Chapter 21 – Nuclear Chemistry

The study of nuclear chemistry and physics is important for several reasons. Controversies about nuclear weapons, power, and waste surround us. The more information you have the better you will be able to make decisions regarding this matter.

The use of radioactive materials is here with us to stay. The goal of the elimination of nuclear weapons is laudable but unlikely to actually occur in the foreseeable future. The elimination of nuclear power in the US is more likely, but that won’t occur for decades at the earliest. It is also unlikely that nuclear power will be eliminated in all countries in our lifetimes. Finally, nuclear medicine is still the best way to diagnose and/or cure many conditions from thyroid problems to cancer. Again, while drug therapies may one day supplant nuclear medicine, that day is still far off. Even if tomorrow, all of the above uses of things nuclear ended, much of the waste generated in the past will be around for thousands to billions of years. As a society, we have to make decisions about what to do with that waste.

21.1 Radioactivity

We begin with a short review from CHM 211. (Go back and review Chapter 2, sections 1-3.) Nuclei are composed of positively charged protons and uncharged neutrons. These particles are collectively called nucleons. Nuclei are expressed by the symbol $^A_Z\text{Sy}$ where $A$ is the mass number, $Z$ is the atomic number, and Sy is the atomic symbol. Since the atomic symbol indirectly conveys the atomic number, the latter is frequently left off and I will usually do that (e.g. $^{12}\text{C}$, $^{14}\text{N}$, etc.) Some nuclei are inherently unstable and decompose spontaneously through the emission of electromagnetic energy and/or particles. These isotopes
are radioactive and are called radioisotopes.

There are three types of naturally occurring radiation: \( \alpha \)-particle, \( \beta \)-particle, and \( \gamma \)-ray emission. By “naturally occurring,” we mean that these emissions occur in naturally occurring isotopes. As we shall soon see, there are other types of nuclear processes that occur in artificial isotopes.

\( \alpha \)-particle emission is the ejection of a helium nucleus, \(^4\text{He}\) (or helium-4), from the nucleus of another isotope.

\[
^{222}\text{Rn} \rightarrow ^{218}\text{Po} + ^4\text{He}
\]

The reaction written above is called a nuclear reaction. It is similar in some ways to a “normal” (chemical) reaction, but differs in some important ways. First the species shown are atomic nuclei, not atoms. Second, when balancing you must make sure to balance both the atomic numbers and mass numbers. In the example, the mass numbers add to 222 on each side of the equation and the atomic numbers add to 86.

\( \beta \)-particle emission is the ejection of an electron \((-\text{e}^0_1)\) from a nucleus. \( \beta \)-particles are physically identical to the electrons in orbitals outside the nucleus. Designation as a “\( \beta \)-particle” is important because orbital electrons can play a role in nuclear processes (vide infra). They are sometimes designated as: \( -1\beta \). A sample reaction (that we’ll discuss more later) is:

\[
^{14}\text{C} \rightarrow ^{14}\text{N} + ^0\text{e}^-_1
\]

How does the nucleus eject an electron, when, after all, there are no electrons in a nucleus? The nucleus does contain neutrons and they are neutral particles that weigh slightly more than protons. When a neutron decomposes, it breaks up into a proton and an electron. But how does the negatively charged electron escape from the positively charged nucleus? The combined
masses of the proton and electron total to less than that of the neutron and the mass difference is converted to pure energy which is then used to eject the electron from the nucleus. We will discuss this later in the chapter.

γ-ray emission ($^0_0 \gamma$) is the release of pure energy from a nucleus. It usually occurs with other types of emission and is not typically put in the nuclear equation.

There are two other types of nuclear reactions. These occur exclusively in elements that are prepared synthetically (man-made elements).

**Positron emission** occurs when the nucleus ejects a particle with the same mass as the electron, but with a positive charge, $^0_{+1}e$. Although redundant, the “+” sign in the lower part of the symbol is frequently used to prevent confusion as to whether a β-particle was intended or not. A typical positron emission reaction is:

$$^{11}C \rightarrow ^{11}B + ^0_{+1}e$$

Positron emission results from the decomposition of nuclear protons. They are formed when a proton converts to a neutron. Positrons are a form of the anti-matter you have no doubt heard of through StarTrek®. When a positron and an electron collide (and they eventually will), they annihilate. This word has a very specific meaning here. When two particles annihilate they both cease to exist as matter. Nothing except energy remains (as a γ-ray). (This is, in part, why Scotty became so excited whenever he thought the engines would lose containment.)

$$^{1}_{1}H \rightarrow ^0_{+1}e + ^1_{0}n$$

$$^0_{+1}e + ^0_{-1}e \rightarrow ^0_{0}\gamma$$

Electron capture happens when the nucleus removes an electron from an inner shell. (Remember s orbitals have no node at the nucleus.) Electron capture converts a proton into a
21.2 Patterns of Nuclear Stability

As you know, most of the mass of an atom is located in the nucleus. Its density is incomprehensibly large: $2 \times 10^{14}$ g/cm$^3$. Compare this with the most dense element osmium which has a density of about 22 g/cm$^3$. A rough comparison is a grain of sand weighing 800,000 pounds. The difference in densities between observed densities and nuclear densities is the volume swept by electrons. Since electrons weigh next to nothing, large volumes are added to the nucleus with virtually no mass contributed.

Except for hydrogen, all nuclei have multiple protons compressed into a small space. So why doesn’t the nucleus fly apart? The answer is something called the strong nuclear force. It operates over very short distances (about one nuclear diameter) and is very powerful. In small nuclei the force operates over the entire nucleus, but in very large nuclei its full force can’t completely overcome the electrostatic repulsions of protons on opposite sides of the nucleus. Here, the strong nuclear force and electrostatic attraction are comparable and hence the nucleus is unstable. Occasionally a nucleon will decompose to create a more stable nucleus. Later in this chapter, we will calculate the energy of the attraction.

The principal method of predicting nuclear stability is its neutron-to-proton ratio. Low nucleon nuclei should have ratios equal to or very close to one. This ratio gradually increases until for the heaviest stable nuclei it is about 1.5:1. The neutron-to-proton ratio is probably not the cause of nuclear instability, rather it is a symptom.
General nuclear stability rules

1) All nuclei containing 84 or more protons are radioactive. Beginning with polonium the nuclei of all elements are radioactive.

2) All isotopes of technetium (43) and promethium (61) are radioactive.

3) In Chapter 8 you learned the octet rule which specified an electron count for stable ions and bound atoms. A similar rule operates on nuclei. For either or both protons and neutrons a total of 2, 8, 20, 28, 50, 82, or 126 yields a closed shell system. These numbers are called magic numbers.

4) Nuclei with an even number of both protons and neutrons are more stable than an even/odd combination, which in turn are more stable than odd/odd combinations. For the first 20 elements, there are 9 even/even, 10 even/odd, and 1 odd/odd (nitrogen) combinations. At first glance, this might seem to suggest that even/odd is more stable, but remember an even/even combination is not possible for elements with an odd number of protons. Thus, of the first twenty elements, nineteen have even numbers of neutrons in their most stable isotope (the only exception is beryllium).

On page 835 is a graph of all stable nuclei, where their proton total is graphed against their neutron total. As you can see, they form a band. It is called the belt-of-stability. At the far right side of the graph the neutron-to-proton ratio reaches 1.5:1 as described earlier. The reason for the extra neutrons is that they act as spacers between the protons. Their presence helps keep the protons from getting too close and thus reduces electrostatic repulsion. As long as the nucleus is small this works well.

Nuclei outside the belt-of-stability decay to produce nuclei within it. For example, if the neutron-to-proton ratio is too high, the nucleus will convert a neutron into a proton. It will do
this by a $\beta$-particle emission.

$$\frac{1}{0}n \rightarrow \frac{0}{-1}e + \frac{1}{1}H$$

$$^{14}C \rightarrow ^{14}N + ^{0}_{-1}e$$

If the neutron-to-proton ratio is too low the nucleus will convert a proton into a neutron. This can occur by either positron emission or electron capture. It is interesting to note that since

$$^{38}Kr \rightarrow ^{1}n + ^{0}_{+1}e$$

$$^{37}Ar + ^{0}_{-1}e \rightarrow ^{37}Cl$$

these two paths never occur in naturally occurring isotopes, that all naturally occurring radioactive isotopes have too many neutrons. Why might that be?

Nuclei beyond element 83 frequently decay by $\alpha$-particle emission, yet this will not have a large change in the neutron-to-proton ratio. So why does this occur? Earlier we said that in large nuclei, the competition between the strong nuclear force and electrostatic repulsion was the origin of nuclear instability in large nuclei. $\alpha$-particle emission allows a nucleus to rapidly reduce the number of nucleons it possesses.

The radioactive decay series displayed on p. 837 (Figure 21.4) shows how $\alpha$-particle emission takes uranium from being radioactive to stable lead in a series of fairly large steps. None of the other emission methods allows the loss of nucleons, only their interconversion.

21.3 Nuclear Transmutations

Nuclear transmutation is the induced conversion of one nucleus into a different one. The word induced is important because spontaneous conversions result from normal radioactive decay. All of the synthetic (man-made) elements result from nuclear transmutation reactions. In
a nuclear transmutation the nucleus of one atom is fired into the nucleus of a second atom at a high velocity. The high speed is required to overcome electrostatic repulsion of the nuclei. (Sometimes neutrons are used in place of other nuclei as the projectile.)

Read the rest of the section on your own.

21.4 Rates of Radioactive Decay

While the rates of radioactive decay vary widely, all radioactive nuclei decay by first-order processes. It would be a good thing for you to review first-order reactions in Chapter 14 now (pp. 537 – 539). Because most people find it easier to discuss decomposition rates in terms of half-lives (time) rather than rate constants (inverse time), the former are usually used in discussions about nuclear stability. Half-lives range from ca. $10^{-18}$ s ($^{9}$B) to ca. $10^{17}$ yr ($^{96}$Zr, NB. The universe is only about $10^{10}$ years old.), a span of 43 orders of magnitude, although more typical values are in the range of hundredths of a second to hundreds of years.

One valuable consequence of first-order decay is the use of radioactive materials to determine the age of objects (called radioactive dating). The most common forms of radioactive dating are carbon-14 and uranium-238 dating.

In the upper atmosphere cosmic rays destroy some nuclei and produce free neutrons, which then can react with atmospheric nitrogen. Please note that these are not chemical reactions, so

$$^{14}\text{N} + ^{1}\text{n} \rightarrow ^{14}\text{C} + ^{1}\text{H}$$

the nitrogen nucleus in the question will almost assuredly be part of a nitrogen molecule. After conversion to carbon-14, the resulting chemical fragment will go on to react chemically. The carbon-14 that results from this collision is unstable and reverts back to nitrogen-14 with a half-life of 5730 years. Carbon-14 dating works by assuming a few things over the past 50,000
\[ ^{14}\text{C} \rightarrow ^{14}\text{N} + ^{0}\text{e} \]

years: (1) the amount of nitrogen in the atmosphere has been constant, (2) solar output has been relatively constant, and (3) the rotation of the Earth ensures that the atmosphere mixes well every few years. There is no argument about the first point and the third point has been demonstrated as true. Researchers have developed a method of dealing with variations in (2). Regular cycles in the Sun’s output exist and are smoothed out over time. Variations in the carbon-14 produced are averaged away as it progresses into the lower atmosphere where it becomes useful for dating purposes.

Carbon-14 atoms are eventually converted into \(^{14}\text{CO}_2\) which is breathed in by plants and incorporated into their structures. These plants are eventually eaten by animals, which in turn are eaten by others. Thus, \(^{14}\text{C}\) makes it into every living creature, including you. That’s right, a very small percentage of the carbon in your body is radioactive and decaying as you read this. Because of the assumptions made above, that amount remains constant during the entire lifecycle of an organism. This is important because it means that the ratio of \(^{12}\text{C}\) to \(^{14}\text{C}\) stays constant until an organism dies. On death, no new carbon-14 is ingested and the amount present in the organism begins to decline. Since the initial ratio and the decay rate are known, the ratio in a sample will yield the age of an organism when it died (\textit{vide infra}). The upper limit on age determination by this method is about 50,000 years.

Similarly, the decay of uranium-238 and potassium-40 give the ages of very old geological samples. The former has a half-life of 4.5 billion years and the ratio of uranium-238 to lead-206 is used to determine the age of rocks. If a rock contains lead-206 as its only lead isotope, it is assumed that all of the lead in the rock comes from uranium-238 decay. The presence of lead-208, in addition to the lead-206, suggests another source for the lead.
Calculations

Since these are first-order processes: \( k = \frac{0.693}{t_{\frac{1}{2}}} \), \( \ln \frac{N_t}{N_0} = -kt \) where \( N \) is the number of radioactive nuclei, and rate = \( kN \).

Ex. 21.7 I’m going to work this problem a little differently from the book. Use whichever method seems best for you.

You will need \( \ln \frac{N_t}{N_0} = -kt \).

\[ k = \frac{0.693}{t_{\frac{1}{2}}} = \frac{0.693}{4.5 \times 10^9 \text{ yr}^{-1}} = 1.54 \times 10^{-10} \text{ yr}^{-1} \]

we can substitute moles for atoms since both are counting terms

\[ \text{mol}_{\text{Pb}} = (0.257 \text{ mg}) \left( \frac{1 \text{ g}}{10^3 \text{ mg}} \right) \left( \frac{1 \text{ mol}}{206 \text{ g}} \right) = 1.25 \times 10^{-6} \text{ mol}_{\text{Pb}} \]

\[ \text{mol}_{\text{U}}(\text{total}) = (1.00 \text{ mg}) \left( \frac{1 \text{ g}}{10^3 \text{ mg}} \right) \left( \frac{1 \text{ mol}}{238 \text{ g}} \right) = 4.20 \times 10^{-6} \text{ mol}_{\text{U}} \]

\[ \text{mol}_{\text{U}}(\text{init}) = 1.25 \times 10^{-6} \text{ mol}_{\text{Pb}} + 4.20 \times 10^{-6} \text{ mol}_{\text{U}} = 5.45 \times 10^{-6} \text{ mol}_{\text{U}} \]

\[ \ln \frac{4.20 \times 10^{-6} \text{ mol}_{\text{U}}}{5.45 \times 10^{-6} \text{ mol}_{\text{U}}} = -(1.54 \times 10^{-10} \text{ yr}^{-1})t \]

\[ t = 1.7 \times 10^9 \text{ yr} \quad \text{(only two SF because of } t_{\frac{1}{2}}) \]

21.5 Detection of Radioactivity

The most common instrument used to measure radioactivity is the Geiger counter. The device is an insulated metal tube with a metal rod in the center (attached to one end of the tube). A window that allows radiation to enter the tube covers the other end of the tube. The tube and
rod are hooked to opposite ends of a battery and a detector. The tube is also filled with argon gas because it is inert. When an α- or β-particle strikes the rod or walls a signal is sent to the detector. When a γ-ray enters it ionizes one of the argon atoms which then strikes the tube walls.

Read about scintillation counters and radiotracers on your own.

21.6 Energy Changes in Nuclear Reactions

Earlier, in CHM 211, you learned the Law of Conservation of Mass (p. 36). It said that the sum of the masses of the reactants in a chemical reaction equaled the sum of the masses of the products. It turns out that this is not, technically speaking, true. The burning of one mole of methane, CH₄ (80 g for one mole of methane), results in a 10 µg reduction in mass. This amount is far too small to be measured. (N.B. Weighing a 10 µg sample is comparatively easy. Measuring a 10 µg change in a 100 g sample is essentially impossible.) This tiny change is extraordinarily important as we shall soon see.

In nuclear reactions, mass converts to energy (and vice-versa) according to Einstein’s famous equation, E = mc². In fact, all nuclear reactions result in measurable mass changes. The fission of one pound of uranium-235 (ca. 2 moles) results in well under a one gram loss, yet results in an energy output equal to burning 3 million pounds of coal. An important question is why do substantive mass changes occur in nuclear reactions?

First, once physicists could accurately determine the weights of subatomic particles, it quickly noted that the mass of all nuclei were smaller than the sums of the masses of their constituent nucleons.

Ex. ¹⁹F: measured mass = 18.9984 amu

calculated mass = 9(1.00728 amu) + 10(1.00866 amu)
\[ \Delta m = 19.1521 \text{ amu} - 18.9984 \text{ amu} = 0.1537 \text{ amu} \]

\( \Delta m \) is called the mass defect and in this case represents just under one percent of the calculated (expected) mass. The energy associated with this mass defect is calculated by:

\[
\Delta E = (\Delta m)c^2 = (0.1537 \text{ amu}) \left( \frac{1 \text{ g}}{6.022 \times 10^{23} \text{ amu}} \right) \left( \frac{1 \text{ kg}}{10^3 \text{ g}} \right) (3.00 \times 10^8 \text{ m/s})^2 
\]

\[ = 2.30 \times 10^{-11} \text{ J (per nucleus)} \]

This value is called the nuclear binding energy and appears very small, but now we convert it to a mole of fluorine atoms and we find:

\[
\Delta E = \left( \frac{2.30 \times 10^{-11} \text{ J}}{\text{nucleus}} \right) \left( \frac{6.022 \times 10^{23} \text{ nuclei}}{\text{mol}} \right) \left( \frac{1 \text{ kJ}}{1000 \text{ J}} \right) = 1.38 \times 10^{10} \text{ kJ/mol}
\]

This is 14 billion kilojoules released when a mole (ca. 19 g) of fluorine nuclei are broken up into constituent nucleons. Compare this with a typical chemical reaction: burning one mole of methane (16 g + 64 g of oxygen) yields only 2 kJ. To put this in further perspective, the Grand Coulee Dam is the largest hydroelectric dam in the US and would have to have to run full out (6500 megawatts) for over 30 minutes to put one mole of fluorine nuclei together from its constituent nuclei. Another value may put this in better perspective, the number of one pound boxes of corn flakes necessary to produce the same amount of energy:

\[
\text{boxes} = \left( \frac{1.4 \times 10^{10} \text{ kJ}}{\text{mol}} \right) \left( \frac{1 \text{ Cal}}{4.18 \text{ kJ}} \right) \left( \frac{1 \text{ oz}}{110 \text{ Cal}} \right) \left( \frac{\text{box}}{16 \text{ oz}} \right) = 1.9 \text{ million boxes of corn flakes}
\]

We can now answer a question raised on p. 4 concerning why the nucleus remains intact. The nucleus is held together by the expenditure of a tremendous amount of energy. When a nucleus fragments some of that energy is released (in reality, the break-up to individual nucleons
is incomplete and clusters of nucleons (i.e. the nuclei of other atoms) form). As you might guess even a fraction of this energy can have enormous practical consequences.

An interesting aside comes from dividing the nuclear binding energy by the number of nucleons. The result is plotted for nuclei on p. 849. It turns out that iron-56 is the most stable nucleus and this too has important consequences. Nuclei lighter than iron-56 will tend to fuse together, while those with higher masses will tend to split apart. Stars are made mostly of hydrogen until they are quite old. Our sun has been burning for about 5 billion years and is still about 75% hydrogen and 25% helium. The burning that you observe is the tremendous gravity of a star creating the conditions necessary for fusion to naturally occur. As lighter nuclei fuse together to form more stable heavier nuclei, energy is released. The highest mass nucleus that can form in a star is iron-56.

So where do cobalt and the next 65 or so elements come from? At the end of its life a star may explode (a supernova). When this happens the energy of the explosion causes some nuclei to fuse together into the heavier nuclei. When these nuclei are projected into space they are frozen into a (more or less) eternal existence.

21.7 Nuclear Fission

Nuclear fission is the process in which an external particle causes a nucleus to cleave into smaller parts. Of particular importance is when “slow neutrons” strike uranium-235 and plutonium-239 nuclei. In this situation, the neutrons cleave nuclei releasing more than one neutron.

\[ ^{235}\text{U} + ^{1}\text{n} \rightarrow ^{137}\text{Te} + ^{97}\text{Zr} + 2^{1}\text{n} \]

or

\[ ^{235}\text{U} + ^{1}\text{n} \rightarrow ^{142}\text{Ba} + ^{91}\text{Kr} + 3^{1}\text{n} \]
This is important because a runaway reaction acceleration can occur. If most of the neutrons escape the sample (such that fewer than one per reaction strike another uranium nucleus) the reaction will eventually stop. If average number of neutrons captured totals more than one (by even a tiny amount) the reaction will accelerate uncontrollably and an explosion will result.

The minimum mass of fissionable material required to maintain a chain reaction is called its critical mass. The bomb described on p. 851 is actually quite primitive, although it has been speculated that if terrorists were to build a bomb this is the design they would employ. It is the design of the “Little Boy” bomb dropped on Hiroshima in 1945 and is the more dangerous of the nuclear weapons designs because if the two parts accidentally come into contact with each other, boom. The method used in more sophisticated weapons is a shape charge. In it, a chemical explosive surrounds a subcritical mass of uranium (or plutonium). When the explosive detonates it liquefies the metal and forces it inward (implosion). This increases the density of the metal and, at some point, it becomes so dense that neutron capture becomes sufficiently efficient that it detonates. It is safer than the other design because the explosive requires an electrical impulse to explode and when the weapons are on the ground they are disconnected from a power source.

Richard Rhodes’ *The Making of the Atomic Bomb* presents a wonderful history of nuclear physics and the Manhattan Project.

21.8 Nuclear Fusion

Currently nearly all nuclear events occurring on Earth that are of practical significance relate to nuclear fission. As noted earlier, the Sun operates by nuclear fusion. This is the process by which two nuclei are forced to combine into a single nucleus. When this occurs tremendous amounts of energy are released. It has the advantage of using non-radioactive and inexhaustible
hydrogen as a fuel. It has one significant disadvantage. To start a fusion reaction, a temperature well in excess of 1 million degrees is needed. No known material can withstand those temperatures, so a device called a tokamak is used. This is a toroid (donut) shaped device in which a magnetic field is generated around the inside of the donut. The magnetic fields help heat the plasma (a fourth state of matter) and keep it from approaching the device walls. To date no such device has ever sustained nuclear fusion. The best guess I have heard is at least 40 years in the future before any practical device is developed. We study nuclear fusion because it offers the possibility of generating nuclear power with little or no nuclear waste.

Uncontrolled nuclear fusion has been achieved on Earth in the form of thermonuclear weapons. The hydrogen bomb is a fusion weapon that uses as its trigger (initiator) an old-fashioned fission bomb. The Making of the Hydrogen Bomb by Richard Rhodes provides an excellent account.

21.9 Biological Effects of Radiation

Before we go into detail, we need to talk about how radiation damages substances in a general sense. All of the particulate radiation encountered here possesses electrical charge. Cations may oxidize materials they come into contact and anions may reduce them. The charge on these species in some ways limits the damage they do because they cannot penetrate deeply into a substance because there is a sea of electrons and nuclei they must pass through. It usually doesn’t take long for the other charged particles to slow and finally stop them. We’ll come back to this shortly.

The other kind of radiation is pure energy. In this chapter the radiation of concern is $\gamma$-rays. But cosmic rays, X-rays, and even UV radiation are related. They are dangerous because when
they strike a molecule and are absorbed, the energy is distributed within the molecule. In the case of UV radiation, there isn’t much energy there and usually nothing significant happens. But it is possible for that energy to break some chemical bond in the molecule or to ionize it.

High-energy radiation is sometimes called ionizing radiation because it knocks electrons off water molecules. The resultant cation can then react with other water molecules to generate free radicals. Hydroxyl radicals are extremely reactive and will go after DNA and

$$H_2O + \gamma\text{-ray} \rightarrow H_2O^+ + e^-$$

$$H_2O^+ + H_2O \rightarrow H_3O^+ + \cdot OH$$

other biologically active molecules with gusto. Dietary and cosmetic products frequently claim to be able to protect you from these free radicals.

So how dangerous are the various radiation sources? With the exception of medicinal uses of radiation, it is always bad for you. In this one exception it is good, only because the alternative is worse. That said, our bodies are constantly bombarded with radiation of various sorts on a daily basis and have been since humans first walked the planet. The point here is we have natural defenses against radiation. The better your body’s defense is, the less likely you are to get a disease (frequently cancer) from radiation.

One type of radiation you can do nothing about is the carbon-14 decaying in your body right now. Others you can have some, but not total control over. For example, some areas of the country have higher levels of radon than others. You can install blowers to keep it from building up in your basement or move to a place where there is less radon in the soil. You can live closer to sea level (higher altitudes result in higher exposures to cosmic rays). Human made sources include X-rays, consumer products, and nuclear waste. Though, unless you live very close to a nuclear power plant this is probably not an issue.
Of the types of radiation presented in this chapter, \( \alpha \)-particles are least dangerous. They barely penetrate the skin (the top layer of which is not living tissue anyway). Thus, your clothing and skin provide very adequate protection from sources of alpha particles (with one exception, \textit{vide infra}). In many places in your body, \( \beta \)-particles can penetrate to your bone, but not into it. Even so, a good distance of air and may be some kind of wrapping will protect most people, in most situations from \( \beta \)-particles. The good news is that nearly all \( \gamma \)-rays pass through you without stopping. The bad news is those that do get absorbed are ionizing radiation. Very few things will act as insulation to protect you from gamma rays (e.g. 10” of lead). You want to avoid \( \gamma \)-ray sources like the plague.

I’ll say just a few words about radon. Its an odorless, tasteless, colorless, non-reactive radioactive gas that occurs naturally just about everywhere. It is an \( \alpha \)-particle emitter. From

\[
^{222}\text{Rn} \rightarrow ^{218}\text{Po} + ^{4}\text{He}
\]

the previous discussion you might think the stuff was nothing to worry about, but it is the number two cause of lung cancer (behind cigarette smoking). Why is this \( \alpha \)-particle emitter bad? My guess is that your lungs are one of the few places your body has living tissue in direct contact with the outside world. When an \( \alpha \)-particle hits a lung cell its hitting living tissue, whereas on your hand it hits a cell that no longer reproduces. Second, as your book notes the product of this decay is another radioactive element that can shoot a second \( \alpha \)-particle into lung tissue. Again remember your body has natural defense systems to protect itself from this. Cancer results (at least in part) in the mechanism breaking down.

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