# Chapter Two: Radioactivity Basics

With some background relating to how and why we encounter nuclear radiation generally, we can now turn to a more in-depth discussion of the various types of radioactive decays that lead to such radiation, why these decays occur, and how we can quantify the rate at which decays occur for a given material.

## 2.1 Types of Radioactive Decay

In Chapter 1 we learned about the three main types of radioactive decay and what those decays produce. We will revisit those here in more detail and introduce some of the less common types of decays. Figure 12 provides a more comprehensive list* of the different types of decays with some details about the particle or electromagnetic radiation emitted and the general decay process involved, along with an illustration of the decay process.

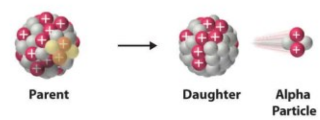
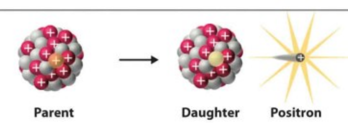
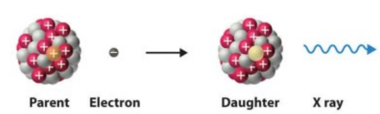
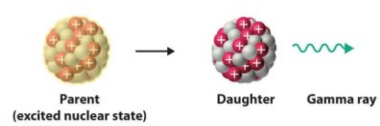
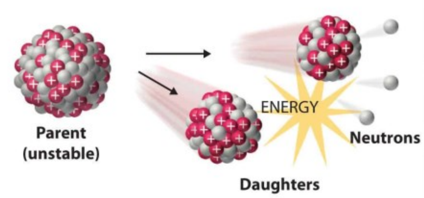
| Decay Type | Radiation Emitted | Generic Equation | Model |
|---|---|---|---|
| Alpha decay | $^{4}_{2}\alpha$ | $^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}\alpha$ |   |
| Beta decay | $^{0}_{-1}\beta$ | $^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}\beta$ |   |
| Positron emission | $^{0}_{+1}\beta$ | $^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}X' + {}^{0}_{+1}\beta$ |   |
| Electron capture | X rays | $^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}X'$ + X ray |   |
| Gamma emission | $^{0}_{0}\gamma$ | $^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$ |   |
| Spontaneous fission | Neutrons | $^{A+B+C}_{Z+Y}X \longrightarrow {}^{A}_{Z}X' + {}^{B}_{Y}X' + C\,{}^{1}_{0}n$ |   |

*Figure 12*: *Table of types of radioactive decays.*

* Many details of these decays are omitted, including different products that can arise from the same decay types and additional products that are produced as part of these decay processes.

Each of the ***radioactive decay*** processes depicted in Figure 12 involve the release of energy in the form of radiation by an unstable nucleus. Unstable nuclei are considered radioactive, meaning they will undergo radioactive decay at some point. These different types of radioactive decay are governed by fundamental physics forces (strong, weak, electromagnetic), but it is ultimately the strong nuclear force that dictates the dynamics of the nucleus which determine stability. It is impossible to know exactly when a single atom will undergo radioactive decay, we can only state with what probability an atom will decay within some time period. This means that radioactive decays are what we call a stochastic (random) process. We will learn more about the consequences of stochasticity in Part 3, where we discuss statistics in the context of measuring and quantifying radiation.

When an unstable nucleus undergoes radioactive decay, the decaying nucleus is the *parent radionuclide*, or radioisotope. Through this decay process, it will produce at least one *daughter nuclide* along with the radiation produced. Through the discussion of various types of radioactive isotopes in the next section, we will learn what makes certain isotopes unstable, but it is important to highlight here that unstable isotopes will undergo decay processes that involve transmutation – the daughter nuclide will have a different number of protons, neutrons, or both. Following this decay, often the daughter nuclide will be in an excited state, in this case the excess energy will be emitted in the form of a gamma-ray.

To review, the most common radioactive decays involving transmutation are alpha decays: the release of a helium nucleus – two protons and two neutrons, and beta decays: the release of an electron – a proton transitions to a neutron by releasing an electron[*]. The fundamental physics force at play in these two cases are not the same. In the case of alpha decays, as well as any type of decay that involves the release of a nucleon or group of nucleons, it is the strong force governing the decay. The strong force is the force that keeps atomic nuclei bound together, in the same way that the electromagnetic force keeps electrons bound to the atom. The release of nucleons from the nucleus involves overcoming the binding energy holding the nucleus together. The laws of physics require that if the total energy of nucleons within the nucleus is high enough to overcome the binding energy, a decay must occur and the likelihood of this decay depends on the size of the energy imbalance[†].

In the case of *beta decays*, and *beta-plus decays*[‡] – when a neutron transitions to a proton by releasing a positron (or anti-electron)[§], it is the weak force that is governing the process. There may be some new concepts here, including the weak force and anti-particles. The positron is the anti-matter partner to the electron. Essentially you can think of anti-particles as the mirror image of a particle, in the sense that all physics properties of the particle are the reverse, with the

[*] And an anti-neutrino – an extremely light elementary particle produced only in these types of processes.
[†] There is a subtlety here because the charge involved (electrons surrounding the positively charged alpha) should leave the alpha trapped inside the nucleus. We must turn to quantum tunneling to overcome this and allow the alpha to escape – the probability of tunneling also depends on how much excess energy is available.
[‡] Often the term beta decay is used to describe either type of decay, and some times any type of decay that involves neutron to proton (or vice versa) transitions.
[§] and a neutrino.

exception of the mass. When a particle and its anti-particle encounter each other, they will annihilate and release energy equivalent to the combined mass and energy of the pair. The weak force is a nuclear force, only applying on the sub-atomic scale, but not plaingy a direct role in nuclear structure. This means that this force is generally not as familiar to us despite being integral to radioactive decay processes that we encounter all the time.

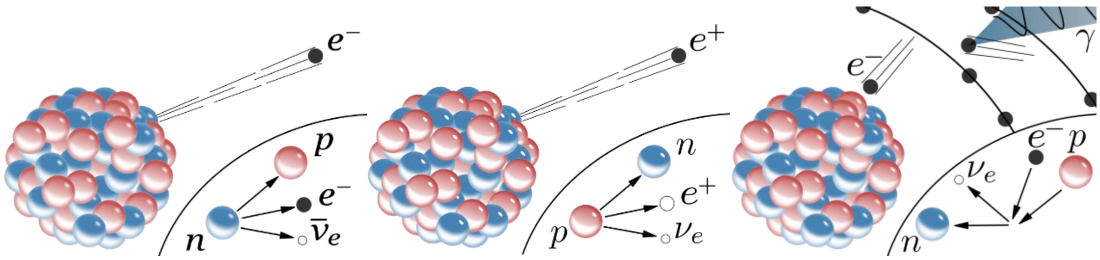



*Figure 13: Illustrations of the beta-type decay processes involving neutron to or from proton transitions: beta decay (left), beta-plus decay (middle) and electron capture (right).*

Essentially, the weak force governs processes that involve transitions between elementary particles (as opposed to composite particles). Protons and neutrons are not actually elementary particles, they are made up of quarks. In beta-type decays (Figure 13), within the proton or neutron there is a quark transition taking place[*]. The symmetries involved necessitate that electromagnetic charge be conserved, which is why either an electron or positron must be emitted; and that something called lepton number be conserved, which necessitates that an anti-neutrino or neutrino also be emitted along with the electron or positron. There is a related type of weak decay, *electron capture* (see Figure 12 and Figure 13), that can occur in place of a beta decay. In cases where the parent nuclide instability is the result of too many protons, but the nuclide lacks sufficient energy to produce a positron (which has mass), this is the only decay channel available. Again, the details of this involve a quark transition changing a proton to a neutron, with an electron from an inner atomic energy state being absorbed. The loss of that electron requires that a neutrino be ejected – to preserve lepton number, and the subsequent empty electron state will be filled by an outer electron[†] along with the release of an X-ray. In all of the decay processes involving a beta-type decay, there is a transition that changes the number of protons and neutrons in the nucleus, thus causing a transmutation.

The remaining radioactive decay processes that involve transmutation are much less common than alpha or beta-type decays. These include a range of *cluster decays* in which the parent nuclide ejects a small cluster of protons and neutrons (that are bound in the form of a recognized nucleus) – technically alpha decays could fall into this category, but their prevalence in nature sets them apart[‡]. Nuclei that undergo cluster decays are generally predominately alpha emitters with a much less probable cluster decay channel. *Spontaneous fission* – the fragmenting

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[*] A down quark in the neutron transitions to an up quark in the proton or vice versa.
[†] Higher energy level in the atomic structure.
[‡] Cluster decays also involve quantum tunnelling and are lower probability because of the higher mass of the cluster compared to the mass of an alpha.

of a parent nuclide into two or three daughter nuclides – can occur in nature, though only rarely and only in very heavy nuclei. Unlike cluster decays, this fission process involves the spontaneous break up of the nucleus into fragments of similar size, with a probability for a range of fragments, rather than fixed daughter products. Often following this fission process the daughter fragments will remain in an excited state that leads to the additional release of a number of individual neutrons.

This *neutron decay* is another rare type of decay usually seen following spontaneous fission. It will also occur in induced fission processes – a fact that is integral to sustained fission reactions – but this decay can occur in isolation as well. As we will discuss in detail in the next section, nuclides that undergo beta-minus or beta-plus decays are unstable because they contain too many neutrons or protons respectively. The beta decay is the most likely way of lowering the number of excess nucleons, but the emission of a single neutron or proton (*proton decay*) from the nucleus would accomplish the same thing. These processes are rare as they require the same overcoming of binding energies that alpha decays do and there is an alternative – beta decay[*].

## 2.2 Radioactive Isotopes

### 2.2.1 Instability

In the previous section, as part of the discussion of different types of radioactive decays, we briefly touched on what makes a particular isotope unstable. Fundamentally this comes down to the number of neutrons and protons in the nucleus and the ability for those protons and neutrons to stay bound together. Naively, from electromagnetism we know that the protons in the nucleus are repelling each other. And we can expect that the more protons, the harder it will be for the attractive strong nuclear force holding everything together to combat that repulsion force. Similarly, it makes intuitive sense that if you increase the number of neutrons so that there are more neutrons than protons, this will help to overcome the repulsive force of the protons. We can quantify the interplay between the number of protons and neutrons in terms of the ratio of neutrons to protons. Too low a ratio corresponds to too many protons without enough neutrons to mitigate the corresponding repulsive forces. As we increase the number of protons in the nucleus, an increasing number of neutrons is needed to overcome the greater repulsive forces, so this ratio must increase as the overall size of our nucleus increase. We can see this in Figure 12, which shows the chart of nuclides along with the "band of stability", which is close to a one-to-one ratio for very light nuclides, but quickly trends towards more neutrons.

However, this conceptualization cannot help us understand why too many neutrons would lead to instability. From the discussion of beta decay, we know that a common type of radioactive decay is the transition of a neutron to a proton, and that this occurs because there are too many neutrons. In our discussion of the production of gamma-rays in Chapter 1, we

[*] It is a subtle but powerful property of particle physics that any type of decay that is physically allowed will occur. The probability for an allowed process depends on the other decay channels available, specifically how plentiful and energetically advantageous the various channels are.

learned that the nucleus has a similar "shell" structure to that of electrons around the atom. More accurately, these shell models describe the discrete energy states allowed for the neutrons and protons in the nuclear case and for electrons in the atomic case*. As a result of the discrete and restricted energy states available, a high enough number of neutrons (or protons) relative to protons (or neutrons) will require a higher total binding energy than a nucleus with one more proton (or neutron) and one less neutron (or proton). If that energy difference is greater than the energy required to release a beta-minus (or beta-plus), a decay will be possible†.

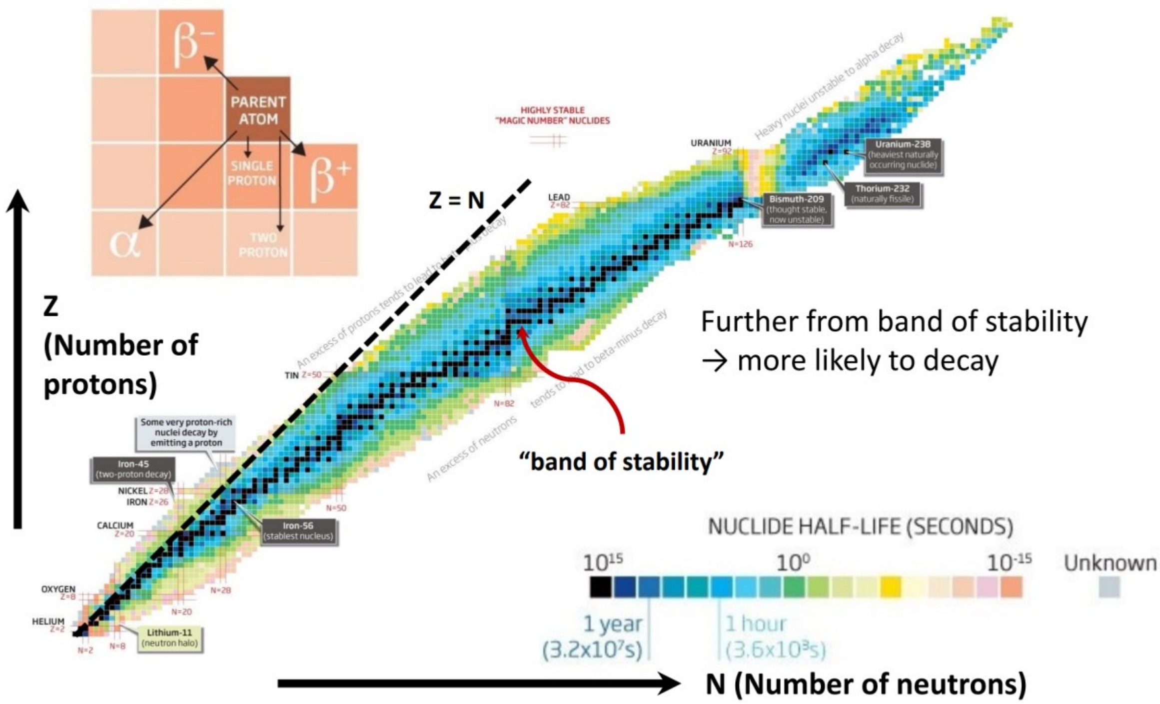


*Figure 14*: *Chart of nuclides showing the color-coded half-lives and highlighting some features of this chart. The number of protons (Z) increase along the y-axis and the number of neutrons (N) along the x-axis. The Z=N line is indicated with a dashed black line and the stable nuclides (black squares) follow a "band of stability" that deviates from that line.*

With this understanding of how instability can result from too many protons or neutrons, we can explore some properties of this type of instability, using Figure 14 as a guide. First, we can observe that there is a so called "band of stability" that follows the neutron-to-proton ratio mentioned previously and that this ratio increases as the number of protons and neutrons increases. We see that as the number of protons or neutrons moves away from this band, the half-life for unstable nuclides decreases – meaning these isotopes are less stable. This same chart is depicted in Figure 15 where the types of decays that will occur (or are most likely) are indicated. As the nucleus gets heavier, even with a good neutron-to-proton ratio, stability will become less likely because alpha decay becomes possible – because the binding energy of the daughter nuclide and the alpha combined is lower than the binding energy required for the heavier parent

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* In particle physics this is understood to be a result of the Pauli exclusion principle. [See Wikipedia for more info.]

† Recall that any time any type of decay is possible, it will have some probability of occurring.

nuclide. In Figure 14 we can see that the heaviest stable isotope is lead-208 (Pb-208) (this may be hard to pick out, Pb has a Z of 82 and N of 126). In Figure 15, it looks like there is an isotope with one more proton that is stable. This isotope is bizimuth-209, which has been found to be unstable with a half-life of ~$10^{19}$ years, which is why it appeared stable initially.

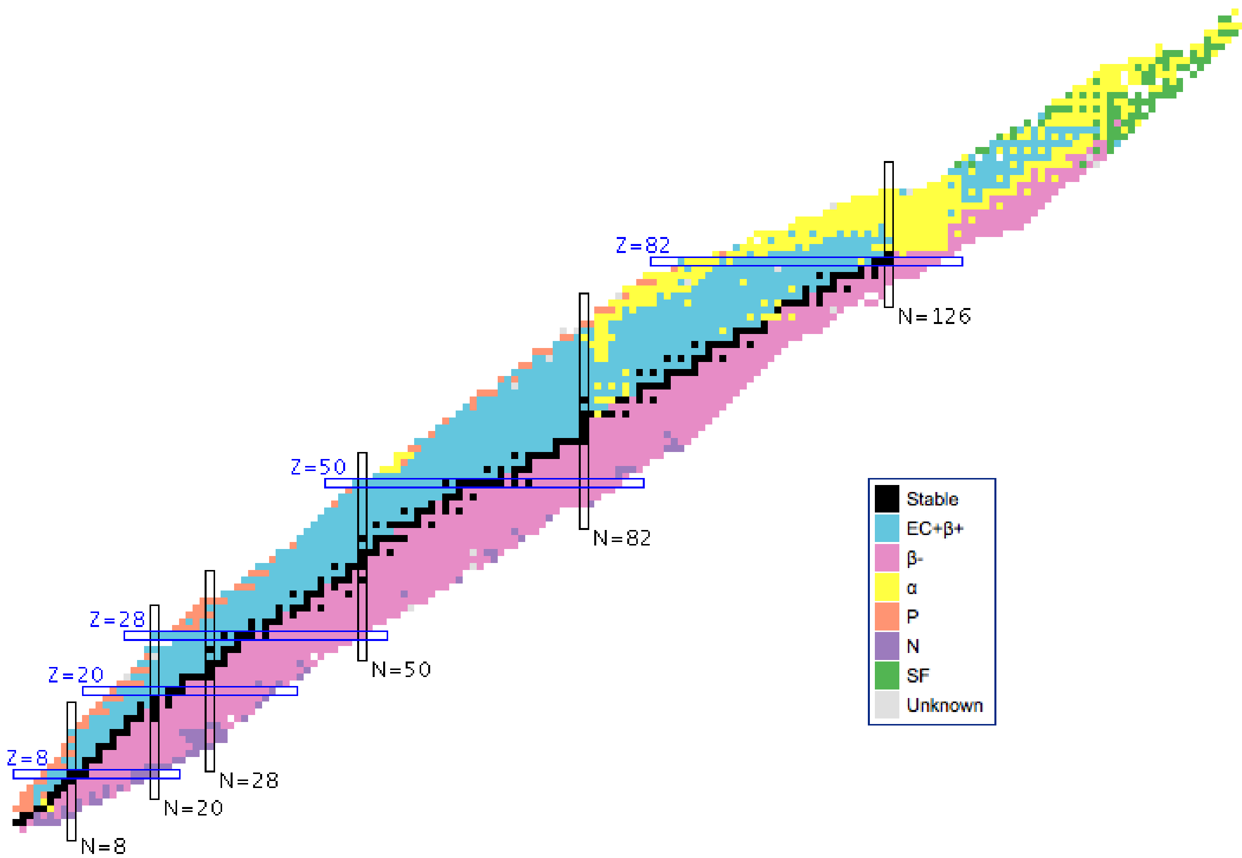


*Figure 15: Chart of nuclides with the most likely decay process indicated according to the Legend. As in Figure 12, the number of protons (Z) increases along the y-axis (not shown) and the number of neutrons (N) along the x-axis (not shown).*

We can also see that above Pb-208 alpha decays become a much more common type of decay. This should make sense now that we understand more about why decays occur: these nuclei are heavy enough to allow for alpha decay and this is more probable than beta decays because it allows for a larger energy transition, since an alpha is so much more massive than an electron. We still see that far from the ideal neutron-to-proton ratio beta decay alternatives again dominate. This should also make sense, as the interplay between allowed energy levels within the nucleus and the relative number of protons and neutrons will still mean that beta decay is a transition to a lower energy state, and an easier energy transition than alpha decay.

Several of the lower probability types of decay are also highlighted in Figure 15, such as proton and neutron decay and spontaneous fission. We can see that proton and neutron decay only dominate for isotopes very far from the band of stability. Again, this is because it takes more energy to eject a free proton or neutron than just an electron or positron through beta decay. Spontaneous fission only becomes the most likely decay channel for the heaviest elements, none of which are naturally occurring (see the note in Figure 14 on uranium). This does not mean that spontaneous fission does not occur in nature, only that it is never the most likely decay process for naturally occurring isotopes.

One final observation of nuclear stability worth touching on is the isotope types being highlighted by the blue bars in Figure 15 and red lines in Figure 12. These are isotopes that have a "magic number" of protons or neutrons, making them highly stable. Under the nuclear shell model – which is just an empirical model for describing nuclear structure – these isotopes contain enough protons or neutrons to fully fill the outer energy shell. This is analogous to the low reactivity of noble gases, which can be understood based on the atomic shell model*.

### 2.2.2 Decay Chains

Once an unstable isotope has decayed, the daughter nuclide may still be unstable. We have already touched on the case of the daughter nuclide being in an excited state, leading the emission of a gamma-ray. This is a kind of instability, but not the type we have discussed thus far, in which there are too many nucleons of some type. For very heavy nuclides, or those very far from the band of stability, a single alpha or beta-type decay will move the daughter closer to stability but may not be sufficient to reach a stable state. The daughter nuclide will then undergo further decay processes. This leads to a series of decays following from the initial parent isotope, called a ***decay chain***. This series of decays will continue until the final decay, where a stable isotope is the daughter.

For example, to use one of the most common sources of natural radiation, we can look at the decay process for Uranium. Uranium has two isotopes that we find in significant abundance naturally, uranium-238 (U-238) and 235 (U-235). Figure 16 shows the full decay chain for U-238.

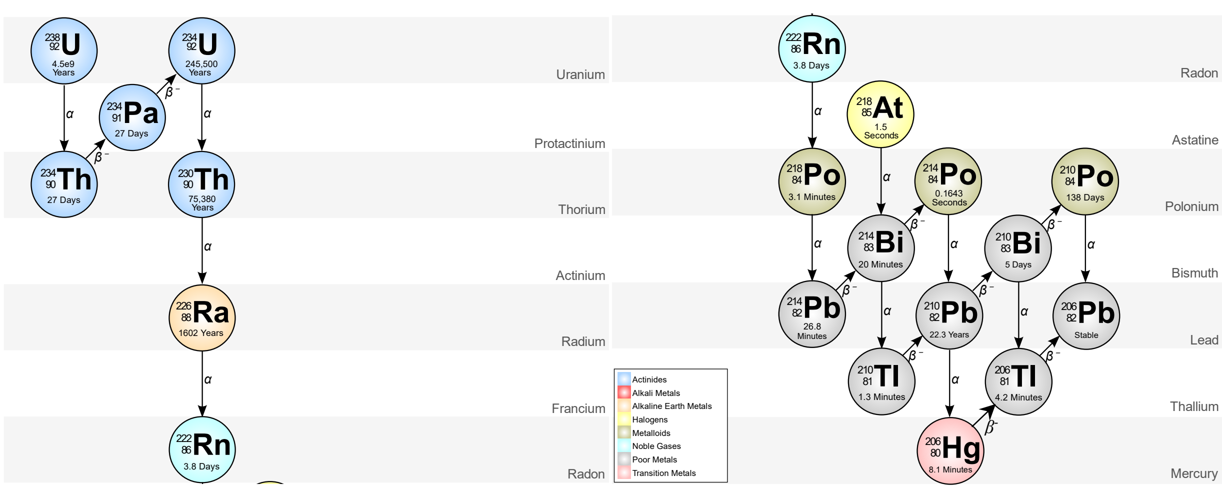


*Figure 16: The uranium-238 decay chain. The first half of the decay chain, down to radon-222 is shown on the left. The second half, continuing from Radon-222 down to lead-206 on the right. The half-life is stated below the chemical symbol for each isotope and the subsequent decay types are indicated along the arrows to the next daughter.*

* It is not necessary that you be familiar with the atomic shell model. Essentially this also an empirical model describing the preferred number of electrons occupying each energy level for an atom, which helps us to understand how various molecular bonds are formed and which elements are more or less likely to react.

The process for U-235 would be similar but will of course involve a slightly different set of daughters – many will be isotopes of the same element. Looking at the decay chain for U-238, we see that the first decay process is an alpha decay to thorium-234 (Th-234), which itself has a half-life of 27 days. Note that given the short half-life of this particular thorium isotope, this is not the isotope found in any abundance in nature. If we follow along in this process, we also find radium-226 (Ra-226) a few decays further along in the chain. We see here that the half-life for Ra-226 is more than 1,000 years. This is short compared to the half-life or the original parent U-238 isotope (4.5 x $10^9$ years), but long enough that we will find a significant amount of Ra-226 in nature[*]. Directly following Ra-226 is radon-222 (Rn-222), which you might remember as our primary source of background exposure. We will discuss in more detail how we can determine the exposure, or dose, from this type of source in Chapter 3, but take moment now to consider why this might be. Note that radon is a gas that can be inhaled, with several daughters that follow having short half-lives (seconds or minutes) before we reach lead-210 (Pb-210), all of which will go through alpha or beta decays – which we have learned cannot penetrate dense materials such as human tissue. We also see that this decay chain ends on a lead isotope, lead-206 (Pb-206), which is stable. It should not be surprising that generally the decay chains for heavy isotopes terminate with a stable lead isotope, given that this is the heaviest element that has stable isotopes.

## 2.3 Quantifying Radioactivity

We now understand the types of decays that unstable isotopes can undergo, and generally what types of decays to expect for different isotopes based on the number of protons and neutrons in those isotopes. As we discussed in Chapter 1, these decays occur because the combination of decay products is energetically favorable, but there can be multiple decay modes for which this is true. For all modes, we cannot say exactly when a decay will occur, or which type will occur, we can only state the probability for a decay (of any type) to occur within some time. This probabilistic nature of radioactive decays leads us to describe radioactivity in terms of rates of decay rather than absolute numbers of decays.

### 2.3.1 Activity

***Activity*** is the rate of decay of a radioactive material, so the number of decays that occur within some time period. If we have $N$ radioactive isotopes, that number will be changing over time, as those isotopes decay. The activity ($A$) can then be defined in terms of the change in $N(t)$ between $t_0$ and $t_1$ as:

$$A = \frac{N(t_1) - N(t_0)}{t_1 - t_0} \qquad \text{Eq. 1}$$

[*] This was one of the first radioactive isotopes discovered, used widely for florescence in watch dials and decorations before the dangers were fully appreciated.

Note that because we are losing isotopes as they decay, $N(t_1)$ will always be less than $N(t_0)$. However, we would consider the rate of decay to be positive, so it is more accurate to describe the activity as the negative rate of change:

$$A = -\frac{\Delta N}{\Delta t} \qquad \text{Eq. 2}$$

We can now ask how we determine that actual rate of decay, or activity, for a given isotope. We learned in Chapter 1 that we cannot say exactly when a particular atom will undergo a radioactive decay, but we can state the rate at which we expect decays to occur over time. Intuitively, we expect there to be more decays occurring if we have more radioactive isotopes. Another way of saying this is that the rate of decay, the activity, is proportional to the number isotopes:

$$\mathrm{A} \propto \mathrm{N}$$

The proportionality constant represents the rate at which we expect decays to occur, and is called the ***decay constant***, denoted with the symbol **λ**. The activity can then be defined in terms of λ as:

$$\mathrm{A} = -\frac{\Delta N}{\Delta t} = \lambda N \qquad \text{Eq. 3}$$

From this, we can derive the equation for the time-dependent number of atoms of this isotope. This will require a little calculus, and it is not necessary for you to be able to derive this yourself, so don't worry if you are unfamiliar with any of the steps we take here. Equation three is what is called a differential equation, because the derivative of $N$ with respect to $t$ is related to $N$ itself. We can solve this as follows:

$$-\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda \mathrm{N}$$

$$\Rightarrow \frac{\mathrm{d}N}{\mathrm{N}} = -\lambda \mathrm{dt}$$

$$\int_0^t \frac{\mathrm{d}N}{\mathrm{N}} = -\int_0^t \lambda \mathrm{dt}$$

The integral of $1/N$ is $\ln(N)$

$$\ln(\mathrm{N(t)}) - \ln(\mathrm{N_0}) = -\lambda \mathrm{t}$$

$$\ln\left(\frac{\mathrm{N(t)}}{\mathrm{N_0}}\right) = -\lambda \mathrm{t}$$

$$\frac{\mathrm{N(t)}}{\mathrm{N_0}} = e^{-\lambda \mathrm{t}}$$

$$\mathrm{N(t)} = \mathrm{N_0} e^{-\lambda \mathrm{t}} \qquad \text{Eq. 4}$$

We have now defined the number of atoms for a radioactive isotope as a function of time. Similarly, because activity depends directly on the number of isotopes, it will also change over time:

$$A(t) = -\frac{dN(t)}{dt}$$

$$A(t) = \lambda N_0 e^{-\lambda t}$$

$$A(t) = A_0 e^{-\lambda t} \qquad \text{Eq. 5}$$

### 2.3.2 Half-life

Through this derivation, we find that the number of atoms is decreasing exponentially over time, with the exponential rate depending on the decay constant. We also learned in Chapter 1 that a useful way of quantifying the rate of decay for a particular isotope is the half-life – the time it takes for half of the atoms of that type to decay away. We can derive the relationship between the decay constant and the half-life $(t_{1/2})$:

$$N(t_{1/2}) = \frac{1}{2}N_0 = N_0 e^{-\lambda t_{1/2}}$$

$$\Rightarrow \frac{1}{2} = e^{-\lambda t_{1/2}}$$

$$\ln\left(\frac{1}{2}\right) = -\lambda t_{1/2}$$

$$\ln(2) = \lambda t_{1/2}$$

$$\Rightarrow \lambda = \frac{\ln(2)}{t_{1/2}} \qquad \text{Eq. 6}$$

With Eq. 3 and Eq. 6, we can now determine the activity of any material containing radioactive isotopes if we know how much of the radioactive isotope is contained in the material and the half-life of that isotope (we can assume that if we have determined an isotope to be unstable, we know the half-life). Note that this result also tells us that the units for the decay constant are inverse seconds (1/s).

### 2.3.2 Decay Probability

From Eq. 4 and Eq. 5 we know that the rate of decay at time $t$ is $\lambda N_0 e^{-\lambda t}$. For a single atom, this is simply $\lambda e^{-\lambda t}$ and represents the probability of a single atom decaying as a function of time, call this $P(t)$. The probability of a single atom decaying in some time interval, $\Delta t$ is then $P(t)\Delta t$. This can be expressed as $p$ and calculated as follows:

$$p = \int_0^t \lambda e^{-\lambda t} dt$$

Note: the integral of an exponential is an exponential

$$p = \lambda \left[\frac{-1}{\lambda} e^{\lambda t}\right]_0^t$$

$$p = -(e^{-\lambda t} - e^0)$$

$$p = 1 - e^{-\lambda t}$$ Eq. 7

To build our intuition around this, we can consider the case of an isotope with a very long half-life. Conceptually, we would expect that an isotope with a very long half-life has a very low probability of decaying over short time scales (say one second). From Eq. 6 we know that for $t_{1/2} \gg 1$ we will have $\lambda \ll 1$. This means that in Eq. 7, the exponential term has an exponent $\lambda t \ll 1$. We can use an approximation (the Taylor series) for exponentials of the form:

$$e^{-\lambda t} \approx 1 + (-\lambda t)$$

$$\Rightarrow p = \lambda t$$

In Part II, we will see how the probabilistic nature of isotope decay, and the probability of single decays being small, helps us to model the statistics of radioactivity.

### 2.3.4 Branching Ratios

In the discussion of instability in the previous section (2.2), there were several references to decay channels. The possibility of different decay channels means that each channel will have some probability of occurring. The combination of all channels is what gives us the total rate of decay for a particular isotope. However, it is important to distinguish between the different decay channels, as they will involve different types of radiation (alpha, beta, etc.) carrying different amounts of energy and therefore having a different impact on exposure.

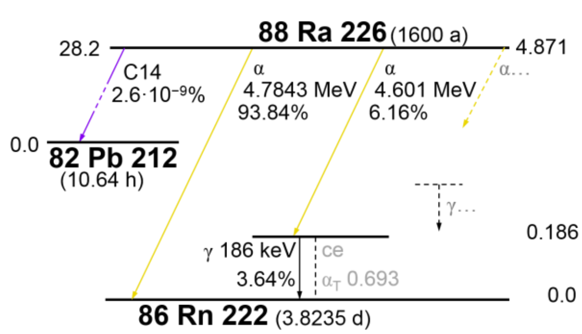


*Figure 17: The decay scheme for radium 226 showing the different decay channels labeled by decay type, decay energy, and the corresponding branching ratio (%). The parent/daughter half-lives are indicated in parenthesis in years (a), days (d), or hours (h) next to the isotope label. Dashed line decay types indicate those that are not listed due to low relative probabilities compared to the primary decays of that type. The excess energy (in MeV) for a given state is indicated by the number to the right (or left) of the horizontal line for that state.*

We can quantify the relative probability for a given type of decay by the ***branching ratio*** – the fraction of all decays for the parent isotope. We can use a *decay scheme* – diagram showing all properties of the different decay channels – to explore branching ratios for a particular decay. Figure 17 shows the decay scheme for Ra-226 as an example. From our exploration of the decay chain for uranium, we might already be anticipating that alpha decays should be the primary, or only, decay channel for this isotope. The decay scheme shows three decay channels. The percent values indicated with each channel indicate the branching ratio. So, this decay scheme indicates that 93.84% of all Ra-226 decays will involve an alpha with an energy of 4.7843 MeV*.

Another 6.16% of decays involve an alpha of a slightly lower energy, 4.601 MeV. This second decay option takes us to the same daughter, Rn-222, but in an excited state with an excess 186 keV of energy†. You can see this from the 0.186 next to the state, or from the subsequent gamma decay, which carries 186 keV. The scheme also indicates that this gamma decay will occur 3.64% of the time, that is the total percent of Ra-226 decays that result in the emission of a 186 keV gamma-ray, not the percent of 4.601 MeV alpha decays that then have a gamma-ray emission – so this is the absolute branching ratio for the gamma emission, not a relative branching ratio.

Effectively, these two alpha decays make up 100% of Ra-226 decays (93.84% + 6.16% = 100%). However, the decay scheme includes other decays. First, there is the shaded alpha with the dotted yellow arrow. This indicates that there are several other alpha decays that can occur (with the shaded gamma indicating that these decays are too excited states that will have subsequent gamma emissions). However, these decays have probabilities so low that they do not contribute significantly to the observed alpha decays, they are only indicated here for completeness. Similarly, this scheme also includes a decay involving the emission of a carbon 14 (C-14) atom. This is an example of a cluster decay, and is extremely rare, occurring only $2.6 \times 10^{-9}$% of the time.

This type of decay scheme can be a useful visualization of important properties of the decay channels for isotopes of interest. In general, there are a range of resources that can be used to determine the dominant decay channels, decay types, decay energies, and branching ratios, etc.

## 2.4 Units

When quantifying activity, it is necessary to define the units used. We defined activity generally as the rate of decay, or number of decays in some time range. In the choice of units,

* 1 eV = 1 electron-volt – the kinetic energy required gained by an electron being accelerated through a potential difference of 1 volt. An MeV is a mega-electron-volt, or $10^6$ eV. We can relate this to the SI unit for energy (Joules) as: 1 eV = $1.602 \times 10^{-19}$ Joules. This will come up in understanding radiation dose, which depends on the energy of the radiation absorbed.

† The astute observer may notice that this is more energy than the difference in the energies of the two alpha decay channels. Given that energy should be conserved, how can this be? There is another example of this same property shown in this scheme related to the total excess energy of the Ra-226 and the energy carried away by the various decays.

we can specify the time range, and in some cases the number of decays a specific source will undergo in that time range. For example, the first unit used to describe activity, which persists now for historical reasons, is the Curie. The ***Curie (Ci)*** was defined in 1910 as the number of disintegrations (decays) of radium-226 that will occur in one second. This unit makes sense historically, as Marie Curie was one of the three scientists credited with the discovery of radioactivity, and Ra-226 was one of the first radioactive materials discovered (by Curie) and was used extensively in radioactivity applications at the time. However, it is not a very meaningful unit when compared to most sources – radium is extremely radioactive:

$$1\ \text{Ci} = 3.7 \times 10^{10}\text{decays/s.}$$

Note: Most lab sources are much less active than this, with activity in the $\mu Ci$ range.

In 1974, the SI (International System of Units) unit for activity was defined and given the name Becquerel – named for Henri Becquerel, another of the three scientists credited with the discovery of radioactivity. The ***Becquerel (Bq)*** is defined as 1 disintegration (decay) per second. We can relate these two units, which should be clear based on the definition of the Bq:

$$1\ \text{Ci} = 3.7 \times 10^{10}\text{Bq.}$$

Most lab sources are in the $kBq$ or $MBq$ range. So sources used in the lab do produce quite a lot of radiation, it is only a small amount when compared to radium.

The Bq seems much more intuitive as a unit, as it does not require knowledge of the decay rate for radium. However, whether we use Ci or Bq, the significance of the actual activity value for a given material is only meaningful once we have some context for how activity relates to the radiation dose imparted because of that activity. We will discuss how we determine radiation dose from activity in Chapter 3.

## Chapter Summary/Key Takeaways

- Types of radioactive decay beyond alpha, beta, and gamma include additional beta-type decays: beta-plus (positron emission), electron capture, and much less common types of decay like spontaneous fission, and neutron/proton decay.
- Radioactive decay occurs because the nucleus is unstable. This instability arises from too many neurons, too many protons, or both. The type of instability determines the most likely types of decay that will occur: beta-minus, beta-plus or electron capture, or alpha respectively.
- A ***decay chain*** describes the series of decays from an initial *parent isotope* down to the final stable isotope into which the last daughter decays.
- We quantify how radioactive a material is as the ***Activity*** – the number of radioactive decays per time. We specify this in units of decays per second – ***Becquerel ($Bq$)***. The historical unit that is also often used to quantify activity is Curie ($Cu$) ($3.7 \times 10^{10} Bq$).
- Activity is the rate of radioactive decay, defined as:

$$A = -\frac{\Delta N}{\Delta t} = \lambda N$$

- The decay constant for a specific isotope, $\lambda$, is the probability for a decay to occur. It can be defined in terms of the half-life as:

$$\lambda = \frac{\ln(2)}{t_{1/2}}$$

- The ***branching ratio*** describes the fraction, or percent, of all decays of an isotope that involve a given type of decay.

## Review Questions

- Why is radon such a significant source of the average yearly radiation exposure for people? How might you expect exposure levels to vary – both in terms of location and exposure levels (recall what we learned in Chapter 1)?
- If you had a .25kg thorium rock – meaning it has a significant amount of thorium in it, say ~3% of the rock mass – how would you determine the activity of the rock? See the example problem on the next page for tips.
- From the example problem (next page), we know how much activity the human body produces from C-14. Assuming human bones contain the same proportion of carbon (it's actually a little higher), and that bone makes up 15% of the human body mass, how would you determine the age of a skeleton if given the activity of the skeleton?

## Example Problem

- The human body is 23% carbon. A small percentage of all carbon is carbon 14 (C-14)[*], it has a relative abundance of 1 in $10^{12}$ carbon atoms. Therefore, a small percentage of all carbon in our bodies is C-14[†]. C-14 is unstable, with a half-life of 5730 years. Assuming a mass of 70 kg on average for the human body, we can determine how radioactive the average human will be as a result of the carbon in our bodies. In other words, what is the Activity of the human body from C-14?
  - Recall the equation for Activity ($A = \lambda\mathrm{N}$). We need to determine the number of C-14 atoms in the human body, and the decay constant for C-14.
  - Note: the molar mass ($M_C$) of carbon is 12.011g/mol
  - Avogadro's number: $N_A = 6.02 \times 10^{23}$ atoms/mol

Step 1. $C_{mass} = 70\, kg\ *\ 0.23\ =\ 16\, kg$ of carbon in the body

Step 2. $\mathrm{N_{C-14}} = \mathrm{N_C} * 1 \times 10^{-12}$

Step 3. $\mathrm{N_C}\ =\ \mathrm{C_{mass}(g)/M_C(g/mol)} *\ \mathrm{N_A(atoms/mol)}$

Step 4. $\mathrm{N_C} = 16 \times 10^3/12.011 * 6.02 \times 10^{23} = 7.8 \times 10^{26} atoms$

Step 5. $\mathrm{N_{C-14}} = 7.8 \times 10^{14} atoms$

Step 6. $\lambda = \frac{ln(2)}{t_{1/2}} = \frac{\ln(2)}{5730(\mathrm{years})}$

Step 7. $A = \lambda N = N * \frac{ln(2)}{5730(years)} = 9.426 \times 10^{10} \mathrm{decays/year}$

Step 8. $N_{seconds/year} = 365(\mathrm{days/year}) * 24(\mathrm{hrs/day}) * 3600(\mathrm{second/day})$

1. $= 3.1536 \times 10^7$

Step 9. $A = \frac{9.426\times10^{10}\mathrm{decays/year}}{N_{seconds/year}} = 2989\ \mathrm{decays/second}$

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[*] How C-14 makes its way into our environment is an interesting process, it does not have a long enough half-life to persist without being replenished. This process occurs through interactions of cosmic rays with nitrogen in our atmosphere.

[†] Chemically all isotopes of an element will behave the same (a difference in the number of neutrons, which are neutral, does not affect chemical properties). Therefore, any molecules containing carbon can contain any isotope of carbon, including C-14.