Chapter Three: Radiation in matter and Radiation Dose

In Chapters 1 and 2 we learned about the types of radiation produced through radioactive decays, why those decays occur, and how we quantify the rate at which they occur. We also briefly discussed the ways in which we can limit our exposure to different types of radiation through shielding, distance, and time. In this chapter, we will explore in much more detail how radiation actually interacts in matter: what happens when an alpha particle, an electron, or a gamma-ray encounters the atoms in a material. Understanding these interactions is essential for two reasons: first, it tells us how to effectively shield against different types of radiation; and second, it allows us to quantify the radiation dose, that is the amount of energy actually absorbed by a material, including our own bodies, as a result of exposure to radiation.

This chapter is organized into two main sections. In Section 3.1, we explore the physics of how different types of radiation interact in matter, including the dominant interaction mechanisms for charged particles and gamma-rays. In Section 3.2, we build on that understanding to define and calculate radiation dose, working through several examples that illustrate how we determine the actual energy absorbed by the human body from different sources of radioactivity.

3.1 Radiation Interactions in Matter

Before we can understand how radiation is detected, how shielding works, or how radiation dose is determined, we first need to understand how different types of radiation interact with the atoms in the materials they encounter. As we will see, the nature of these interactions depends critically on the properties of the radiation (its charge, mass, and energy) as well as the properties of the material it is passing through.

3.1.1 Properties of Decay Products

Let us begin by revisiting the major types of radiation produced in radioactive decays, focusing now on the properties that determine how each type will interact in matter.

Heavy charged particles, such as alpha particles (helium nuclei), protons, and fission products, share several important characteristics. They carry charge (positive, in all of these cases), they have significant mass, and they carry substantial kinetic energy. Alpha particles, for example, are typically emitted with energies in the range of 4 to 6 MeV. These are large, energetic, charged particles. As we will see, all three of these properties play a role in how they interact with matter.

Electrons (beta particles) also carry charge, but they are much smaller and lighter than alpha particles. The energies of beta particles can range from near zero up to a few MeV, depending on the specific decay. The rest mass energy of an electron is 511 keV (0.511 MeV), which we can determine from the relationship between mass and energy, $E = mc^2$. While electrons share the property of charge with heavy charged particles, their much smaller size leads to qualitatively different interaction behavior, as we will discuss shortly. Positrons (beta-plus particles) have the same mass as electrons and would interact in a similar manner, with one important difference at the end of their path that we will address below.

Gamma-rays are fundamentally different from charged particles. They have no charge and no mass, they are pure electromagnetic energy. Despite having effectively no size, gamma-rays still interact with matter through electromagnetic processes. However, because they lack charge and mass, their probability of interaction is much lower than that of charged particles, and the mechanisms of interaction are quite different.

Finally, ***neutrons*** have no charge but do have significant mass, comparable to that of a proton. Because they lack charge, neutrons cannot interact through the electromagnetic force the way charged particles do. Instead, neutrons interact through the strong nuclear force, the same force that holds the nucleus of an atom together. This makes neutrons more difficult to detect, and their interactions require specialized consideration that is beyond the scope of our discussion here.

3.1.2 Radiation in a Vacuum: Isotropic Emission and the Inverse-Square Law

Before considering interactions in matter, it is useful to think about what happens when radiation is emitted into a vacuum, where there are no particles for it to interact with. As we discussed in Chapter 1, all types of radiation are emitted ***isotropically***, meaning uniformly in all directions. There is no preferred direction for any radioactive decay.

Because the radiation spreads uniformly outward, at any distance r from the source, the radiation is distributed over the surface area of a sphere of that radius. The ***flux*** -- the number of particles passing through a unit area -- at distance r is therefore:

$$Flux = A / (4\pi r^2)$$

where A is the activity of the source (decays per second). If we place a detector of cross-sectional area A_D at that distance, the number of particles passing through the detector is simply the flux multiplied by the detector area, and then by the intrinsic detection efficiency. The key takeaway here is the ***$1/r^2$*** dependence: as we move farther from the source, the number of detected particles drops as the square of the distance. This is the inverse-square law that we introduced in Chapter 1.

3.1.3 Charged Particle Interactions: The Coulomb Force

Now let us consider what happens when radiation encounters matter, when there are atoms in the path of the radiation. For charged particles, the dominant mechanism of interaction is the ***Coulomb force***. The Coulomb force is the fundamental electromagnetic force between charged particles: like charges repel, and opposite charges attract. The strength of this force depends on the charges involved and drops off as $1/r^2$, just as the intensity of radiation does with distance.

Any charged particle passing through a material will interact with the electrons surrounding the atoms in that material through this Coulomb force. Even if the incoming particle does not physically collide with an electron, it will exert a force on nearby electrons as it passes, transferring some energy in the process. The closer the charged particle passes to an electron, the stronger the force and the greater the energy transfer. This means that charged particles do not need to make direct contact with atomic electrons to lose energy, they are constantly interacting with the electrons around them through the Coulomb force as they travel through a material.

3.1.4 Heavy Charged Particles in Matter

Consider an alpha particle traveling through some material, say, the gas inside a detector, or a piece of shielding. The alpha particle is large and carries significant positive charge (+2e). As it passes through the material, it interacts with the electrons orbiting the atoms via the Coulomb force. Because the alpha particle is so much more massive than the electrons it encounters, each individual interaction has only a small effect on the alpha particle itself. A useful analogy is that of a ***bowling ball rolling through a set of pins***: the bowling ball knocks over the pins, transferring energy to them, but continues on its path with relatively little change to its own trajectory or speed.

How does the energy transfer depend on the energy of the alpha particle? One might naively expect that a higher-energy alpha particle would lose a larger fraction of its energy in each interaction, but in fact the opposite is true. Returning to our bowling ball analogy, if you throw the bowling ball with great force, it will knock down pins aggressively but barely slow down, the energy transferred to each pin is a very small fraction of the bowling ball's total energy. If instead you roll the ball gently, it may come to a stop before reaching the end of the lane, because each collision now costs a larger *fraction* of its remaining energy.

The same principle applies to alpha particles. A high-energy alpha particle transfers energy to electrons as it passes, but each transfer represents a small percentage of the alpha's total energy. As the alpha particle slows down and loses energy, each subsequent interaction removes a larger fraction of what remains. This means that the ***rate of energy loss increases*** as the particle slows down. The alpha particle deposits more and more energy per unit distance as it approaches the end of its path, until it is finally brought to a stop and fully absorbed within the material.

Because of their large size, high charge, and high interaction probability, alpha particles have very short ranges in most materials. Even a thin sheet of paper, or the outer dead layers of our skin, is sufficient to fully stop alpha particles. This is why, as we discussed in Chapter 1, alpha radiation is primarily a concern when radioactive materials are ingested or inhaled, only then can the alpha particles deposit their energy within sensitive internal tissue.

3.1.5 Electrons in Matter

Electrons (beta particles) also interact through the Coulomb force, but their behavior in matter is quite different from that of heavy charged particles. The key difference is size: the incoming beta particle is the same type of particle, and therefore the same size and mass, as the orbital electrons it encounters in the material. Rather than a bowling ball plowing through pins, a better analogy is now a ***pool ball fired toward other pool balls*** on a table.

Because the beta particle is similar in mass to the electrons it interacts with, two important differences emerge compared to the heavy charged particle case. First, the probability of interaction is lower, because the smaller size of the electron means it is less likely to pass close enough to an orbital electron for a significant energy transfer. Second, when an interaction does occur, the effect on the beta particle is much more dramatic, it can lose a large fraction of its energy in a single collision and be significantly deflected from its original path. If you have played pool, you know that the cue ball can be dramatically redirected by a collision with another ball, sometimes even stopping entirely while the target ball carries away all of the energy.

The net result is that electrons follow a much more erratic, scattered path through a material compared to the relatively straight path of an alpha particle. The probability that a beta particle is fully absorbed within a material depends on several factors:

- ***Thickness***: A thicker absorber provides more opportunities for interactions, making it more likely that the electron will lose all of its energy before exiting.

- ***Density (Z)***: The denser the material (which correlates with the atomic number *Z* of the atoms in the material) the more electrons are available to interact with, increasing the probability of absorption.

- ***Energy***: Higher-energy electrons can travel farther before being fully absorbed, much as a higher-energy alpha particle can penetrate deeper into a material.

As we demonstrated in class with our shielding experiments, thin layers of aluminum are effective at stopping beta radiation. The count rate from a beta source dropped dramatically with increasing aluminum thickness, from roughly 2,000 counts per minute with no shielding to near-background levels with the thickest aluminum shield.

One additional point worth noting is what happens to an electron or positron when it reaches the end of its path. A beta-minus (electron), having lost all of its kinetic energy, will simply be captured by one of the ionized atoms in the material, filling a vacancy left by a previously ejected electron. A ***positron***, however, faces a very different fate. As the anti-particle of the electron, a positron that comes to rest near an electron will ***annihilate***, meaning the particle and anti-particle combine and their combined mass is converted entirely into energy in the form of two gamma-rays. Conservation of momentum requires that these two gamma-rays travel in opposite directions, and conservation of energy requires that each carry at least 511 keV (the rest mass energy of an electron). This annihilation radiation is a distinctive signature of positron-emitting isotopes and is the basis for PET (Positron Emission Tomography) imaging in medicine.

3.1.6 Gamma-Ray Interactions in Matter

Gamma-rays present a fundamentally different interaction scenario. With no charge and no mass, gamma-rays interact with matter through three distinct mechanisms, each with its own probability of occurrence depending on the energy of the gamma-ray and the properties of the material.

Photoelectric Absorption

In ***photoelectric (PE) absorption***, a gamma-ray photon is completely absorbed by an electron in the material. The photon transfers all of its energy to the electron, which is then ejected from the atom. The kinetic energy of the ejected electron is equal to the energy of the incoming photon minus the binding energy of the electron within the atom:

$$E_{electron} = E_{\gamma} - E_{binding}$$

The ejected electron then behaves like any other energetic electron traveling through the material. It will interact with other electrons through the Coulomb force, losing energy through the same processes we described in the previous section, until it is fully absorbed.

The probability of photoelectric absorption depends strongly on both the atomic number of the absorbing material and the energy of the photon. Empirically, this probability is proportional to:

$$P_{PE} \propto Z^{n} / E^{3.5}$$

where n is a value that depends somewhat on energy but is typically around 4 to 5 in the energy range relevant to nuclear radiation. The strong dependence on Z explains why high-Z materials like lead are such effective gamma-ray shields. The strong inverse dependence on energy ($E^{3.5}$) means that photoelectric absorption is most important at lower photon energies: as the energy increases, this type of interaction becomes increasingly unlikely.

Compton Scattering

In ***Compton scattering***, the gamma-ray photon does not transfer all of its energy to the electron. Instead, it "bounces off" the electron, much like one billiard ball glancing off another. The photon is deflected at some angle θ with reduced energy, while the electron recoils at a different angle, carrying the energy that the photon lost.

The energy of the scattered photon can be determined from conservation of energy and momentum. The result is:

$$E'_{\gamma} = E_{\gamma} / (1 + (E_{\gamma} / m_{e} c^{2})(1 - \cos\vartheta))$$

where E'_{γ} is the energy of the scattered photon, E_{γ} is the original photon energy, $m_e c^2$ = 511 keV is the rest mass energy of the electron, and θ is the scattering angle of the photon. From this equation we can see that the photon loses the most energy when it scatters backward (θ = 180°) and the least when it barely grazes the electron (θ near 0°).

The probability of Compton scattering is directly proportional to the atomic number *Z* of the material (not a high power of *Z* as with photoelectric absorption), and it does not depend strongly on the energy of the photon. However, the energy of the photon does affect the angular distribution of the scattering: higher-energy photons are more likely to scatter at small forward angles (barely deflected), while lower-energy photons have a more uniform angular distribution and are more likely to scatter at large angles, even backward.

Pair Production

The third mechanism, ***pair production***, is essentially the reverse of the electron-positron annihilation we discussed earlier. If a gamma-ray has sufficient energy, it can spontaneously convert into an electron-positron pair in the vicinity of a nucleus. The minimum energy required for this process is twice the rest mass energy of an electron:

$$E_{threshold} = 2 \times m_e c^2 = 2 \times 511\ keV = 1.022\ MeV$$

Any energy the photon carries beyond this threshold is shared as kinetic energy between the electron and positron. The probability of pair production depends on the atomic number *Z* of the material but does not depend strongly on photon energy beyond the threshold requirement.

Both the electron and positron produced will then interact in the material as described in Section 3.1.5. The positron will eventually annihilate with an electron, producing two 511 keV gamma-rays, which themselves may interact further in the material.

3.1.7 Gamma-Ray Attenuation

The three interaction mechanisms described above combine to determine the overall probability that a gamma-ray will interact as it passes through a material. We describe this combined effect through an ***attenuation coefficient***, which accounts for the probabilities of photoelectric absorption, Compton scattering, and pair production.

The intensity of gamma radiation passing through an absorber decreases exponentially with the thickness of the material:

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

where I_0 is the initial intensity, μ is the total attenuation coefficient (which depends on the material and the photon energy), and *x* is the thickness of the absorber. This exponential behavior is analogous to the exponential decay of radioactive isotopes. At each step through the material, there is some probability that a photon will interact, and the number of surviving (unattenuated) photons decreases accordingly.

From the energy dependencies of the three interaction types, we can understand the overall behavior of gamma-ray attenuation as a function of energy. At low energies, photoelectric absorption dominates and the attenuation coefficient is high. As energy increases, photoelectric absorption drops off sharply (as $E^{-3.5}$), and Compton scattering becomes the dominant process, providing a relatively constant probability of interaction. At very high energies (above 1.022 MeV), pair production begins to contribute and becomes increasingly important.

This energy dependence has practical consequences. Very high-energy gamma-rays are not efficiently absorbed through photoelectric absorption, and very low-energy gamma-rays are absorbed readily. There is an intermediate energy range where gamma-rays are most penetrating, making shielding more challenging. As we observed in our classroom demonstration, even dense materials like our tungsten alloy (comparable to lead in density) only partially attenuated the gamma radiation from our source, with count rates decreasing from roughly 340 CPM with no shielding, to about 200 CPM with one layer, and down to roughly 50 CPM, approaching background levels, only after four layers of shielding.

3.2 Radiation Dose

Now that we understand how different types of radiation interact in matter, we can address a critically important question: how much energy from a radioactive source is actually absorbed by a material, and specifically by the human body? The answer to this question is what we call radiation ***dose***, and it provides the link between the activity of a source and its potential impact on our health.

3.2.1 Absorbed Dose: The Gray

In Chapter 2, we learned to quantify how radioactive a material is in terms of its activity, the number of decays per second, measured in Becquerels. However, knowing the activity alone does not tell us about the impact of that radiation. For that, we need to know how much energy is actually deposited in the material the radiation passes through.

The ***absorbed dose*** is defined as the energy absorbed per unit mass of material. The SI unit for absorbed dose is the ***Gray (Gy)***, defined as:

1 Gray = 1 Joule / kilogram

You may also encounter the older unit, the ***rad***, which is related to the Gray by a simple conversion:

1 rad = 0.01 Gray (or equivalently, 1 Gray = 100 rad)

To determine the absorbed dose from a radioactive source, we need to consider two things: (1) how much energy each decay produces, and (2) how much of that energy is actually absorbed in the material of interest. As we learned in Section 3.1, the answer to the second question depends strongly on the type of radiation:

- ***Alpha particles*** are very likely to interact in matter and will be fully absorbed in almost any material of reasonable thickness. For dose calculations involving alpha sources that are inside the body, we can generally assume that all of the kinetic energy is absorbed.

- ***Beta particles (electrons)*** are also likely to be fully absorbed in many materials, though this depends on the thickness and density of the material. For sources inside the human body, it is generally safe to assume that beta particles are fully absorbed within the body.

- ***Gamma-rays*** are much less likely to interact, and only a fraction of the gamma-ray energy produced will typically be absorbed within a given material. The fraction absorbed depends on the material's thickness, density, and the energy of the gamma-rays, as described by the attenuation coefficient discussed in Section 3.1.7.

There is one additional subtlety for beta decays that is important to keep in mind. As we discussed in Chapter 2, beta decays share the available decay energy between the beta particle and a neutrino. Because the energy is shared, the beta particle does not always carry the same energy, its energy can range from zero up to the maximum decay energy. On average, the beta particle carries approximately ***one third*** of the maximum energy. Therefore, when calculating dose from beta emitters, we should use 1/3 the listed maximum beta energy to get a more accurate estimate of the average energy deposited per decay.[17]

3.2.2 Example: Self-Dose from Carbon-14

To illustrate how absorbed dose is calculated, let us return to the Carbon-14 example from Chapter 2. We determined that the activity of C-14 in the average human body is approximately 2,989 Bq (decays per second). We can now take this one step further and determine how much dose this corresponds to.

C-14 has only one decay mode: a beta decay with 100% branching ratio. The maximum beta energy is 156 keV (0.156 MeV). Since we are considering a source that is distributed throughout the body, and since beta particles produced inside the body will be fully absorbed within the body, we can assume complete energy absorption.

Step 1. Determine the energy per decay in Joules:

$$E_{decay} = 0.156\ MeV \times 1.602 \times 10^{-13}\ J/MeV = 2.50 \times 10^{-14}\ J$$

Step 2. Account for the average beta energy (multiply by 1/3):

$$E_{avg} = 2.50 \times 10^{-14} \times 0.3 = 0.833 \times 10^{-14}\ J\ per\ decay$$

Step 3. Determine the energy deposited per second (using our activity of 2,989 Bq):

$$Power = 2{,}989\ decays/s \times 0.833 \times 10^{-14}\ J/decay = 2.49 \times 10^{-11}\ J/s$$

Step 4. Convert to dose rate by dividing by body mass (70 kg):

[17] This is an approximation. The actual energy spectrum of beta particles is not perfectly uniform, and the true average is somewhat less than half the maximum energy for most beta emitters, but using half is a reasonable estimate for our purposes.

Dose rate = 2.49×10^{-11} *J/s ÷ 70 kg =* 3.56×10^{-13} *Gy/s*

Step 5. Convert to an annual dose:

Annual dose = 3.56×10^{-13} *Gy/s ×* 3.154×10^{7} *s/year ≈ 11 µGy/year*

If we use the maximum energy rather than the average (as a rough upper bound), we would get approximately 34 µGy/year. Either way, this represents the unavoidable ***self-dose*** -- the dose you receive simply from the radioactive carbon that is a natural part of your body.

3.2.3 Example: Dose from Cesium-137 in Food

Now let us consider a more complex example that involves multiple decay modes and introduces the question of gamma-ray absorption. Cesium-137 is a man-made isotope that was introduced into our environment primarily through nuclear weapons testing and nuclear accidents, as we discussed in Chapter 1. Because cesium mimics potassium in biological systems, it can be found at trace levels in food, particularly in fish and other biological materials.

Using measurements from the Berkeley RadWatch program, a sample of Pacific cod was found to contain Cs-137 at an activity of approximately 0.6 Bq per kilogram of fish. Let us determine the total dose a person would receive from consuming one kilogram of this fish.

Cs-137 Decay Modes:

Cs-137 has two primary beta decay channels:

- **94.7% of decays**: Beta emission at a maximum energy of 0.514 MeV, followed by a gamma emission of 0.662 MeV approximately 85% of the time (through an intermediate excited state of Ba-137m).
- **5.3% of decays**: Beta emission at a maximum energy of 1.176 MeV, with no subsequent gamma emission.

We will calculate the dose from the beta and gamma components separately, since they are absorbed differently.

Beta Dose

The effective energy per decay from beta emissions, accounting for branching ratios, is:

$$E_\beta = (0.947 \times 0.514) + (0.053 \times 1.176) = 0.549 \text{ MeV per decay}$$

Converting to Joules and applying the factor of 1/3 for the average beta energy:

$$E_{\beta,avg} = 0.549 \times 1.602 \times 10^{-13} \times 0.333 = 2.93 \times 10^{-14} \text{ J per decay}$$

With an activity of 0.6 Bq, the dose rate in our 70 kg body is:

$$\text{Dose rate} = 0.6 \times 2.93 \times 10^{-14} / 70 = 2.5 \times 10^{-16} \text{ Gy/s}$$

Cesium has a ***biological half-life*** of approximately 70 days, meaning that through normal biological processes, half of the cesium will be eliminated from the body every 70 days. This is distinct from the nuclear half-life of 30 years. To determine the total dose:

$$\textit{Total beta dose} = 2.5 \times 10^{-16} \times 70 \times 86{,}400 \approx 1.5\ \textit{nanoGy}$$

Gamma Dose

For the gamma component, 85% of all decays produce a 0.662 MeV gamma-ray. Unlike beta particles, the gamma-ray carries the full energy of the transition, there is no neutrino sharing the energy:

$$E_{\gamma} = 0.85 \times 0.662 \times 1.602 \times 10^{-13} = 9.01 \times 10^{-14}\ \textit{J per decay}$$

However, we cannot assume that all of this gamma energy is absorbed within the body. To estimate the fraction absorbed, we approximate the human body as a sphere of water with a radius of about 20 cm. Using the attenuation coefficient for water at 662 keV, the fraction of gamma-rays that interact within this sphere turns out to be approximately 50%. Applying this correction and the biological half-life:

$$\textit{Total gamma dose} \approx 2.3\ \textit{nanoGy}$$

Total Dose from the Fish

The total dose from consuming one kilogram of this cod is the sum of the beta and gamma contributions:

$$\textit{Total dose} \approx 1.5 + 2.3 \approx 3.8\ \textit{nGy}$$

For perspective, recall that the self-dose from C-14 in our bodies is on the order of 17 to 34 μGy per year, roughly ***five orders of magnitude*** (100,000 times) larger than the dose from this kilogram of fish. This comparison illustrates an important point: the dose from trace levels of man-made radioactive contamination in food, while measurable, is extraordinarily small compared to the unavoidable dose we receive from the natural radioactivity within our own bodies.

3.2.4 Equivalent Dose: The Sievert

The absorbed dose in Grays tells us how much energy is deposited per unit mass, but it does not fully capture the biological impact of that radiation. Different types of radiation cause different amounts of biological damage, even when they deposit the same amount of energy. The reason comes back to the interaction mechanisms we discussed in Section 3.1.

Recall that an alpha particle, because of its large mass and charge, deposits its energy in a very concentrated manner, plowing through tissue like a bowling ball, disrupting many atoms along a short path. A beta particle or gamma-ray, by contrast, deposits its energy more diffusely over a longer path. The concentrated energy deposition from alpha particles causes more severe damage to biological structures such as DNA, making alpha radiation more biologically harmful per unit of energy absorbed.

To account for this, we define the ***equivalent dose***, measured in ***Sieverts (Sv)***. The equivalent dose is calculated by multiplying the absorbed dose by a ***radiation weighting factor*** (w_R) that depends on the type of radiation:

$$\text{Equivalent Dose (Sv)} = \text{Absorbed Dose (Gy)} \times w_R$$

Radiation Type	Weighting Factor (w_R)
Beta particles (electrons)	1
Gamma-rays	1
Alpha particles	20
Neutrons	5-20 (energy dependent)

As with the Gray and the rad, there is an older unit for equivalent dose: the ***rem*** (roentgen equivalent man), related to the Sievert by:

1 rem = 0.01 Sv   (or equivalently, 1 Sv = 100 rem)

For beta and gamma radiation, the weighting factor is 1, so the equivalent dose in Sieverts is numerically equal to the absorbed dose in Grays. However, for alpha radiation, the weighting factor of 20 means that the equivalent dose is 20 times the absorbed dose. This is why inhaled alpha emitters like radon, despite depositing relatively modest amounts of energy, represent such a significant health concern.

3.2.5 Effective Dose and Whole-Body Dose

In our dose calculations above, we divided the total energy absorbed by the mass of the entire body (70 kg), effectively spreading the dose uniformly throughout the body. This gives us what is called the ***effective dose*** or ***whole-body dose equivalent***. This is a useful simplification for comparing doses from different sources, and it is the standard way that regulatory agencies like the EPA report radiation exposure levels.

However, it is important to recognize that this is an approximation. In reality, the dose may be concentrated in specific organs or tissues rather than spread uniformly. Consider radon, which we learned in Chapter 1 is the single largest contributor to our background radiation exposure (about 43% of the average annual dose). When we inhale radon gas, the radon and its short-lived daughters (several of which undergo alpha decay) deposit their energy primarily in the lungs -- not uniformly throughout the body. The actual dose to the lung tissue is therefore much higher than the effective whole-body dose would suggest.

This is one reason radon exposure is such a significant health concern. Not only does it involve alpha radiation (with its weighting factor of 20), but the dose is concentrated in a single organ rather than being distributed throughout the body. When more precise dose assessment is needed, for example, in occupational radiation safety, organ-specific doses are calculated rather than relying on the whole-body approximation.

3.2.6 Sources Inside vs. Outside the Body

Throughout our examples, we have considered sources of radiation that are inside the body. This is the relevant scenario for ingested or inhaled radioactive materials. For sources ***outside*** the body, the situation is somewhat different.

For external sources, alpha and beta radiation are generally not a significant concern because they are stopped by the outer layers of skin before they can reach sensitive internal tissue. This is consistent with what we learned in Chapters 1 and 3.1, alpha particles are stopped by a sheet of paper (or the dead outer layers of skin), and beta particles are stopped by thin layers of denser material.

Gamma radiation, however, can penetrate the body from external sources. In this case, the dose calculation involves determining how many gamma-rays from the external source actually pass through the body and what fraction of those are absorbed. This depends on the activity of the external source, its distance from the body (inverse-square law), and the attenuation within the body, similar to the calculation we performed for the gamma component of the Cs-137 example, but with the source located outside rather than inside.

Chapter Summary/Key Takeaways

- Charged particles (alpha and beta) interact with matter primarily through the **Coulomb force**, the electromagnetic force between charged particles. The probability and nature of these interactions depend on the charge, mass, and energy of the incoming particle.

- **Alpha particles** behave like bowling balls passing through pins: they lose energy gradually through many small interactions, depositing all of their energy over a short path. The rate of energy loss increases as the particle slows down, leading to complete absorption within a short distance in most materials.

- **Beta particles (electrons)** behave more like pool balls colliding with other pool balls: each interaction can cause a significant change in the electron's direction and energy. Electrons follow erratic paths and may or may not be fully absorbed, depending on the thickness and density of the material.

- **Gamma-rays** interact through three mechanisms: **photoelectric absorption** (dominant at low energies, probability ~ $Z^n/E^{3.5}$), **Compton scattering** (dominant at intermediate energies, probability ~ Z), and **pair production** (only possible above 1.022 MeV, probability ~ Z). The combined effect leads to exponential attenuation of gamma-ray intensity with material thickness.

- **Absorbed dose** is the energy deposited per unit mass, measured in **Gray** (Gy = J/kg) or rad (1 rad = 0.01 Gy). Determining dose requires knowing both the energy produced per decay and the fraction of that energy absorbed in the material.
- For beta decays, the beta particle shares the decay energy with a neutrino, so the average beta energy is approximately **half** the maximum listed energy.
- **Equivalent dose**, measured in **Sievert** (Sv) or rem (1 rem = 0.01 Sv), accounts for the different biological effectiveness of different radiation types using weighting factors: 1 for beta/gamma, 20 for alpha particles.
- **Effective dose** (whole-body dose) spreads the absorbed energy over the entire body mass, providing a useful but approximate measure for comparing different exposure scenarios. In reality, dose may be concentrated in specific organs (e.g., radon dose in the lungs).
- The self-dose from C-14 in the human body (~17 µGy/year) is roughly five orders of magnitude larger than the dose from consuming a kilogram of fish contaminated with trace Cs-137 (~5 nanoGy total), illustrating that natural internal radiation far exceeds typical doses from man-made contamination at environmental levels.

Review Questions

- Why does an alpha particle lose an increasing fraction of its energy per interaction as it slows down? How does this relate to the "bowling ball and pins" analogy discussed in this chapter?
- Explain why Compton scattering depends linearly on Z while photoelectric absorption depends on a high power of Z. What does this mean for the relative importance of these two interaction types in different materials?
- If you were told that a food sample contained 1 Bq/kg of a pure beta emitter with a maximum energy of 0.5 MeV, how would you estimate the dose from consuming 0.5 kg of that food? What assumptions would you need to make?
- Why is radon responsible for such a large fraction of the average person's annual radiation dose, despite the fact that alpha particles are easily shielded by even a sheet of paper? Consider both the type of radiation involved and where the dose is deposited.

Example Problem

A worker inhales a small amount of radon gas (Rn-222) that results in 100 Bq of activity from alpha-emitting daughters deposited in the lungs. The alpha energy for the relevant decay is 6.0 MeV. Assume that the lungs have a mass of approximately 1 kg and that all alpha energy is fully absorbed within the lung tissue. The biological half-life of these radon daughters in the lungs is approximately 30 minutes.

Determine:

(a) The absorbed dose rate in the lungs (in Gy/s).

(b) The total absorbed dose in the lungs (in Gy) over the biological residence time.

(c) The equivalent dose in the lungs (in Sv), accounting for the alpha radiation weighting factor.

(d) The effective whole-body dose (in Sv), assuming a body mass of 70 kg.

Solution:

Step 1. Energy per decay:

$$E = 6.0\ MeV \times 1.602 \times 10^{-13}\ J/MeV = 9.61 \times 10^{-13}\ J$$

Step 2. Dose rate in lungs:

$$Dose\ rate = (100 \times 9.61 \times 10^{-13}) / 1\ kg = 9.61 \times 10^{-11}\ Gy/s$$

Step 3. Total dose over biological half-life (~30 min = 1800 s):

$$Total\ absorbed\ dose = 9.61 \times 10^{-11} \times 1800 = 1.73 \times 10^{-7}\ Gy \approx 0.17\ \mu Gy$$

Step 4. Equivalent dose (multiply by alpha weighting factor of 20):

$$Equivalent\ dose = 0.17\ \mu Gy \times 20 = 3.5\ \mu Sv\ (in\ the\ lungs)$$

Step 5. Effective whole-body dose (spread over 70 kg body):

$$Effective\ dose = 3.5\ \mu Sv \times (1\ kg / 70\ kg) = 0.05\ \mu Sv$$

Note how the equivalent dose in the lungs is 20 times the absorbed dose due to the alpha weighting factor, and the effective whole-body dose is much smaller because the energy is concentrated in only ~1/70th of the body mass.