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DEPARTMENT OF CHEMISTRY  
CHM 101 (General Chemistry 1) – Dr. Sobola & Prof. Adeniyi  
**RADIOACTIVITY**

In **chemical reactions**, only the outer electrons of the atoms are disturbed. The nuclei of the atoms are not affected. In **nuclear reactions**, however, the nuclear changes that occur are independent of the chemical environment of the atom. For example, the nuclear changes in a radioactive  ${}^3_1\text{H}$  atom is the same if the atom is part of an  $\text{H}_2$  molecule or incorporated into  $\text{H}_2\text{O}$ .

There are two types of nuclear reactions:

1. Radioactive decay
2. Nuclear bombardment reaction

**Radioactive Decay (Radioactivity)**

**Radioactive decay** occurs when a nucleus spontaneously disintegrates, giving off radiation. Depending on the nucleus, the radiation consists of one or more **electrons**, nuclear particles (such as **neutrons**), smaller nuclei (usually **helium-4 nuclei**), and **electromagnetic radiation**.

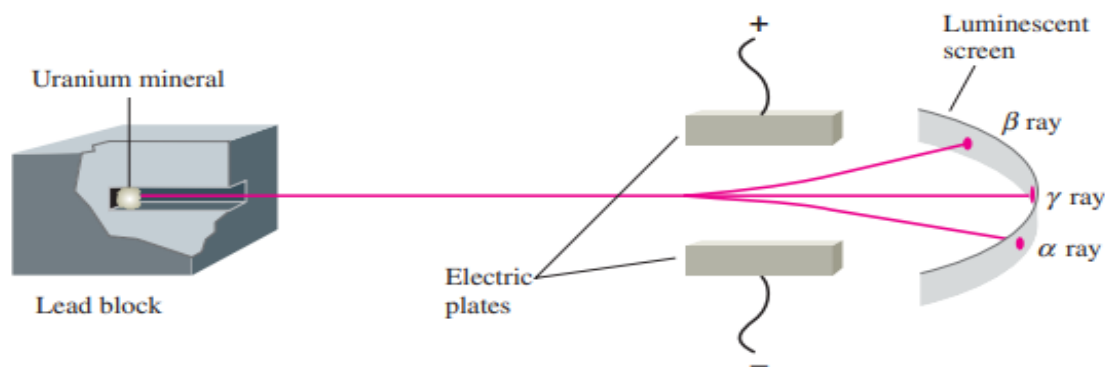
Antoine Henri Becquerel discovered the phenomenon of radioactivity in 1896. He found that photographic plates develop bright spots when exposed to uranium minerals and concluded that the minerals give off some radiation.

The radiation from uranium minerals was later shown to be separable by electric (and magnetic) fields into three types: **alpha ( $\alpha$ )**, **beta ( $\beta$ )**, and **gamma ( $\gamma$ ) rays**.

Alpha rays bend away from a positive plate and toward a negative plate, indicating a **positive charge**; they are now known to consist of helium-4 nuclei (nuclei with two protons and two neutrons).

Beta rays bend in the opposite direction, indicating a **negative charge**; they are now known to consist of high-speed electrons.

Gamma rays are unaffected by electric and magnetic fields: they are a form of **electromagnetic radiation** that is like X-rays, except they are higher in energy with shorter wavelengths (about 1 pm or  $1 \times 10^{-12} \text{ m}$ ).



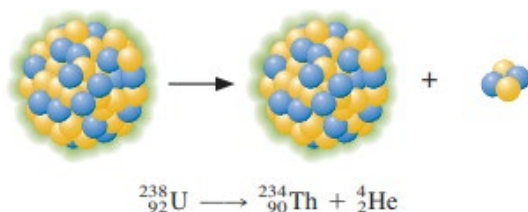
**Figure 1: Separation of the radiation from a radioactive material (uranium mineral)**

Uranium minerals contain several radioactive elements, each emitting one or more radiations. Uranium-238, the main uranium isotope in uranium minerals, emits alpha rays and decays or disintegrates to thorium-234 nuclei.

**Nuclear Equations**

We can write an equation for the nuclear reaction corresponding to the decay uranium-238 much as we would write an equation for a chemical reaction. You represent the uranium-238 nucleus by the nuclide symbol  ${}^{238}_{92}\text{U}$ .

The radioactive decay of  ${}^{238}_{92}\text{U}$  by alpha-particle emission (loss of a  ${}^4_2\text{He}$  nucleus) is written as:



The product, in addition to helium-4, is thorium-234.

This is an example of a nuclear equation, a symbolic representation of a nuclear reaction.

Reactant and product nuclei are represented in nuclear equations by their nuclide symbols.

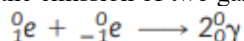
Other particles are given the following symbols, in which the subscript equals the charge, and the superscript equals the total number of protons and neutrons in the particle (mass number):

Proton	${}^1_1\text{H}$	or	${}^1_1\text{P}$
Neutron	${}^1_0\text{n}$		
Electron	${}^0_{-1}\text{e}$	or	${}^0_{-1}\beta$
Positron	${}^0_1\text{e}$	or	${}^0_1\beta$
Gamma photon	${}^0_0\gamma$		

The decay of a nucleus with the emission of an electron,  ${}^0_{-1}\text{e}$ , is usually called **beta emission**, and the emitted electron is sometimes labeled  ${}^0_{-1}\beta$ .

A **positron** is a particle like an electron, having the same mass but a positive charge.

Positrons are annihilated as soon as they encounter electrons. When a positron and an electron collide, both particles vanish with the emission of two gamma photons that carry away the energy.



A **gamma photon** is a particle of electromagnetic radiation of short wavelength (about 1 pm or  $1 \times 10^{-12} \text{ m}$ ) and high energy.

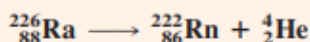
### Example 20.1

### Writing a Nuclear Equation

Write the nuclear equation for the radioactive decay of radium-226 by alpha decay to give radon-222. A radium-226 nucleus emits one alpha particle, leaving behind a radon-222 nucleus.

**Problem Strategy** Use the list of elements on the inside back cover to obtain the atomic numbers of radium and radon, so you can write their nuclide symbols for the nuclear equation. The nuclide symbol of the alpha particle is  ${}^4_2\text{He}$ .

**Solution** The nuclear equation is



**Answer Check** Make sure that you have written the nuclide symbols with the correct superscripts and subscripts.

### Exercise 20.1

Potassium-40 is a naturally occurring radioactive isotope. It decays to calcium-40 by beta emission. When a potassium-40 nucleus decays by beta emission, it emits one beta particle and gives a calcium-40 nucleus. Write the nuclear equation for this decay.

During a nuclear reaction, the total charge is conserved or remains constant. This means that the sum of the subscripts (number of protons, or positive charges, in the nuclei) for the products must equal the sum of the subscripts for the reactants.

Similarly, the total number of nucleons (protons and neutrons) is conserved or remains constant during a nuclear reaction. This means that the sum of the superscripts (mass numbers) for the reactants equals the sum of the superscripts for the products.

**Note that if all reactants and products but one are known in a nuclear equation, the identity of that one nucleus or particle can be easily obtained.** This is illustrated in the next example:

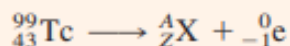
### Example 20.2

Technetium-99 is a long-lived radioactive isotope of technetium. Each nucleus decays by emitting one beta particle. What is the product nucleus?

**Problem Strategy** First, write the nuclear equation using the symbol  ${}^A_Z\text{X}$  for the unknown nuclide or particle.

Then, solve for  $A$  and  $Z$  using the following relations: (1) the sum of the subscripts for the reactants equals the sum of the subscripts for the products, and (2) the sum of the superscripts for the reactants equals the sum of the superscripts for the products.

**Solution** Technetium-99 has the nuclide symbol  ${}^{99}_{43}\text{Tc}$ . A beta particle is an electron; the symbol is  ${}^0_{-1}\text{e}$ . The nuclear equation is



From the superscripts, you can write

$$99 = A + 0, \text{ or } A = 99$$

Similarly, from the subscripts, you get

$$43 = Z - 1, \text{ or } Z = 43 + 1 = 44$$

Hence  $A = 99$  and  $Z = 44$ , so the product is  ${}^{99}_{44}\text{X}$ . Because element 44 is ruthenium, symbol Ru, you write the product nucleus as  ${}^{99}_{44}\text{Ru}$ .

#### Exercise 20.2

Plutonium-239 decays by alpha emission, with each nucleus emitting one alpha particle. What is the other product of this decay?

#### Nuclear Stability

The existence of stable nuclei with more than one proton is due to the nuclear force. The nuclear force is a strong force of attraction between nucleons that acts only at very short distances (about  $10^{-15}\text{m}$ ). *Beyond nuclear distances, these nuclear forces become negligible.* Therefore, two protons that are much farther apart than  $10^{-15}\text{m}$  repel one another by their like electric charges.

Inside the nucleus, however, two protons are close enough together for the nuclear force between them to be effective. This force in a nucleus can more than compensate for the repulsion of electric charges and thereby give a stable nucleus.

Nuclear stability depends on three different factors:

- i. **Presence of Magic numbers**
- ii. **Deviation from Band of Stability ---Neutron to proton ratio (N/P)**
- iii. **Pairs of Protons and pairs of Neutrons**

The protons and neutrons in a nucleus appear to have energy levels, much like the electrons in an atom. The shell model of the nucleus is a nuclear model in which protons and neutrons exist in levels or shells, analogous to the shell structure that exists for electrons in an atom.

Experimentally, note that nuclei with certain numbers of protons or neutrons appear to be very stable. The shell model later explained these numbers, which are called magic numbers and are associated with exceptionally stable nuclei.

According to this theory, **a magic number is the number of nuclear particles in a completed shell of protons or neutrons.** Because nuclear forces differ from electrical forces, these numbers are not the same as those for electrons in atoms. **For protons, the magic numbers are 2, 8, 20, 28, 50, and 82.**

**Neutrons have these same magic numbers and the magic number 126. For protons, calculations show that 114 should also be a magic number.**

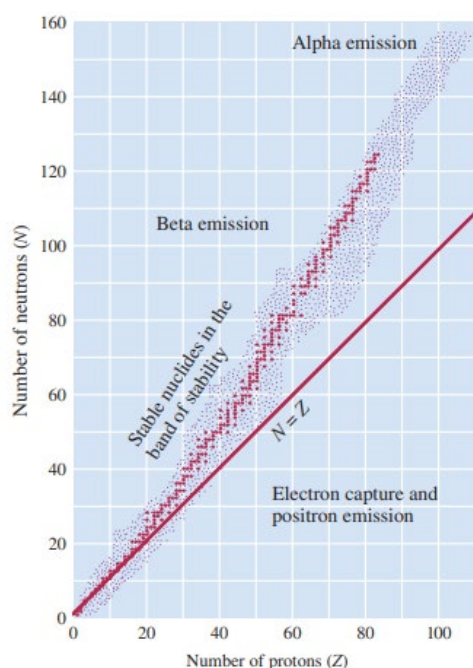
Evidence also points to the remarkable stability of pairs of protons and neutrons, analogous to the stability of pairs of electrons in molecules. Table 20.1 lists the number of stable isotopes that have an even number of protons and an even number of neutrons (157). By comparison, only 5 stable isotopes have an odd number of protons and an odd number of neutrons.

TABLE 20.1	Number of Stable Isotopes with Even and Odd Numbers of Protons and Neutrons			
	Number of Stable Isotopes			
	157	52	50	5
Number of protons	Even	Even	Odd	Odd
Number of neutrons	Even	Odd	Even	Odd

### Band of Stability

When you plot each stable nuclide on a graph with the number of protons ( $Z$ ) on the horizontal axis and the number of neutrons ( $N$ ) on the vertical axis, these stable nuclides fall in a specific region or band of the graph.

**The band of stability is the region in which stable nuclides lie in a plot of a number of protons against a number of neutrons.**



**Figure 2: Band of Stability**

The stable nuclides, indicated by black dots, cluster in a band. Nuclides to the left of the band of stability usually decay by beta emission, whereas those to the right usually decay by positron emission or electron capture. Nuclides of  $Z > 83$  often decay by alpha emission.

### Nuclear Decay

For nuclides up to  $Z = 20$ , the ratio of neutrons to protons is about 1.0 to 1.1. As  $Z$  increases, however, the neutron-to-proton ratio increases to about 1.5. This increase in neutron-to-proton ratio with increasing  $Z$  is believed to result from the increasing repulsions of protons from their electric charges. More neutrons are required to give attractive nuclear forces to offset these repulsions. When the number of protons becomes very large, the proton-proton repulsions become so great that stable nuclides are impossible.

**No stable nuclides are known with atomic numbers greater than 83.**

On the other hand, all elements with  $Z$  equal to 83 or less have one or more stable nuclides, except for technetium ( $Z = 43$ ) and promethium ( $Z = 61$ ).

### Exercise 20.3: Predicting the Relative Stabilities of Nuclides

One of the nuclides in each of the following pairs is radioactive; the other is stable. Which is radioactive and which is stable? Explain.

- a.  $^{208}_{84}\text{Po}$ ,  $^{209}_{83}\text{Bi}$     b.  $^{39}_{19}\text{K}$ ,  $^{40}_{19}\text{K}$     c.  $^{71}_{31}\text{Ga}$ ,  $^{76}_{31}\text{Ga}$

**Problem Strategy** You must decide which nuclide of each pair is more likely to be stable, based on the general principles stated in the preceding text.

**Solution** a. Polonium has an atomic number greater than 83, so  $^{208}_{84}\text{Po}$  is **radioactive**. Bismuth-209 has 126 neutrons (a magic number), so  $^{209}_{83}\text{Bi}$  is **expected to be stable**.

b. Of these two isotopes,  $^{39}_{19}\text{K}$  has a magic number of neutrons (20), so  $^{39}_{19}\text{K}$  is **expected to be stable**. The isotope  $^{40}_{19}\text{K}$  has an odd number of protons (19) and an odd number of neutrons (21). Because stable

odd-odd nuclei are rare, you might expect  $^{40}_{19}\text{K}$  to be **radioactive**.

c. Of the two isotopes,  $^{76}_{31}\text{Ga}$  lies farther from the center of the band of stability, so it is more likely to be radioactive. For this reason, you expect  $^{76}_{31}\text{Ga}$  to be **radioactive** and  $^{71}_{31}\text{Ga}$ , which has an even number of neutrons and is close to the atomic mass of gallium, to be **stable**.

**Answer Check** When trying to determine whether a nuclide is radioactive, always first perform the simple check to see if the atomic number is greater than 83.

**Exercise 20.3** Of the following nuclides, two are radioactive. Which are radioactive and which is stable? Explain. a.  $^{118}_{50}\text{Sn}$ ; b.  $^{76}_{33}\text{As}$ ; c.  $^{227}_{89}\text{Ac}$ .



## Types of Radioactive Decay

There are six common types of radioactive decay; the first five are listed in Table 20.2.

Type of Decay	Radiation	Equivalent Process	Resulting Nuclear Change		Usual Nuclear Condition
			Atomic Number	Mass Number	
Alpha emission ( $\alpha$ )	${}^4_2\text{He}$	—	−2	−4	$Z > 83$
Beta emission ( $\beta$ )	${}^0_{-1}\text{e}$	${}_0^1\text{n} \longrightarrow {}_1^1\text{p} + {}^0_{-1}\text{e}$	+1	0	$N/Z$ too large
Positron emission ( $\beta^+$ )	${}^0_1\text{e}$	${}_1^1\text{p} \longrightarrow {}_0^1\text{n} + {}^0_1\text{e}$	−1	0	$N/Z$ too small
Electron capture (EC)	x rays	${}_1^1\text{p} + {}^0_{-1}\text{e} \longrightarrow {}_0^1\text{n}$	−1	0	$N/Z$ too small
Gamma emission ( $\gamma$ )	${}^0_0\gamma$	—	0	0	Excited

Nuclides outside the band of stability (Figure 20.3) are generally radioactive.

**Nuclides to the left of the band of stability have a neutron-to-proton ratio ( $N/Z$ ) larger than that needed for stability. These nuclides tend to decay by beta emission.**

Beta emission reduces the neutron-to-proton ratio, *because in this process a neutron is changed to a proton*. The product is a stabler nuclide.

In contrast, **nuclides to the right of the band of stability have a neutron-to-proton ratio smaller than that needed for stability. These nuclides tend to decay by either positron emission or electron capture.**

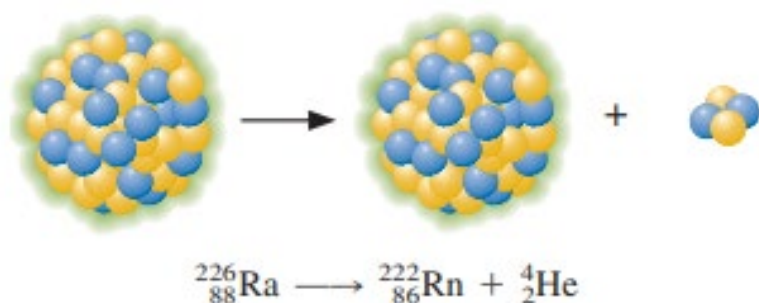
**Both processes convert a proton to a neutron, increasing the neutron-to-proton ratio** and giving a stable product nuclide.

The types of radioactive decay expected of unstable nuclides are noted in Figure 20.3

### 1. Alpha emission

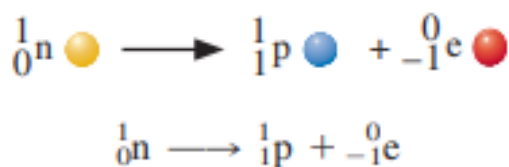
This is the emission of a  ${}^4_2\text{He}$  nucleus, or alpha particle, from an unstable nucleus. An example is the radioactive decay of radium-226.

The product nucleus has an atomic number that is two less and a mass number that is four less than that of the original nucleus.

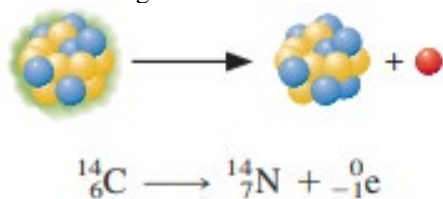


### Beta emission ( ${}^0_{-1}\text{e}$ )

This is the emission of a high-speed electron from an unstable nucleus. Beta emission is equivalent to the conversion of a neutron to a proton.

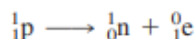
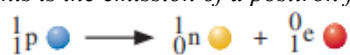


An example of beta emission is the radioactive decay of carbon-14. The product nucleus has an atomic number that is one more than that of the original nucleus. The mass number remains the same

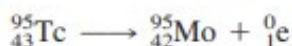
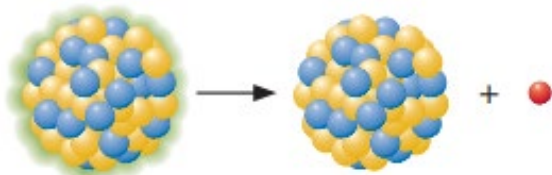


### Positron emission ( ${}^0_{+1}e$ )

This is the emission of a positron from an unstable nucleus, which is equivalent to the conversion of a proton to a neutron.



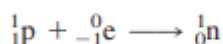
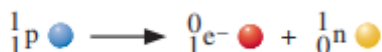
The radioactive decay of technetium-95 is an example of positron emission.



The product nucleus has an atomic number one less than that of the original nucleus, but the mass number remains the same.

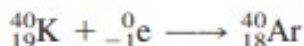
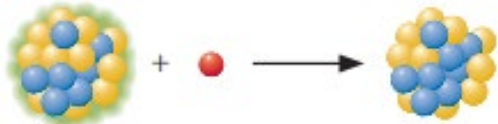
### Electron capture (abbreviated EC):

This is the decay of an unstable nucleus by capturing or picking up an electron from an inner orbital of an atom. A proton is changed to a neutron, as in positron emission.



An example is given by potassium-40, which has a natural abundance of 0.012%.

Potassium-40 can decay by electron capture, as well as by beta and positron emissions. The equation for electron capture is:



The product nucleus has an atomic number one less than that of the original nucleus, but the mass number remains the same.

### Gamma emission ( ${}^0_0\gamma$ )

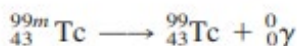
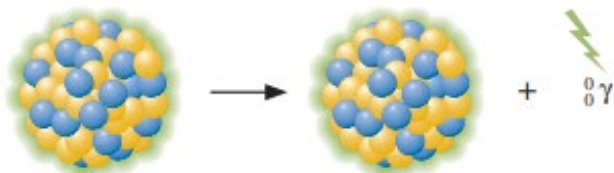
This is the emission from an excited nucleus of a gamma photon, corresponding to radiation with a wavelength of about  $1 \times 10^{-12}\text{m}$ . In many cases, radioactive decay results in a product nucleus that **is in an excited state**.

As in the case of atoms, the excited state is unstable and goes to a lower-energy state with the emission of electromagnetic radiation. For nuclei, this radiation is in the gamma-ray region of the spectrum.

Gamma emission often occurs very quickly after radioactive decay. In some cases, however, an excited state has a significant lifetime before it emits a gamma photon.

**A metastable nucleus is a nucleus in an excited state with a lifetime of at least one nanosecond ( $1 \times 10^{-9}\text{s}$ ).**

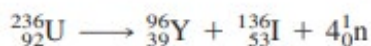
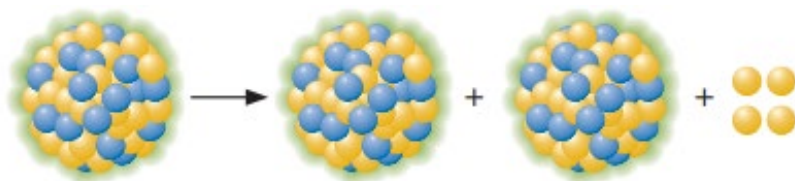
In time, the metastable nucleus decays by gamma emission. An example is metastable technetium-99, denoted by  ${}^{99m}_{43}\text{Tc}$ , which is used in medical diagnosis.



The product nucleus is simply a lower-energy state of the original nucleus, so there is no change in atomic number or mass number.

### Spontaneous fission

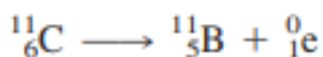
This is the spontaneous decay of an unstable nucleus in which a heavy nucleus of a mass number greater than 89 splits into lighter nuclei, and energy is released. For example, a uranium-236 atom can spontaneously undergo the following nuclear reaction:



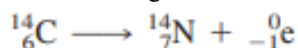
### Further Examples of Radioactive Decay

Consider a series of isotopes of a given element, such as carbon. Carbon-12 and carbon-13 are stable isotopes, whereas the other carbon isotopes are radioactive.

The isotopes of mass number smaller than 12 decay by positron emission. For example, carbon-11 decays by positron emission to boron-11:



Carbon-11 has a neutron-to-proton ratio of 5/6 (0.8), which increases in the product boron-11 to 6/5 (1.2). Carbon isotopes with a mass number greater than 13 decay by beta emission. Carbon-14 decays by beta emission to produce nitrogen-14.



Carbon-14 has a neutron-to-proton ratio of 8/6 (1.3), which decreases in the product nitrogen-14 to 7/7 (1.0).

**Note:** *Positron emission and electron capture* are competing radioactive decay processes, and what is observed depends on the relative rates of the two processes.

The rate of **electron capture** increases with atomic number of the decaying nuclide and therefore becomes **important in heavier elements**.

**Positron emission** is generally seen **in lighter elements**.

However, in the very heavy elements, especially those with  $Z$  greater than 83, radioactive decay is often **by alpha emission**.

### Example 20.4

### Predicting the Type of Radioactive Decay

Predict the expected type of radioactive decay for each of the following radioactive nuclides: a.  ${}_{20}^{47}\text{Ca}$ ; b.  ${}_{13}^{25}\text{Al}$ .

**Problem Strategy** Compare each nuclide with the stable nuclides of the same element. A nuclide with an  $N/Z$  ratio greater than that of the stable nuclides is expected to exhibit beta emission. A nuclide with an  $N/Z$  ratio less than that of the stable nuclides is expected to exhibit positron emission or electron capture; electron capture is important with heavier elements. Since you are comparing nuclides of the same  $Z$ , you can compare mass numbers ( $= N + Z$ ), rather than  $N/Z$ .

**Solution** a. The atomic mass calcium is 40.1 amu, so you expect calcium-40 to be a stable isotope. Calcium-47 has a mass number greater than that of the stable



isotope, so you expect it to decay by **beta emission**. (This is the observed behavior of calcium-47.)

- b. The atomic mass of aluminum is 27.0 amu, so you expect aluminum-27 to be a stable isotope. The mass number of aluminum-25 is less than 27, so you expect aluminum-25 to decay by either **positron emission or electron capture**. Positron emission is actually observed.

**Answer Check** To answer these types of questions correctly, you must understand how the  $N/Z$  ratio of nuclides determines the type of emission from radioactive nuclides.

**Exercise 20.4** Predict the type of decay expected for each of the following radioactive nuclides: a.  $^{13}_{7}\text{N}$ ; b.  $^{26}_{11}\text{Na}$ .

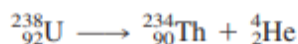
### Radioactive decay Series

All nuclides with atomic numbers greater than  $Z = 83$  are radioactive. Many of these nuclides decay by alpha emission. Alpha particles, or  $^4_2\text{He}$  nuclei are especially stable and are formed in the radioactive nucleus at the moment of decay. Emitting an alpha particle reduces the nucleus's atomic number, becoming more stable. However, if the nucleus has a very large atomic number, the product nucleus is also radioactive.

Natural radioactive elements, such as uranium-238, give a radioactive decay series.

**A radioactive series is a sequence in which one radioactive nucleus decays to a second, which then decays to a third, and so forth.** Eventually, a stable nucleus, an isotope of lead, is reached.

Three radioactive decay series are found naturally. One of these series begins with uranium-238. Figure 3 shows the sequence of nuclear decay processes. In the first step, uranium-238 decays by alpha emission to thorium-234.



Thorium-234 decays by beta emission to protactinium-234, which decays by beta emission to uranium-234. After the decay of protactinium-234 and the formation of uranium-234, there are several alpha-decay steps. The final product of the series is lead-206.

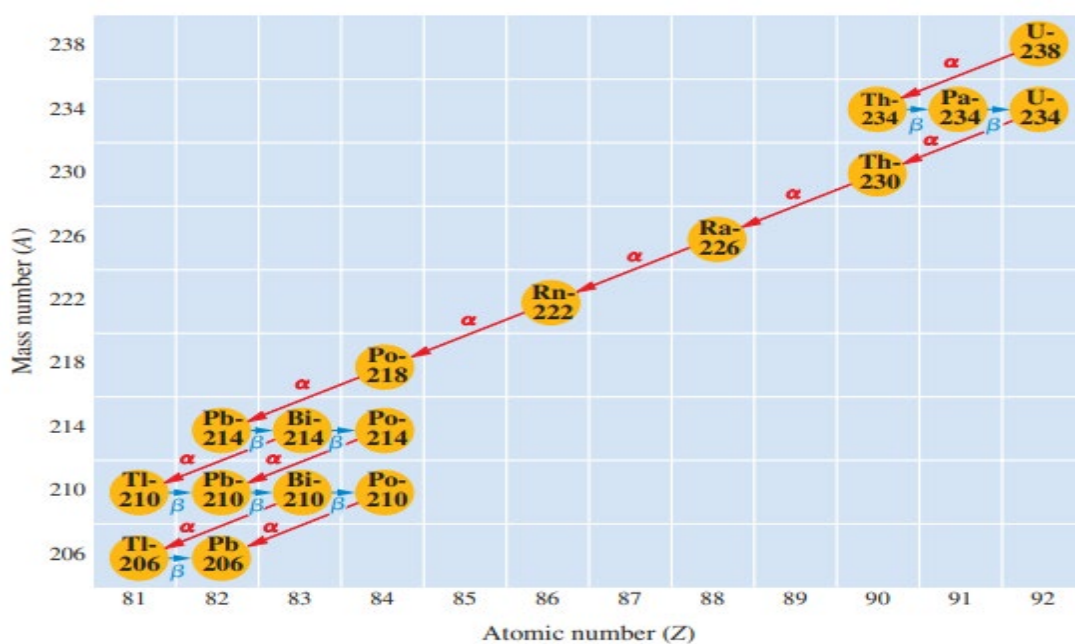
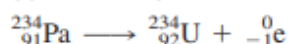
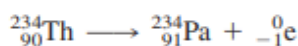


Figure 3: Uranium-238 radioactive decay series

Natural uranium is 99.28%  $^{238}_{92}\text{U}$ , which decays as we have described. However, the natural element also contains 0.72%  $^{235}_{92}\text{U}$ . This isotope starts a *second radioactive decay series, which consists of a sequence of alpha and beta decay, ending with lead-207.*

*The third naturally occurring radioactive decay series begins with thorium-232 and ends with lead-208.*

**All three radioactive decay series found naturally end with an isotope of lead.**

## NUCLEAR BOMBARDMENT

The nuclear reactions discussed in the previous section are radioactive decay reactions, in which a nucleus spontaneously decays to another nucleus and emits a particle, such as an alpha or beta particle.

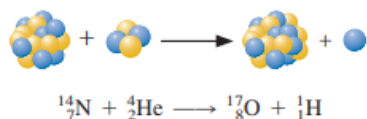
The second type of nuclear reaction is a **nuclear bombardment reaction**, in which a nucleus is bombarded or struck by another nucleus or by a nuclear particle. If there is sufficient energy in this collision, the nuclear particles of the reactants rearrange to give a product nucleus or nuclei.

In 1919, **Ernest Rutherford** discovered that processes that can be controlled in the laboratory can change the nucleus of one element into the nucleus of another element.

### Transmutation

**Transmutation is changing one element to another by bombarding the element's nucleus with nuclear particles or nuclei.**

Rutherford used a radioactive element as a source of alpha particles and allowed these particles to collide with nitrogen nuclei. He discovered that protons are ejected in the process. The equation for the nuclear reaction is given below:

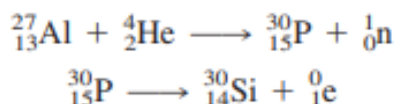


The experiments were repeated on other light nuclei, most of which were transmuted to other elements with the ejection of a proton. These experiments yielded two significant results.

*First, they strengthened the view that all nuclei contain protons.*

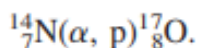
*Second, they showed for the first time that changing one element into another under laboratory control is possible.*

When beryllium is bombarded with alpha particles, penetrating radiation is given off that is not deflected by electric or magnetic fields. The particles are called neutrons. The reaction that resulted in the discovery of the neutron is:



Phosphorus-30 was the first radioactive nucleus produced in the laboratory. Since then, over a thousand radioactive isotopes have been made.

Nuclear bombardment reactions are often referred to by an abbreviated notation. For example, the nuclear reaction below is abbreviated as:

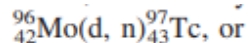


*In this notation, you first write the nuclide symbol for the original nucleus (target). Then, in parentheses, you write the symbol for the projectile particle (incoming particle), followed by a comma and the symbol for the ejected particle. After the last parenthesis, you write the nuclide symbol for the product nucleus.*

The following symbols are used for particles:

Neutron	n
Proton	p
Deuteron, $^2_1\text{H}$	d
Alpha, $^4_2\text{He}$	$\alpha$

Technetium was first prepared by directing deuterons, or nuclei of hydrogen-2 atoms, from a cyclotron to a molybdenum target. The nuclear reaction is:



**Example 20.5****Using the Notation for a Bombardment Reaction**

- a. Write the abbreviated notation for the following bombardment reaction, in which neutrons were first discovered.



- b. Write the nuclear equation for the bombardment reaction denoted  ${}^{27}_{13}\text{Al}(\text{p}, \text{d}){}^{26}_{13}\text{Al}$ .

**Problem Strategy** Understand and use the abbreviated notation and particle symbols for nuclear reactions.

**Solution** a. The notation is  ${}^9_4\text{Be}(\alpha, \text{n}){}^{12}_6\text{C}$ .

- b. The nuclear equation is



**Answer Check** You can check your answers by working backward to see whether they lead to the representations given in the problem.

**Exercise 20.5**

- a. Write the abbreviated notation for the reaction



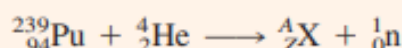
- b. Write the nuclear equation for the bombardment reaction  ${}^{12}_6\text{C}(\text{d}, \text{p}){}^{13}_6\text{C}$ .

**Determining the Product Nucleus in a Nuclear Bombardment Reaction**

Plutonium-239 was bombarded by alpha particles. Each  ${}^{239}_{94}\text{Pu}$  nucleus was struck by one alpha particle and emitted one neutron. What was the product nucleus?

**Problem Strategy** Apply a strategy similar to that used to solve Example 20.2.

**Solution** You can write the nuclear equation as follows:



To balance this equation, write

$$239 + 4 = A + 1 \quad (\text{from superscripts})$$

$$94 + 2 = Z + 0 \quad (\text{from subscripts})$$

Hence,

$$A = 239 + 4 - 1 = 242$$

$$Z = 94 + 2 = 96$$

The product is  ${}^{242}_{96}\text{Cm}$ .

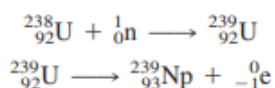
**Answer Check** Be careful in problems like this where the nuclides have coefficients; in those cases, make sure that you count correctly.

**Exercise 20.6** Carbon-14 is produced in the upper atmosphere when a particular nucleus is bombarded with neutrons. A proton is ejected for each nucleus that reacts. What is the identity of the nucleus that produces carbon-14 by this reaction?

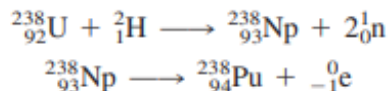
### Trans-uranium Elements

The trans-uranium elements are elements with atomic numbers greater than that of uranium ( $Z = 92$ ), **the naturally occurring element of greatest Z**.

In 1940, E. M. McMillan and P. H. Abelson, at the University of California at Berkeley, discovered the first transuranium element. They produced an isotope of element 93, which they named **neptunium**, by bombarding uranium-238 with neutrons. This gave uranium-239, by the capture of a neutron, and this nucleus decayed in a few days by beta emission to neptunium-239.



The next transuranium element to be discovered was plutonium ( $Z = 94$ ). Deuterons, the positively charged nuclei of hydrogen-2, were accelerated by a cyclotron and directed at a uranium target to give neptunium-238, which decayed to plutonium-238.



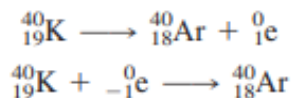
Another isotope of plutonium, plutonium-239, is now produced in large quantities in nuclear reactors, as described in Section 20.7. Plutonium-239 is used for nuclear weapons.

### Applications of Nuclear Radiations

1. Preparation of elements not available naturally, especially the trans-uranium elements.
2. Radioactive decay of a nuclide is constant; this rate can serve as a clock for dating very old rocks and human implements.

**Dating wood and similar carbon-containing objects** that are several thousand to fifty thousand years old can be done with **radioactive carbon, carbon-14, which has a half-life of 5730 y**.

Other similar dating methods have been used to determine the age of rocks and meteorites. One method depends on the radioactivity of naturally occurring **potassium-40**, which decays by positron emission and electron capture (as well as by beta emission).



The **oldest rocks on earth** have been dated at  **$3.8 \times 10^9$  years**, but radio dating and other evidence suggest the earth's age is  **$4.6 \times 10^9$  years**.

3. Some radioisotopes are used as radioactive tracers in chemical analyses.  
*A radioactive tracer is a very small amount of radioactive isotope added to a chemical, biological, or physical system to study the system.*  
The advantage of a radioactive tracer is that it behaves chemically just as a nonradioactive isotope does. Still, it can be detected in exceedingly small amounts by measuring the radiations emitted.
4. Nuclear chemistry is used to analyze elements in a sample using Neutron activation analysis.  
*Neutron activation is the analysis of elements in a sample based on the conversion of stable isotopes to radioactive isotopes by bombarding a sample with neutrons*
5. Radioisotopes, such as radium-226 and its decay product radon-222, are used in medicine to treat cancer.
6. The greatest advances in using radioactive isotopes have been diagnosing disease.

**Technetium-99m** is the radioactive isotope most often used to develop images (pictures) of internal body organs. It has a half-life of 6.02 h and decays by gamma emission to technetium-99 in its nuclear ground state.

**Thallium-201** is a radioisotope used to determine whether a person **has heart disease** (caused by the narrowing of the arteries to the heart).

*More than a hundred different radioactive isotopes have been used in medicine.*

*Besides technetium-99m and thallium-201, other examples include **iodine-131**, used to measure thyroid activity; **phosphorus-32**, used to locate tumours; and **iron-59**, used to measure the rate of formation of red blood cells.*