11.5 Numerical Dating with Nuclear Decay

Discuss three ways that atomic nuclei change and explain how unstable isotopes are used to determine numerical dates.

In addition to establishing relative dates by using the principles described in the preceding sections, scientists can also obtain reliable numerical dates for events in the geologic past. For example, we know that Earth is about 4.6 billion years old and that the dinosaurs became extinct about 66 million years ago. Dates that are expressed in millions and billions of years truly stretch our imagination because our personal calendars involve time measured in hours, weeks, and years. In this section you will learn about radioactivity and its application in radiometric dating. Our understanding of changes in the nuclei of atoms has allowed us to determine that geologic time is vast. This immense span is often referred to as *deep time*. Radiometric dating allows us to measure it quantitatively.

Reviewing Basic Atomic Structure

Recall from Chapter 2 that each atom has a *nucleus* that contains protons and neutrons and that the nucleus is orbited by electrons. *Electrons* have a negative electrical charge, and *protons* have a positive charge. A *neutron* has no charge (it is electrically neutral), but it can be converted to a positively charged proton plus a negatively charged electron.

The *atomic number* (each element's identifying number) is the number of protons in the nucleus. Every element has a different number of protons and thus a different identifying atomic number (hydrogen = 1, carbon = 6, oxygen = 8, uranium = 92, etc.). Atoms of the same element always have the same number of protons, so the atomic number stays constant.

Practically all of an atom's mass (99.9 percent) is in the nucleus, indicating that electrons have virtually no mass at all. So, by adding the protons and neutrons in an atom's nucleus, we derive the atom's *mass number*. The number of neutrons can vary, and these variants, or *isotopes*, have different mass numbers.

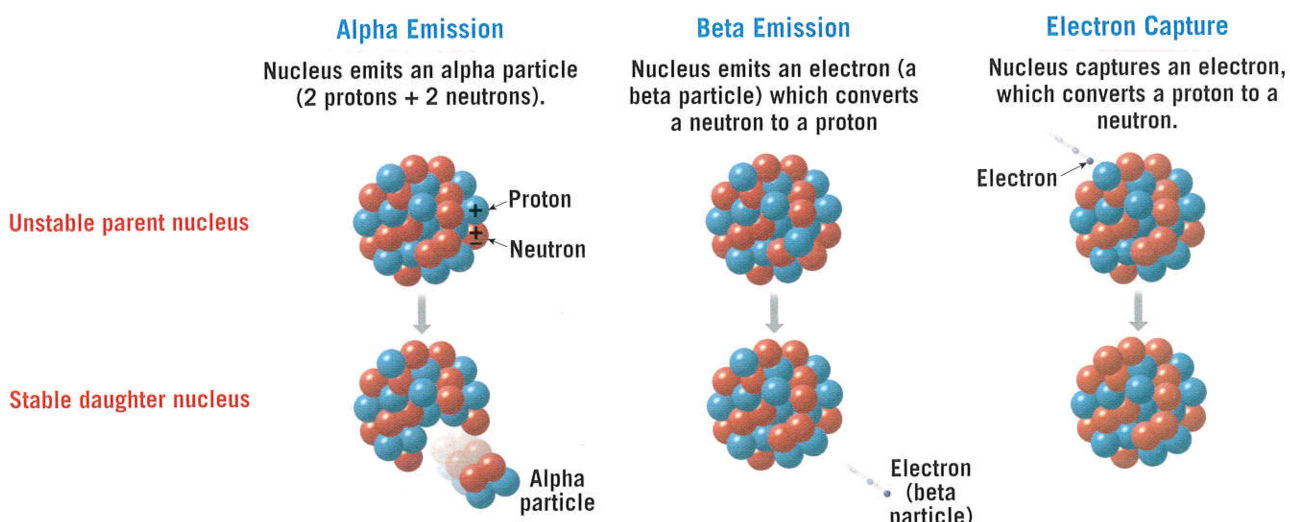
For example, uranium's nucleus always has 92 protons, so its atomic number is always 92. But its neutron population varies, so uranium has three isotopes: uranium-234 (protons + neutrons = 234), uranium-235, and uranium-238. All three isotopes are mixed in nature. They look the same and behave the same in chemical reactions.

Changes to Atomic Nuclei

Usually, the forces that stabilize atomic nuclei are strong. However, in some isotopes, the forces that bind protons and neutrons are not strong enough to keep them together forever. Such nuclei are *unstable* and spontaneously break apart in a process called **nuclear decay** (also called **radioactive decay**). As time goes by, more and more of the unstable atoms decay, producing an ever-growing number of stable isotopes. Not all isotopes are unstable—there are stable isotopes, too—but here we focus on the unstable isotopes and the stable isotopes they produce.

What happens when unstable atoms break apart? Three common types of nuclear decay are illustrated in Figure 11.19:

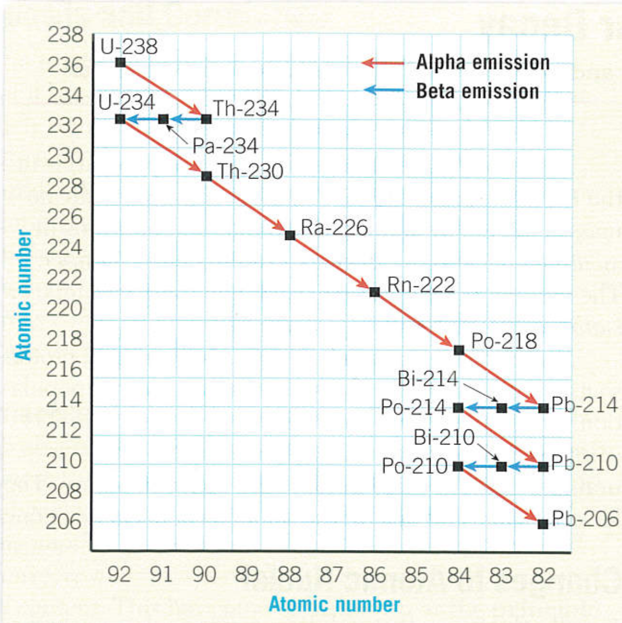
- Alpha particles (α particles) may be emitted from the nucleus. An alpha particle is composed of 2 protons



Result of process:	Alpha Emission	Beta Emission	Electron Capture
Change in atomic number (number of protons)	–2	+1	–1
Change in mass number (number of protons + neutrons)	–4	no change	no change

◀ **Figure 11.19 Char[...] atomic nuclei** Notic[...] that in each example[...] number of protons (a[...] number) in the nucle[...] changes, thus produ[...] different element.

ure 11.20 **Decay 238** Uranium-238 is ample of a nuclear series. Before the end product 06) is reached, many ent isotopes are ced as intermediate



artFigure 11.21 **ging parent/ nter ratios** Change onential. Half of the ble parent atoms n after one half-life. a second half-life, uarter of the parent remain, and so forth.

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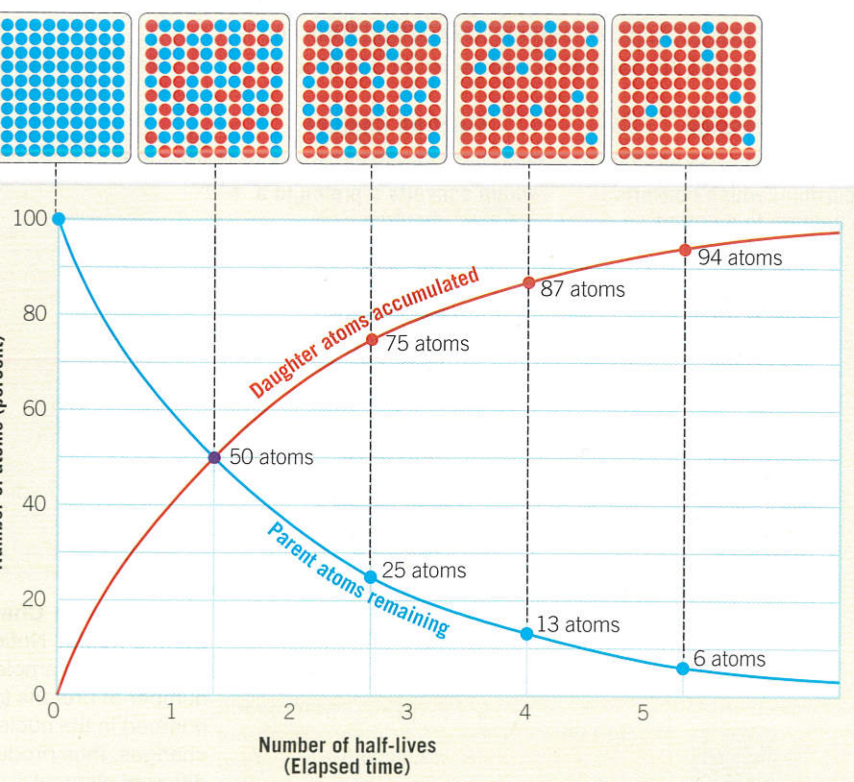
and 2 neutrons. Thus, the emission of an alpha particle means that the mass number of the isotope is reduced by 4, and the atomic number is lowered by 2.

- When an electron (often confusingly referred to as a "beta particle," or β particle), is emitted from a nucleus, the mass number remains unchanged because electrons have practically no mass. However, the electron is produced when a neutron (which has no charge) decays to produce the electron plus a proton. Because the nucleus now contains one more proton than before, the atomic number increases by 1. It's no longer the same element!
- Sometimes an electron is captured by the nucleus. The electron combines with a proton and forms an additional neutron. As in the last example, the mass number remains unchanged. However, because the nucleus now contains one fewer proton, the atomic number decreases by 1.

An unstable (radioactive) isotope is referred to as the *parent*, and the isotopes resulting from the decay of the parent are termed the *daughter products*. But the path from parent to daughter isn't always direct. Uranium-238, one of the most important isotopes for geologic dating, provides an example of the complexity (**Figure 11.20**). When the radioactive parent, uranium-238 (atomic number 92, mass number 238) decays, it follows a number of steps, emitting a total of 8 alpha particles and 6 electrons before finally becoming the stable daughter product lead-206 (atomic number 82, mass number 206).



Radiometric Dating

Nuclear decay provides a reliable way of calculating the ages of rocks and minerals that contain particular unstable isotopes. The procedure is called **radiometric dating**. Radiometric dating is reliable because the rates of decay for many isotopes have been precisely measured and do not vary under the physical conditions that exist in Earth's outer layers. Therefore, each unstable isotope used for dating has been decaying at a fixed rate since the formation of the mineral crystals in which we find it, and the products of its decay have been accumulating in that crystal at a corresponding rate. For example, some minerals are able to incorporate uranium atoms in their crystal lattice. When such a mineral crystallizes from magma, it contains no lead (the stable daughter product) from previous decay. The radiometric "clock" starts at this point. As the uranium in this newly formed mineral decays, atoms of the daughter product accumulate, trapped in the crystal, and eventually build up to measurable levels. Similarly, when a crystal of feldspar forms, some of the potassium atoms incorporated into its lattice will be the unstable isotope potassium-40. These atoms will decay at a steady rate by electron capture to produce the daughter argon-40. Over time, there is less and less of the parent potassium and more and more of the daughter argon.

Half-Life

The time required for half of the nuclei in a sample of a given unstable isotope to decay is called the **half-life** of that isotope. Half-life is a common way of expressing the rate of radioactive decay. **Figure 11.21** illustrates what occurs when a radioactive parent decays directly into its stable daughter product. When the quantities of parent and daughter are equal (ratio 1:1), we know that one half-life has transpired. When one-quarter of the original parent atoms remain and three-quarters have decayed to the daughter product, the parent/daughter ratio is 1:3, and we know that two half-lives have passed. After three half-lives, the ratio of parent atoms to daughter atoms is 1:7 (one parent atom for every seven daughter atoms).

If the half-life of a radioactive isotope is known and the parent/daughter ratio can be determined, the age of the sample can be calculated. For example, assume that the half-life of a hypothetical unstable isotope is 1 million years, and the parent/daughter ratio in a sample is 1:15. This ratio indicates that four half-lives have passed and that the sample must be 4 million years old.

Notice that the *percentage* of radioactive atoms that decay during one half-life is always the same: 50 percent. However, the *actual number* of atoms that decay with the passing of each half-life continually decreases. Thus, as the percentage of radioactive parent atoms declines, the proportion of stable daughter atoms rises, with the increase in daughter atoms just matching the drop in parent atoms. This fact is the key to radiometric dating.

Using Unstable Isotopes

Of the many radioactive isotopes that exist in nature, five have proved particularly useful in providing radiometric ages for ancient rocks (**Table 11.1**). Rubidium-87, thorium-232, and the two listed isotopes of uranium are used only for dating rocks that are millions of years old, but potassium-40 is more versatile. Although the half-life of potassium-40 is 1.3 billion years, analytical techniques make it possible to detect tiny amounts of its stable daughter product, argon-40, in some rocks that are younger than 100,000 years. Another important reason for its frequent use is that potassium is an abundant constituent of many common minerals, particularly micas and feldspars.

A Complex Process Although the basic principle of radiometric dating is simple, the actual procedure is quite complex. The chemical analysis that determines the quantities of parent and daughter must be painstakingly precise. In addition, some radioactive materials do not decay directly into the stable daughter product, and this fact may further complicate the analysis. In the case of uranium-238, there are 13 intermediate unstable daughter products formed before the 14th and last daughter product, the stable isotope lead-206, is produced (see Figure 11.20).

Table 11.1 Isotopes Frequently Used in Radiometric Dating of Rocks

Radioactive Parent	Stable Daughter Product	Currently Accepted Half-Life Values
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	704 million years
Thorium-232	Lead-208	14.1 billion years
Rubidium-87	Strontium-87	47.0 billion years
Potassium-40	Argon-40	1.3 billion years

Sources of Error It is important to understand that an accurate radiometric date can be obtained only if there has been no leakage of parent or daughter isotopes between the mineral crystal and its surroundings in the time since the mineral formed. This is not always the case. In fact, a limitation of the potassium-argon method arises from the fact that argon is a gas, and it may leak from minerals, resulting in a radiometric age that is lower than the actual age. Indeed, losses can be significant if the rock is subjected to high temperatures. If the rock is heated to the point where *all* of the argon in its minerals escapes, then its radiometric clock will be reset, and radiometric dating will give the time of thermal resetting, not the true age of the rock.

For other radiometric clocks, a loss of daughter atoms can occur if the rock has been subjected to weathering or leaching. To avoid such a problem, one simple safeguard is to use only fresh, unweathered material and not samples that exhibit signs of chemical alteration.

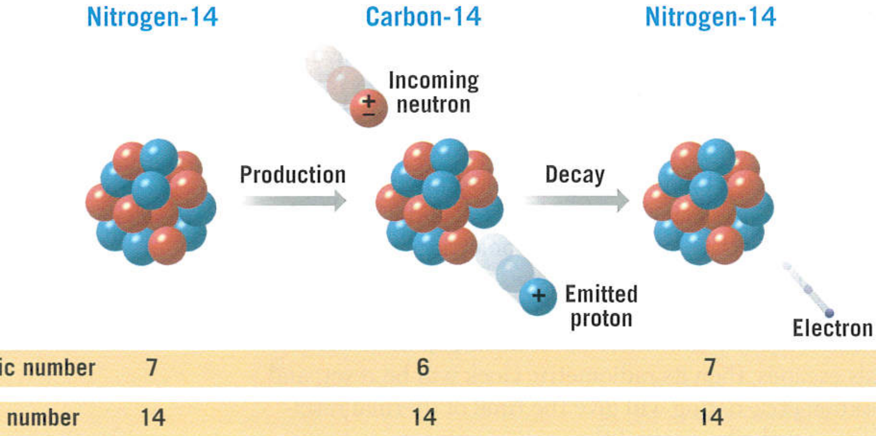
To guard against error in radiometric dating, scientists often use cross-checks, subjecting a sample to two different methods. If the results agree, the likelihood is high that the date is reliable. If the results are appreciably different, other cross-checks must be employed to determine which, if either, is correct.

Earth's Oldest Rocks Radiometric dating has produced literally thousands of dates for events in Earth history. Rocks exceeding 3.5 billion years in age are found on all of the continents. Earth's oldest rocks (so far) may be as old as 4.28 billion years (b.y.). Discovered in northern Quebec, Canada, on the shores of Hudson Bay, these rocks may be remnants of Earth's earliest crust. Rocks from western Greenland have been dated at 3.7 to 3.8 b.y., and rocks nearly as old are found in the Minnesota River valley and northern Michigan (3.5 to 3.7 b.y.), in southern Africa (3.4 to 3.5 b.y.), and in western Australia (3.4 to 3.6 b.y.). Tiny crystals of the mineral zircon having radiometric ages as old as 4.3 b.y. have been found in younger sedimentary rocks in western Australia. The source rocks for these tiny durable grains either no longer exist or have not yet been found.

Radiometric dating has vindicated the ideas of Hutton, Darwin, and others, who more than 150 years ago inferred that geologic time must be immense. Indeed, modern dating methods have proved that there has been enough time for the processes we observe to have accomplished tremendous tasks.

Dating with Carbon-14

It is possible to date some relatively recent events by using carbon-14. Carbon-14 is the radioactive isotope of carbon. The process is often called **radiocarbon dating**. Because the half-life of carbon-14 is only 5730 years, radiocarbon dating can be used for dating events from the historic past as well as those from very recent



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geologic history. In some cases carbon-14 can be used to date events as far back as 70,000 years.

Carbon-14 (^{14}C) is continuously produced in the upper atmosphere as a result of cosmic-ray bombardment. Cosmic rays (high-energy particles) shatter the nuclei of gas atoms, releasing neutrons. Some of the neutrons are absorbed by nitrogen atoms (atomic number 7, mass number 14), causing each nucleus to emit a proton. As a result, the atomic number decreases by 1 (to 6), and a different element, carbon-14, is created (**Figure 11.22**). This isotope of carbon quickly becomes incorporated into carbon dioxide, which circulates in the atmosphere and is absorbed by living matter. As a result, all organisms—including you—contain a small amount of carbon-14. You "top off" your ^{14}C levels every time you eat something.

As long as an organism is alive, the decaying radiocarbon is continually replaced, and the proportions of carbon-14 and carbon-12 remain constant. Carbon-12 is the stable and most common isotope of carbon. However, when any plant or animal dies, the amount of carbon-14 gradually decreases as it decays to nitrogen-14 by beta emission. By comparing the proportions of carbon-14 and carbon-12 in a sample, radiocarbon dates can be determined. It is important to emphasize that carbon-14 can only be used to date organic materials, such as wood, charcoal, bones, flesh, and cloth.

▲ **Figure 11.23** **Cave art** Chauvet Cave in southern France, discovered in 1994, contains some of the earliest-known cave paintings. Radiocarbon dating indicates that most of the images were drawn between 30,000 and 32,000 years ago. (Photo by Javier Trueba/MSF/Science Source)

Although carbon-14 is only useful in dating the last small fraction of geologic time, it is a valuable tool for anthropologists, archaeologists, and historians, as well as for geologists who study very recent Earth history (**Figure 11.23**). In fact, the development of radiocarbon dating was considered so important that the chemist who discovered this application, Willard F. Libby, received a Nobel Prize in 1960.

CONCEPT CHECKS 11.5

1. List four ways that unstable nuclei change. For each type, describe how the atomic number and atomic mass change.
2. Sketch a simple diagram that explains the idea of half-life.
3. Why is radiometric dating a reliable method for determining numerical dates?
4. For what time span does radiocarbon dating apply?

11.6 Determining Numerical Dates for Sedimentary Strata

Explain how reliable numerical dates are determined for layers of sedimentary rock.

Although reasonably accurate numerical dates have been worked out for the periods of the geologic time scale, the task is not without difficulty. The primary difficulty in assigning numerical dates to units of time is that not all rocks can be dated by using radiometric methods. For a radiometric date to be useful, all the minerals in the rock must have formed at about the same time. For this reason, unstable isotopes can be used to determine when minerals in an igneous rock crystallized and when pressure and heat created new minerals in a metamorphic rock.

However, samples of sedimentary rock can only rarely be dated directly by radiometric means. Although a detrital sedimentary rock may include particles that contain unstable isotopes, the rock's age cannot be accurately determined because the grains composing the rock are not the same age as the rock in which they occur. Rather, the sediments have been weathered from rocks of diverse ages.

Radiometric dates obtained from metamorphic rocks may also be difficult to interpret because the age of a