# Nuclear Chemistry

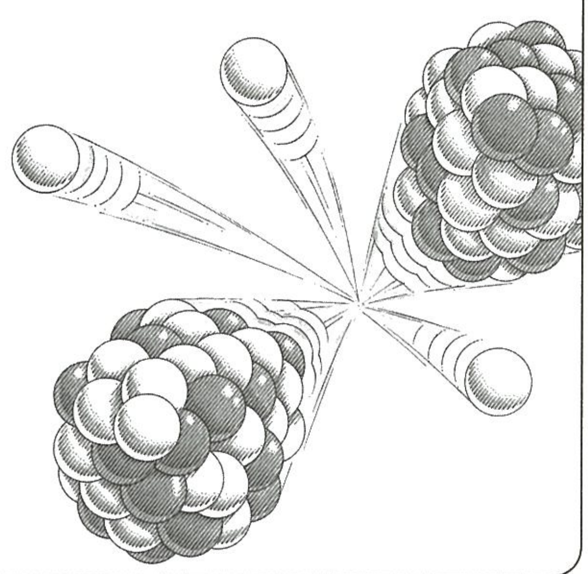
TOPIC 12

## What You Know About Nuclear Chemistry

***Are you ready for a debate?***

Danger! Danger! Nuclear radiation! Or is it so dangerous? In addition to generating power, scientists make daily use of nuclear energy in industry, medicine, and research. As you study this topic, think about the pros and cons of nuclear power.

- **What makes nuclear power unique?**
- **How are nuclear reactions different from ordinary chemical reactions?**
- **Is nuclear chemistry a natural or human-made phenomenon?**
- **What are the uses and dangers of nuclear chemistry?**



# TOPIC 12 Nuclear Chemistry

## Vocabulary

| | | |
|---|---|---|
| alpha particle | fusion | radioisotope |
| artificial transmutation | gamma ray | tracer |
| beta particle | half-life | transmutation |
| fission | natural transmutation | |

## Topic Overview

Most chemical reactions involve either the exchange or sharing of electrons between atoms. Nuclear chemistry is quite different in nature because it involves changes in the nucleus. When the atomic nucleus of one element is changed into the nucleus of a different element, the reaction is called a **transmutation.** In this topic you will study various types of transmutations and learn about properties of radioactive substances.

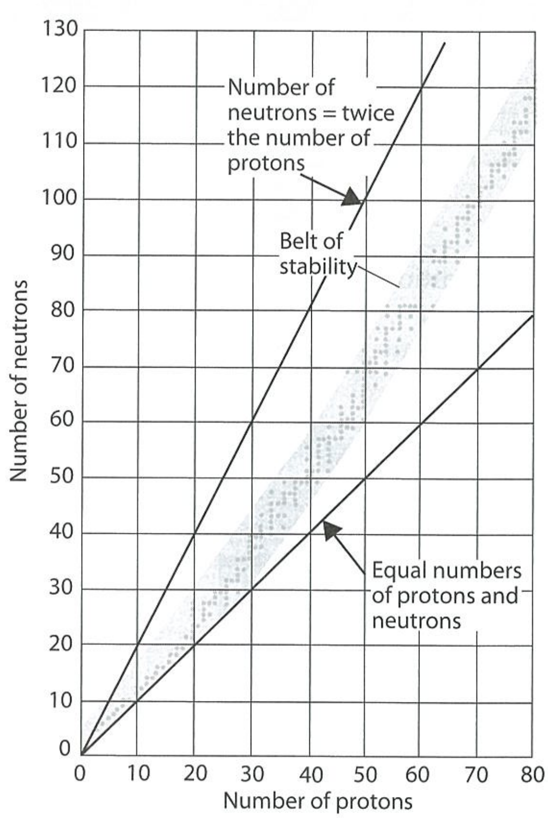



**Figure 12-1. Composition of stable nuclei**

## Stability of Nuclei

Nuclei are composed of combinations of protons and neutrons. Hydrogen, with one proton, is the only element that does not contain one or more neutrons. Most nuclei are stable; that is, they are found within the "belt of stability" shown in Figure 12-1. It is the ratio of neutrons to protons that determines the stability of a given nucleus. The ratio in all nuclei with atomic numbers greater than 83 makes those nuclei unstable.

Because of this instability, all nuclei with atomic numbers greater than 83 are also radioactive, as explained in the next paragraph. For any element, an isotope that is unstable and thus radioactive is called a **radioisotope.**

An unstable nucleus decays in a series of steps which eventually produce a stable nucleus in the belt of stability. When an unstable nucleus decays, it emits radiation in the form of alpha particles, beta particles, positrons, and/or gamma radiation. An **alpha particle** is a helium nucleus composed of two protons and two neutrons. It is represented by the symbol $^{4}_{2}He$ or the symbol $\alpha$, which is the Greek letter alpha. A **beta particle** ($\beta^-$) is an electron whose source is an atomic nucleus, while a positron ($\beta^+$) is identical to an electron except that it has a positive charge. Almost all nuclear decay also releases some energy in the form of **gamma rays** ($\gamma$), which are similar to X rays but have greater energy.

Figure 12-2 shows how alpha particles, beta particles and gamma rays react to an electric field. Table 12-1 summarizes information about each type of radiation.

Radiation can be harmful when it interacts with living things. Serious damage occurs when radioactivity causes ionization of normal tissue. When molecules in a cell are ionized, they may no longer carry on their normal functions and thus may cause the death of the cell. Other interactions of radioactivity with the DNA of a cell may cause mutations to occur. When these mutations occur in sperm or egg cells, they can cause mutations to be transmitted from generation to generation.

## Alpha Decay

When an unstable nucleus emits an alpha particle, the nucleus is called an alpha emitter. Alpha emission is characteristic of heavy nuclei, especially of atoms with atomic numbers greater than 82. As a nucleus emits an alpha particle, its atomic number decreases by two (the two protons of the alpha particle), and its mass number decreases by four (the two protons and two neutrons of the alpha particle). For example, when radium-226 emits an alpha particle, its atomic number decreases by two, from 88 to 86. It is then no longer an atom of radium; it has become an atom of radon (atomic number 86). During the process, the nucleus has lost a total of 4 amu, and the new radon nucleus has a total mass of 222. The alpha decay of radium-226 is shown in Figure 12-3. The process is a transmutation because the atom undergoes a change in its atomic number and becomes a different element.

Alpha decay can be summarized as follows.

- atomic number decreases by two
- number of protons decreases by two
- number of neutrons decreases by two
- mass number decreases by four

## Beta Decay

A nucleus that emits a beta particle as a result of nuclear disintegration is said to undergo beta decay and is called a beta emitter. Beta decay is interpreted as the emission of an

### Memory Jogger

A notation frequently used to show the makeup of a nucleus or subatomic particle uses a superscript before the symbol of the element to show the mass, in amu, of the particle. It also uses a subscript beneath the superscript to show the charge on the particle. For example, $^{35}_{17}Cl$ represents the nucleus of a chlorine atom. It has a mass of 35 amu and a charge of 17+. Note that for an element, the charge equals the atomic number. For a particle such as a beta particle, the symbol $^{0}_{-1}e$ shows that the particle has no appreciable mass and a charge of 1−.

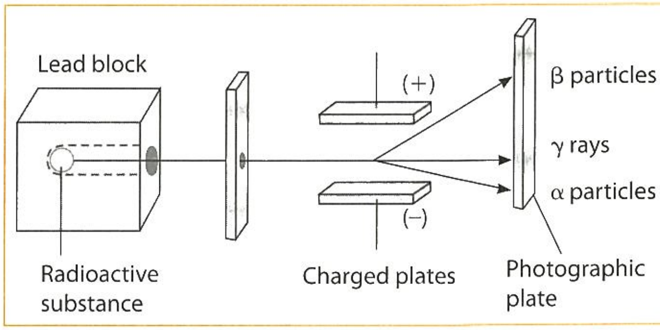
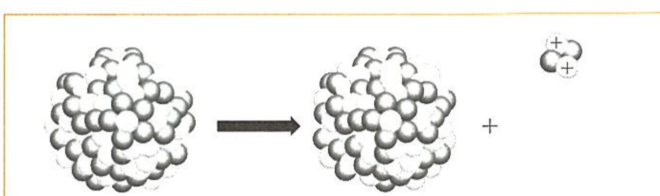



**Figure 12-2. Separation of radioactive emissions:** Because they are positively charged, alpha particles are attracted to the negative plate. Because they are negatively charged, beta particles are attracted to the positively charged plate. Because they have no charge, gamma rays are undeflected in an electrical field. Alpha particles are not deflected as much as beta particles because alpha particles are more massive.

**Table 12-1. Some Common Forms of Radiation**

| Particle | Mass | Charge | Symbol | Penetrating Power |
|---|---|---|---|---|
| Alpha | 4 amu | 2+ | $^{4}_{2}He$, $\alpha$ | low |
| Beta | 0 amu | 1− | $^{0}_{-1}e$, $\beta^-$ | moderate |
| Positron | 0 amu | 1+ | $^{0}_{+1}e$, $\beta^+$ | moderate |
| Gamma | 0 amu | none | $\gamma$ | high |



$$^{226}_{88}Ra \longrightarrow\ ^{222}_{86}Rn + ^{4}_{2}He$$

**Figure 12-3. Alpha decay:** In alpha decay, a nucleus ejects an alpha particle and becomes a smaller nucleus with less positive charge.

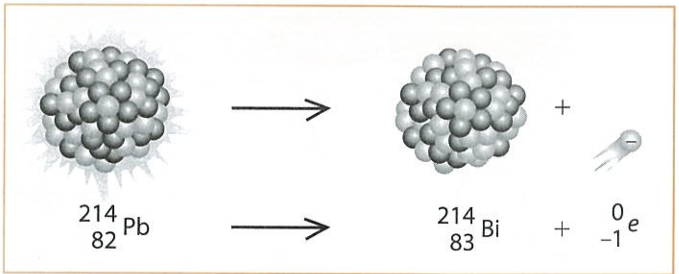



**Figure 12-4. Beta decay:** Beta decay has the effect of turning a neutron in the nucleus into a proton and an electron.

electron during the conversion of a neutron to a proton.

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

When a nucleus emits a beta particle, which has a charge of 1−, the charge on the nucleus increases by one, which also means that the atomic number increases by one. The beta decay of lead-214 to bismuth-214 is shown in Figure 12-4.

Beta decay can be summarized as follows.

- atomic number increases by one
- number of protons increases by one
- number of neutrons decreases by one
- mass number remains the same

### Positron Emission

Positron emission is interpreted as the production of a positron during the conversion of a proton to a neutron.

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

When a nucleus emits a positron, which has a charge of 1+, the charge on the nucleus decreases by one, and thus the atomic number decreases by one. For example the positron emission of potassium-37 to argon-37 is represented by the following equation.

$$^{37}_{19}\mathrm{K} \rightarrow ^{37}_{18}\mathrm{Ar} + ^{0}_{+1}e$$

Positron emission can be summarized as follows.

- atomic number decreases by one
- number of protons decreases by one
- number of neutrons increases by one
- mass number remains the same

**Digging Deeper**

Although positron emission is a natural type of transmutation, there is another reaction that will produce the same result. When a radioactive nucleus captures one of its least energetic electrons, the result is the same as a positron emission.

$$^{37}_{19}\mathrm{K} + ^{0}_{-1}\mathrm{e} \rightarrow ^{37}_{18}\mathrm{Ar}$$

This capture of a low-energy electron is called a K-capture.

## Nuclear Equations

As you have seen in this section, nuclear reactions can be represented by equations. As in chemical equations, mass and charge must balance on both sides of the equation.

For example, the following equation is balanced because the sum of charges and the sum of mass numbers are the same on both sides of the equation. For this equation, the sum of the charges of reactants equals 9 and so does the sum of the charges of the products. The sum of the mass numbers of the reactants is 18, which balances the sum of the mass numbers of the products.

$$^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$$

By using the concept of the conservation of charge and mass number, you can identify a missing particle in an equation.

## SAMPLE PROBLEM

What particle is represented by X in the following equation?

$$^{27}_{13}Al + ^{1}_{0}n \rightarrow ^{24}_{11}Na + X$$

**SOLUTION:** Identify the known and unknown values.

| *Known* | *Unknown* |
|---|---|
| charge and mass numbers for Al, neutron, and Na | identity of X = ? |

**1.** Balance charge on both sides of the equation:

The sum of the charges on the left is 13. Therefore, the sum on the right must also be 13. Na accounts for 11, so X must have a charge of 2.

**2.** Balance mass numbers on both sides of the equation:

The sum of the mass numbers on the left is 28, so the sum on the right must also be 28. Na accounts for 24, so X must have a mass number of 4.

The particle with an atomic number of 2 and a mass number of 4 is the alpha particle ($^{4}_{2}He$). X is an alpha particle.

## Review Questions — Set 12.1

**1.** Which particle has the greatest mass?
(1) an alpha particle (3) an electron
(2) a beta particle (4) a neutron

**2.** In the following equation, which particle is represented by the letter X?

$$^{14}_{6}C \rightarrow ^{14}_{7}N + X$$

(1) an alpha particle (3) a neutron
(2) a beta particle (4) a proton

**3.** Which radioactive emanations have a charge of 2+?
(1) alpha particles (3) gamma rays
(2) beta particles (4) neutrons

**4.** Which species has a negative charge?
(1) a lithium ion (3) an aluminum ion
(2) an alpha particle (4) a beta particle

**5.** According to Reference Table N in the *Reference Tables for Physical Setting/ Chemistry*, a product of the radioactive decay of Ra-226 is
(1) $^{4}_{2}He$ (2) $^{226}_{89}U$ (3) $^{0}_{-1}e$ (4) $^{230}_{90}U$

**6.** Which equation represents nuclear disintegration resulting in release of a beta particle?
(1) $^{220}_{87}Fr + ^{4}_{2}He \rightarrow ^{224}_{89}Ac$
(2) $^{239}_{94}Pu \rightarrow ^{235}_{92}U + ^{4}_{2}He$
(3) $^{32}_{15}P + ^{0}_{-1}e \rightarrow ^{32}_{14}Si$
(4) $^{198}_{79}Au \rightarrow ^{198}_{80}Hg + ^{0}_{-1}e$

**7.** In the nuclear equation $^{232}_{90}Th \rightarrow ^{228}_{88}Ra + X$, the letter X represents
(1) an alpha particle (3) a gamma ray
(2) a beta particle (4) a neutron

**8.** In the reaction $^{238}_{92}U \rightarrow X + ^{4}_{2}He$, the particle represented by X is
(1) $^{234}_{90}Th$ (2) $^{234}_{92}U$ (3) $^{238}_{93}Np$ (4) $^{242}_{94}Pu$

**9.** The notation for the nuclide $^{137}_{55}Cs$ gives information about
(1) mass number, only.
(2) atomic number, only.
(3) both mass number and atomic number.
(4) neither mass number nor atomic number.

10. In which reaction does the letter X represent an alpha particle?

(1) $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + X$ (3) $^{230}_{90}Th \rightarrow ^{230}_{88}Ra + X$

(2) $^{234}_{90}Th \rightarrow ^{235}_{91}Pa + X$ (4) $^{234}_{92}U \rightarrow ^{234}_{90}Th + X$

11. What does the X represent in the following reaction?

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

(1) a released electron
(2) another neutron
(3) energy converted from mass
(4) mass converted from energy

12. Which of the following nuclear reactions is classified as positron decay?

(1) $^{37}_{19}K \rightarrow ^{37}_{18}Ar + ^{0}_{+1}e$ (3) $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He$

(2) $^{42}_{19}K \rightarrow ^{42}_{20}Ca + ^{0}_{-1}e$ (4) $^{3}_{1}H \rightarrow ^{0}_{-1}e + ^{4}_{2}He$

13. Which isotope is represented by the X when the following equation is correctly balanced?

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{1}_{1}H + X$$

(1) $^{17}_{2}O$ (2) $^{17}_{8}O$ (3) $^{17}_{9}F$ (4) $^{19}_{9}F$

14. Which element has no stable isotopes?

(1) $_{27}Co$ (2) $_{51}Sb$ (3) $_{90}Th$ (4) $_{82}Pb$

15. Write balanced nuclear equations for each of the following:

(a) beta decay of Pb-210
(b) beta decay of Cs-137
(c) alpha decay of Rn-222
(d) alpha decay of Au-185
(e) positron emission of Fe-53
(f) positron emission of Ca-37

## Transmutations

Nuclear reactions can be either naturally occurring or artificial. Alpha, beta, and positron decay are **natural transmutations** that occur as a result of unstable neutron-to-proton ratios. When bombarding the nucleus with high-energy particles brings about the change, the process is given the name of **artificial transmutation.** Scientists in research and commercial settings perform artificial transmutations.

**Types of Transmutations** There are two types of artificial transmutations. The first type involves the collision of a charged particle with a target nucleus. If charged particles such as protons or alpha particles are to react with atomic nuclei, they must have sufficient energy to overcome the repulsive forces that exist between positively charged objects. Scientists can supply this energy by accelerating charged particles in devices called cyclotrons and synchrotrons, which use magnetic or electrostatic fields to speed up protons and other charged particles.

A second type of artificial transmutation occurs when a neutron collides with a target nucleus. Neutrons can be obtained as by-products of nuclear reactors similar to those used to generate electricity. Because the neutron does not possess a charge, it is not repelled by the target nucleus and can be captured by the "strong" force that holds protons and neutrons in the nucleus. These reactions are used to prepare radioactive nuclei from stable nuclei. Listed below are a few examples.

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U$$

$$^{59}_{27}Co + ^{1}_{0}n \rightarrow ^{60}_{27}Co$$

$$^{32}_{16}S + ^{1}_{0}n \rightarrow ^{32}_{15}P + ^{1}_{1}H$$

It is easy to tell the difference between natural and artificial transmutation. Natural transmutation consists of a single nucleus undergoing decay. Artificial transmutation will have two reactants, a fast-moving particle and a target material.

## Review Questions Set 12.2

16. The nuclear reaction

$$^{4}_{2}He + ^{27}_{13}Al \rightarrow ^{30}_{15}P + ^{1}_{0}n$$

is an example of

(1) nuclear fusion
(2) nuclear fission
(3) natural transmutation
(4) artificial transmutation

17. Which particle is represented by X in the following transmutation?

$$^{234}_{90}Th \rightarrow ^{234}_{91}Pa + X$$

(1) $^{0}_{-1}e$ (2) $^{4}_{2}He$ (3) $^{1}_{1}H$ (4) $^{0}_{+1}e$

18. Which equation represents a nuclear reaction that is an example of an artificial transmutation?

(1) $^{43}_{21}Sc \rightarrow ^{43}_{20}Ca + ^{0}_{+1}e$
(2) $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$
(3) $^{10}_{4}Be \rightarrow ^{10}_{5}B + ^{0}_{-1}e$
(4) $^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$

19. Which particle is represented by X in the following transmutation?

$$^{131}_{53}I \rightarrow ^{131}_{54}Xe + X$$

(1) alpha (2) beta (3) neutron (4) proton

20. What is the charge of the element represented by X in the following transmutation?

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + X + 3\,^{1}_{0}n$$

(1) 36 (2) 89 (3) 92 (4) 93

21. Which species is represented by X in the following transmutation?

$$^{9}_{4}Be + ^{1}_{1}H \rightarrow ^{4}_{2}He + X$$

(1) $^{8}_{3}Li$ (2) $^{6}_{3}Li$ (3) $^{8}_{5}B$ (4) $^{10}_{5}B$

22. Which species is represented by X in the following transmutation?

$$^{7}_{3}Li + X \rightarrow ^{8}_{4}Be$$

(1) $^{1}_{1}H$ (2) $^{2}_{1}H$ (3) $^{3}_{2}He$ (4) $^{4}_{2}He$

23. What is the identity of particle X in the following transmutation?

$$^{9}_{4}Be + X \rightarrow ^{6}_{3}Li + ^{4}_{2}He$$

(1) $^{1}_{1}H$ (2) $^{2}_{1}H$ (3) $^{0}_{-1}e$ (4) $^{1}_{0}n$

## Fission and Fusion

A **fission** reaction involves the splitting of a heavy nucleus to produce lighter nuclei. A **fusion** reaction involves the combining of light nuclei to produce a heavier nucleus. In both types of reactions, the total mass of the products is less than the total nuclear mass of the reactants.

### Conversion of Matter to Energy

At first glance this loss of mass seems to contradict our concept that matter (mass) can neither be created nor destroyed. Properly expressed, the law states that the total amount of matter and energy cannot be destroyed. The loss of mass in these nuclear reactions represents a conversion of some matter into energy. The relationship was expressed by Albert Einstein in his famous equation

$$E = mc^2$$

where $E$ is energy, $m$ is mass, and c is the speed of light, which is $3.00 \times 10^8$ m/s. Because the speed of light is such a large number, you can see that the conversion of a minute amount of matter produces an extremely large amount of energy.

The energy produced by nuclear reactions is far greater than that of ordinary chemical reactions. The conversion of 1.00 g of matter into energy yields $9.00 \times 10^{13}$ J. When 1.00 g of methane is burned in an ordinary chemical reaction, there is a release of $5.56 \times 10^4$ J of energy.

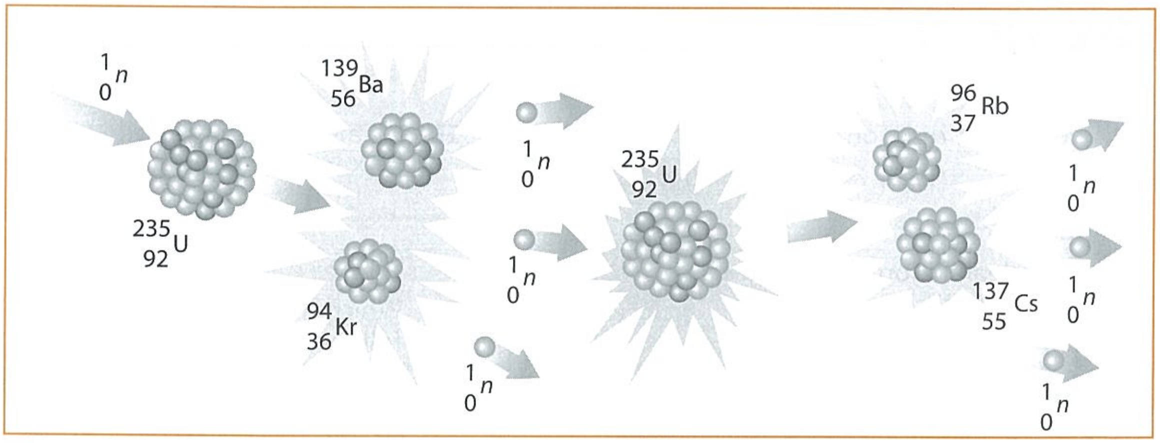



**Figure 12-5. Fission:** Fission involves the splitting of a large nucleus into middle-weight nuclei and neutrons.

Gram for gram, the nuclear reaction gives off over a billion times as much energy.

This conversion of matter into energy occurs when protons and neutrons are combined into nuclei. The total mass of the nucleus is less than the sum of the masses of the individual protons and neutrons. The matter that has been converted into energy is called the mass defect.

## Fission Reactions

A fission reaction begins with the capture of a neutron by the nucleus of a heavy element such as uranium-235 or plutonium-239. The nucleus produced by the capture is unstable. It immediately splits, undergoing the process of fission. The products of fission are two middle-weight nuclei, one or more neutrons, and a large amount of energy. A small amount of matter from the original atom of uranium or plutonium is converted into energy.

$$ {}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}n + \text{energy} $$

The products shown in this equation are only two of more than 200 different radioactive products that may be produced by the fission process. Some other possible products are shown in Figure 12-5.

## Fusion Reactions

Fusion reactions involve the combining of light nuclei to form heavier ones. The most common example of fusion occurs in the sun where hydrogen nuclei react in a series to produce helium nuclei. These fusion reactions produce the huge amounts of energy released by the sun. One of the possible series of reactions involving the fusion of hydrogen nuclei to form helium and release energy is given by the following sequence.

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{+1}e $$

$$ {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} $$

$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} $$

$$ {}^{3}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{0}_{+1}e $$

While these reactions produce the energy from the sun, they are not yet available to produce energy here on Earth. Extremely high temperatures and pressures are needed to allow the positively charged hydrogen nuclei to fuse into helium. When methods are developed that will contain a reaction such as these and make it practical, an important new energy source will have been developed. One major advantage of fusion as an energy source is that the products are not highly radioactive, like the products of fission reactions.

## Review Questions — Set 12.3

**24.** High energy is a requirement for fusion reactions to occur because the nuclei involved

(1) attract each other because they have like charges
(2) attract each other because they have unlike charges
(3) repel each other because they have like charges
(4) repel each other because they have unlike charges

**25.** When a uranium nucleus breaks up into fragments, which type of nuclear reaction occurs?

(1) fusion
(2) fission
(3) replacement
(4) redox

**26.** Which pair of nuclei can undergo a fusion reaction?

(1) potassium-40 and cadmium-113
(2) zinc-64 and calcium-44
(3) uranium-238 and lead-208
(4) hydrogen-2 and hydrogen-3

**27.** What process is represented by the following reaction?

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + \text{energy}$$

(1) fission
(2) fusion
(3) artificial transmutation
(4) alpha decay

**28.** During a fission reaction, which type of particle is captured by a nucleus?

(1) deuteron
(2) electron
(3) neutron
(4) proton

**29.** What is the primary result of a fission reaction?

(1) conversion of mass to energy
(2) conversion of energy to mass
(3) binding together of two heavy nuclei
(4) binding together of two light nuclei

**30.** Compared to an ordinary chemical reaction, a fission reaction will

(1) release smaller amounts of energy
(2) release larger amounts of energy
(3) absorb smaller amounts of energy
(4) absorb larger amounts of energy

**31.** Which type of reaction produces energy and intensely radioactive waste products?

(1) fusion of tritium and deuterium
(2) fission of uranium
(3) burning of heating oil
(4) burning of wood

**32.** Which process occurs in a controlled fusion reaction?

(1) Light nuclei collide to produce heavier nuclei.
(2) Heavy nuclei collide to produce lighter nuclei.
(3) Neutron bombardment splits light nuclei.
(4) Neutron bombardment splits heavy nuclei.

**33.** Consider this reaction.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{138}_{56}Ba + ^{95}_{36}Kr + 3\,^{1}_{0}n + \text{energy}$$

This equation can best be described as

(1) fission
(2) fusion
(3) natural decay
(4) endothermic

## Half-Life

Radioactive substances decay at a constant rate that is not dependent on factors such as temperature, pressure, or concentration. It is also a random event. That is, it is impossible to predict when a given unstable nucleus will decay. However, the number of unstable nuclei that will decay in a given time in a sample of the element can be predicted. The time it takes for half of the atoms in a given sample of an element to decay is called the **half-life** of the element. Each isotope has its own half-life. The shorter the half-life of an isotope, the less stable it is. Table N in *Reference Tables for Physical Setting/Chemistry* lists various isotopes together with their half-lives and the mode by which they decay. Figure 12-6 shows the decay of carbon-14.

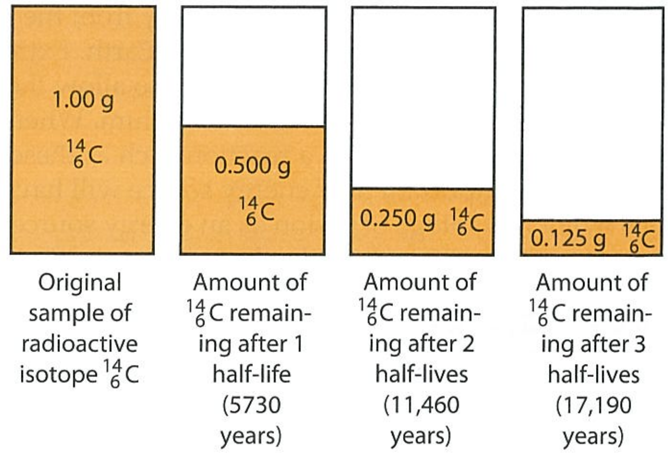



**Figure 12-6. The half-life of C-14**

If radioactive substance X has a half-life of 5 s, each five seconds will result in the amount of X present at the beginning of the time being reduced by half. If 20 g of X begins to decay, after 5 s only 10 g will remain. Five seconds later, only 5 g of the original 20 g will remain. $(1/2 \times 1/2 = 1/4)$. The fraction remaining after a given number of half-lives is calculated using the relationship

$$\text{fraction remaining} = (1/2)^n$$

where $n$ is equal to the number of half-lives. The number of half-lives is calculated by dividing the total time that the substance has decayed by the half-life of the isotope.

## SAMPLE PROBLEM

Most chromium atoms are stable, but Cr-51 is an unstable isotope with a half-life of 28 days.

**(a)** What fraction of a sample of Cr-51 will remain after 168 days?

**(b)** If a sample of Cr-51 has an original mass of 52.0 g, what mass will remain after 168 days?

**SOLUTION:** Identify the known and unknown values.

| Known | Unknown |
|---|---|
| half-life of Cr-51 = 28 days | fraction of Cr-51 remaining after 168 days = ? |
| time = 168 days | mass of Cr-51 remaining after 168 days = ? g |
| original mass = 52.0 g | |

**1.** Determine how many half-lives elapse during 168 days.

$$\text{Number of half-lives} = \frac{\text{time elapsed (t)}}{\text{half-life (T)}} = \frac{168 \text{ days}}{28 \text{ days/half-life}} = 6 \text{ half-lives}$$

**2.** Calculate the fraction remaining.

$$\text{Fraction remaining} = (1/2)^{t/T} = (1/2)^6 = 1/64$$

The fraction of Cr-51 remaining after 168 days will be 1/64 of the original.

**3.** Calculate the mass remaining.

$$\text{mass remaining} = \text{original mass} \times \text{fraction remaining} = 52.0 \text{ g} \times 1/64 = 0.813 \text{ g}$$

Mass remaining can also be calculated by dividing the current mass by 2 at the end of each half-life.

After 1 half-life, mass = 52.0 g/2 = 26.0 g
After 2 half-lives, mass = 26.0 g/2 = 13.0 g
After 3 half-lives, mass = 13.0 g/2 = 6.50 g
After 4 half-lives, mass = 6.50 g/2 = 3.25 g
After 5 half-lives, mass = 3.25 g/2 = 1.63 g
After 6 half-lives, mass = 1.63 g/2 = 0.815 g

## SAMPLE PROBLEM

How much was present originally in a sample of Cr-51 if 0.75 mg remains after 168 days?

**SOLUTION:** Identify the known and unknown values.

| *Known* | *Unknown* |
|---|---|
| half-life of Cr-51 = 28 days | original mass = ? g |
| time = 168 days | |
| final mass = 0.75 mg | |

From the previous sample problem, 168 days represents 6 half-life periods for Cr-51. The sample will double for each half-life period. Multiply the remaining amount by a factor of 2 for each half-life.

$$\text{original mass} = \text{final mass} \times 2^n$$
$$= 0.75 \text{ mg} \times 2^6$$
$$= 48 \text{ mg}$$

The initial amount of a substance can be determined from the half-life, the amount remaining, and the time passed. When determining an original amount, each half-life represents a doubling of the amount present.

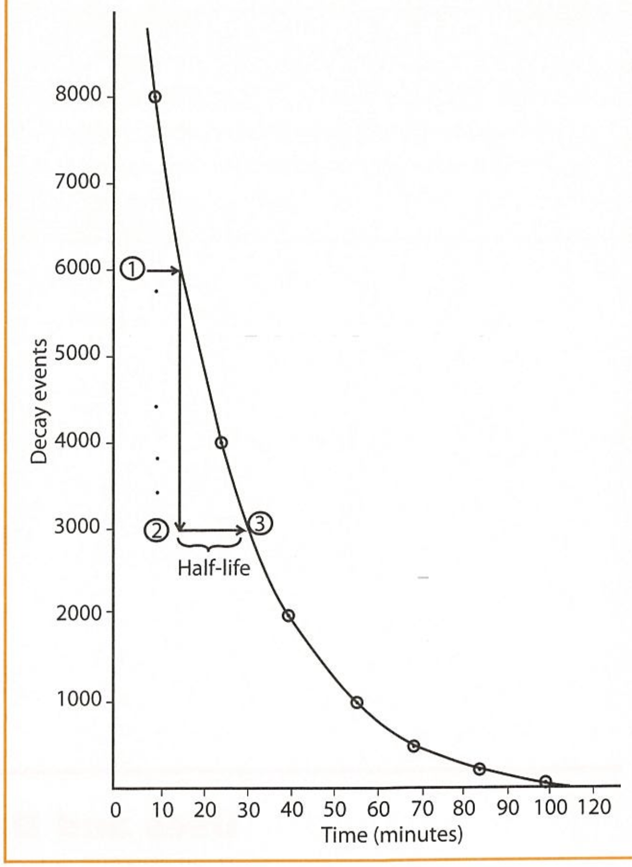



**Figure 12-7. A hypothetical half-life**

**Graphing Half-Life Data** As a radioactive substance decays, a Geiger counter can be used to record the individual decay events. When this data is graphed, it provides a way to measure the half-life of an isotope. Figure 12-7 is a graph of the data of the decay of a hypothetical radioisotope. To determine the half-life, select a convenient count on the $y$-axis (1). Draw a vertical line to a value of half of the original (2). In this case the line extends from 6000 counts to 3000 counts. The half-life is represented by the time segment on the $x$-axis (2 to 3), or 15 minutes. It does not matter where you begin, the half-life will still be the same. Simply draw a line to reduce the count by half, and then read the half-life.

## Review Questions — Set 12.4

**Refer to Table N in *Reference Tables for Physical Setting/Chemistry* for half-life values as needed.**

**34.** After 62.0 hours, 1.0 g remains unchanged from a sample of $^{42}$K. How much $^{42}$K was in the original sample?

(1) 8.0 g (2) 16 g (3) 32 g (4) 64 g

**35.** If 80 mg of a radioactive element decays to 10 mg in 30 min, what is the element's half-life in minutes?

(1) 10 (2) 20 (3) 30 (4) 40

**36.** In 6.20 h, a 100.-g sample of Ag-112 decays to 25.0 g. What is the half-life of Ag-112?

(1) 1.60 h (2) 3.10 h (3) 6.20 h (4) 12.4 h

**37.** Which of the following 10-g samples of a radioisotope will decay to the greatest extent in 28 days?

(1) P-32 (2) Kr-85 (3) Fr-220 (4) I-131

**38.** How many hours are required for potassium-42 to undergo three half-life periods?

(1) 6.2 h (2) 12.4 h (3) 24.8 h (4) 37.2 h

39. What is the mass of K-42 remaining in a 16-g sample of K-42 after 37.2 h?

(1) 1.0 g (2) 2.0 g (3) 8.0 g (4) 4.0 g

40. If 3.0 g of Sr-90 in a rock sample remained in 1999, approximately how many grams of Sr-90 were present in the original rock sample in 1943?

(1) 9.0 g (2) 6.0 g (3) 3.0 g (4) 12 g

41. A sample of I-131 decays to 1.0 g in 40 days. What was the mass of the original sample?

(1) 8.0 g (2) 16 g (3) 32 g (4) 4.0 g

42. What is the total mass of Rn-222 remaining in an original 160-mg sample of Rn-222 after 19.1 days?

(1) 2.5 mg (2) 5.0 mg (3) 10 mg (4) 20 mg

43. Which radioactive sample would contain the greatest remaining mass of the radioactive isotope after 10 years?

(1) 2.0 grams of Au-198
(2) 2.0 grams of K-42
(3) 4.0 grams of P-32
(4) 4.0 grams of Co-60

44. A radioactive element has a half-life of 2 days. Which fraction represents the amount of an original sample of this element remaining after 6 days?

(1) $\frac{1}{8}$
(2) $\frac{1}{2}$
(3) $\frac{1}{3}$
(4) $\frac{1}{4}$

45. Which of the following radioisotopes has the shortest half-life?

(1) $^{14}C$
(2) $^{3}H$
(3) $^{37}K$
(4) $^{32}P$

46. As the temperature of a sample of a radioactive element decreases, the half-life of the element

(1) decreases
(2) increases
(3) remains the same
(4) varies with the pressure

47. If one-eighth of the mass of the original sample of a radioisotope remains unchanged after 4800 years, the isotope could be

(1) H-3
(2) K-42
(3) Sr-90
(4) Ra-226

## Uses and Dangers of Radioisotopes

Radioisotopes have many practical applications in industry, medicine, and research. They also have potential dangers because of harm that could be done by the radiation released.

### Uses of Radioisotopes

The following applications represent just a few of the many uses of radioisotopes. Although they must be used with proper precautions, certain radioisotopes provide information that could not be determined from isotopes that are not radioactive.

**Dating** Carbon-14 is perhaps best known for its use in dating previously living materials. There is an extremely small amount of C-14 in the atmosphere. When an organism is alive, it uses this radioactive carbon in the same way as it uses stable C-12. When the organism dies, it no longer takes in any carbon.

Each gram of carbon in a living organism emits about 15 disintegrations per minute (dpm). After the organism dies and time passes, the radioactive C-14 continues to decay, but it is not replaced. Therefore the dpm decreases with time. Because the half-life of C-14 is 5730 years, after that time period there will only be about 7 dpm for each gram of carbon in the organism. Therefore, a reading of 7 dpm/g carbon indicates the remains are about 5700 years old, while a reading of 3.5 dpm would show a material to be about twice as old, about 11,000 years. After about four half-lives, C-14 becomes ineffective as a method for dating materials because too little C-14 remains to be accurately measured.

U-238 is a radioactive material that spontaneously decays through a series of steps until it forms stable Pb-206. As time passes, the amount of lead in the sample will increase as the amount of uranium decreases. Scientists can use the ratio of U-238/Pb-206 to date rocks and other geological formations.

**Chemical Tracers** The ability to detect radioactive materials and their decay products makes it possible to determine their presence or absence in a substance. Any radioisotope used to follow the path of a material in a system is called a **tracer.** If radioactive P-31 is present in fertilizer administered to a plant, the uptake of the phosphorus can be traced by detectors. Scientists can then determine the proper amounts and timing of fertilizer applications. C-14 is another tracer used to map the path of carbon in metabolic processes.

**Industrial Applications** Radioactive isotopes and gamma rays are absorbed in varying amounts by different materials. The thicker the material, the more radiation that will be absorbed. Thus, radiation products can be used to measure the thickness of materials such as a plastic wrap or aluminum foil or to test the strength of a weld.

**Medical Applications** Certain radioisotopes that are quickly eliminated from the body and have short half-lives are important as tracers in medical diagnosis. Many are also used in treatment of various disorders and diseases. Others might be used to make materials free from bacteria or other disease-causing organisms.

I-131 has uses both in the detection and treatment of thyroid conditions. Because iodine accumulates in the thyroid gland, small amounts of I-131 can be administered to a patient and a radiogram made of the thyroid to diagnose a disorder. When a person has an overactive thyroid (hyperthyroidism), I-131 can be given in large enough doses to destroy some of the thyroid and reduce its production of thyroxin.

Cobalt-60 emits large amounts of gamma radiation as it decays. These rays can be aimed at cancerous tumors. The rapidly growing cells of the tumor are more likely to be killed than normal cells by the gamma rays.

Intense beams of gamma radiation can be used to irradiate foods to kill bacteria. Certain types of foods, such as spices, are irradiated on a regular basis. Irradiation of produce and meats has also been approved in many locations. By killing the bacteria present, the food lasts longer without spoiling and causes fewer bacterial infections in those who consume it. Other destruction of bacteria by radiation is also important. Co-60 and Cs-137 are two of the sources of gamma radiation currently being used to destroy anthrax bacilli.

Technetium, atomic number 43, is a radioactive element that is rapidly absorbed by cancerous cells. When Tc-99 is given to patients with cancerous tumors, it accumulates in the tumor and can easily be detected by a scan. When radioisotopes are used for diagnostic purposes, it is advantageous if they have a short half-life and are quickly eliminated by the body so that they do not damage healthy tissue.

## Radiation Risks

The uses of radiation are not without risks. While radioisotopes can be used to kill cancerous cells, they also have the potential of damaging normal tissue. High doses of radiation can cause serious illness and death. Radiation can cause mutations that could potentially be passed from generation to generation.

Nuclear power plants are a particular problem. After the fuel rods no longer have enough uranium to make them useful in the reactor, they contain many decay products, many with long half-lives. It is difficult to store and dispose of these waste products.

Of major concern to many people is the overall safety issue of nuclear power plants themselves. While the plants are designed to protect the public, there is still a danger of a nuclear accident that might release radioactivity into the air or water. The 1986 accident at Chernobyl in Ukraine destroyed farmland that will probably be unusable for generations.

## Review Questions — Set 12.5

**48.** Which radioisotope is used for diagnosing thyroid disorders?

(1) cobalt-60
(2) uranium-238
(3) lead-206
(4) iodine-131

**49.** Which procedure is based on the half-life of a radioisotope?

(1) accelerating to increase kinetic energy
(2) radiation to kill cancer cells
(3) counting to determine a level of radioactivity
(4) dating to determine age

**50.** Radiated food can be safely stored for a longer time because radiation

(1) prevents air oxidation
(2) prevents air reduction
(3) kills bacteria
(4) causes bacteria to mutate

**51.** A radioactive-dating procedure to determine the age of a mineral compares the mineral's remaining amounts of U-238 and the isotope

(1) Pb-206
(2) Bi-206
(3) Pb-214
(4) Bi-214

**52.** Which isotopic ratio needs to be determined when the age of ancient wooden objects is investigated?

(1) U-235 to U-238
(2) H-2 to H-3
(3) N-16 to N-14
(4) C-14 to C-12

**53.** Which two characteristics do radioisotopes have that are useful in medical diagnosis?

(1) long half-lives and slow elimination from the body
(2) long half-lives and quick elimination from the body
(3) short half-lives and slow elimination from the body
(4) short half-lives and quick elimination from the body

**54.** A radioisotope is called a tracer when it is used to

(1) kill bacteria
(2) kill cancerous tissue
(3) determine the age of animal skeletal remains
(4) determine the path of an element in an organism

**55.** Which radioactive isotope is used in geological dating?

(1) U-238 (2) I-131 (3) Co-60 (4) Tc-99

**56.** Which isotope can be used as a tracer to study the age of organic material?

(1) C-12 (2) C-14 (3) Sr-88 (4) Sr-90

**57.** Brain tumors can be located by using an isotope of

(1) C-14 (2) I-131 (3) Tc-99 (4) U-238

# Practice Questions for the New York Regents Exam

TOPIC 12

**Directions**
Review the Test–Taking Strategies section of this book. Then answer the following questions. Read each question carefully and answer with a correct choice or response.

## Part A

1 Samples of elements that are radioactive must contain atoms
(1) with stable nuclei
(2) with unstable nuclei
(3) in the excited state
(4) in the ground state

2 Organic molecules react to form a product. These reactions can be studied using
(1) Sr-90 (2) Co-60 (3) N-16 (4) C-14

3 Radiation used in the processing of food is intended to
(1) increase the rate of nutrient decomposition
(2) kill microorganisms that are found in food
(3) convert ordinary nutrients to more stable forms
(4) replace chemical energy with nuclear energy

4 The age of certain minerals can be determined if they contain the nuclide
(1) P-32 (3) U-238
(2) Co-60 (4) Au-198

5 The course of a chemical reaction can be traced by using a
(1) polar molecule (3) stable isotope
(2) diatomic molecule (4) radioisotope

6 Bombarding a nucleus with high-energy particles that change it from one element into another is called
(1) a half-reaction
(2) a breeder reaction
(3) artificial transmutation
(4) natural transmutation

7 An alpha decay results in the formation of a new element with the atomic number
(1) increased by two (3) decreased by two
(2) increased by four (4) decreased by four

8 When a radioactive nucleus emits a beta particle, the atom's
(1) mass number is increased by 1
(2) mass number is decreased by 1
(3) atomic number is increased by 1
(4) atomic number is decreased by 1

9 As the temperature increases, pressure remaining constant, the half-life of a radioactive element
(1) decreases (3) remains the same
(2) increases (4) depends on the mass

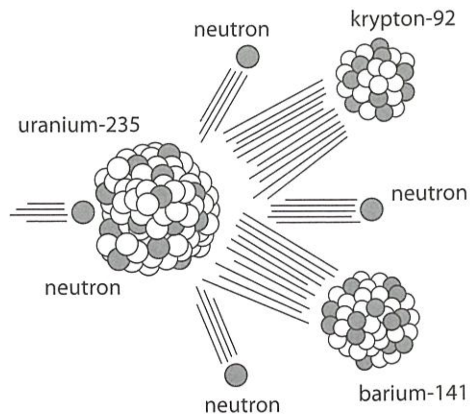
10 Which of the following is not deflected by an electric field?
(1) alpha (3) positron
(2) beta (4) gamma ray

## Part B–1

11 Which statement explains why fusion reactions are difficult to initiate?
(1) Positive nuclei attract each other.
(2) Positive nuclei repel each other.
(3) Neutrons prevent nuclei from getting close enough to fuse.
(4) Electrons prevent nuclei from getting close enough to fuse.

12 Which particle has the greatest chance of overcoming the electrostatic forces surrounding the nucleus of an atom?
(1) an alpha particle (3) a proton
(2) a beta particle (4) a neutron

13 The diagram below shows a nuclear reaction in which a neutron is captured by a heavy nucleus. Which type of reaction is illustrated by the diagram?




(1) an endothermic fission reaction
(2) an exothermic fission reaction
(3) an endothermic fusion reaction
(4) an exothermic fusion reaction

14 Given the balanced equation representing a nuclear reaction:

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

Which phrase identifies and describes this reaction?

(1) fission, mass converted to energy
(2) fission, energy converted to mass
(3) fusion, mass converted to energy
(4) fusion, energy converted to mass

15 Consider this reaction.

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + ^{1}_{0}n$$

This reaction can best be described as

(1) beta decay
(2) artificial transmutation
(3) fission
(4) fusion

16 When I-131 undergoes radioactive decay, which element is formed?

(1) Te-132
(2) Xe-131
(3) I-130
(4) Sb-127

17 Which is a gaseous radioactive waste product that is released into the atmosphere after it has decayed to a safe radiation level?

(1) radon-222
(2) radium-226
(3) cesium-137
(4) cobalt-60

18 Which particle is represented by X in the following correctly balanced nuclear equation?

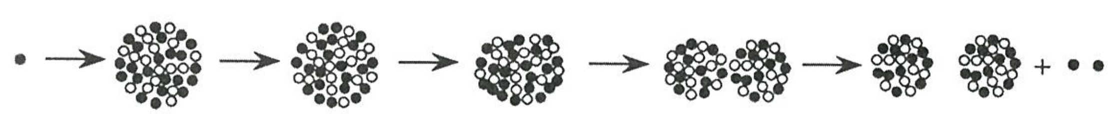
$$^{12}_{6}C + ^{249}_{98}Cf \rightarrow ^{257}_{104}Unq + 4X$$

(1) $^{14}_{7}H$ (2) $^{1}_{0}n$ (3) $^{4}_{2}He$ (4) $^{0}_{-1}e$

19 The diagram below shows a nuclear reaction in which a neutron is captured by a heavy nucleus.

Which type of reaction is illustrated by the diagram?

(1) an endothermic fission reaction
(2) an exothermic fission reaction
(3) an endothermic fusion reaction
(4) an exothermic fusion reaction




20 In which list can all particles be accelerated by an electric field?

(1) alpha particles, beta particles, and neutrons
(2) alpha particles, beta particles, and protons
(3) alpha particles, protons, and neutrons
(4) beta particles, protons, and neutrons

21 In which process is mass converted to energy by the process of fission?

(1) $^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$
(2) $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{87}_{35}Br + ^{146}_{57}La + 3^{1}_{0}n$
(3) $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He$
(4) $^{2}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He$

22 Energy is released during the fission of Pu-239 atoms as a result of the

(1) formation of covalent bonds.
(2) formation of ionic bonds.
(3) conversion of matter to energy.
(4) conversion of energy to matter.

23 Atoms of I-131 spontaneously decay when the

(1) stable nuclei emit alpha particles.
(2) stable nuclei emit beta particles.
(3) unstable nuclei emit alpha particles.
(4) unstable nuclei emit beta particles.

## Parts B–2 and C

**Base your answers to questions 24 through 26 on the information below.**

When a uranium-235 nucleus absorbs a slow moving neutron, different nuclear reactions may occur. One of these possible reactions is represented by the complete, balanced equation below.

Eq. 1: $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{36}Kr + ^{142}_{56}Ba + 2^{1}_{0}n + \text{energy}$

For this reaction, the sum of the masses of the products is slightly less than the sum of the masses of the reactants. Another possible reaction of U-235 is represented by the incomplete, balanced equation below.

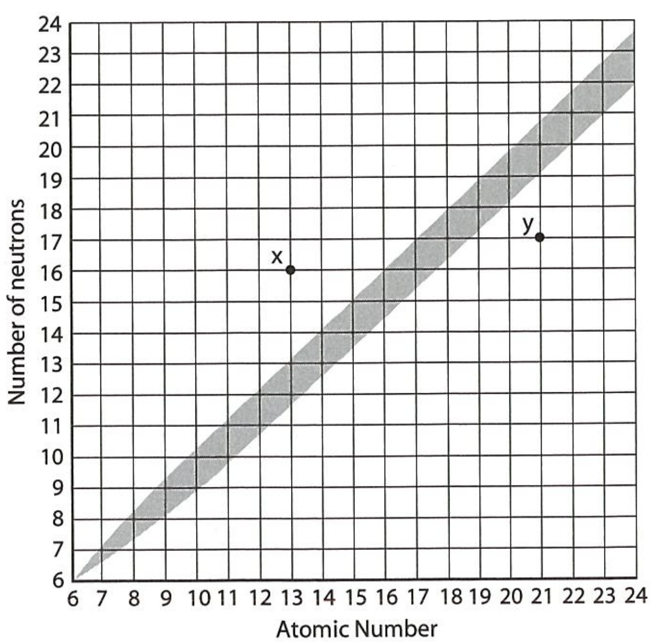
Eq. 2: $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{38}Sr + \_\_\_\_ + 2^{1}_{0}n + \text{energy}$

24 Identify the type of nuclear reaction represented by equation 1.

25 Write a notation for the missing product in equation 2.

26 The half-life of Kr-92 is known to be 1.84 sec. If 6.0 milligrams remain after 7.36 seconds, what was the original mass of a sample of this isotope?

**Base your answers to questions 27 through 29 on the graph below which depicts the zone of stability for elements 6–24.**




27 Identify the nuclide located at position "x" on the graph. Include the mass and nuclear charge values.

28 Plot the point representing the product formed from the beta decay of particle "x".

29 Write a positron decay equation for the particle located at position "y". Include masses and nuclear charge values for all particles.

**Base your answers to questions 30 and 31 on the information below.**

In 1955 a team of scientists at the University of California produced a new element by bombarding an Es-253 target with accelerated alpha particles using a cyclotron. The collision of the einsteinium-253 isotope with the alpha particles caused an artificial transmutation in which the new element was produced along with a neutron.

30 Write a nuclear equation that accurately describes the transmutation that took place. Be sure to include the identity of the new element as well as mass and charge values for each particle.

31 The newly discovered element was found to decay at a rate such that a 1.00 milligram sample was reduced to 0.125 milligrams in a period of 3.81 hours. Determine the half-life of the new element.

**Base your answers to questions 32 through 35 on the following.**

Given the nuclear equation:

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

32 State the type of nuclear reaction represented by the equation.

33 The sum of the masses of the products is slightly less than the sum of the masses of the reactants. Explain this loss of mass.

34 This process releases greater energy than an ordinary chemical reaction does. Name another type of nuclear reaction that releases greater energy than an ordinary chemical reaction.

35 Explain how exposure to the products of this reaction can be harmful to humans.

**Base your answers to questions 36 and 37 on the information below.**

In living organisms, the ratio of the naturally occurring isotopes of carbon, C-12 to C-13 to C-14 is fairly consistent. When an organism such as a woolly mammoth died, it stopped taking in carbon, and the amount of C-14 present in the mammoth began to decrease. For example, one fossil of a woolly mammoth is found to have 1/32 of the amount of C-14 found in living organisms.

**36** Identify the type of nuclear reaction that caused the amount of C-14 in the woolly mammoth to decrease after the organism died.

**37** Determine the total time that has elapsed since this woolly mammoth died.

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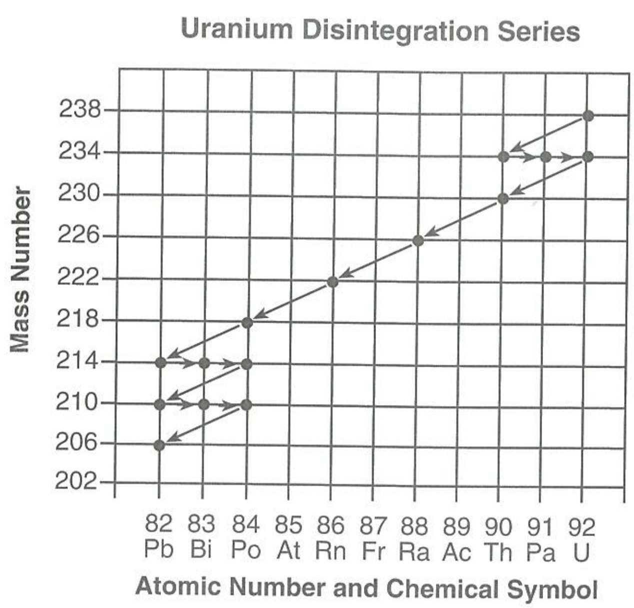
**Base your answers to questions 38 and 39 on the information below.**

A U-238 atom decays to a Pb-206 atom through a series of steps. Each point on the graph below represents a nuclide and each arrow represents a nuclear decay mode.




**38** Based on the graph, what particle is emitted during the decay of a Po-218 particle?

**39** Explain why the U-238 disintegration series ends with Pb-206.

**Base your answers to questions 40 and 41 on the information below.**

Some radioisotopes used as tracers make it possible for doctors to see the images of internal body parts and observe their functions. The table below lists information about three radioisotopes and the body part each radioisotope is used to study.

**Medical Uses of Some Radioisotopes**

| Radioisotopes | Half-Life | Decay Mode | Body Part |
|---|---|---|---|
| Na-24 | 15 hours | Beta | Circulatory system |
| Fe-59 | 44.5 days | Beta | Red blood cells |
| I-131 | 8.1 days | Beta | thyroid |

**40** Write the equation for the nuclear decay of the radioisotope used to study red blood cells.

**41** It could take up to 60. hours for a radioisotope to be delivered to a hospital from the laboratory where it was produced. What fraction of an original sample of Na-24 remains unchanged after 60. hours?

---

**Base your answers to questions 42 through 44 on the information below.**

The radioisotope uranium-238 occurs naturally in Earth's crust. The disintegration of this radioisotope is the first in a series of spontaneous decays. The seventh decay in this series is an alpha decay which produces the radioisotope polonium-218 that has a half-life of 3.04 minutes. Eventually, the stable isotope lead-206 is produced by the alpha decay of an unstable nuclide.

**42** Explain, in terms of electron configuration, why atoms produced in the sixth decay of the series do not readily react to form compounds.

**43** Complete the decay equation below that represents the final decay in the series

$$^{210}_{84}Po \rightarrow \_\_\_\_ + ^{206}_{82}Pb$$

**44** An original mass of Po-218 of 8.00 milligrams is allowed to decay. Determine the mass of the sample that remains unchanged after 12.16 minutes.