PART I: Getting to Know Our Radioactive World

This section will focus on an introduction to radiation and radioactivity. We will consider the units and concepts necessary to explore the properties of radioactive materials and the impact those materials have on us and our environment. We will cover the basic physics concepts related to how radiation is produced, the unique characteristics of radiation produced from radioactive materials, and the contexts in which we encounter radioactivity. We will discuss how we quantify the impact of radioactivity on our environment and on our health, and how we are able to detect the presence of radioactive materials.

In Chapter I we get a basic introduction to radiation. You will learn about radiation in our environment, the common types of radiation we encounter, and how we can limit exposure. In Chapter II we learn in more detail how radioactive decays occur and how we quantify those decays. In Chapter III we go into detail on how radiation interacts in matter and how we quantify radiation exposure. We then learn about the various technologies for detecting radiation in Chapter IV.

Chapter One: Radiation in Our Environment

In any discussion of radioactivity, it is first important to establish what we mean when we talk about radiation in our environment, and for this we must first agree on a definition of radiation.

1.1 Radiation

In the most general case, radiation is simply the emission or transmission of *energy* in the form of waves or particles through space or through any material. When most people think of radiation, they are thinking of electromagnetic (EM) radiation, which is more formally described classically as waves formed by the synchronized oscillations of electric and magnetic fields. The most obvious example of EM radiation is visible light, but this is just one small region on the electromagnetic spectrum. This spectrum includes, in order of increasing energy: radio waves; microwaves; infrared, visible, and ultraviolet (UV) light; x-rays; and gamma-rays (see Figure 1). Note that it is common in physics for us to refer to all types of EM radiation as light, since it is fundamentally the same thing. The primary differences are in our perception and our use of light at different wavelengths. However, there are real differences in the dynamics that govern different regions of the spectrum, with types commonly identified as light (infrared, visible, and UV) providing a bridge between types generally described classically as waves (radio, micro) and those that behave more like particles (x-rays and gamma-rays).

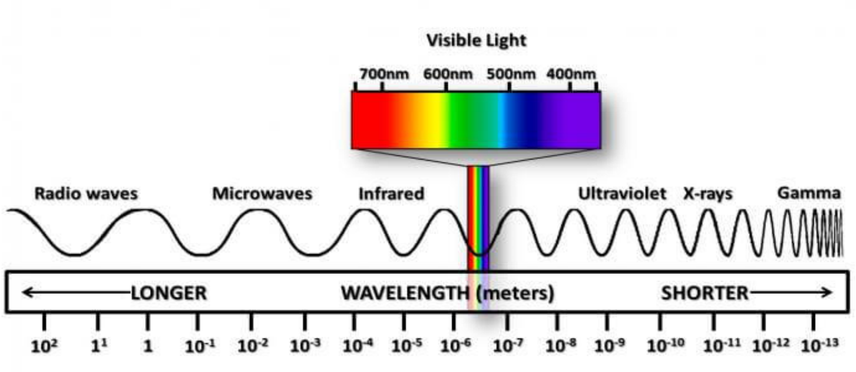


Figure 1: Electromagnetic spectrum highlighting the different types of electromagnetic energy produced in different ranges of frequencies/wave-lengths. Visible light is highlighted to show the relevant wavelengths in more detail.

We will choose more carefully descriptive terms as we consider how different types of radiation are actually produced, focusing on the EM spectrum. At the lower energy (longer wavelength) end of the spectrum, radiation like radio waves can be thought of as continuous electromagnetic oscillations – radiation produced through the non-linear motion (acceleration) of charged particles. As we move to higher energies, into the visible light range, we start to see EM radiation produced through discrete energy transitions within the sub-structure of atoms that result in the release of electromagnetic energy. We will discuss the discrete nature of these types of EM radiation in more detail in later chapters.

There are other types of waves which are not generally thought of as carrying energy, such as sound waves, but fundamentally these and other compression waves (which require a medium to be transmitted) are also transmitting energy. In fact, compression waves are transmitting energy through the interaction of particles – which is why a medium is required for such waves to be transmitted. All particles have energy that can be absorbed by other particles through various types of interactions, thereby transmitting that energy and serving as a form of radiation. In some cases, this can even include fully absorbing the particle. In this course, much of the radiation we will discuss is transmitted in this way – through the emission and absorption of energetic particles.

Now that we understand radiation in the most general sense, we can move to the more specific types of radiation to which we are referring when discussing radioactivity. In this case, we are specifically focusing on what is called ***ionizing radiation***, that is: radiation that caries enough energy to eject electrons from atomic orbit, creating an ion. The creation of ions through the interaction of radiation at these energies changes the chemical properties of those atoms, potentially breaking the molecular structure they are contained within and damaging the structure or material those atoms make up. This is what makes ionizing radiation unique, and potentially harmful, and what makes this type of radiation and the ability to detect it an important component of all areas of nuclear science. In the next section, we will learn more about ionizing radiation specifically.

Throughout the remainder of this text, when discussing radiation, it will be ***ionizing radiation***, and more especially ***nuclear radiation***, that is being referenced even if not explicitly described as such.

1.2 Ionizing Radiation

As we have discussed, radiation can be transmitted through waves or particles. When considering transmission through waves, the range of the electromagnetic spectrum that carries enough energy to cause ionization is the highest frequency, shortest wavelength region, which includes the short-wavelength portion of the UV spectrum, X-rays, and gamma-rays. There is not an exact energy at which radiation becomes ionizing, because different atoms and molecules will ionize at different energies. When considering radiation in the UV and X-ray range, this type of radiation is commonly produced by the largest electron transitions in atoms, or in other words, the transition (or capture) of excited (or ejected electrons) back to the lowest energy orbitals around the atom (Figure 2 - left).

Gamma-rays, on the other hand, are produced from similar types of energy transitions of nucleons within the nucleus of the atom (Figure 2 - right). The nuclear binding energies are typically much higher than for electrons around atoms, and thus gamma-rays typically cover a much higher range of energies, meaning they can often ionize multiple atoms before losing enough energy to be fully absorbed. Although the atomic and nuclear binding energies differ, transitions occurring in the outermost orbitals for nucleons for some atoms can produce gamma-rays that are lower energy than X-rays produced from the innermost orbitals for electrons in other atoms. So again, there is not a clear separation between the range of energies that are classified as X-rays and those classified as gamma-rays. Instead, the distinction between gamma-rays and X-rays is specifically to do with how they are produced – through electron transitions or nucleon transitions – rather than by a specific threshold in the electromagnetic energy spectrum.

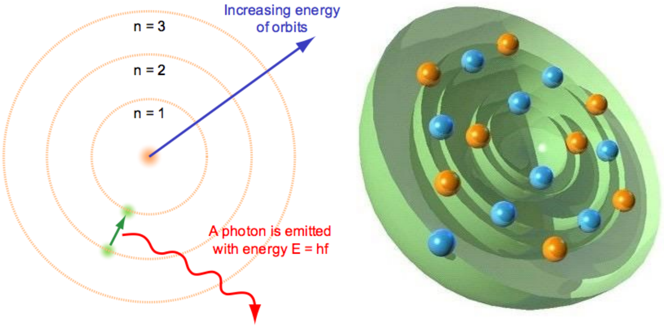


Figure 2: (left) Cartoon shell-model diagram illustrating the discrete energy levels for electrons in an atom and how they transition. (right) Cartoon shell-model for the nucleus of an atom illustrating how nucleons (protons and neutrons) also occupy discrete energy levels within the nucleus.

In addition to *gamma-rays* (Figure 3 – right), particles moving at high enough speeds can also be ionizing. This can include sub-atomic particles, ions, or atoms. The most common types of ionizing particles produced through radioactive decays include *alpha decays* (helium nuclei) and *beta decays* (electrons) (Figure 3 – left and middle respectively). There are other types of ionizing particles that we will encounter naturally as a result of cosmic rays – most commonly these would be muons. Cosmic radiation, though not originating from the radioactive decays that lead to other sources of nuclear radiation, is typically included in most discussions of nuclear or ionizing radiation as it has a similar impact and represents a significant source of exposure to ionizing radiation.

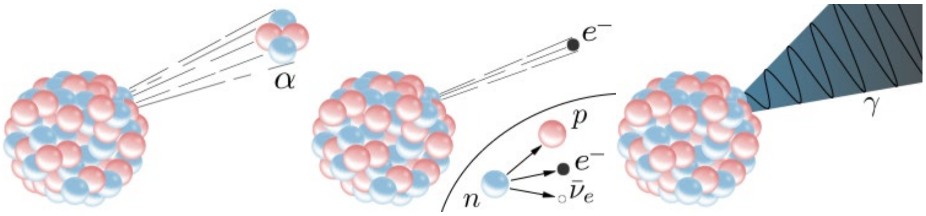


Figure 3: Illustrations showing the three most common types of nuclear decays: alpha (left), beta (center), and gamma (right).

All of the types of the ***nuclear radiation*** discussed here are produced in one of two ways. Most commonly, nuclear radiation is produced through naturally occurring processes such as the radioactive decay of a variety of natural sources and the interaction of cosmic rays with our atmosphere. In some cases, nuclear radiation can come from man-made sources that have been introduced into our environment through human activity involving nuclear power and nuclear. In the next section, we will explore how these different sources of ionizing radiation contribute to the constant background radiation present in our environment.

1.3 Limiting Radiation Exposure

In the previous section we discussed what makes ionizing radiation unique and identified a few types of ionizing radiation. The changing chemical properties that materials exposed to nuclear radiation will undergo can lead to lasting damage to those materials – including to human tissue. In small doses, radiation exposure is a minor issue; however, as the level of exposure increases, so too does the associated health risk. Therefore, it is good to minimize our exposure to radiation as much as reasonably possible considering the source and relative risk.

1.3.1 Shielding Materials

Focusing on the most common types of nuclear radiation – alpha, beta, and gamma – we can now consider what types of materials might serve to shield us from exposure to such radiation. Figure 4 highlights some common examples of shielding materials that are effective against these types of radiation. We will discuss how radiation interacts in matter, which determines how effective shielding might be, in much more detail in Chapter 3.

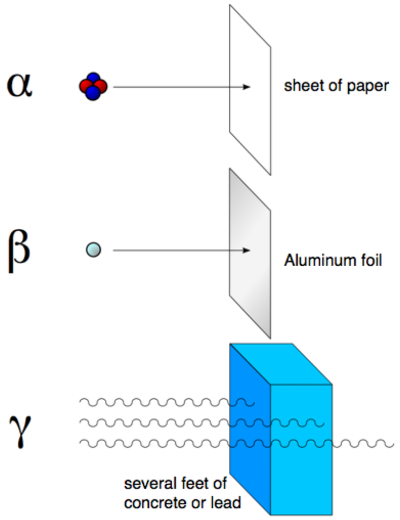


Figure 4: Illustration of types of shielding materials effective for different types of radiation.

Because alpha radiation is a high energy helium nucleus, it is comparable in size to other materials on the atomic scale, and therefore has a relatively high probability of interacting in any medium compared to the other common forms of radiation. Low-density materials like paper, or the outer (dead) layers of our skin, are sufficient to stop alpha radiation. For this reason, sources of alpha radiation are typically only a significant source of exposure when ingested, where the alpha can be absorbed internally in our organs. As electrons, beta particles are much smaller than alphas. Even so, their mass and size still lead to a high enough probability of interacting with matter to make low-density metals, such as thin layers of aluminum – or again the outer layers of our skin – effective in stopping beta radiation before it can penetrate further. This means that like alpha radiation, beta radiation is only a significant source of exposure for humans when sources are ingested.

When considering how to effectively shield against gamma radiation, the massless nature of gamma-rays necessitates the use of significantly more dense materials. Gamma-rays can travel very far in most materials without interacting. This makes them less dangerous generally because of the lower probability of interaction in our bodies, but also means that external sources of gamma radiation will lead to exposure unless we are able to put a significant amount of dense material, such as lead, in between us and the source. Even then, such materials will only reduce the rate of gamma radiation, not fully stop all gamma-radiation.

1.3.2 Distance

In many cases, access to shielding materials is limited. More especially, in the case of gamma radiation, where shielding is only partially effective, other ways of limiting exposure are worth considering. One somewhat obvious way of limiting exposure is to stay far away from obvious sources of radiation. Intuitively, the farther we are from a source of any type of radiation (be it light, sound, or otherwise) the less intense that source will be – meaning the less exposure to the energy being produced, but why? This results from a fundamental property of geometry that applies when considering the intensity – flux, energy density, or rate of exposure – of anything being emmitted from a source. In the case of radiation, the alpha, beta, or gamma-rays are being emitted from a source isotropically (uniformly in all directions).

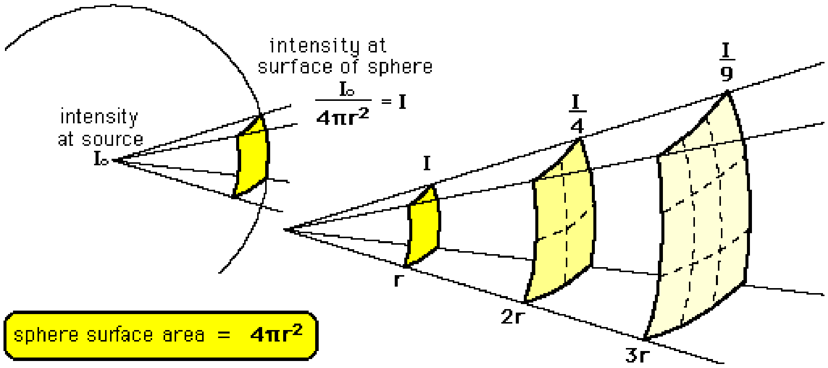


Figure 5: Graphic showing how distance from a source causes the intensity of radiation from that source to drop of as function of 1/r2 – the inverse square law.

Figure 5 illustrates how the intensity of a radioactive source depends on distance from the source. Fundamentally, as the flux of radiation travels uniformly out from the source, the density of the radiation at a given distance, r, relative to the initial rate of emissions at the source, is spread out across the surface area of a sphere with the radius of the sphere being the distance from the source. For this reason, the amount of radiation experienced will drop as a function of the increasing radius ($1/r^2$) as the distance from the source increases. This is known as the inverse-square law and is not unique to radiation. This is a fundamental property of nature that dictates the intensity of any type of light, the strength of forces such as gravity, coulomb forces between charged particles, and so on, as well as and the intensity of compression waves such as sound, waves in water, or earthquakes.

1.3.3 Time

Although distance is an important and effective way of limiting radiation exposure in many cases, it is not always possible to control our distance from a particular radiation source. There is one relatively straightforward way we can limit our exposure – by limiting the amount of time we spend in close proximity to that source. Even if we cannot directly control the time spent in proximity to a radiation source, the intensity of the source will drop over time. This is again a fundamental property not unique to radioactive decays that applies in any example of a desintigration or transformation of some element or material. If we were to start with 100 unstable atoms that will decay over time, the number of atoms we have at a later time will be less, so there will be fewer atoms remaining to continue decaying, meaning that the rate of decay will also decrease over time.

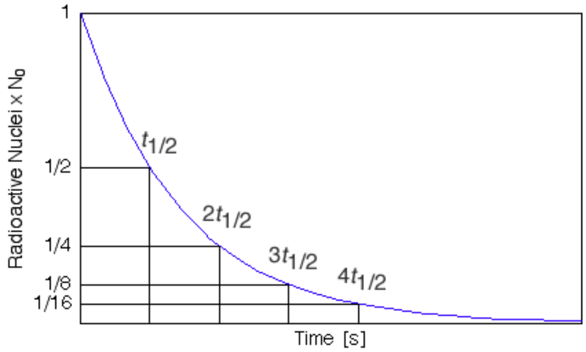


Figure 6: This graph shows the number of radioactive nuclei vs time, indicating the point at which the number of nuclei decreases by half based on the half-life.

For any radioactive isotope, if we start with some number of atoms of that isotope, we can state how long it will take for half of those isotopes to undergo a radioactive decay, which will lead to a transition to a different isotope. This is defined as the ***half-life($t_{1/2}$)*** of the isotope. In Figure 6, we can see how the relationship between the number of radioactive isotopes and the corresponding half-life are related. As we step up incrementally in the number of half-lives that have gone by, we see the number of radioactive nuclei drop in half. We can see from this graph that as the number of nuclei decreases, the half that decay over the next half-life will also be smaller. Therefore, for a given material we can use the half-life to determine how long it would take for the number of decays occurring over time to drop below some rate – giving us a way to estimate when the radiation exposure from this source would no-longer be of concern. Again, we will discuss this in much more detail in Chapter 3.

1.4 Background Radiation

There are many sources of radiation, overwhelmingly naturally occurring, that we encounter constantly. Small amounts of radioactive material are present in everything around us simply as a result of the natural abundance of some unstable elements and isotopes. There are a few specific elements that contribute to the majority of background radiation we encounter in our environment, and we will highlight those here. First, it is helpful to get a sense of the relative amount of exposure people get, on average, from different source categories. Figure 7 shows a pie chart that breaks down different types of exposure. In this chart, we see that almost half of our exposure comes from a single component, radon – we will learn how and why radon is a primary exposure source as we discuss the types of radiation produced from radioactivity. The next most significant source is actually from medical sources – a growing source primarily from imaging technologies such as X-rays, CT-scans, SPECT and PET scans, that is highly dependent on a person's unique medical needs.. It is also worth noting that, on average, manmade sources contribute to only 1% of the total exposure people experience over time.

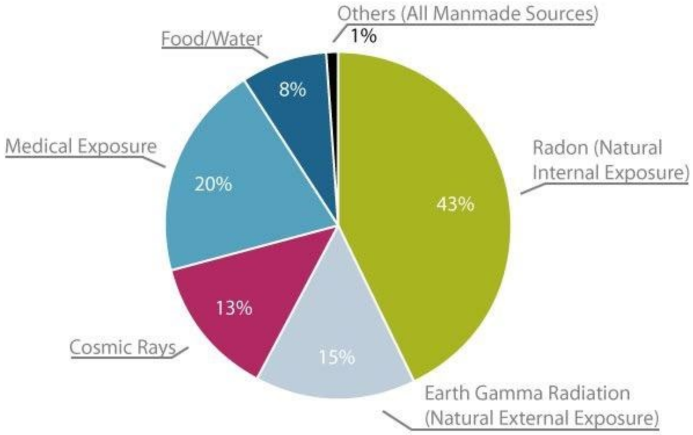


Figure 7: Pie chart of the different sources of radiation exposure for the average person in the US.

The remaining categories of sources shown in Figure 7, along with the radon exposure already mentioned, come from a range of commonly occurring materials that contain the most abundant radioactive isotopes in nature (see Figure 8 for examples). To understand why various materials produce some radiation, we will take a moment to discuss briefly how radioactivity arises. We will discuss radioactivity in much more detail in Chapter 2. Recall that the nucleus of an atom contains protons and neutrons, and that chemical elements are defined uniquely by the number of protons contained within the nucleus. The number of neutrons in the nucleus for a particular element can vary, and these different versions of the element are referred to as ***isotopes***. Several different isotopes of the same element may occur naturally at ***different relative abundances***, and some of these isotopes may be unstable – meaning that they will undergo radioactive decay over time. It is these unstable isotopes that we find all around in our environment and that are the source of all nuclear radiation.

1.4.1 Natural Radiation Sources

As an example of a common natural source of radioactivity, we can consider potassium. Biological materials generally contain potassium, as it is present in a wide range of proteins and enzymes necessary for life. There is a specific isotope of potassium (K), K-40, which occurs naturally and is not stable. For this reason, biological materials will all be slightly radioactive. The presence of K-40 in living things is one of the reasons that food and water make up ~8% of our exposure (see Figure 7). A common example used in this case is bananas, as they are known to contain a large amount of potassium. It is worth mentioning that bananas are not uniquely radioactive, or even the largest source of potassium people generally encounter in their diet.

Figure 8: Various examples of common materials that contain radioactive elements and produce radiation.

There are also some elements for which there is no stable version, leading to much higher overall levels of radiation when those elements are present because radioactive decay is not limited to only a small fraction of the elemental isotopes. The most common examples of these types of elements are uranium and thorium. Figure 5 shows two examples of materials that will typically contain some small amount of uranium and thorium – soil and rocks. Typically, only trace amounts (~6 ppm) of these elements will be found in rocks, and even lower amounts in soil, but some types of minerals (phosphates) often contain much higher levels. A map of uranium concentrations, as an example, is shown in Figure 9 (left), where we see that there is roughly a factor of 10 variation in concentration levels. Looking at a map of exposure intensity for gamma-ray sources in Figure 9 on the right, we see that exposure levels fallow a similar pattern to uranium concentrations, with a corresponding factor of 10 variation in intensity. Here again it becomes clear that the average exposure of ~15% (see Figure 5) from terrestrial sources is only an average, there can be quite a lot of variation in actual exposure levels depending on where somebody lives. In fact, as we will learn, Radon is a biproduct of uranium and thorium and exposure will similarly vary widely depending on region and local rock and soil compositions.

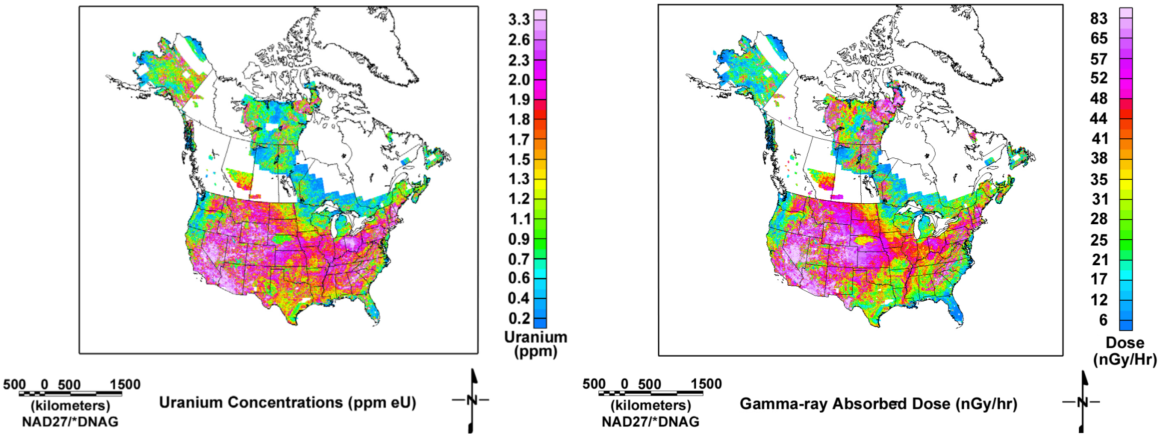


Figure 9: Intensity map of the US and Canada for uranium concentration in parts-per-million (ppm) on the left and for the radiation exposure rate from gamma-rays on the right.

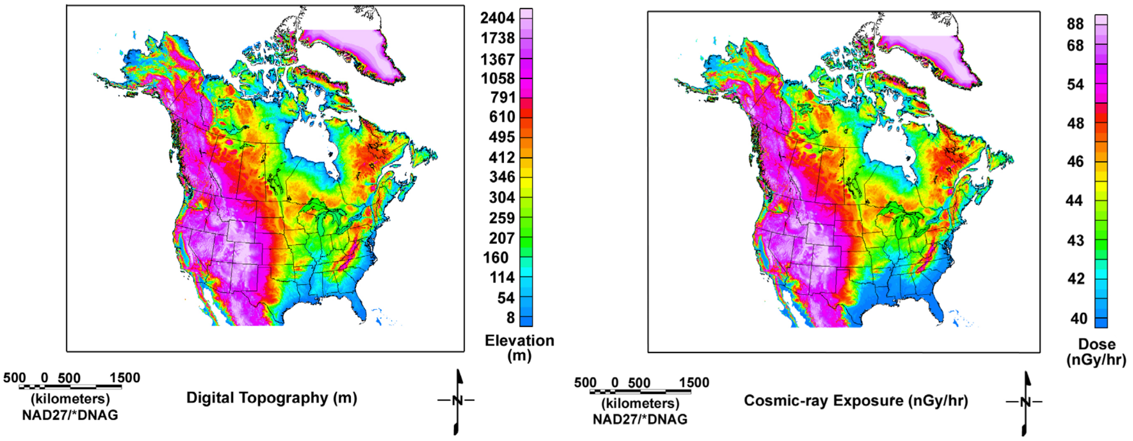


Figure 10: Intensity maps for the US and Canada of uranium concentration in parts-per-million (ppm) (upper left), total radiation exposure rate from gamma-rays absorbed (upper right), radiation exposure from cosmic-ray radiation (bottom right), and a topographical map (bottom left).

Finally, it is worth briefly discussing how cosmic radiation contributes to our exposure, as this is another significant source (~13%) of exposure. Cosmic rays are high energy protons, neutrons, or nuclei, originating from outside earth – often even from outside our solar system, though solar activity can contribute. These particles then interact in our atmosphere. Many cosmic rays will reach earth without interacting in our atmosphere, but generally when we are discussing radiation from cosmic rays, we are considering secondary particles produced through the interactions of those original cosmic rays in our atmosphere. Even those secondary particles will have the potential to interact further in our atmosphere and not reach the surface of the earth. Generally, the more atmosphere between us and space, the more protection we have against cosmic radiation, so we would expect altitude to be the dominant contributing factor to determining cosmic radiation levels. The maps of elevation (left) and exposure resulting from cosmic radiation (right) in Figure 10 illustrates this direct relationship between altitude and cosmic radiation levels. In this case, the atmosphere is serving to shield us from cosmic-ray radiation, providing a clear example of what we will discuss next – how we might limit our exposure to ionizing radiation.

1.4.2 Man-made Radiation Sources

Though generally small (<1%), part of our background radiation exposure comes from man-made sources. It is worth discussing some of these sources to understand how they have been introduced into our environment and how they can contribute to our overall exposure to radiation. The testing of nuclear weapons is, by far, the most significant vector for the introduction of radioactive isotopes into the environment that are not found naturally. Many of the same isotopes will also be introduced into our environment through major accidents involving nuclear power plants, but the extremely rare nature of such accidents leaves weapons testing as the main contributor. For this reason, open air nuclear weapons testing has not been done in the United States since 1992, and was stopped in other nuclear countries at around the same time. The mining and use of Uranium can, of course, have other environmental consequences that include the potential for increased exposure to radiation produced directly or indirectly from the mined Uranium. In these cases, this leads to an increase in exposure from natural sources that already contribute to our background radiation exposure. We will learn more about how this type of exposure can impact our health in later chapters.

In both nuclear weapons and nuclear power, it is the process of nuclear fission – the breakup of heavy nuclei and subsequent release of energy – that leads to the production of several highly radioactive fission fragments. In terms of long-term environmental impact, cesium-137 (Cs-137) and strontium-90 (Sr-90) are the most dangerous. Table 1 lists these isotopes, as well as iodine-131 (I-131) – the most significant source of radiation immediately following a release of fission materials – along with illustrations of the radioactive decay processes these isotopes undergo. The table also lists two types of half-lives for these isotopes: the nuclear half-life we have already discussed, and the biological half-life related to how long these isotopes will stay in the body after being ingested.

One reason these isotopes can have a lasting health impact is because of the way they behave in the body. Despite the short half-life for I-131 (8 days), the fact that humans require iodine biologically, most especially for thyroid function, means that a large influx of I-131 into the environment through nuclear activity can lead to an increased risk of thyroid cancer for people in the fallout area. It is worth noting, however, that this is an acute risk due to the short nuclear half-life of I-131 and while there is the potential for this to impact people far from the initial contamination site, it is still relatively localized. It is also worth noting that while the exposure risk is acute, it can take quite a lot longer for an increase in the rate of thyroid cancer to manifest.

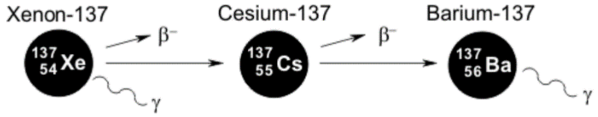
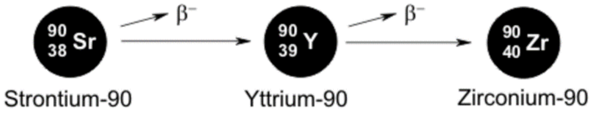
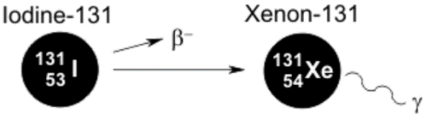
Isotope	Radioactive decay process	Half-life
Cesium-137 (Cs-137)	β & γ decays 	nuclear $t_{1/2} \approx 30$ years biological $t_{1/2} \approx 70$ days
Strontium-90 (Sr-90)	β decay only 	nuclear $t_{1/2} \approx 30$ years biological $t_{1/2} \approx 30$ years
Iodine-131 (I-131)	β & γ decays 	nuclear $t_{1/2} \approx 8$ days biological $t_{1/2} \approx 80$ days

Table 1: Set of common isotopes we see only from human activity related to nuclear fission.

The long nuclear half-lives of Cs-137 and Sr-90 make them of greater concern when considering the environmental impact. Due to the extreme temperatures following a nuclear accident or weapon detonation, the Cs-137 released is highly volatile, meaning that it is quickly introduced into the atmosphere and can travel very far from the initial location. Once in our environment, the relatively long half-life for Cs-137 means that it will persist for hundreds of years. As a result of human activity, there is now a low level of Cs-137 in our atmosphere that can still be observed with the use of highly sensitive equipment, and that is decreasing very slowly over time. While not a level that is considered high enough to pose an increased health risk, it is worth noting that this does leave a lasting global environmental legacy. In the body, cesium will mimic potassium, meaning that once ingested it will distribute relatively evenly throughout the bodies of plants and animals. This is what leads to the biological half-life of 70 days in humans and is what makes high levels of Cs-137 dangerous. At high enough levels this would increase the overall risk of cancer, and at extremely high levels could lead to acute radiation sickness.

Strontium-90 has a similarly long nuclear half-life to Cs-137, but is much less volatile, and therefore less likely to travel far from accident sites. However, the nature of nuclear weapons testing can lead to a much greater spread of Sr-90. Again, as with Cs-137, Sr-90 will mimic elements used in biological processes. In this case, Sr-90 mimics calcium, and will be taken up by living organisms and drawn into the bones and can linger in the body for some time – with a biological half-life of 18 years. This leads to an increased risk of bone cancer and leukemia, and indeed, increased rates of such cancers have been observed during times of atmospheric weapons testing as well as locally near uncontrolled reactor releases in some cases.

1.5 Identifying Radiation Sources

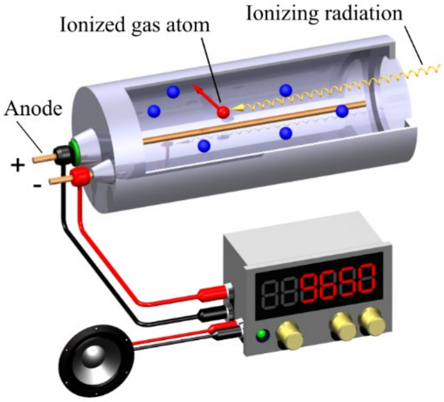


Figure 11: A diagram of a Geiger counter, including the common feature of converting the electrical signal into an audible click.

Now that we know that there are sources of (ionizing) radiation all around us, we can begin to explore how we might identify when we encounter a significant (above background levels) source of radiation. We cannot see ionizing radiation, so we must rely on other means to determine its presence. We can exploit the unique property of the type of radiation we are trying to detect to do just that – the fact that it will create ions when it interacts with matter. Ions, and the corresponding freed electrons, will have charge. We can make use of this fact to manipulate and detect those charged particles, using electric fields. The most common and widely used basic radiation detection device is the Geiger counter, which works as illustrated in Figure 11. Geiger counters use inert gases (often argon), but similar radiation counters can be developed using solid-state materials like silicon. Radiation counters can tell us about relative radiation levels in terms of changes in the count-rate – counts-per-second (CPS) or counts-per-minute (CPM) – measured in the detector. We will discuss radiation detection and detection technologies in much more detail in Chapter 4.

Chapter Summary/Key Takeaways

- Radiation is the transmission of energy through waves or particles. ***Ionizing radiation*** is radiation with enough energy to free electrons from atoms, creating ions.
- Electromagnetic radiation starts to have enough energy to be ionizing in the higher energy portion of the UV-light range and above – which includes X-rays and gamma-rays. Gamma-rays are produced through energy-level transitions of nucleons within the nucleus.
- Radioactive decays produce ionizing ***nuclear radiation*** in the form of alpha particles – helium nucleus, beta particles – electrons or positrons, and gamma-rays – electromagnetic radiation.
- There are three main ways to limit our exposure to different types of nuclear radiation: distance – staying far from highly radioactive sources; time – waiting until sources are no-longer producing significant amounts of radiation (based on half-life); and shielding – using appropriate materials that will stop different types of radiation from reaching us.
- Nuclear radiation comes from unstable isotopes of commonly occurring elements. The most common examples being K-40, all uranium isotopes, and all thorium isotopes.
- On average, almost half of our exposure to nuclear radiation comes from radon – a product of uranium and thorium, while another 8% and 13% comes from common, naturally occurring radioisotopes. Only 1% of our exposure comes from man-made sources, while 20%, on average, comes from medical interventions (medical imaging).
- The most dangerous man-made isotopes are the fission fragments Cs-137 and Sr-90 because of their long half-lives and uptake into living organisms due to their mimicking of chemicals involved in biological processes. Cs-137 can still be found at low levels in our atmosphere and in biological samples.

Review Questions

- Why is ***ionizing radiation*** potentially dangerous while other forms of radiation are generally not considered dangerous?
- What might you do to reduce your radiation exposure from a material producing gamma-radiation? If the material was emitting alpha or beta radiation, under what circumstances might this be a source of exposure and what should you do to protect yourself?
- How would you determine if there was something near you producing more radiation than you would expect to encounter from the usual background sources?

Bibliography

[?] Pauli exclusion principle. *Wikipedia*. https://en.wikipedia.org/wiki/Pauli_exclusion_principle

Figure References

[Figure 1] The Electromagnetic Spectrum. Creator: Mia Kovachi. Source: https://www.thinglink.com/scene/778415948351668224

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[Figure 3] Public domain. Source: Wikimedia commons. Creator: Inductiveload

[Figure 4] Public domain. Source: Wikimedia commons. Creator: Tungsten

[Figure 5] Source: cyberphysics.co.uk

[Figure 6] Public domain. Source unknown.

[Figure 7] Public domain. Source: radwatch.berkeley.edu

[Figure 8] Public domain. Sources unknown.

[Figure 9] *Map of Uranium Concentrations* and *Map of Gamma-ray Absorbed Dose*. Source: US Geological Survey (USGS). https://pubs.usgs.gov/of/2005/1413/maps.htm

[Figure 10] *Map of Digital Elevation* and *Map of Cosmic-ray Exposure*. Source: US Geological Survey (USGS). https://pubs.usgs.gov/of/2005/1413/maps.htm

[Figure 11] *Geiger Muller counter*. Source: Wikimedia commons. Creator: Svjo-2. https://en.wikipedia.org/wiki/Geiger_counter#/media/File:Geiger-Muller-counter-en.png

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[Figure 14] Source: https://www.radiation-dosimetry.org/wp-content/uploads/2019/12/nuclide_chart.jpg. Modifications by author.

[Figure 15] Source: National Nuclear Database Center online, nndc.bnl.gov

[Figure 16] Source: Wikicommons. Modified by Chloe Reynolds based on the Thorium SVG image by Wikipedia contributor BatesIsBack and the Radium Series png image by Wikipedia contributor Tosaka. Cropped for side-by-side display of upper and lower sections by author.

[Figure 17] Source: Nucleonica Decay Schemes, online: https://www.nucleonica.com/wiki/index.php?title=Decay_Schemes