Questions for Conceptual Physics hand out.

- You should have a copy of pages 615, 616, 624, 625, 629 to 633. + 634
- This material also appears in your text book in Chapter 30/31 but the presentation is at a higher level

1. a) What is **half life**?

b) What is the half life of Radium 226?

c) If you start with 1 kg how long until you have less than 1/8 of a kg (see graph).

d) Is it possible to speed up radio active decay or shorten the half life?

2. a) What is natural radiation?

b) Is it the same for every location on Earth?

c) What vacation activity increases your natural radiation?

d) How much of our exposure is from natural radiation?

e) How much of our exposure is from man made sources?

f) What does radiation do to living things and what are you at risk for if your exposure is higher than normal?

3. a) Draw picture of a chain reaction. What makes it a “chain” reaction? Think about the dominos on page 629.

b) What happens to atomic nuclei during a nuclear fission reaction?

c) What is a critical mass. What happens to a chain reaction with a mass of the critical size?

d) What happens to the number of reactions when you have a super critical mass?

e) What is the function of a **moderator** in a nuclear reactor?

f) What is the function of the **control rods** in a nuclear reactor?

39.5 Radioactive Half-Life

Radioactive isotopes decay at different rates. The radioactive decay rate is measured in terms of a characteristic time, the **half-life.** The half-life of a radioactive material is the time needed for half of the radioactive atoms to decay. Radium-226, for example, has a half-life of 1620 years. This means that half of any given specimen of Ra-226 will have undergone radioactive decay by the end of 1620 years. In the next 1620 years, half of the remaining radium will decay, leaving only one-fourth the original number of radium atoms. The other three-fourths are converted, by a succession of disintegrations, to lead. After 20 half-lives, an initial quantity of radioactive atoms will be diminished to about one-millionth of the original quantity.

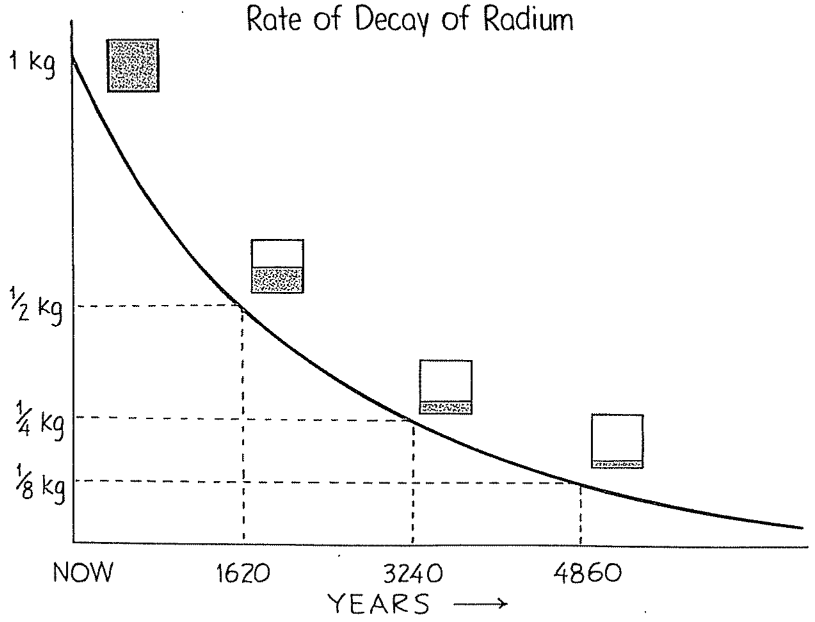

Figure 39.13 ▲
Every 1620 years the amount of radium decreases by half.

The isotopes of some elements have a half-life of less than a millionth of a second, while U-238, for example, has a half-life of 4.5 billion years. The isotopes of each radioactive element have their own characteristic half-lives.

Rates of radioactive decay appear to be absolutely constant, unaffected by any external conditions, however drastic. High or low pressures, high or low temperatures, strong magnetic or electric fields, and even violent chemical reactions have no detectable effect on the rate of decay of an element. Any of these stresses, however severe by ordinary standards, is far too mild to affect the nucleus deep in the interior of the atom.

How do physicists measure radioactive half-lives? They cannot always do it by observing a specimen and waiting until the quantity

LINK TO TECHNOLOGY

Smoke Detectors
Thousands of homes each year are spared fires by smoke alarms that operate by radioactivity. A weak radioactive source, usually the transuranic element americium-241 (atomic number 95) detects the presence of smoke. Alpha rays from the source hit air molecules in the chamber and eject electrons from them, creating ions that provide a slight electric current. If smoke enters this chamber, the ions are disturbed and the current diminishes. Electronic sensors in the circuit detect this reduced current and sound the alarm. Radioactivity used for this purpose saves many lives.

1 Explore 2 Develop 3 Apply

2 **Laboratory Manual** *98*
2 **Concept-Development Practice Book** *39-1*

reduces to half. This is often much longer than a human life span! One can measure, however, the rate at which a substance decays. There are various radiation detectors for doing this (Figure 39.14). The half-life of an isotope is related to its rate of disintegration. In general, the shorter the half-life of a substance, the faster it disintegrates, and the more active is the substance. The half-life can be computed from the rate of disintegration, which can be measured in the laboratory.

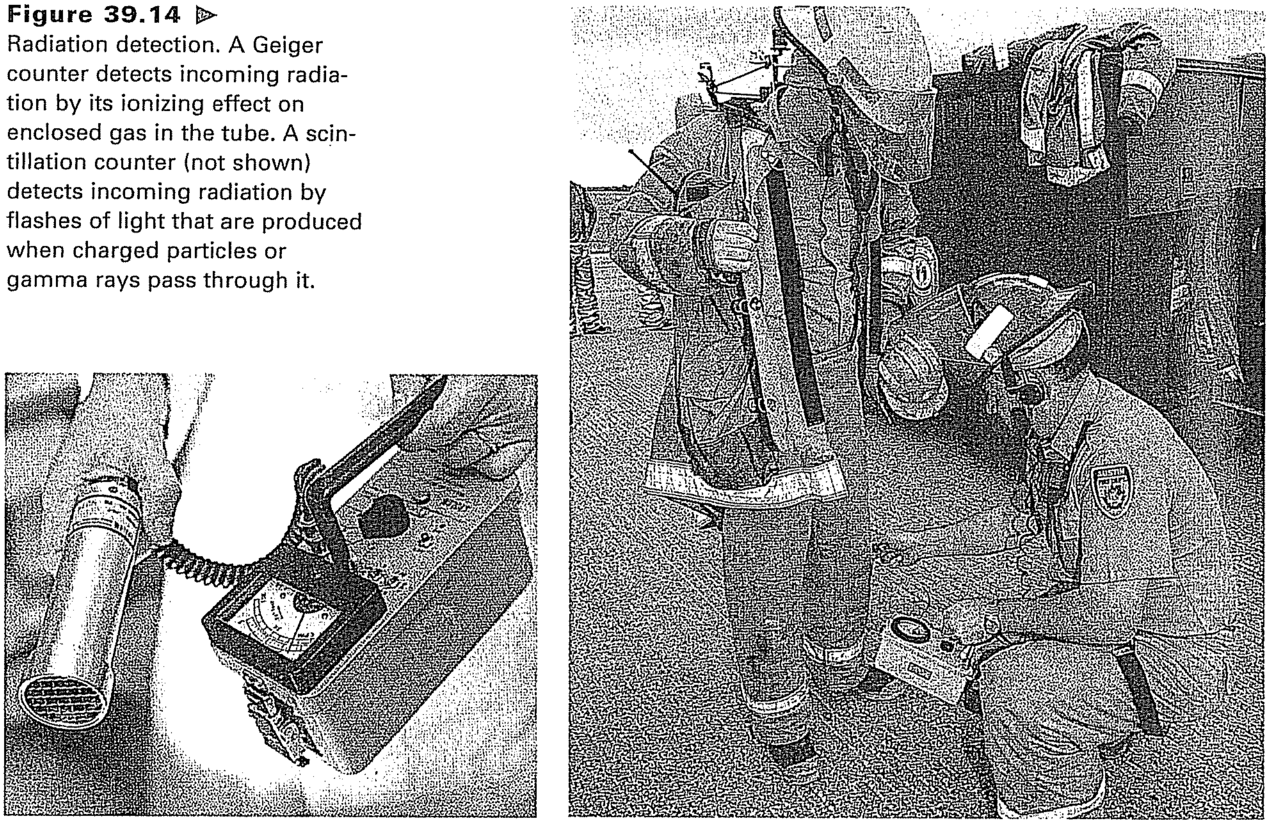

Figure 39.14 ▷
Radiation detection. A Geiger counter detects incoming radiation by its ionizing effect on enclosed gas in the tube. A scintillation counter (not shown) detects incoming radiation by flashes of light that are produced when charged particles or gamma rays pass through it.

Questions

1. If a sample of a radioactive isotope has a half-life of 1 year, how much of the original sample will be left at the end of the second year?
2. If you have equal amounts of radioactive materials, one that has a short half-life and another that has a long half-life, which will give a higher reading on a radiation detector?

Answers

1. One-quarter of the original sample will be left. The three-quarters that underwent decay become one or more different elements altogether.
2. The material with the shorter half-life is more active and will give a higher reading on a radiation detector.

1 Explore 2 Develop 3 Apply

3 **Problem-Solving Exercises in Physics** *18-4*

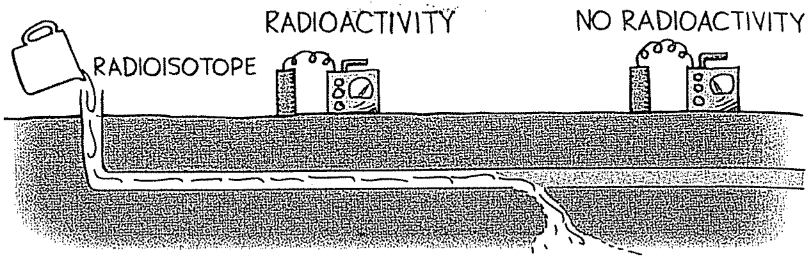

Figure 39.19 ▲
Tracking pipe leaks with radioactive isotopes.

There are hundreds more examples of the use of radioactive isotopes. The important thing is that this technique provides a way to detect and count atoms in quantities too small to be seen with a microscope and too small to be hazardous.*

39.11 Radiation and You

Radioactivity has been around longer than humans have. It is as much a part of our environment as the sun and the rain. It is what warms the interior of Earth and makes it molten. In fact, radioactive decay inside Earth is what heats the water that spurts from a geyser or that wells up from a natural hot spring. Even the helium in a child's balloon is the result of radioactivity. Its nuclei are nothing more than alpha particles that were once shot out of radioactive nuclei.

As Figure 39.20 shows, most radiation you encounter originates in nature. It is in the ground you stand on, and in the bricks and stones of surrounding buildings. Even the cleanest air we breathe is slightly radioactive. This natural background radiation was present before humans emerged in the world. If our bodies couldn't tolerate it, we wouldn't be here.

Much of the radiation we are exposed to is cosmic radiation streaming down through the atmosphere. Most of the protons and other atomic nuclei that fly toward Earth from outer space are deflected away. The atmosphere, acting as a protective shield, stops most of the rest. But some cosmic rays penetrate the atmosphere, mostly in the form of secondary particles such as muons. At higher altitudes, radiation is more intense. In Denver, the "mile-high city," you receive more than twice the cosmic radiation you receive at sea level. A couple of round-trip flights between New York and San Francisco exposes you to as much radiation as in a normal chest X-ray. The air time of airline personnel is limited because of this extra radiation.

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* The use of intense radiation in treating cancer is different. The quantity of radioactive material is then far greater than in research using radioactive tracers, but the benefit is reckoned to outweigh the risk.

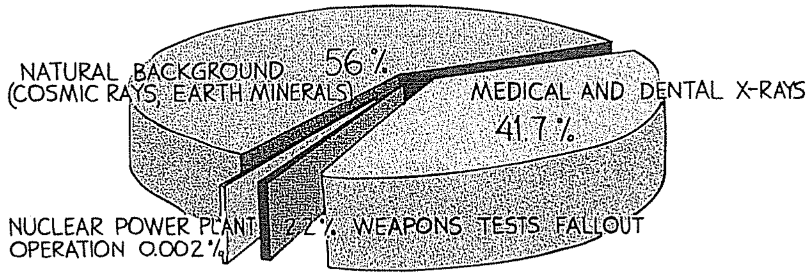


Figure 39.20 ▲
Origins of radiation exposure for an average individual in the United States.

We are bombarded most by what harms us least—neutrinos. Neutrinos are the most weakly interacting particles. They have near-zero mass, no charge, and are produced frequently in radioactive decays. They are the most common high-speed particles known, zapping the universe, and passing unhindered through our bodies by the billions every second. They pass completely through Earth with only occasional encounters. It would take a "piece" of lead 6 light-years in thickness to absorb half the neutrinos incident upon it. About once per year on the average, a neutrino triggers a nuclear reaction in your body. We don't hear much about neutrinos because they ignore us.

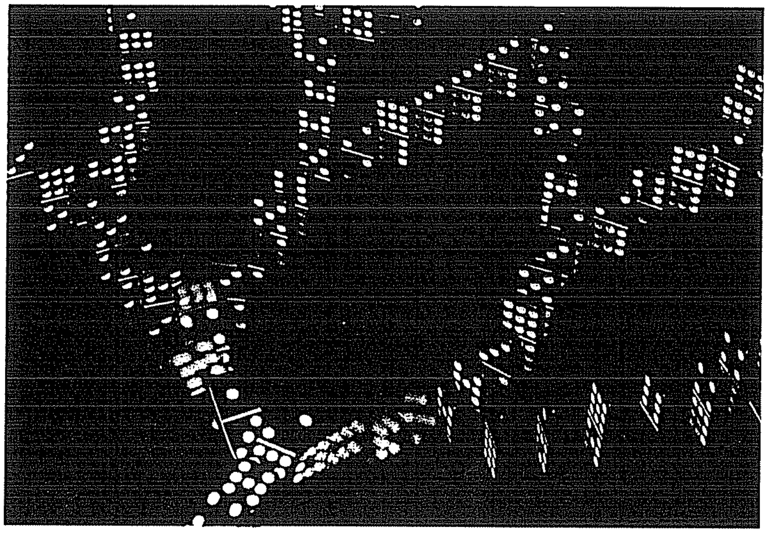
Of the types of radiation we have focused upon in this chapter, gamma radiation is by far the most dangerous. It emanates from radioactive materials and makes up a substantial part of the normal background radiation. Exposure to gamma radiation should be minimized. The cells of living tissue are composed of intricately structured molecules in a watery, ion-rich brine. When gamma radiation encounters this highly ordered soup, it produces damage on the atomic scale. Less damage is done by a beta particle because it does not penetrate as deeply into living matter. Regardless of whether damage is by gamma, beta, or some other kind of radiation, these altered molecules are often more harmful than useful to life processes. Altered DNA molecules, for example, can produce harmful genetic mutations.

Cells can repair most kinds of molecular damage if the radiation they are exposed to is not too intense. This is how we are able to tolerate small radiation doses. On the other hand, people who work around high concentrations of radioactive materials must be specially trained and protected to avoid an increased risk of cancer. This applies to medical people, workers in nuclear power plants, and personnel on nuclear-powered ships. People who receive high doses of radiation (on the order of 1000 times natural background or more) run a greater risk of cancer and have a shorter life expectancy than people who are not so exposed.

Whenever possible, exposure to radiation should be avoided. Unavoidable, however, is the natural radiation that all living beings have always absorbed.

Figure 39.21 ▲
This is the internationally used symbol to indicate an area where radioactive material is being handled or produced.

40 Nuclear Fission and Fusion



Chain reaction.

The discovery of radioactivity in 1896 sparked much interest among many kinds of people. Some people thought it was no more than a scientific curiosity, some thought it would be a cure for medical ailments, and a few thought it might turn out to be a source of plentiful energy to heat homes, power factories, and light up cities at night.

Radioactivity does release energy, but has not become a substantial source of energy for humans. On a small scale it powers small energy sources in spacecraft, and makes a sample of radium warm. On a large scale it melts rocks and is the source of geothermal energy within the earth. In 1939, just before World War II, a nuclear reaction was discovered that released much more energy per atom than radioactivity, and had the potential to be used for both explosions and power production. This was the splitting of the atom, or *nuclear fission.*

A very different nuclear reaction, *nuclear fusion,* can also release huge amounts of energy. Both nuclear fission and nuclear fusion produce vastly more energy per kilogram of matter than any chemical reaction, and even more than most other nuclear reactions. The awesome release of this energy in atomic and hydrogen bombs ushered in the present "nuclear age." Out of the ashes of despair brought about by these bombs, hope grew that atoms could be used for peaceful purposes—that the awesome energy of nuclear reactions could be used for domestic power instead of for arsenals of war.

What exactly are nuclear fission and nuclear fusion? How do they differ? What is the physics that underlies why so much energy is released by these reactions? The answers to these questions are what this chapter is about.

40.1 Nuclear Fission

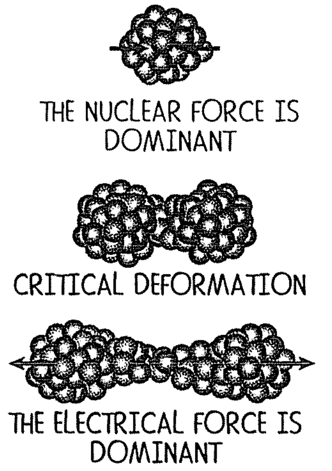
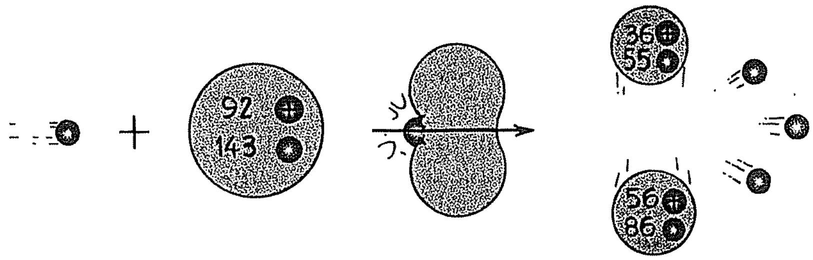


Figure 40.1 ▲
Nuclear deformation leads to fission when repelling electrical forces dominate over attracting nuclear forces.

Biology students know that living tissue grows by the division of cells. The splitting in half of living cells is called *fission*. In a similar way, the splitting of atomic nuclei is called **nuclear fission.**

Nuclear fission involves the delicate balance between the attraction of nuclear strong forces and the repulsion of electrical forces within the nucleus. In all known nuclei the nuclear strong forces dominate. In uranium, however, this domination is tenuous. If the uranium nucleus is stretched into an elongated shape (Figure 40.1), the electrical forces may push it into an even more elongated shape. If the elongation passes a critical point, electrical forces overwhelm nuclear strong forces, and the nucleus splits. This is nuclear fission.

The absorption of a neutron by a uranium nucleus supplies enough energy to cause such an elongation. The resulting fission process may produce many different combinations of smaller nuclei. A typical example is



$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{91}_{36}Kr + ^{142}_{56}Ba + 3(^{1}_{0}n)$$

The energy that is released by the fission of one U-235 atom is enormous—about seven million times the energy released by the explosion of one TNT molecule. This energy is mainly in the form of kinetic energy of the fission fragments, with some energy given to ejected neutrons, and the rest to gamma radiation.

Note that one neutron starts the fission of the uranium atom, and, in this example, three more neutrons are produced when the uranium fissions. Between two and three neutrons are produced in most nuclear fission reactions. These new neutrons can, in turn, cause the fissioning of two or three other nuclei, releasing from four to nine more neutrons. If each of these succeeds in splitting just one atom, the next step in the reaction will produce between 8 and 27 neutrons, and so on. This makes a **chain reaction** (Figure 40.2).

Why do chain reactions not occur in naturally occurring uranium ore deposits? They would if all uranium atoms fissioned so easily. Fission occurs mainly for the rare isotope U-235, which makes up only 0.7% of the uranium in pure uranium metal. When the prevalent isotope U-238 absorbs neutrons from fission, it does not undergo fission. So a chain reaction can be snuffed out by the neutron-absorbing U-238. It is rare for uranium deposits in nature to spontaneously undergo a chain reaction.

If a chain reaction occurred in a chunk of pure U-235 the size of a baseball, an enormous explosion would likely result. If the chain reaction were started in a smaller chunk of pure U-235, however, no

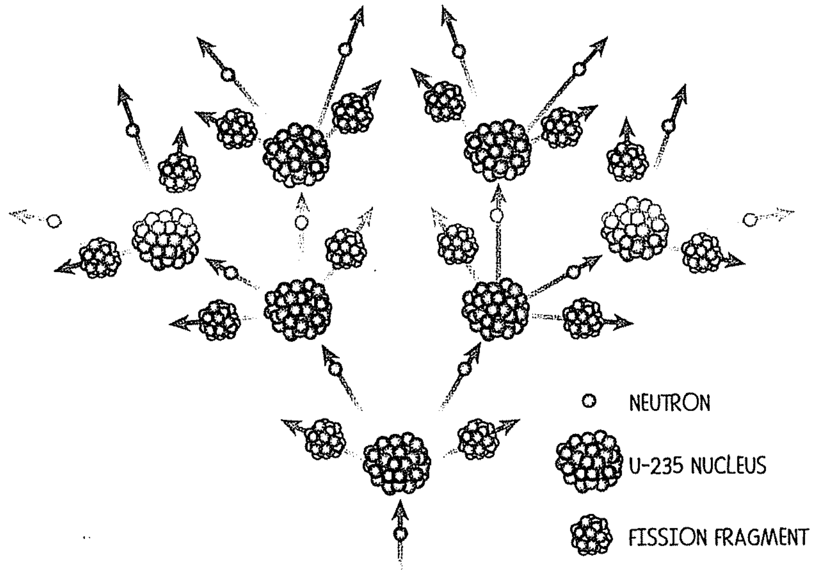


Figure 40.2
A chain reaction.

explosion would occur. Why? Because a neutron ejected by a fission event travels a certain average distance through the material before it encounters another uranium nucleus and triggers another fission event. If the piece of uranium is too small, a neutron is likely to escape through the surface before it "finds" another nucleus. On the average, fewer than one neutron per fission will be available to trigger more fission, and the chain reaction will die out. In a bigger piece, a neutron can move farther through the material before reaching a surface. Then more than one neutron from each fission event, on the average, will be available to trigger more fission (Figure 40.4).The chain reaction will build up to enormous energy.*

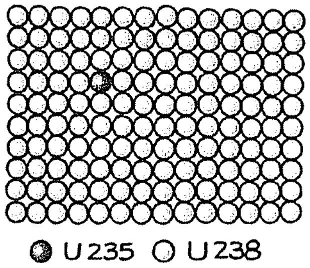


Figure 40.3 ▲
Only 1 part in 140 of naturally occurring uranium is U-235.

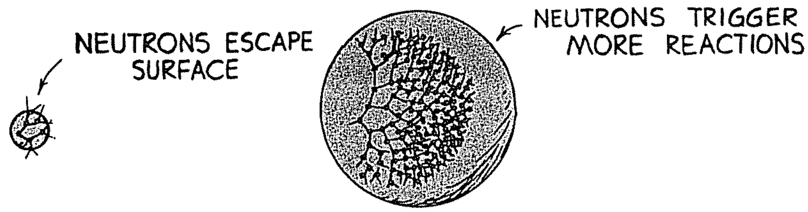


Figure 40.4 ▲
The exaggerated view shows that a chain reaction in a small piece of pure U-235 dies out, because neutrons leak from the surface too easily. In a larger piece, a chain reaction builds up because neutrons are more likely to trigger additional fission events than to escape through the surface.

The **critical mass** is the amount of mass for which each fission event produces, on the average, one additional fission event. It is just enough to "hold even." A *subcritical* mass is one in which the chain reaction dies out. A *supercritical* mass is one in which the chain reaction builds up explosively.

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* Another way to understand this is geometrically. Recall the concept of scaling in Chapter 18. Small pieces of material have more surface relative to volume than large pieces (there is more skin on a kilogram of small potatoes than on a single 1-kilogram large potato). The larger the piece of fission fuel, the less surface area it has relative to its volume.

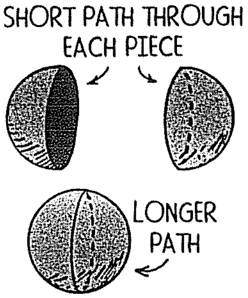

Figure 40.5 ▲
Each piece is subcritical. The average path of a neutron in each piece is short enough that a neutron is likely to escape. When the pieces are combined, the average path of a neutron is greater, and there is less chance that a neutron will escape. The combination may be supercritical.

In Figure 40.5 there are two pieces of pure U-235, each of them subcritical. Neutrons readily reach a surface and escape before a sizable chain reaction builds up. But if the pieces are joined together, there will be more distance available for neutron travel and a greater likelihood of their triggering fission before escaping through the surface. If the combined mass is supercritical, we have a nuclear fission bomb.

The construction of a uranium fission bomb is not a formidable task. The difficulty is separating enough U-235 from the more abundant U-238. It took Manhattan Project scientists and engineers more than two years to extract enough U-235 from uranium ore to make the bomb that was detonated over Hiroshima in 1945. Uranium isotope separation is still a difficult, expensive process today.

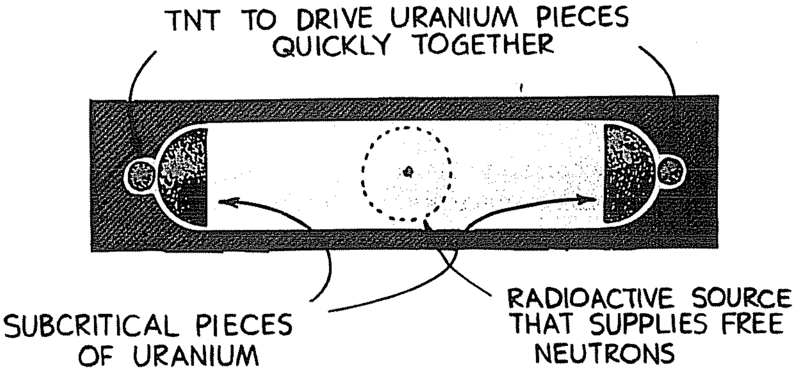

Figure 40.6 ▲
Simplified diagram of an idealized uranium fission bomb. (In an actual "gun-type" weapon, only one of the two pieces of uranium is fired toward the other one, which is the "target.")

■ Questions

1. What is nuclear fission?
2. What is a chain reaction?
3. Five kilograms of U-235 broken up into small separated chunks is subcritical, but if the chunks are put together in a ball shape, it is supercritical. Why?

■ Answers

1. Nuclear fission is the splitting of the atomic nucleus. When a heavy nucleus such as the U-235 nucleus splits into two main parts, there is a large release of energy.
2. A chain reaction is a self-sustaining reaction that, once started, continues because one reaction event triggers one or more additional reaction events.
3. Five kilograms of U-235 in small chunks will not support a sustained reaction because the path for a neutron in each chunk is so short that the neutron is likely to escape through the surface without causing fission. When the chunks are brought together, the average neutron path within the material is much longer and a neutron is likely to cause fission rather than escape.

40.2 The Nuclear Fission Reactor

A better use for uranium than for bombs is for power reactors. About 21% of electric energy in the United States is generated by nuclear fission reactors. These reactors are simply nuclear furnaces, which (like fossil fuel furnaces) do nothing more elegant than boil water to produce steam for a turbine (Figure 40.7). The greatest practical difference is the amount of fuel involved. One kilogram of uranium fuel, less than the size of a baseball, yields more energy than 30 freight-car loads of coal.

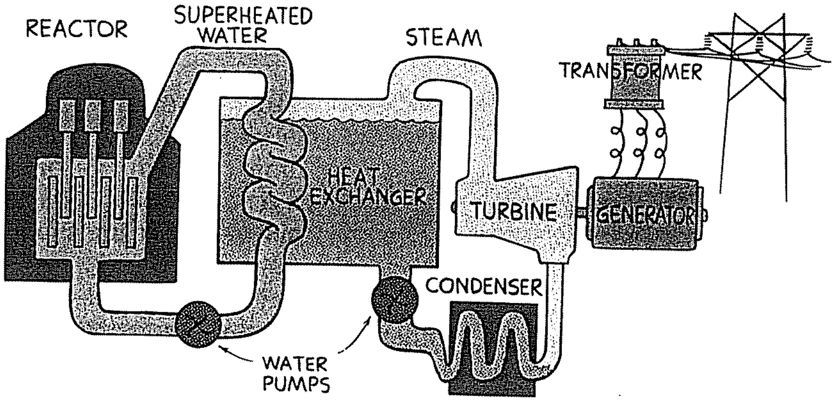

Figure 40.7
Diagram of a nuclear fission power plant.

A reactor contains three main components: the nuclear fuel combined with a moderator to slow down neutrons, the control rods, and water used to transfer heat from the reactor to the generator. The nuclear fuel is uranium, with its fissionable isotope U-235 enriched to about 3%. The moderator may be graphite, a pure form of carbon, or it may be water. Because the U-235 is so highly diluted with U-238, an explosion like that of a nuclear bomb is not possible. Control rods that can be moved in and out of the reactor control the "multiplication" of neutrons, that is, how many neutrons from each fission event are available to trigger additional fission events. The control rods are made of a material, usually the metal cadmium or boron, that readily absorbs neutrons. Heated water around the nuclear fuel is kept under high pressure and thus brought to a high temperature without boiling. It transfers heat to a second, lower-pressure water system, which operates the electric generator in a

Question

What is the function of the control rods in a nuclear reactor?

Answer

Control rods absorb more neutrons when they are pushed into the reactor and fewer neutrons when they are pulled out of the reactor. They thereby control the number of neutrons that participate in a chain reaction.

conventional fashion. In this design two separate water systems are used so that no radioactivity can reach the turbine.

A major drawback to fission power is the waste products of fission. Recall that light atomic nuclei are most stable when composed of equal numbers of protons and neutrons, and that heavy nuclei need more neutrons than protons for stability. So there are more neutrons than protons in uranium—143 neutrons compared with 92 protons in U-235, for example. When uranium fissions into two medium-weight elements, the ratio of neutrons to protons in the product nuclei is greater than for medium-weight stable nuclei. These fission products are said to be "neutron rich." They are radioactive, most with very short half-lives, but some with half-lives of thousands of years. Safely disposing of these waste products requires special storage casks and procedures, and is subject to a developing technology that is less than ideal.

40.3 Plutonium

When a neutron is absorbed by a U-238 nucleus, no fission results. The nucleus that is created, U-239, emits a beta particle instead and becomes an isotope of the first synthetic element beyond uranium—the transuranic element called *neptunium* (named after the first planet discovered from the application of Newton's law of gravitation).* This isotope, Np-239, in turn, very soon emits a beta particle and becomes an isotope of *plutonium* (named after Pluto, the second planet to be discovered via Newton's law). This isotope, Pu-239, like U-235, will undergo fission when it captures a neutron.

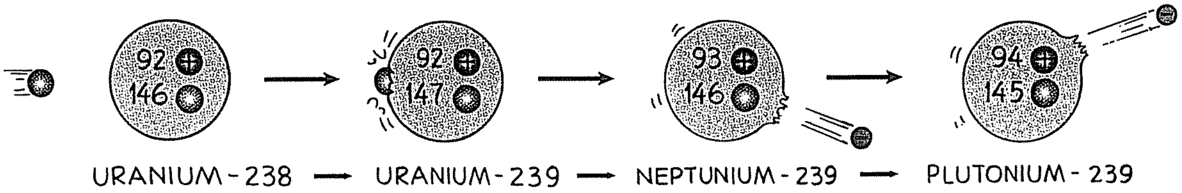

Figure 40.8 ▲
After U-238 absorbs a neutron, it emits a beta particle (and an antineutrino, not shown), which means that a neutron in the nucleus becomes a proton. The atom is no longer uranium, but neptunium. After the neptunium atom emits a beta particle it becomes plutonium.

The half-life of neptunium 239 is only 2.3 days, while the half-life of plutonium 239 is about 24 000 years. Since plutonium is an element distinct from uranium, it can be separated from uranium by ordinary chemical methods. Unlike the difficult process of separating U-235 from U-238, it is relatively easy to separate plutonium from uranium.

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* At this writing, transuranic elements extend to atomic number 111. See the periodic table of the elements, Figure 17.11.