This process, called **annihilation**, is what makes a positron antimatter. Matter and antimatter destroy each other. Thus, a positron is an anti-electron because, when it encounters an electron, the two particles destroy each other, leaving only energy (no mass) behind. This reaction, then, is an example of matter being converted into energy.

In the radioactive process known as positron emission, a proton emits a positron to turn into a neutron:

$$^{8}_{5}\text{B} \rightarrow {}^{8}_{4}\text{Be} + {}^{0}_{+1}\text{e}$$

Notice that this process has the same effect as electron capture, because it transforms a proton into a neutron.

The Rate of Radioactive Decay

As I said before, the reason that unstable nuclei exist in Creation is that although all unstable nuclei *eventually* decay into stable nuclei, this can often take quite some time. How much time does it take? That depends on the parent isotope. All radioactive nuclei have their own specific rate at which they decay. However, all radioactive isotopes do follow the same basic equation:

$$N = N_o \cdot e^{-kt} \tag{16.5}$$

In this equation, N represents either the *number* or *mass* of radioactive isotopes at any given time, N_o is the initial number or mass of radioactive isotopes, and k is a constant that changes from radioactive isotope to radioactive isotope. Often, the rate of an isotope's radioactive decay is expressed in terms of **half-life**, which is given by the following equation:

$$t_{1/2} = \frac{0.693}{k} \tag{16.6}$$

The half-life tells you how long it will take for half of your sample to decay. For example, suppose the half-life of a radioactive isotope is 5 days, and you have 10.0 grams of the isotope. After 5 days, you would have only 5.00 grams, because half will have decayed away. What will you have after another 5 days? You might be tempted to say 0, but the answer is 2.50 grams. Remember, half of the sample decays during the half-life. After the first 5 days, your sample was 5.00 grams. Thus, after the next 5 days, *half of that sample* will decay. Radioactive isotopes, then, never really go away. They just keep decreasing in abundance by half. From a practical standpoint, however, the radioactivity of a sample has generally been reduced to near zero if it passes through a total of 10 half-lives.

Some radioactive decay reactions proceed quickly, and some do not. For example, the alpha decay of ^{214}Po into ^{210}Pb has a half-life of 0.00016 seconds. That's a pretty fast reaction. On the other hand, some radioactive processes are incredibly slow. For example, ^{238}U alpha decays via a reaction whose half-life is 4.41×10^9 *years*! Now *that's* a slow reaction! Thus, unstable nuclei abound in Creation because many of them take a long, long time to decay.

When we look at radioactive decay rates, there is an easy way to analyze the situation and a hard way. The easy way is when the time span you are considering is an integral multiple of the half-life. In that case, you can just keep splitting the sample in half to get the answer. If the time span given is not an integral multiple of the half-life, however, you must use Equation (16.5). See what I mean by studying the following example.

EXAMPLE 16.3

The alpha decay of ^{210}Bi proceeds with a half-life of 5.00 days. A chemist makes 100.0 grams of the isotope.

a. How many grams will be left in 15.00 days?
b. How many grams will be left in 18.00 days?

a. This part is not so bad. The amount of time elapsed is an integral multiple of the half-life. Thus, after 5.00 days, there are only 50.00 grams left, after the next 5.00 days there are only 25.00 grams left, and after a total of 15.00 days, there are only <u>12.50 grams</u>.

b. This one is not so easy, because the elapsed time is not an integral multiple of the half-life. Thus, we need to use Equation (16.5). To use that equation, however, we need to know k. This comes from Equation (16.6):

$$5.00 \text{ days} = \frac{0.693}{k}$$

$$k = \frac{0.693}{5.00 \text{ days}} = 0.139 \frac{1}{\text{days}}$$

Now we can use Equation (16.6):

$$N = N_o \cdot e^{-kt}$$

$$N = (100.0 \text{ grams}) \cdot e^{-(0.139 \frac{1}{\text{days}}) \cdot (18.00 \text{ days})} = \underline{8.19 \text{ g}}$$

ON YOUR OWN

16.7 The half-life of ^{131}I is 8 days. How much of a 10.0 gram sample will be left after 10 days?

The Dangers of Radioactivity

Now that you know a little bit about radioactivity, you might be interested in knowing why everyone is so afraid of it. Well, part of the fear is based on ignorance, and part of the fear is based on fact. Radioactivity *can be* dangerous, but it is *not always* dangerous. That's a good thing, too, because we are *constantly* being exposed to radioactivity. If you have brick or mortar in the walls of your home, they are radioactive. By standing near them, you are exposed to beta particles. You are exposed to gamma rays when you are outside in the sun. If you have a smoke detector in your house, you are exposed to alpha particles, because the main detection component of a smoke detector undergoes alpha decay. In fact, you are exposed to beta particles each time you get close to someone, because people themselves are radioactive! It's a good thing, then, that radioactivity is not always dangerous.

The first thing you have to understand is why radioactivity can be dangerous. Radioactivity does not act like a poison. A poison is dangerous because it chemically reacts with your body, causing chemical processes to occur in your body which should not occur. This upsets your body's chemistry, causing sickness or even death. Some poisons actually build up in your body. As you take them in small doses, they do not cause you any problems. However, as they continue to build up in your body, they eventually start causing chemical reactions that shouldn't happen in your body, and that's when you are in trouble.

Unlike poisons, radioactivity is not dangerous because it can upset your body's chemistry. It also cannot build up in your body. Instead, radioactivity affects your body much like a tiny machine gun. You see, the danger in radiation comes from the particles that are emitted during the radioactive decay. Depending on the isotope involved, radioactive decay involves a nucleus "spitting out" something. In alpha decay, the nucleus spits out an alpha particle. In beta decay, it spits out a beta particle. In gamma decay, the nucleus spits out high energy light. There is nothing chemically poisonous about these things. They are dangerous, however, because they have a lot of energy.

When alpha, beta, or gamma particles collide with atoms or molecules in their way, the energy of the collision can ionize the atom or molecule with which the particle collides. Thus, alpha, beta, and gamma particles are referred to as **ionizing radiation**, because they ionize matter as they pass through it. If you happen to be unfortunate enough to be in the way of the emitted particle, it might collide with one of your cells. The vast majority of the time, when an alpha, beta, or gamma particle collides with a cell, it results in the cell's death, because it ionizes chemicals in the cells that should not be ionized. Every now and again, however, the cell will not die. If the particle hits the cell just right, the resulting ionization might mutate the cell's DNA rather than kill the cell.

Do you see why I say that radioactivity acts like a tiny machine gun? When you have a sample of radioactive material, each atom in that sample can "shoot" a "bullet" (an alpha particle, a beta particle, or a gamma ray). Since there are trillions and trillions of atoms in even a small sample of matter, that means that a sample of radioactive isotopes can shoot off trillions and trillions of these "bullets." If you happen to be in the path of these bullets, each bullet that hits you will most likely kill an individual cell. Thus, a radioactive sample is like a tiny machine gun that kills you one cell at a time. Every now and again, however, rather than killing a cell, the particle will cause a mutation in the cell's DNA.

Sounds dangerous, doesn't it? Well, it *can* be dangerous, but *not necessarily.* You see, your body *expects* cells to die. God therefore designed your body to reproduce cells. This helps you grow and mature, and it also replaces cells that die. When you scratch an itch, for example, you actually kill as many as several hundred cells. This is no problem, as your body quickly replaces them. Thus, as long as your cells do not die faster than they can be replaced by your body, there is no real problem.

When your cells are being destroyed by the little "bullets" that are being "shot" from a sample of radioactive isotopes, then, there is no problem as long as the "bullets" are not killing your cells faster than your body can replace them. If you are exposed to too much radiation too quickly, then your cells will be killed faster than your body can replace them, leading to radiation burns, organ damage, and the like.

What about the chance for mutating a cell's DNA? Isn't that bad? Well, yes, but once again, it depends on the amount of mutation that is going on. Everyone's body has a few mutant cells. Most of them simply die off. The bad thing about mutation is that a mutant cell can result in cancer or some other sickness. This happens only rarely, however, so once again, a few mutant cells in your body is not a bad thing. Everyone has them. The problem only occurs when you have too many mutant cells. Thus, as long as you are not exposed to too much radiation, the danger is minimal.

In the end, then, the important thing to remember about the dangers of radioactivity is that it depends on the level of radioactivity to which you are exposed. A small amount of radioactivity is reasonably safe, a large amount is not. How much radioactivity exposure is too much? Well, nuclear scientists have come up with ways of measuring how much ionizing radiation people are exposed to. They refer to this as the **dose** of radiation to which a person is exposed.

There are two units nuclear scientists use to measure radiation dosage. They are the **rad** (radiation absorbed dose) and the **rem** (roentgen equivalent in man). The rad is the amount of radiation that will deposit 100 Joules of energy into a kilogram of living tissue. This is a fine measure of radiation exposure, but it neglects the fact that certain types of radiation are more damaging to biological systems than others. Alpha particles, for example, do more damage to tissue per Joule they deposit because of the details of how alpha particles ionize matter. As a result, alpha particles are considered "more effective" at destroying living tissue.

To take this into account, nuclear scientists have come up with the **RBE** (relative biological effectiveness) factor. This factor is different for each type of ionizing radiation. Alpha particles, for example have an RBE factor of 4 while gamma and beta particles have an RBE factor of 1. When the number of rads are multiplied by the RBE factor, the result is the dosage in rems.

$$\text{rems} = (\text{RBE}) \times \text{rads} \tag{16.7}$$

Thus, if you are exposed to 0.010 rads of beta particles, your radiation dose is 1 x 0.010 = 0.010 rems. If you are exposed to 0.010 rads of alpha particles, your radiation dose 4 x 0.010 = 0.040 rems.

Remember when I said that brick and mortar are radioactive, as well as smoke detectors and other people? If you add up all of the radiation you are exposed to from such sources, your average radiation dose each year would be about 0.2 rems. Since studies by radiation biologists indicate that a lethal dose of radiation is about 470 rems, the dose of radiation you get as a result of everyday activity is simply too minimal to be worried about.

Even if you are in a position in which you are exposed to large amounts of radioactivity, there are ways you can protect yourself. It is possible to stop the little "bullets" before they ever reach your body. For example, alpha particles are extremely weak in terms of how much matter they can travel through. If you put a piece of paper between you and the radioactive source emitting the alpha particles, the vast majority of those alpha particles will stop in the paper. As a result, they will never hit you. Beta particles can travel through obstacles a bit better. It typically takes a thin sheet of metal to stop most of the beta particles coming from a radioactive isotope that emits them. Finally, gamma rays are the strongest type of radiation, requiring several inches of lead to stop them.

Thus, one way you can protect yourself is to block the radiation before it hits you. This method is called "shielding." The other way you can protect yourself from an intensely radioactive source is to simply move away from it. The farther you move away, the fewer "bullets" can hit you. Of course, most people will never be exposed to a large amount of radiation in their lifetime, so they will never be faced with such a situation.

ON YOUR OWN

14.8 People who regularly work with large samples of radioactive isotopes sometimes wear special suits that are lined with a thin layer of lead or other heavy material. What kinds of radiation are these people protected from when wearing such a suit?

Radioactive Dating

The fact that radioactive isotopes decay at a measurable rate allows scientists to use radioactive decay as a means of dating objects whose age we do not know. This is known as **radioactive dating**. Although radioactive dating can be accurate under certain circumstances, it is important to note that it has some serious weaknesses as well. As a result, radioactive dating techniques must be viewed rather critically. Despite the fact that some scientists will try to convince you that radioactive dating is an accurate means of determining the age of an object, the scientific facts tell quite a different story.

The best way of examining the strengths and weaknesses of radioactive dating is to examine one of the radioactive dating methods in detail. Since ^{14}C is probably the best known radioactive dating technique, I might as well discuss that one. ^{14}C decays by beta decay with a half-life of 5,730 years. It turns out that all living organisms contain a certain amount of ^{14}C, which is part of the reason that all living organisms are radioactive.

Interestingly enough, living organisms continually exchange ^{14}C with their surroundings. Human beings, for example, exhale carbon dioxide, some of which contains ^{14}C. In addition, human beings eat other organisms (plants and animals), which contain ^{14}C as well. Finally, part of the air that we inhale is made up of carbon dioxide, some of which contains ^{14}C. Thus, organisms are continually exchanging ^{14}C with their environment. The practical result of all of this exchange is that, at any time when an organism is alive, it contains the same amount of ^{14}C as does the atmosphere around the organism.

This changes when the organism dies, however. At that point, the ^{14}C exchange ceases. Thus, the organism cannot replenish its supply of ^{14}C, and the amount of ^{14}C in the organism begins to decrease because of the beta decay of ^{14}C. The half-life of this process is 5730 years, so the decay happens slowly. Nevertheless, it is a measurable effect. In general, then, organisms that have been dead a long time tend to have less ^{14}C in them as compared to those that have been dead for only a short time.

Now if you think about it, this fact can be used to measure the length of time that an organism has been dead. After all, if we know how much ^{14}C was in an organism when it died, and if we measure the amount of ^{14}C in it now, the difference will be the amount of ^{14}C that has decayed away. With that information, Equation (16.5) will tell us how long the organism has been dead. Pretty simple, right?

Well, it *would* be simple, *if* we knew how much ^{14}C was in the organism when it died. The problem is, how do we figure that out? After all, no one was around to measure the amount of ^{14}C in the organism when it died; thus, we must make an *assumption* about how much ^{14}C would have been measured if someone had been there to measure it. Now there is nothing wrong with making assumptions in science. The trick is that you have to know your assumptions are accurate.

In the case of ^{14}C dating, scientists assume that, on average, the amount of ^{14}C in the atmosphere has never really changed that much. They assume that the amount of ^{14}C in the atmosphere today is essentially the same as it was 100 years ago, 1,000 years ago, etc. Thus, when the age of a dead organism is being measured with ^{14}C dating, we assume that the amount of ^{14}C it had when it died was the same as the amount of ^{14}C that is in the atmosphere now. That gives us a value for how much ^{14}C was initially in the dead organism. We can measure the amount of ^{14}C that is in the organism now and then determine how long the organism has been dead.

Notice, however, that the age we get from this process is completely dependent on the assumption that we made about how much ^{14}C was in the organism when it died. If that assumption is good, the age we calculate will be accurate. If that assumption is bad, the age we calculate will not be accurate. So the question becomes, "Is the assumption accurate?" In short, the answer is, "No."

Through a process involving tree rings, there is a way we can measure the amount of ^{14}C in the atmosphere in years past. When you cut down a tree, you can count the rings in the tree's trunk to determine how old it is. Each ring represents a year in the life of the tree. We know which ring corresponds to which year by simply counting the rings from the outside of the trunk to the inside. Well, it turns out that through a rather complicated process, you can actually measure the amount of ^{14}C in a tree ring and use it to determine how much ^{14}C was in the atmosphere during the year in which the tree ring was grown. As a result, scientists have determined the amount of ^{14}C in the atmosphere throughout a portion of the earth's past.

It turns out that scientists have studied the ^{14}C content in tree rings that are as many as 3,000 years old. From these measurements, scientists have determined the amount of ^{14}C in the atmosphere over the past 3,000 years. What they have seen is that the amount of ^{14}C has varied by as much as 70% over that time period. The variation is correlated to certain events that occur on the surface of the sun. As a result, *we know* that the amount of ^{14}C in the atmosphere has not stayed constant. Instead, it has varied greatly. Thus, *we know* that the initial assumption of ^{14}C dating is wrong. Thus, one must take most ^{14}C dates with a grain of salt. After all, we know that the assumption used in making those dates is wrong. Consequently, we cannot put too much trust in the results!

Notice that I said we must take "most" ^{14}C dates with a grain of salt. Why "most?" Why not "all?" Well, it turns out that since we can determine the amount of ^{14}C in the atmosphere during the past using tree rings, we can actually use that data to help us make our initial assumption. As a result, the assumption becomes much more accurate. The problem is, however, that we don't have ^{14}C measurements for tree rings that are older than 3,000 years. Thus, we can only make an accurate assumptions for organisms that have died within the last 3,000 years. As long as the organism died in that time range, we can use tree ring data to help us make an accurate assumption of how much ^{14}C was in the organism when it died. For organisms that have died longer than 3,000 years ago, we have no tree ring data, so we have no way to make an accurate assumption. As a result, we cannot really believe the ^{14}C date.

In the end, then, the ^{14}C dating method can be believed for organisms that have been dead for 3,000 years or less. Thus, it is a great tool for archaeology. If an archaeologist finds a manuscript or a piece of cloth (both cloth and paper are made from dead plants), the archaeologist can use ^{14}C dating to determine its age, provided all of the experimental techniques of ^{14}C dating have been followed accurately. As long as the result is about 3,000 years or younger, the date can be believed. If the date turns out to be older than 3,000 years, it is most likely wrong.

So you should see that radioactive dating involves a pretty important assumption. If the assumption is good, the date you get from radioactive dating is good. If the assumption is bad, the result you get from radioactive dating will be bad. Now there are a lot of other radioactive dating techniques besides ^{14}C dating. Unfortunately, they all suffer from a similar malady. In every radioactive dating technique, you must make assumptions about how much of a certain substance was in the object originally. Such assumptions are quite hard to make accurately.

The difficulty of making these assumptions can be seen in the fact that radioactive dates have been demonstrated to be wrong in many, many instances. John Woodmorappe, in his book *Studies in Flood Geology*, has compiled more than 350 radioactive dates that conflict with one another or with other generally accepted dates. These erroneous dates demonstrate that the assumptions used in radioactive dating cannot be trusted. As a result, the dates that one gets from radioactive dating cannot be trusted, either.

Unfortunately, many in the scientific community are unwilling to admit to the inadequacies of radioactive dating, because many scientists like its *results*. Because certain radioactive decay schemes have long, long half-lives, the dates that one calculates from these methods can be breathtakingly large. For example, there are rocks on the planet that radioactive dating techniques indicate are more than 4 *billion* years old. It turns out that many scientists *want* the earth to be that old because they believe in the discredited hypothesis of evolution. This hypothesis *requires* a very old earth, and radioactive dating techniques provide dates that indicate the earth is very old. As a result, they turn a blind eye to the inadequacies of radioactive dating, because it gives them an answer that they want! Hopefully, as time goes on, this unfortunate situation will change!

Other uses of Radioactivity and Ionizing Radiation

Radioactivity has far more reliable applications than the tenuous process of radioactive dating. For example, radiation has revolutionized medicine. When a doctor wants to look at your bones, the doctor gives you an X-ray. This is accomplished by placing the portion of your body that needs to be examined between a sheet of film and a high-intensity gamma ray source. As you are exposed to the gamma rays, some pass through your body and hit the film, while others collide with cells in your body and stop. Gamma rays collide more with the dense portions of your body (the bones) than with the fleshy parts of your body. As a result, the film gets hit by gamma rays more frequently when bone is not between the gamma ray source and the film. When the film is developed, this will result in the parts of the film behind your bones being much whiter than those parts of the film behind the rest of your body. As a result, the gamma rays form an image of your bones on the film.

Now when you get an X-ray, the gamma rays used to make the X-ray work are killing your cells and mutating some DNA. Nevertheless, as I have discussed before, that is not a problem as long as you do not get too many X-rays. Any risk caused by your exposure to gamma rays is far outweighed by the medical benefit of being able to see your bones without surgery. Of course, the person *giving* you the X-ray would be exposed to gamma rays all day if he or she were not shielded from them. That's why the person giving you the X-ray stands behind thick shielding during the X-ray process.

Radioactive isotopes are also used to track things like blood flow inside the body. If a gamma emitting isotope is injected into your bloodstream, doctors can analyze how the blood flows to different parts of your body by detecting where the gamma rays are coming from inside your body. Once again, although this exposes you to gamma rays, the risk is low as long as the amount of exposure is minimized. The diagnostic benefit to such a procedure outweighs the risk of the gamma ray exposure.

Ionizing radiation is even used to kill cancerous cells in tumors and the like. People with thyroid cancer often are given radioactive iodine (^{131}I) to drink. Since iodine collects in your thyroid, drinking radioactive iodine (usually called "the cocktail") will concentrate radiation in your thyroid, killing cancerous cells. The healthy cells will die as well, but your body is more likely to replace the healthy cells and not the cancerous cells, so this is a very popular treatment for thyroid cancer.

Finally, ionizing radiation is even used to keep you safe from fire. Most homes have a smoke detector. In a smoke detector, there are two metal plates hooked to a wire. One plate is hooked to the positive side of the battery and is thus positively-charged. The other is hooked to the negative end of the battery and is thus negatively-charged. An ^{241}Am source is placed under the plates, and it emits alpha particles through a small hole in the bottom plate. As the alpha particles collide with the molecules in the air between the plates, the molecules are ionized. The positive ions travel to the negative plate and the negative ions travel to the positive plate.

When there is no smoke in the air, the ^{241}Am source shoots a steady stream of alpha particles, resulting in a constant rate of ion production. The electronics in the smoke detector detect those ions when they hit their respective plates. When smoke gets between the plates, however, the smoke traps the ions, not allowing them to hit the plates. This causes a drop in the number of ions detected by the electronics, and that causes the alarm to go off.

As with all forms of ionizing radiation, there is a small amount of inherent risk in having a radioactive isotope (the ^{241}Am in the smoke detector) in your house. Nevertheless, the chance of you dying or being hurt in a fire is *millions of times* greater than any chance of your being hurt by one of the alpha particles in the smoke detector. As a result, they are used in homes despite the fact that they are radioactive.

Nuclear Reactions

Although radioactive decay is, by far, the most common nuclear process that occurs on earth, there are other types of nuclear reactions that occur over and over again in outer space as well as in nuclear power plants and nuclear research facilities. These nuclear reactions can usually be classified as one of two types:

Nuclear fusion - The process by which two or more small nuclei fuse to make a bigger nucleus

<u>Nuclear fission</u> - The process by which a large nucleus is split into two smaller nuclei

You have probably heard of both of these processes before, but I want to make sure that you understand them in a thorough way.

I will begin with nuclear fission, which is the basis for nuclear power plants and most nuclear bombs. Usually, nuclear fission begins with a neutron colliding with a large nucleus. For example, if a neutron were to collide with a ^{235}U nucleus, the nucleus would become very unstable. It would be so unstable that it would, in fact, break apart into two smaller nuclei. One possible reaction would be as follows:

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{112}_{45}Rh + ^{121}_{47}Ag + 3^{1}_{0}n$$

Notice what this equation says happened in the reaction. A neutron collided with a ^{235}U nucleus. The result is a ^{112}Rh nucleus, a ^{120}Ag nucleus, and 3 neutrons. Don't be alarmed about the coefficient of 3 next to the neutron on the right side of the equation. Like chemical equations, nuclear equations can also have coefficients. The meaning of these coefficients is the same in both cases. Thus, the 3 simply tells you that 3 neutrons are produced.

Notice also that the equation is balanced. On the left side, there are a total of 92 (92 + 0) protons (subscripts). On the right side, there are also 92 (45 + 47 + 3x0) protons. On the left side, the mass numbers total to 236 (235 + 1). On the right side, the mass numbers also total to 236 (112 + 121 + 3x1). Although this is the first nuclear equation that you have seen with a coefficient, it should not disturb you. You use it just as you would if it were in a chemical equation or an algebraic equation. Since there is a 3 in front of the neutron, you multiply the numbers associated with the neutron by 3.

Now it is very important for you to realize that although the equation above represents a valid reaction that occurs when a neutron collides with a ^{235}U nucleus, it is not the only possible reaction that occurs under those conditions. One of the very interesting aspects of nuclear reactions is that, unlike chemical reactions, the same reactants will not always produce the same products. When a neutron collides with a ^{235}U nucleus, sometimes the nucleus will split apart to give the products listed above. Many times, however, it will split so as to produce other products. For example, the following reaction is even slightly more likely to occur than the one listed above:

$$^{1}_{0}n + ^{235}_{92}U \rightarrow 2^{117}_{46}Pd + 2^{1}_{0}n$$

Notice that this reaction is balanced. In this case, remember that you have to multiply the subscripts and superscripts for Pd by 2 because there is a coefficient in from of Pd as well. It turns out that there are a host of possible products for the neutron-induced fission of ^{235}U. The two equations I have shown you are just a couple of the possible reactions that will occur when a neutron collides with a ^{235}U nucleus. When a bunch of neutrons collide with a bunch of ^{235}U nuclei, many different kinds of products are produced.

Notice something else about both of the reactions I have listed. In each case, the reaction produces more than one neutron. Since a neutron is one of the reactants in the fission reaction, this sets up a very interesting situation. Imagine that you have a large sample of ^{235}U. Suppose one neutron collides with one nucleus in this sample and a fission reaction results. What will happen next? Well, the neutrons produced in this reaction can go out *and start more fission reactions, each of which will produce even more neutrons which can go out and start even more reactions*. Thus, a single neutron can start a series of events that will result in more and more fission reactions occurring.

What do we call this? We call it a **chain reaction**. Nuclear fission can result in chain reactions because the very process of nuclear fission forms one of the reactants. Thus, as long as there is enough ^{235}U around, the number of fission reactions occurring each second can grow and grow and grow.

What's the practical upshot of all of this? Well, if you sum up the masses of the products in a fission reaction, you will find that the sum is less than that of the reactants. This means that fission reactions produce energy, because the mass that is "missing" in the product gets converted directly to energy. Well, if the number of fission reactions grows each second, then the amount of energy being released grows each second. If the amount of energy released gets large enough, an explosion will occur.

This is, of course, the idea behind a nuclear bomb. In a nuclear bomb, the chain reaction goes out of control, producing an enormous amount of energy in a short period of time. This results in a devastating explosion. Remember, however, that you can only produce enough energy to make an explosion if there is *enough* ^{235}U. The amount of ^{235}U necessary to allow a fission chain reaction to sustain the process of fission indefinitely is called the **critical mass** of ^{235}U.

Critical mass - The amount of fissioning nucleus necessary for the chain reaction to be self-sustaining

If you have a critical mass of ^{235}U just "lying around" in the right geometry, a self-sustained reaction is inevitable. That's because the earth is constantly being bombarded by neutrons from the sun. Thus, eventually a single neutron will start a single fission reaction, and the chain reaction will keep the reaction going indefinitely. However, that in itself might not lead to an explosion. In order for an explosion to occur, the chain reaction must spin out of control. This will happen only if the critical mass of ^{235}U is highly concentrated.

Luckily, of course, the two nuclei that are used in nuclear bombs (^{235}U and ^{238}Pu) are very rare. The isotope ^{235}U, in fact, makes up only 0.7% of all uranium on the earth. In order to make a bomb, then, the amount of ^{235}U in a sample of uranium must be increased. This process, called **isotopic enrichment**, separates out the other isotopes of uranium, trying to leave behind only ^{235}U. This allows nuclear chemists to concentrate ^{235}U so as to get a critical mass of the isotope. The problem is, since ^{235}U is nearly identical to the other isotopes of uranium, this process is *very* difficult. In fact, the only thing that is secret about making a nuclear bomb is the means by which

^{235}U (or ^{238}Pu) is enriched from natural supplies. Anyone with even the most basic nuclear training can make a nuclear bomb. Making the *fuel* for the bomb is impossible, however, unless you know the secret technological steps necessary to enrich the ^{235}U (or ^{238}Pu) content in order to achieve a concentrated critical mass.

The other kind of nuclear reaction that I want to discuss is nuclear fusion. You can view nuclear fusion as the opposite of nuclear fission, because it takes small nuclei and makes them bigger. For example, ^{2}H nuclei can collide with each other and stick together, forming ^{3}He and a neutron:

$$2{}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{1}_{0}\text{n}$$

This kind of reaction also produces energy, because there is less mass in the products than there is in the reactants.

You should notice a contrast between nuclear fusion and nuclear fission. Nuclear fusion has small nuclei as the reactants and nuclear fission has large nuclei as reactants. If you think about this in terms of nuclear binding energy, this should make some sense to you. Go back and take a look at Figure 16.1. According to this figure, the most stable nucleus in Creation is ^{56}Fe, because it has the most binding energy per nucleon. What does this mean? Well, it means that as long as nuclei are smaller than ^{56}Fe, they are "willing" to fuse with other nuclei so as to become more like ^{56}Fe. Nuclei heavier than ^{56}Fe, however, have no desire to fuse, because they would "like" to lose nucleons so as to become more like ^{56}Fe. Thus, nuclear fusion reactions between nuclei lighter than ^{56}Fe are spontaneous, whereas nuclear fusion reactions between ^{56}Fe nuclei and those that are heavier are not spontaneous. In the same way, nuclear fission reactions can be spontaneous for nuclei heavier than ^{56}Fe, but not for ^{56}Fe and those nuclei that are lighter.

Wait a minute. If fusion reactions between nuclei lighter than ^{56}Fe can be spontaneous, why don't all light nuclei fuse until they become ^{56}Fe? In the same way, why don't all heavy nuclei fission until they because ^{56}Fe? Although fusion reactions are spontaneous for light nuclei, they proceed so slowly as to be non-existent unless the nuclei can be forced close to one another. This is tough because, since nuclei are positively charged, they repel each other. Thus, unless there is enough activation energy to push the nuclei very close to one another, the nuclei will never fuse at any kind of appreciable rate.

Is there any place that such activation energy exists? Well, it exists in nuclear research labs where huge instruments called **particle accelerators** accelerate nuclei to such high speeds that they have enough energy to get close to and fuse with other nuclei. It also exists in stars, where the gravitational force is so strong and the temperature is so high that nuclei have enough energy to get close enough to fuse. In fact, most (if not all) of the sun's energy comes from the fusion of light nuclei into heavier nuclei.

Study the following examples so that you are sure you understand how to deal with fission and fusion reactions.

EXAMPLE 16.4

Fill in the blank for the nuclear fusion reaction below:

$$2\,{}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + \_\,{}^{1}_{0}\text{n}$$

In order for this to be a valid reaction, it must balance. This means that the sum of the superscripts on both sides of the equation must equal each other as well as the sum of the subscripts. This is already the case for the subscripts. However, in order for the superscripts on the right side to equal 6, there must be 2 neutrons. Thus, the answer is:

$$\underline{2\,{}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2\,{}^{1}_{0}\text{n}}$$

What is the missing reactant in the following equation? Is this fusion or fission?

$${}^{1}_{0}\text{n} + \_\_\_ \rightarrow {}^{112}_{45}\text{Rh} + {}^{123}_{49}\text{In} + 3\,{}^{1}_{0}\text{n}$$

In order to get the subscripts to balance, the subscript in the blank must be 94. The chart tells us, then, that the symbol is Pu. To get the superscripts to balance, the superscript in the blank must be 237. That way the sum of the mass numbers on the left side (1 + 237) equals the sum of the mass numbers on the right side (112 + 123 + 3x1). Thus, the missing reactant is $\underline{{}^{237}_{94}\text{Pu}}$. This is fission, because a large nucleus is splitting into smaller nuclei.

ON YOUR OWN

16.9 What is the missing reactant in the following nuclear equation?

$${}^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \rightarrow \_\_\_ + {}^{1}_{0}\text{n}$$

16.10 Is the reaction above a fusion or fission reaction?

Using Nuclear Reactions to Make Energy

As I have already noted, nuclear fission is used in today's nuclear power plants in order to make electricity. You should have learned in your first-year physics course that power plants turn the mechanical motion of magnets and loops of wire into electricity. To produce the motion, they use steam that comes from boiling water. The fuel in an electrical power plant, then, is simply used to boil water. Coal-burning power plants use the heat of combustion of coal to boil water. Nuclear power plants simply use the heat of a nuclear fission reaction to boil the water.

The wonderful thing about using nuclear fission to make electricity is that the fuel for nuclear fission is reasonably cheap and will last a long, long time. The downside is that nuclear fission can be quite dangerous. Now it is important to realize that the danger of nuclear fission is *not* that a nuclear power plant can create a nuclear explosion. That's physically impossible! In order to make a nuclear explosion, you must have a critical mass of the fissioning isotope and it must be highly concentrated. Since nuclear power plants *do not* have a concentrated critical mass of the fissioning isotope, they *cannot* explode.

Even though nuclear power plants cannot explode, other nasty things can happen. In a normally operating nuclear power plant, the rate at which the fission processes occur is heavily controlled. If the control operations fail, then the chain reaction starts producing too much energy. This will not lead to an explosion, but it can produce so much heat that everything in the vicinity, including the reactor itself, will begin to melt. When this happens, it is called a **meltdown**, and the results can be devastating.

This is what happened at the Chernobyl nuclear power plant in the former Soviet Union. This particular nuclear power plant did not have many safety protocols and, when the primary system which helps control the rate of the nuclear reaction failed, there was nothing that could keep the reaction from running out of control. As a result, the reactor began to melt. This caused widespread fire throughout the plant and resulted in the release of an enormous amount of radioactive isotopes. More than 30 people were killed as a result of the fires and structural damage in the power plant itself, and thousands were exposed to high levels of radiation. To this day, no one can live near where the plant was, because the radioactive contamination is so high.

Nuclear power in the form of nuclear fission, then, can be quite dangerous. You have to understand, however, that *all* forms of power production are dangerous. Since 1900, for example, more than 100,000 people have been killed in American coal mines due to mining accidents and black lung, a malady that is caused by exposure to too much coal dust. Coal is used primarily for the production of energy. Studies indicate that nuclear power is responsible for less death and fewer health maladies than any other form of power production that we have today.

Nuclear power in the form of fission also has another serious drawback: the by-products are radioactive. We have no safe way of disposing this radioactive waste. This can eventually lead to serious environmental problems. Of course, other forms of energy production also lead to serious environmental problems. Coal-burning power plants, for example, dump pollution into the air. The *amount* of pollution they dump into the atmosphere has been reduced considerably. Nevertheless, they still emit pollutants. They are, in fact, the principal contributors to the acid rain problem.

Although nuclear power in the form of nuclear fission can be dangerous and polluting, it is not clear that it is any more dangerous and polluting than other forms of energy production. There are those who think it is, in fact, one of the safest and cleanest forms of energy production. In France, for example, the scientific community is so convinced that nuclear power is (overall) the safest form of power production that more than 90% of the country runs on electricity produced by nuclear power plants.

In order to make energy production safer, better for the environment, and longer-lasting, scientists are trying to use nuclear fusion instead of nuclear fission to produce electricity. Nuclear fusion has no harmful by-products. Remember, when nuclear fusion occurs between two hydrogen atoms, the products are helium and a free neutron. Helium is not radioactive, and has no toxic chemical properties either. Thus, using nuclear fusion to produce electricity would completely eliminate the radioactivity problem caused by nuclear fission. It is also much safer than nuclear fission. Experiments indicate that nuclear fusion is much easier to halt, allowing for the nuclear fusion process to be stopped quickly. This would avert any meltdown possibilities. Finally, the fuel for nuclear fusion (^{2}H) is virtually unlimited and very inexpensive. Nuclear power from nuclear fusion, then, would be safe, cheap, and almost limitless.

Why don't we use nuclear fusion to make electricity, then? The answer is that from a *technological* viewpoint, we have not mastered the process yet. We *know* that nuclear fusion can be used to make energy. After all, it powers the sun. However, nuclear fusion can happen in the sun because of the intense heat and pressure in the sun's core. In order to get nuclear fusion to work, we have to essentially re-create that environment here on earth. That's a tough job! Right now, nuclear physicists can, indeed, cause nuclear fusion to occur in a variety of different ways. However, in each way used so far, there is an enormous amount of energy wasted in order to create the conditions necessary for the nuclear fusion. As a result, the total energy produced is rather small. In other words, right now we have to put an enormous amount of energy into a nuclear fusion reaction, and we don't get much more than that amount of energy back. As a result, nuclear fusion is not an economically viable process for the large-scale production of energy.

In the end, then, we know that there are some drawbacks to nuclear fission. Some consider those drawbacks to be quite serious, others consider them to be about the same or even a little less than what other forms of power production have. If scientists are ever able to overcome the technological problems associated with nuclear fusion, the result would be a much safer, cleaner, and cheaper form of power production. Whether that will ever happen, however, remains to be seen.