mechanisms and combinations of radiation occur during radioactive decay. Radioactivity is measured in units of becquerels or curies.

Radioactive material is any material containing unstable (radioactive) atoms. Radioactive materials therefore emit radiation. The material will remain radioactive until all its unstable atoms decay, but practically speaking, after the material has gone through 10 half-lives there are so few radioactive atoms present that it may no longer be detectable. **Radioactive contamination** is radioactive material in a place where it is not desired. We expect and desire to have radioactive material in sample vials and sealed sources. If the radioactive material leaks to the outside of the containers or onto the floor, it becomes contamination. Contamination is usually measured in units of activity (becquerels, microcuries, or disintegrations per minute) per unit area. Typically, an area is considered to be contaminated if it measures 1000 dpm per 100 cm^2. A disintegration is the ejection of an alpha or beta particle from a nucleus. A dpm, or disintegrations per minute, are the number of alpha or beta particles ejected from a nucleus in a minute. Contamination is usually found with a GM counter, and the disintegrations are found by

$$\text{dpm} = \frac{\text{cpm}}{\text{efficiency}}$$

where efficiency is the efficiency of the detector.

Normally, radiation does not make things radioactive. Something that is exposed to radiation does not become radioactive (neutron radiation being a significant exception). Putting something next to radioactive material does not make it radioactive, although if they touch each other some radioactive material may rub off and contaminate the nonradioactive item. A person who is exposed to radiation does not become radioactive—even if a large overdose occurs the person may suffer biological damage but they do not become radioactive and thus they do not pose a radioactive hazard to others.

5.2 Units of Radiation Exposure and Dose

In order to discuss radiation protection adequately, it is necessary to consider the units used. Unlike units of radioactivity (becquerels or curies), dose is concerned with the portion of energy deposited into the material by the radiation. It is the absorbed energy that determines the biological effect. In order to evaluate the amount of energy deposited in material, the duration of exposure, the area irradiated, and the type and energy of the radiation must be considered. There are several terms used to describe the radiation received.

Exposure

Exposure is defined as a measure of a photon's ability to produce ionizations in air. The unit of exposure is the roentgen (R), equivalent to 2.58×10^{-4} coulombs per kg of dry air. The use of the roentgen is restricted to X-ray or gamma radiation (photons) and only applies in air. It was developed because it is easy to measure. The exposure rate is the exposure per unit time (R/hr). Although the units roentgen and R/hr are still used, they are archaic. Typically, instruments labeled with the unit R really mean the unit rad, which is discussed next.

Absorbed dose

Although it is easier to measure the radiation in air, it is more useful to know how it is affecting other materials, like human tissue. A unit of **absorbed dose** was defined as the energy deposited in matter. The absorbed dose can be expressed in terms of the energy deposited, E_d, in a material of mass, m, by

$$\text{Absorbed dose} = \frac{E_d}{m}$$

The historical unit of absorbed dose is the **rad**. By definition:

$$1 \text{ rad} = 100 \text{ erg/g} = 0.01 \text{ J/kg}$$

The SI unit corresponding to the rad is the **Gray** (Gy):

$$1 \text{ Gy} = 1 \text{ J/kg}$$
$$1 \text{ Gy} = 100 \text{ rad}$$

Since biological effects result from energy imparted to tissue, the absorbed dose is closely associated with biological effects. Unlike the roentgen, the absorbed dose applies to any medium. Furthermore, while roentgens refer only to photons, the absorbed dose may be used for any type of ionizing radiation, e.g., alpha, beta, or neutrons.

Dose equivalent

Radiation damage depends on the energy deposited and how concentrated it is. If all of the energy of the incident radiation is deposited in a small volume, the chance of biological damage such as cancer is higher than if the same energy is deposited over a larger volume. The body has the ability to repair the radiation damage if it is not too concentrated. Therefore, radiation that deposits all of its energy in a small volume does more biological damage for the amount of energy deposited. The energy deposited per unit distance traveled by the particle is known as **linear energy transfer** (LET). Radiation with higher LET does more biological damage per total energy deposited. The conversion factor to change energy deposited (rad) into biological damage is the **quality factor**, Q. Quality factors represent ratios of the biological response by one type of radiation compared to another. Table 5.1 shows quality factor values.

The quality factor can be used to express the energy deposited in biological tissue with a unit that represents the biological damage, **rem**. The rem reflects not only the amount of energy deposited but also the amount of biological damage derived from such energy. It is equal to the product of the rad and the quality factor—this product is called the **dose equivalent**.

$$\text{rem} = \text{rad} \times Q$$

The SI unit corresponding to the rem is the **Sievert** (Sv):

$$1 \text{ Sv} = 1 \text{ Gy} \times Q$$
$$1 \text{ Sv} = 100 \text{ rem}$$

Radiation	Q
X-ray, gamma	1
Beta	1
Alpha, heavy recoil nuclei	20
Neutrons; unknown energy	10
Neutrons; thermal	2
Neutrons; fast	11

Table 5.1: Quality factors are derived from their LET. The most important quality factors are those for alpha, beta, gamma, X-rays, and neutrons of unknown energy.

Regulations governing ionizing radiation exposure are expressed in rem. Most facilities work with nuclides that only emit X-ray, gamma or beta. Since their quality factors are all equal to one, 1 R $\approx$ 1 rad = 1 rem. Because of this, the terms dose and dose equivalent are often used interchangeably, especially when talking about dose rates. If one is working with emitters with $Q > 1$, great care should be taken to use the correct terms.

Example 5.1 If a person is exposed to a 1 mrad from a neutron source, what is the dose equivalent?

Solution. Since the energy of the neutron source was not specified, we will use a quality factor of 10 from table 5.1.

$$\begin{aligned}\text{Dose Equivalent} &= \text{Absorbed Dose} \times Q \\ &= 1 \text{ mrad} \times 10 \\ &= 10 \text{ mrem}\end{aligned}$$

□

In cases of dose to internal organs, an additional modifying factor is included. This factor corrects for non-uniform distribution of the radionuclide in the body. For example, if the lungs were exposed to a certain dose from internally deposited radioactive material, the overall risk to the body is less than if the entire body were exposed to the same dose. The ratio of the organ risk to the whole body is known as the **weighting factor**, w_f. By definition, all of the weighting factors add up to one. Table 5.2 lists the weighting factors that the Nuclear Regulatory Commission uses.

5.3 Sources of Background Radiation

Apart from the radiation that workers may receive while performing their work, they are also exposed to radiation from the environment. Everyone is exposed to some

Organ or tissue	Weighting Factor
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surface	0.03
Remainder of body	0.30

Table 5.2: Weighting factors for internal organs.

radiation even though they may not work with radioactive material. This natural source of exposure is referred to as **background radiation**.

Background radiation has three main sources: cosmic radiation, cosmogenic sources, and primordial sources. Cosmic radiation affects people directly; the other two sources of radioactive material reach humans through the earth's soil, air, and water. Artificial sources also have a contribution. Although the amount which each of these factors contributes varies with the locale, each locale will have a background level.

The study of these factors is of value for a number of reasons. Foremost among these is that the use of such data provides a basis or standard from which allowable exposure limits for radiation workers may be developed. Also, in areas where the background levels are much higher, knowledge may be gained about human hereditary effects at these increased levels. To date, no correlation has been shown between cancer or genetic defects and areas with higher background levels of radiation.

Cosmic radiation

Cosmic rays refer to high-energy, extraterrestrial radiation. This radiation primarily comes from outside the solar system. Primary cosmic radiation is 87% protons, 12% alpha particles, and 1% other light nuclei. When the high-energy particles of the cosmic rays collide with atoms of the atmosphere, many products are emitted: electrons, photons, protons, neutrons, and other exotic particles, such as mesons. These, in turn, produce other secondary radiation as they collide with elements or decay on the way toward the earth's surface. Thus, a multiplication or shower occurs in which as many as a thousand secondary particles may result from a single primary ray. Most primary rays are absorbed in the upper 10% of the atmosphere. At the earth's surface, cosmic rays are almost wholly secondary in nature and consist of 63% mesons, 15% electrons, and 21% neutrons. At sea level the dose rate from ionizing radiation is about 50 mrem/year at middle latitudes. This dose rate increases with altitude and decreases with latitude.

Cosmogenic sources

In addition to the direct radiation, cosmic radiation produces radioactive nuclides in the atmosphere. The cosmic radiation hits O_2 or N_2 in the atmosphere and produces nuclear transformations. The largest cosmogenic isotopes are ^{3}H (tritium) and ^{14}C. These isotopes circulate through the atmosphere, and we are exposed to it through our air, water, and food. Approximately 200,000 atoms of ^{14}C from cosmogenic sources decay in the human body every minute; ^{14}C produces a weak beta particle that does not leave the body, so the dose is all internal.

Primordial sources

When the earth was formed some 4.5 billion years ago, many radioactive isotopes were present. Today, the only isotopes still around are the long-lived ones and the decay products of the long lived ones. The most important primordial isotopes are ^{235}U, ^{238}U, ^{233}Th, and ^{40}K.

Uranium and thorium are in the earth's crust almost everywhere. In the top foot of an average acre of topsoil there are 10 kg of uranium and 30 kg of thorium. Additionally, as discussed in chapter 2, they decay into nuclides that are also radioactive. These materials expose people to ionizing radiation externally through the soil and building materials, and they also enter the body through food and water. Their largest impact, however, is through the air.

The background that is found in air is due mainly to the presence of radon gas, formed as decay products of the uranium and thorium series. The decay of ^{238}U proceeds to the gas ^{222}Rn. Although uranium and its decay products are present everywhere in the earth's crust, they normally stay there and only reach us in minute quantities. However, radon is a noble gas and diffuses up through the earth's surface to become airborne. In turn, the decay products of the gas attach to dust in the air. It is common that the levels indoors are much higher than those outdoors, and the basement has higher levels than the rest of the house. Over half of the background dose people normally receive is due to radon gas, although there has not been a demonstrated link between lung cancer and household levels of radon.

Other than radon, the largest source of radiation dose to the public is from potassium. Potassium-40 is left over from the formation of the earth (its half-life is 1.26 billion years). Since about 0.011% of all potassium is ^{40}K and 0.2% of the human body is potassium, approximately 200,000 atoms of ^{40}K decay in a person's body each minute. ^{40}K produces a beta particle and a 1.46 MeV gamma so the dose is not only internal, but it also hits people standing nearby.

Artificial sources

Several sources of radioactive materials contributing to background radiation are a direct result of technology. These sources include fallout from weapons testing, radionuclides generated from power reactors and coal burning plants, wastes from various nuclear industries, and medical therapies. By far the largest source of artificial sources for Americans is diagnostic X-rays.

Radiation Source	Dose (mrem/year)
Natural radon gas	200
internal isotopes	40
Medical diagnostic X-rays	40
Cosmic rays	30
Terrestrial isotopes	30
Nuclear medicine	14
Consumer products	10
Occupational dose	1
Miscellaneous artificial	< 0.1
Nuclear power	< 0.001
Total:	**365**

Table 5.3: Average annual effective dose to the U.S. public.

Table 5.3 shows the approximate average annual effective dose of various sources of ionizing radiation to U.S. public. Note that this averages about 1 mrem per day.

5.4 Radiation Effects

A great many agents can cause injuries to cells. When such injury occurs the effects are the same regardless of the agent that caused the damage. Ionizing radiation produces damage to cells, but in a mostly nonspecific way. That is, other physical and chemical substances cause the same effects and the body responds the same regardless of the cause. The effect of radiation on cells is well understood.

Radiation passing through cells can ionize atoms in the cell structure. These changes affect the forces that bind the atoms together into molecules. If the molecule breaks up, some of the parts will be charged. These fragments are called radicals and ions; they are not chemically stable. Because the cell has a high water content, the most important radicals are those formed from water molecules. Further effects are produced when the radicals and ions interact with other cell material. In this way, damage is caused in a direct or an indirect manner. Of the damage that is done, the effects are greatest in the nucleus of the cell, but injury to the cytoplasm can also cause serious effects in the cell. The cell processes will be affected in varying degrees. The most likely event is that the radical or ion causes no damage to the cell. The next most likely event is that damage to the cell will be repaired by action of the cell itself or by replacement of badly injured cells in a given tissue through mitosis of healthy cells. The radiation damage may kill the cell. Another effect is that the cell may be unable to reproduce. There is also a possibility that the radiation may damage the cell to produce a cancerous tumor.

Factors affecting radiation effects

Radiation effects are not dependent solely on the amount of radiation received. Other factors influence the biological effects of radiation. The rate at which a radiation dose is received is an important factor in determining its effect. This is because living tissue is not inert; as soon as damage is produced, healing will begin. Thus, if a particular dose is delivered over a long period of time, it is possible that repair may keep up with the damage so that no detectable change would be produced. On the other hand, if the same dose is delivered all at once, a noticeable reaction may result. A dose delivered in a short period of time (e.g., less than 24 hours) is called an **acute dose**. A dose delivered over a long period of time is called a **chronic dose**.

As discussed previously, the type of radiation is an important factor in determining its effect. Radiation with a high Linear Energy Transfer (LET), such as alpha particles, have a greater biological effect for the energy deposited. The damage is concentrated in a few cells and can overwhelm their repair mechanism.

In general, the larger the area of the body that receives a dose, the greater the damage. Extremities are less sensitive than internal organs. Cells that are well oxygenated — that is, those with a good blood supply — are more sensitive.

The age of the exposed individual can greatly affect sensitivity to radiation. When organs are developing before birth the sensitivity is high, because differentiating cells and cells undergoing rapid division are more easily damaged. Similarly, in the period between birth and maturity, high rates of cell division and further differentiation make a child more sensitive to radiation dose. An adult is more resistant to radiation effects. Similarly, for older persons whose life expectancy has decreased, radiation effects that might appear only after a long time, for example tumor induction, would not be as significant as with younger people.

Since the cells that make up the tissues of the body differ both in structure and function, one might suspect that their response to radiation would also differ. Such is the case, and this property is known as the **radiosensitivity** of the cell. It has been found that the radiosensitivity of a tissue is directly proportional to the reproductive capacity and varies inversely with the degree of differentiation. Other factors include the metabolic state of the cell, the state of cell division, and the state of nourishment.

Thus, cells that are most active in reproducing themselves, cells that have a high metabolic rate (rate of chemical changes in the cell), and those cells that are more nourished than others are more sensitive to radiation. Moreover, cells not fully mature will also be more harmed by radiation than mature cells. In the body, the digestive system, bone marrow, lymphoic tissues, and the reproductive organs rank among the most radiosensitive. Muscle, nerve, and bone cells are the least radiosensitive.

Types of dose effects

One may broadly classify biological effects as somatic, genetic, or teratogenic. **Somatic effects** include any and all types of damage that affect only the individual who was exposed to the radiation; **genetic effects** are those effects that can be transmitted to a future generation, and **teratogenic effects** are those in an exposed fetus. Thus, damage to the genes of a somatic cell may produce damage to an offspring cell, but this would be a somatic effect since that genetic damage cannot be passed on to offspring. The term genetic damage refers to chromosome and/or gene mutations in the egg or sperm cells, which affects the offspring. Genetic effects have never been observed in human beings, even following Hiroshima, Nagasaki, and Chernobyl. They have been observed in plants and animals and are considered possible for humans. Teratogenic effects, sadly, are well documented in the survivors of nuclear weapons.

Somatic effects can be further subdivided into prompt and delayed effects. **Prompt effects**, including radiation sickness, are discussed below. **Delayed effects** include cataracts and bone deformation, but the major delayed effect is cancer. The clinical effects following an acute (short term) dose of ionizing radiation are given in table 5.4.

Additionally, there are two families of somatic effects: stochastic and deterministic (also called non-stochastic). **Stochastic effects** occur randomly with the probability of the occurrence related to the dose. There is no relationship between severity and dose. That means that a larger dose increases the chances of the occurrence, but it does not increase the severity of occurrence. The primary example of a stochastic effect is cancer: a larger dose increases the chance of cancer but does not guarantee that cancer will occur. Moreover, the cancers are not worse at higher doses. **Deterministic** or **non-stochastic effects** will nearly always produce a predicted effect at a definite dose. There is a minimum dose required to produce effect called "threshold" dose. The magnitude of effect increases with dose. Thus, if you get enough radiation this effect will occur, and larger doses will increase the severity. The primary examples are acute radiation sickness, erythema, and cataracts. The concept of the median lethal dose (LD_{50}) is the acute dose at which 50% of those exposed would die within 30 days. For humans, the best estimate places the LD_{50} between 300 and 500 rad.

Internal dose

With external radiation, the dose to an individual can be reduced with shielding, distance, or shortening of the exposure time. An **internal dose** due to the deposition of radionuclides inside the body as a result of ingestion, inhalation, or skin absorption poses an entirely different problem, and the effect depends on several factors. In this case, nuclides whose radiation have very short ranges (high LET) are the most hazardous, for they dissipate all their energy within a very restricted volume of tissue. Thus, alpha emitters present the greatest internal hazard. The physical and chemical form of the radioactive material also determines its effects.

An added hazard from internal emitters exists where a given radionuclide is selectively concentrated in the body, rather than generally distributed, since it will produce a more intense local irradiation. Examples of this selective concentration are iodine in the thyroid gland, or plutonium, radium, and strontium in the bones.

The radiation dose from an internal radioactive source continues only as long as the nuclide remains in the system. This factor is influenced by both the radiological half-life of the particular nuclide and its **biological half-life**—that is, the length of time until one-half of a given amount is excreted. The **effective half-life** ($t_{1/2,E}$) of the radioactive material is given by the expression

$$t_{1/2,E} = \frac{(t_{1/2} \times t_{1/2,B})}{(t_{1/2} + t_{1/2,B})}$$

where $t_{1/2}$ is the radiological half-life and $t_{1/2,B}$ is the biological half-life.

Acute effects

For a very large dose delivered in a very short time, the prompt effects are (unfortunately) well documented. One prompt effect is on the gastrointestinal system. The intestinal epithelium are rapidly changing cells in the intestinal lining. When these are damaged the results are dehydration, diarrhea, hemorrhaging, and infection. The **hemopoietic effects** describe how the blood system responds. White blood cell count is immediately reduced increasing the chance of infection. Platelet count drops increasing the risk of internal bleeding. The red blood cell count drops due to bone marrow damage if the dose is over 200 rad. Skin reddening (**erythema**) is likely above 200 rad skin dose. Other skin effects can include hair loss (**epilation**), blistering, ulceration, and necrosis. Temporary sterility is caused in men above 30 rad, and in women above 300 rad. Above 600 rad, the central nervous system fails.

Dose-effect curve

Scientists try to develop a relationship between radiation dose and effect. The major difficulty is that mostly all the observed effects are at high doses and dose rates, and these must be extrapolated to low doses and dose rates. The problem is complicated because such low dose effects generally develop years after the dose. Also, the same effects may be caused by something other than the radiation. Figure 5.1 shows the commonly accepted models. Note that all predictions below a dose of approximately 10 rem are speculation. Curve A assumes that at some unspecified low **threshold dose**, there is no biological effect—the cell repairs itself. Thus, a dose below point a has no adverse effects. Curve B assumes that the effects are linear down to zero dose with no threshold — the **linear no threshold** effect (LNT). Therefore, cutting the dose in half reduces the effect by half, but it is never zero for any dose.

Note the tentative dotted line below zero on the vertical access on Curve A. Some scientists believe that low levels of radiation are good for humans. Similar to many trace elements, a small amount may be necessary for good health but a large amount can be toxic. This theory is known as **hormesis**. However, the

Dose (rad)	Probable observed effect of acute whole body dose
Below 25	No observable effects.
25 to 100	Chromosomal aberrations. Temporary depression of red and white blood cell levels. Lymph nodes and spleen injured. No externally observable effects.
100 to 300	Mild to severe nausea, malaise, and infection. Moderate blood changes. Recovery expected within a few weeks.
300 to 600	Severe nausea, malaise, diarrhea, and infection within a few hours. Loss of hair after 2 weeks. Recovery from 1 to 12 months at the lower end of the dose range; only 20% survive at the upper end of the range. Probably fatal above 350 rad without treatment.
Over 600	Same as above plus impairment of the central nervous system. Incapacitated above 1000 rad. Death is expected.

Table 5.4: Prompt effects of an acute radiation dose. Note the virtual absence of any symptoms in the range below 100 rad. Some people would be expected to have mild symptoms in the range 25-100 rad because of differences among individuals. Below 25 rad, however, no symptoms at all are expected except a slight increase in the cancer risk. Note that the units are rad, not mrad.

overwhelming majority of scientists disagree, and regulations and policies assume that a small amount of risk is associated with any radiation dose. All regulations are based on the linear no threshold effect.

5.5 Risks in Perspective

No increase in cancer risks have been observed for doses below 10 rem. We assume that there is an increased cancer risk, but there may be no increased risk at all. The cancer rate among Americans is approximately 20%; thus a person has a one in five chance of getting cancer regardless of any occupational radiation dose. The linear no threshold model predicts that a radiation worker who gets an additional 5 rem during his career (which is above the average) increases his chance of cancer by 0.1%—from 20% to 20.1%. To put radiation dose in perspective, note the estimated loss of life expectancy from various health risks in table 5.5.

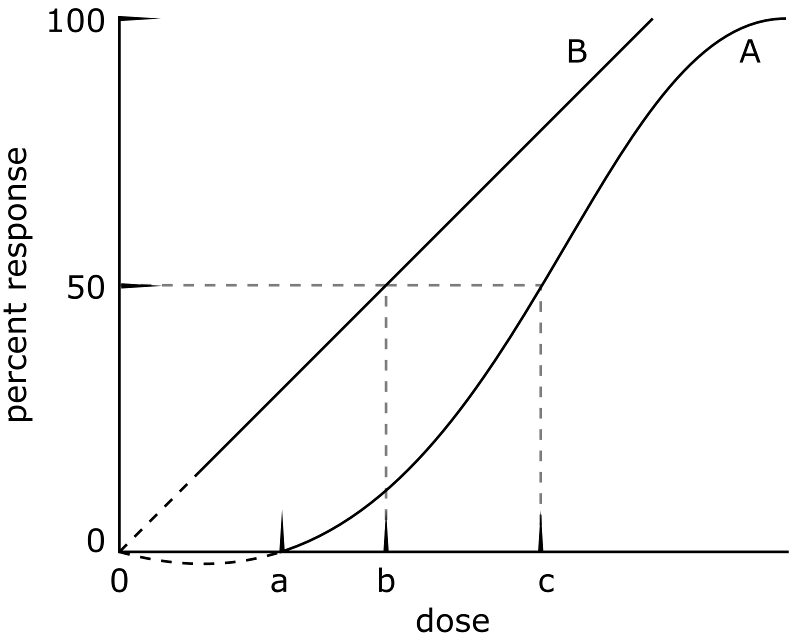

Figure 5.1: Dose-effect curves for the threshold and linear no threshold models.

5.6 ALARA: As Low As Reasonably Achievable

The **ALARA** (As Low As Reasonably Achievable) philosophy is one of the basic principles of health physics. It says that since any radiation dose has a potential risk involved, each action should be taken considering the potential risk and the benefit to be gained, and the action should be designed to minimize the risk (i.e., the radiation dose). This is true regardless of whether any regulatory limits are approached. This philosophy is supported by the federal and state governments, and by Reed College. The highest yearly whole-body radiation dose at Reed was about 200 mR and was received by the reactor health physicist who was performing an operation requiring close handling of a very large source. Only a few individuals have received doses of more than 50 mrem; most have recorded doses of zero. There is no reason why doses cannot be kept just as low in the future.

The primary method of controlling dose is engineering controls—the facilities and labs are designed to reduce dose. The second method is administrative controls—rules and procedures are in place to reduce dose. The last method is personal protective equipment—respirators, etc. Three factors that primarily determine the dose one receives in a given situation are: (1) the time of dose; (2) distance from the source; and (3) amount of shielding present.

Health risk	Estimated loss of life expectancy
Smoking 20 cigarettes a day	6 years
Overweight by 15%	2 years
Average U.S. alcohol consumption	1 year
Agricultural accidents	320 days
Construction accidents	227 days
Automobile accidents	207 days
Home accidents	74 days
Radiation exposure of 1 rem per year for 50 years	54 days
All natural hazards (earthquake, floods, lightning, etc.)	7 days
Medical radiation	6 days

Table 5.5: Estimated loss of life expectancy from various health risks. The radiation dose of 1 rem per year is exceptionally high.

Time

The time factor means that the longer one remains in a radiation field, the greater the dose received will be:

$$\text{Total dose} = \text{Dose rate} \times \text{Time}$$

Sometimes work must be performed in a strong radiation field. In this case, the work should be planned outside the work area so that a minimum amount of time is used to complete the job. All tools and supplies should be assembled beforehand and a mock-up and practice may be done. If the time required for one worker to complete the job would result in a large dose, then a team of workers should take turns—this would mean a smaller dose for several people instead of a large dose for one individual.

> **Example 5.2** Assume that work must be done in a gamma field of 50 mR/hr. If we want to arbitrarily limit the dose to 30 mrem, how long can someone work in this area?
>
> *Solution.* The Q for gamma rays is 1, so the dose rate equivalent is 50 mrem/hr.
>
> $$\begin{aligned} \text{Total dose} &= \text{Dose rate} \times \text{Time} \\ \Longrightarrow \text{Time} &= \frac{\text{Total Dose}}{\text{Dose Rate}} \\ &= 30 \text{ mrem}/50 \text{ mrem/hr} \\ &= 0.6 \text{ hours} = \boxed{36 \text{ minutes}} \end{aligned}$$
>
> □

Distance

The dose rate given by a radiation field decreases with distance from the source. For a point source of penetrating radiation, the decrease in dose rate is inversely proportional to the square of the distance between any two radial points from the source. If DR_1 and DR_2 are the dose rates at two distances d_1 and d_2 respectively, we know that

$$\frac{DR_1}{DR_2} = \left(\frac{d_2}{d_1}\right)^2$$

Or, rearranging the terms,

$$DR_1\,(d_1)^2 = DR_2\,(d_2)^2$$

This **inverse square law** can be utilized only when the dimensions of the source and the measuring device are small compared with the distance between them and the distances are measurements in air or vacuum. For other than point sources, the dose rate will decrease inversely with distance, but not necessarily as the square of the distance. Although dose is always lower at greater distances from a source, the mathematical equation for inverse square only works for photon sources; betas and alphas have fixed ranges in various material.

Example 5.3 If a gamma source measures 300 mR/hr at one foot, what will it measure at three feet?

Solution. Starting with the previous equation, we can solve for DR_2 to get

$$\begin{aligned} DR_2 &= \frac{DR_1}{(d_2/d_1)^2} \\ &= \frac{300 \text{ mR/hr}}{(3/1)^2} \\ &= \boxed{33 \text{ mR/hr}} \end{aligned}$$

□

Example 5.4 If we assume the source described above is to be handled at a distance of 1 inch, then what will be the absorbed dose (in rem) to the hands if it is handled for 10 minutes?

Solution. Since the source is gamma, use a Q of 1. So 300 mR = 300 mrem.

$$\begin{aligned} DR_2 &= \frac{DR_1}{(d_2/d_1)^2} \\ &= \frac{300 \text{ mrem/hr}}{((1/12)/1)^2} \\ &= 43000 \text{ mrem/hr} = 43 \text{ rem/hr} \\ \Longrightarrow \text{Dose} &= (43 \text{ rem/hr}) \times (1/6 \text{ hr}) \\ &= \boxed{7.2 \text{ rem}} \end{aligned}$$

□

If *a priori* knowledge exists of the activity of a sample, and if it is only gamma emitting, then the following equation can be used to determine the dose rate

$$DR = \frac{6\,CE}{d^2}$$

where DR is the dose rate in rem/hr, C is activity in curies, E is the energy of the gamma ray in MeV, and d is the distance from the point source in feet. Commonly, a source will emit gammas of several different energies; in that case, we sum the energies:

$$DR = \frac{6\,C}{d^2}(E_1 + E_2 + \cdots + E_n)$$

A gamma ray is not always emitted after a disintegration, so some references will list the probability of emission for each gamma energy. In that case, the substitution $E \rightarrow E \times p$ should be made, where p is the probability of emission. If this information is unavailable, simply assume $p = 1$ for each gamma energy.

Example 5.5 What is the dose rate at 2 feet from a 0.7 curie cobalt-60 source?

Solution. Consulting the chart of the nuclides, we see that cobalt-60 primarily emits two gammas with energies 1.173 MeV and 1.332 MeV. An online database of radioactive nulides [ie.lbl.gov/tio/nucSearch.asp] gives the probability of emission for both of these gammas as nearly 100%. So, we can compute the dose rate using

$$\begin{aligned} DR &= \frac{6CE}{d^2} \\ &= \frac{(6)(0.7)(1.173 + 1.332)}{2^2} \\ &= \boxed{2.63 \text{ rem/hr}} \end{aligned}$$

□

Shielding

Shielding is a medium of some thickness that will stop or effectively attenuate radiation. The effectiveness of the shield is determined by the interactions between the incident radiation and the atoms of the absorbing medium. The interactions that take place depend mainly upon the type of radiation, the energy of the radiation, the atomic number of the absorbing medium, and its density. Shielding materials and properties for the different types of radiation were discussed in chapter 3, Interactions of Radiation with Matter.

In choosing a shielding material, our first consideration must be personnel protection. However, other factors may influence our choice of material: is it economical, is it too heavy, how much space is there for the shield, does it have proper structural strength, and will it create a toxicity problem?

Other Considerations

There are other considerations that can help to reduce radiation dose. **Source reduction** involves reducing the quantity or strength of the radioactive sources that produce the dose. **Contamination control** can reduce the source material and will significantly reduce the chance of internal contamination. **Pathway control** reduces the chances of inhalation, ingestion, injection, and skin absorption. Related to personal protection, **waste reduction** is important. This is an attempt to reduce the volume of radioactive waste produced. This can be done by, for instance, segregating contaminated from non-contaminated waste, or limiting the materials that might be contaminated. Remember: reduce, reuse, recycle.

Chapter 6

Common Radionuclides

6.1 Tritium

Symbol: ^{3}H
States or Forms: Soluble except in gaseous form

Physical Characteristics

Radioactive Half Life: 12 years
Decay Type: β^{-}
Maximum Energy Emission: 0.0186 MeV
Maximum Range in Air: 0.6 cm
Maximum Range in Water or Tissue: 0.0006 cm

Hazard Category

A Level (High Hazard): $>$ 10.0 Ci
B Level (Moderate Hazard): $>$ 25 mCi to 10.0 Ci
C Level (Low Hazard): 1 mCi to 25 mCi

Radiological Characteristics

- 0% of beta particle energy transmitted through dead layer of skin.

Critical Organ: Body water or tissue
Routes of Intake: Ingestion, inhalation, puncture, wound, skin absorption
Internal Exposure and Contamination: Primary radiological concerns with ^{3}H
External Exposure: External exposure from weak ^{3}H beta particles is not a major radiological concern.

Dosimetry

Film badges and dosimeter rings are not appropriate for monitoring ^{3}H. Its beta particle is not a major external radiological concern.

Bioassay Requirements

Routine urinalysis is needed after handling 100 μCi or greater of ^{3}H. Spot checks may be necessary following spills or incidents of contamination.

External Radiation Hazards and Shielding

There is minimal external hazard with ^{3}H, i.e., the vial containing the ^{3}H provides sufficient shielding from the beta particles. If the skin is contaminated with ^{3}H, the betas will not be able to penetrate through the dead layer of skin. However, if ^{3}H is absorbed into the body via ingestion or cuts in the skin, it will cause a radiation dose.

Hazards if Internally Deposited

Annual Limit of Intake: 80 mCi by ingestion or inhalation
Derived Air Concentration: 2×10^{-5} μCi/mL

Survey Instrumentation

- Tritium cannot be detected using a GM-tube or a NaI survey meter.

- Wipe tests, using liquid scintillation counters, are required to detect ^{3}H contamination.

Problems and Precautions

- It is assumed that ingested or inhaled ^{3}H labeled compounds are instantly distributed throughout the organs and tissues of the body, where they are retained with the biological half-life of 10 days.

- Lab coats and protective gloves should always be worn when working with ^{3}H to keep skin free from contamination, and gloves should be changed often.

- All waste in a ^{3}H work area is considered to be contaminated. Work areas should be kept free of unnecessary items.

- Wastes should be segregated into those with ^{3}H and ^{14}C only.

6.2 Carbon - 14

Symbol: ^{14}C
States or Forms: Soluble, except in gaseous form

Physical Characteristics

Radioactive Half Life: 5730 years
Decay Type: β^-
Maximum Energy Emission: 0.156 MeV
Maximum Range in Air: 21-25 cm
Maximum Range in Water or Tissue: 0.028 cm
Maximum Range in Plexiglas or Lucite: 0.025 cm

Hazard Category

A Level (High Hazard): $>$ 1.0 Ci
B Level (Moderate Hazard): $>$ 10 mCi to 1.0 Ci
C Level (Low Hazard): 0.1 mCi to 10 mCi

Radiological Characteristics

- 17% of a beta particle's energy is transmitted through the dead layer of skin.

Critical Organ: Fat Tissue
Routes of Intake: Ingestion, inhalation, puncture, wound, skin absorption
Internal Exposure and Contamination: Primary radiological concerns with ^{14}C
External Exposure: External exposure from weak ^{14}C beta particles is not a major radiological concern.

Dosimetry

Film badges and dosimeter rings are not appropriate for monitoring ^{14}C exposure.

Bioassay Requirements

Urinalysis and breath measurements of CO_2 may be require after spills or incidents of contamination.

External Radiation Hazards and Shielding

There is a minimal external hazard with ^{14}C, i.e., the glass vial containing the ^{14}C provides sufficient shielding from the beta particles. If the skin is uniformly contaminated with ^{14}C, 1μCi/cm^2 will deliver a dose of 1100 mrems per hour to the basal skin cells.

Hazards if Internally Deposited

Annual Limit of Intake: 2400 μCi by ingestion or inhalation
Derived Air Concentration: 1×10^{-6} μCi per mL

Survey Instrumentation

- A GM-tube can be used to detect ^{14}C; however, the survey meter probe must be within 1 inch of the source.
- GM-tubes have a very low efficiency (around 3%) for counting low energy ^{14}C beta particles.
- Wipe tests, using liquid scintillation counters, are required to detect removable ^{14}C contamination.

Problems and Precautions

- Lab coats and protective gloves should always be worn when working with ^{14}C to keep skin free of contamination, and gloves should be changed often.
- All waste in a ^{14}C work area is considered to be contaminated. Work areas should be kept free of unnecessary items.
- Wastes should be segregated to those with ^{3}H and ^{14}C only.
- It is assumed that ingested or inhaled ^{14}C labeled compounds are instantly distributed throughout the organs and tissues of the body, where they are retained with the biological half-life of 40 days.

6.3 Phosphorus-32

Symbol: ^{32}P
States or Forms: Soluble

Physical Characteristics

Radioactive Half Life: 14.3 days
Decay Type: β^-
Maximum Energy Emission: 1.71 MeV
Maximum Range in Air: 600 cm
Maximum Range in Water or Tissue: 0.76 cm
Maximum Range in Plexiglas or Lucite: 0.61 cm

Hazard Catagory

A Level (High Hazard): > 100 mCi
B Level (Moderate Hazard): > 2 mCi to 100 mCi
C Level (Low Hazard): 0.01 mCi to 2 mCi

Radiological Characteristics

- 95% of beta particle energy is transmitted through dead layer of skin.

Critical Organs: Body tissues - 70%, Bone - 30%
Routes of Intake: Ingestion, inhalation, puncture, wound, skin absorption
Internal Exposure and Contamination: Primary radiological concerns ^{32}P
External Exposure: Primary radiological concern with ^{32}P

Dosimetry

Film badges and dosimeter rings should be used if 1 millicurie or more is to be handled at a given time, or if millicurie levels are used frequently.

Bioassay Requirement

Urinalysis may be required after spills or incidents of contamination.

External Radiation Hazards and Shielding

Assuming there is no backscatter or self-absorption, the dose rate at 10 cm is 2.7 rads/hour from an unshielded 1mCi dried sample of ^{32}P. If the skin is contaminated with ^{32}P, 1 microcurie/cm^2 will deliver a dose of 9200 miilirads per hour (mrad/hr) to the basal cells of the epidermis. Lead foil or sheets, or other high density materials, should **never** be used to shield ^{32}P directly due to the production of penetrating Bremsstrahlung x-rays. Lead materials can be used as shielding from Bremsstrahlung x-rays **only** if behind low-density plexiglass, acrylic, lucite, or wood shielding.

Hazards if Internally Deposited

Annual Limit of Intake:
600 μCi by ingestion (all compounds)
900 μCi by inhalation (except phosphates)
400 μCi by inhalation (phosphates)
Derived Air Concentration:
2×10^{-5} μCi/mL

Survey Instrumentation

A GM-tube survey detector with a frisker probe can be used to detect ^{32}P. A low-energy NaI probe can only be used to detect Bremsstrahlung x-rays. Liquid scintillation counters should be used to detect removable surface ^{32}P contamination using smear or swabs.

Problems and Precautions

- Phosphorus-32 is commonly the highest energy radionuclide encountered in a research setting, and thus requires special caution. Exposure should be avoided and handling should be limited as much as possible.
- Always wear a lab coat, disposable gloves, and safety goggles when working with ^{32}P.
- Bremsstrahlung x-ray production must be avoided by working behind low Z shielding, preferably transparent materials.
- Surveys should be conducted frequently and gloves should be changed often. Waste should be segregated to those with half-lives of less than 19 days.

6.4 Sulfur-35

Symbol: ^{35}S
States or Forms: Soluble, except in gaseous form

Physical Characteristics

Radioactive Half Life: 87 days
Decay Type: β^-
Maximum Energy Emission: 0.167 MeV
Maximum Range in Air: 26 cm
Maximum Range in Water or Tissue: 0.04 cm
Maximum Range in Plexiglas or Lucite: 0.025 cm

Hazard Category:

A Level (High Hazard): > 1 Ci
B Level (Moderate Hazard): > 20 mCi to 1 Ci
C Level (Low Hazard): 0.1 mCi to 20 mCi

Radiological Characteristics

- About 15% of beta particle energy is transmitted through dead layer of skin.

Critical Organs: Testes
Routes of Intake: Ingestion, inhalation, puncture, wound, skin absorption
Internal Exposure and Contamination: Primary radiological concern with ^{35}S
External Exposure: Minimal concern for ^{35}S

Dosimetry

Film badges and dosimeter rings are not appropriate for monitoring ^{35}S exposure.

Bioassay Requirements

Urinanalysis may be required after spills or incidents of contamination,

External Radiation Hazards and Shielding

There is minimal external hazard with ^{35}S, i.e., the glass vial containing the ^{35}S provides sufficient shielding from the beta particles; however, lucite or plexiglas may be used as shielding. If the skin is uniformly contaminated with ^{35}S, 1 microcurie/cm^2 will deliver a dose of 1200 millrads per hour to the basal skin cells.

Hazards if Internally Deposited

Annual Limit of Intake: 1×10^4 μCi by ingestion
Derived Air Concentration: 2×10^{-8} μCi per mL

Survey Instrumentation

- A GM-tube can be used to detect ^{35}S; however, the survey meter probe must be within an inch of the source.
- A GM-tube with a frisker probe has a very low counting efficiency for ^{35}S, about 4%.
- Liquid scintillation counters should be used to detect removable surface ^{35}S contamination using smears or swabs.

Problems and Precautions:

- Lab coats and protective gloves should always be worn when working with ^{35}S to keep skin free from contamination, and gloves should be changed often,
- All waste in a ^{35}S work area is considered to be contaminated. Work areas should be kept free of unnecessary items.
- ^{35}S compounds are often volatile or produce volatile products. ^{35}S should be opened and handled in a fume hood.
- Activated charcoal should be used when incubating samples.
- Waste should be segregated to those with half-lives greater than 90 days and those with half-lives less than 90 days.

6.5 Iodine-125

Symbol: ^{125}I
States or Forms: Inorganic, Free Iodine

Physical Characteristics

Radioactive Half Life: 60 days
Decay Type: Electron capture, Gamma
Maximum Energy Emission: 0.035 (Gamma)

Hazard Category:

A Level (High Hazard): > 10 mCi
B Level (Moderate Hazard): 200 μCi to 10 mCi
C Level (Low Hazard): 0.1 μCi to 200 μCi

Radiological Characteristics

Critical Organ: Thyroid
Routes of Intake: Ingestion, inhalation, skin absorption
Internal Exposure and Contamination: Primary radiological concerns with ^{125}I
External Exposure: Concern for ^{125}I

Dosimetry

Film badges and dosimeter rings should be used if 5 mcuries or more is to be handled at a given time, or if mCi levels are handled frequently.

Bioassay Requirements

Thyroid scans

External Radiation Hazards and Shielding

The exposure rate at 1 cm for 1 mCi is 1.5 rads per hour. The exposure rate varies directly with activity and inversely with the square of the distance. 1/32 of an inch of lead shielding should be used when working with concentrations of > 1 μCi. Half an inch of lead shielding should be used with concentration of greater than 1 mCi.

Hazards if Internally Deposited

Annual Limit of Intake: 400 μCi by ingestion or 600 μCi by inhalation
Derived Air Concentration: 3×10^{-8} μCi per mL

Survey Instrumentation

- GM-tubes have a poor efficiency of detection for ^{125}I.
- Surveys should be done by a wipe tests or NaI scintillation probes should be used.

Problems and Precautions

- Store NaI-125 solutions at room temperature because freezing results in subsequent volatilization of radioiodine.
- Avoid acidic solutions to minimize volatilization.
- Wear two pair of gloves when handling radioiodine compounds.

Chapter 7

Glossary

7.1 Basic Nuclear Terms

atomic mass unit (amu) Carbon-12 was defined to weigh exactly 12 amu, and therefore, one amu is one-twelfth the mass of a neutral atom of C-12. (1 amu $= 1.66 \times 10^{-24}$ g)

atomic number (Z) The number of protons in the nucleus of an atom.

electron volt (eV) A unit of energy equal to the amount of energy gained by an electron passing through a potential difference of 1 volt.

ion Atomic particle, atom, or chemical radical with an electrical charge, either negative or positive.

isotopes Nuclides having the same number of protons in the nuclei, hence having the same atomic number, but differing in the number of neutrons and therefore in mass number. Almost identical chemical properties exist among isotopes of a particular element.

mass number (A) The number of protons and neutrons in the nucleus of an atom.

nuclide An atom characterized by its mass number, atomic number, and energy state of its nucleus.

7.2 Basic Radiation Terms

ionizing radiation Ionizing radiation is radiation with enough energy so that during an interaction with an atom, it can remove tightly bound electrons from their orbitals, causing the atom to become charged or ionized. Examples are gamma rays, alpha particles, and beta particles.

non-ionizing radiation Non-ionizing radiation is radiation without enough energy to remove tightly bound electrons from their orbitals around atoms. Examples are microwaves and visible light.

health physics Health physics is an interdisciplinary science with applications toward the radiation protection of humans and the environment. Health physics combines elements of physics, biology, chemistry, statistics, and electronic instrumentation to provide information that can be used to protect individuals from the effects of radiation.

radiation Radiation is energy in transit in the form of high-speed particles and electromagnetic waves. We encounter electromagnetic waves every day. They make up our visible light, radio and television waves, ultraviolet (UV), and microwaves. These examples of electromagnetic waves do not cause ionizations of atoms because they do not carry enough energy to separate molecules or remove electrons from atoms.

radioactive contamination Radioactive contamination is radioactive material distributed over some area, equipment, or person. It tends to be unwanted where it is and has to be cleaned up (decontaminated).

radioactive half-life The time required for a radioactive substance to lose 50 percent of its activity by decay.

radioactive material Radioactive material is any material that contains radioactive atoms.

radioactivity Radioactivity is the spontaneous transformation of an unstable atom and often results in the emission of radiation. This process is referred to as a transformation, decay, or disintegration of an atom.

specific activity Total activity of a given radionuclide per unit mass or volume. Examples are Bq/g or mCi/mL.

7.3 Common Types of Radiation

alpha (α) An alpha is a particle that is composed of two neutrons and two protons, which is emitted from the nucleus of an atom. It is identical to the nucleus of a helium atom, without the electrons.

beta (β) A beta is a high-speed particle, identical to an electron, emitted from the nucleus of an atom.

bremsstrahlung X-rays are produced by the acceleration or deceleration of charged particles. For example, a beta particle passing by an atom will be deflected by the electric field of the nucleus, causing a change in velocity (deceleration). It is German for "braking radiation."

electron capture A mode of radioactive decay involving the capture of an orbital electron by its nucleus, resulting in conversion of a proton to a neutron.

gamma (γ) Gamma rays are electromagnetic waves or photons emitted from the nucleus of an atom.

internal conversion A mode of radioactive decay that occurs when energy from an excited nucleus is transferred to an orbital electron. As a result, the electron is ejected from the electron cloud, and the radiation from the atom is in the form of an electron instead of a gamma ray.

neutrino (ν) A neutrino is a particle with zero rest mass and zero charge that is emitted from the nucleus of an atom in conjunction with types of radioactive decay to conserve fundamental principles.

positron (e^+) A positron is a particle that has the same mass as an electron and the same amount of charge, although the charge is positive.

X-rays X-rays are photons emitted as a result of energy changes in electrons. These energy changes are typically a result of transitions between electron orbital shells, although they are also emitted through other mechanisms like bremsstrahlung. X-rays are not emitted from the nucleus.

7.4 Common Units (US)

curie (Ci) The curie is a unit used to measure radioactivity. One curie is the quantity of a radioactive material that will have 37,000,000,000 transformations in one second. Radioactivity is often expressed in more manageable units such as thousandths (mCi), millionths (μCi), or even billionths (nCi) of a curie.

rad (radiation absorbed dose) The rad is a unit used to measure a quantity called absorbed dose. This relates to the amount of energy actually absorbed in some material, and is used for any type of radiation and any material. One rad is defined as the absorption of 100 ergs per gram of material. The unit rad can be used for any type of radiation, but it doesn't describe the biological effect from different radiations. The SI unit for the rad is the gray (see below).

rem (roentgen equivalent mammal) The rem is a unit used to derive a quantity called equivalent dose. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is often expressed in terms of thousandths of a rem, or mrem. To determine equivalent dose (rem), you multiply absorbed dose (rad) by an appropriate quality factor (Q).

roentgen (R) The roentgen is a unit used to measure a quantity called exposure. This can only be used to describe an amount of gamma and X-rays, and only in air. One roentgen is equal to depositing 2.58×10^{-4} coulombs per kg of dry air. It is a measure of the ionizations of the molecules in a mass of air. The main advantage of this unit is that it is easy to measure directly, but it is limited because it is only for deposition in air, and only for gamma and X-rays.

7.5 Common Units (SI: International Standard)

becquerel (Bq) The becquerel is a unit used to measure radioactivity. One becquerel is defined as one disintegration per second. Often radioactivity is expressed in larger units like thousands (kBq), millions (MBq), or even billions (GBq) of becquerels.

gray (Gy) The gray is a unit used to measure a quantity called absorbed dose. This relates to the amount of energy actually absorbed in some material, and is used for any type of radiation and any material. One gray is equal to one joule of energy deposited in one kg of a material. The unit gray can be used for any type of radiation, but it doesn't describe the biological effects of the different radiations. Absorbed dose is often expressed in terms of hundredths of a gray, or centigrays. One gray is equivalent to 100 rads.

sievert (Sv) The sievert is a unit used to derive a quantity called equivalent dose. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is often expressed in terms of millionths of a seiverts, or micro-seiverts. To determine equivalent dose (Sv), you multiply absorbed dose (Gy) by a quality factor (Q) that is unique to the type of incident radiation. One sievert is equivalent to 100 rem.

7.6 Radiation Detection

attenuation Process by which a beam of radiation is reduced in intensity when passing through material. It is a combination of absorption and scattering processes.

background radiation Ionizing radiation arising from sources other than the one directly under consideration. Background radiation due to cosmic rays and the natural radioactivity of materials in the earth and building materials is always present.

efficiency The ratio of the count rate detected by a radiation detection instrument and the actual disintegration rate of the material being counted.

Geiger-Mueller (GM) counter A radiation detection and measurement instrument. A gas-filled detector useful for finding contamination.

half value layer The thickness of any specified material necessary to reduce the intensity of an X-ray or gamma ray beam to one-half its original value.

ionization chamber (IC) A radiation detection and measurement instrument. A gas-filled detector useful for measuring dose rates.

scintillation counter A radiation detection and measurement instrument in which light flashes are produced in a scintillator by ionizing radiation and converted into electrical pulses by a photomultiplier tube.

thermoluminescent dosimeter (TLD) A dosimeter made of a crystalline material that stores energy when hit by ionizing radiation and releases the energy in the form of visible light when heated. The amount of light released can be used as a measure of absorbed dose.

optically stimulated luminescence dosimeter (OSL) A dosimeter made of aluminum oxide that stores energy when hit by ionizing radiation, and releases the energy in the form of visible light when stimulated with laser light. The amount of light released can be used as a measure of absorbed dose.

7.7 Terms Related to Radiation Dose

acute dose A radiation dose received over a short period of time.

ALARA An acronym for As Low As Reasonably Achievable. The principal that radiation doses should be kept as low as reasonably achievable while taking into account economic and social factors.

annual limit on intake (ALI) The derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year. ALI is the smaller value of intake of a given radionuclide in a year by the reference person that would result in a CEDE of 5 rem or a CDE of 50 rem to any individual organ or tissue.

biological half-life The time required for the body to eliminate by biological processes one-half of the amount of a substance that has entered it.

chronic dose A radiation dose recieved over a long period of time.

committed dose equivalent (CDE) The dose equivalent to organs or tissues of reference that will be received from an intake of radioactive material by an individual during the 50-year period following the intake.

committed effective dose equivalent (CEDE) The sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the CDE to these organs or tissues.

deep-dose equivalent (DDE) The dose equivalent at a tissue depth of 1 cm from external radiation.

deterministic effect Deterministic, or non-stochastic, effects are effects that can be related directly to the dose received. The effect is more severe with a higher dose, i.e., a radiation burn gets worse as dose increases. It typically has a threshold below which the effect will not occur. A skin burn from radiation is a deterministic effect.

dose A general term denoting the quantity of radiation or energy absorbed in a specified mass.

dose equivalent The product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest.

effective half-life Time required for a radioactive nuclide in the body to be diminished 50 percent as a result of the combined action of radioactive decay and biological elimination.

eye dose The dose equivalent at a tissue depth of 0.3 cm from external sources to the lens of the eye.

genetic effects Effects from an agent that are seen in the offspring of the individual who received the agent. The agent must be encountered pre-conception.

linear energy transfer (LET) Average amount of energy lost per unit track length by individual particles or photons while passing through an absorbing medium.

quality factor (Q) The LET-dependent modifying factor used to derive dose equivalent from absorbed dose.

shallow-dose equivalent The dose equivalent at a tissue depth of 0.007 cm from external exposure of the skin or an extremity.

somatic effects Effects from an agent, such as radiation, that are seen in the individual who receives the agent.

stochastic effects Effects that occur on a random basis, with its effect being independent of the size of dose. The effect typically has no threshold and is based on probabilities, with the chances of seeing the effect increasing with dose. Cancer is a stochastic effect.

teratogenic effects Effects from an agent that are seen in the offspring of the individual who received the agent. The agent must be encountered during the gestation period.

total effective dose equivalent (TEDE) The sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures). TEDE = DDE + CEDE.

weighting factor The proportion of the risk of stochastic effects for an organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly.