Learning Cycle 9
Radioactivity
IT'S DECAYING
Exploration

Problem

What is a half-life, and how can radioactive decay be simulated?

Materials

Box with lid or a plastic cup (or plastic sandwich container) with lid, M&Ms, Skittles, AlkaSeltzer tablets, graph paper, colored pencils, ruler, approximately 100 red, blue, and yellow painted cubes or die with dots on some of the sides

Procedure

Part A: Half-life of M&Ms

Materials that are radioactive give off small particles of energy as they make a transition to another element that is more stable. It is important to know about how long a radioactive material will remain in the unstable state. One measure of the time an element remains in a given unstable state is called a *half-life*. In this activity you will learn about radioactive decay and the half-life of unstable elements.

1. Place the M&Ms in the box with the lid on securely. A cup could also be used. The M&Ms represent radioactive atoms.

2. Shake the box or cup several times.

3. Open the box. Remove all of the M&Ms with the M showing, and replace each one with a Skittle, which represents a stable daughter product. If a cup is used, empty the contents on a sheet of paper.

4. Repeat until one or no M&Ms remain, recording the number of M&Ms and Skittles remaining after each shake in a data table. See the example table below. Note: you may not have exactly 100 M&Ms at the beginning.

Shake Number	Number of M&Ms Remaining	Number of M&Ms Removed	Number of Skittles Remaining
0	100	0	0
1	53	47	47

5. Graph the remaining number of M&Ms vs the shake number and the number of Skittles vs the shake number. The two graphs should be illustrated on one sheet of graph paper. Color code these graphs so you can distinguish them from one another.

6. Draw a smooth line that best fits the points for each graph.

Developing and Using Scientific Ideas

1. What pattern do you observe in the graphs?

2. Approximately what percent of the remaining M&Ms were removed (decayed) and replaced by stable daughter Skittles on each shake? Explain your reasoning.

3. If each shake represents a half-life for the M&Ms, how would you describe a half-life?

Procedure

Part B: Half-life of Cubes

1. Examine the painted cubes or die. Based on your observations and the results of your graphs in Part A, what is the *probability* that a side with one dot will show up for each colored cube or die?

2. Since the different colors of cubes or die represent different *radioactive elements,* or elements that randomly decay to lighter elements, what is the probability that each color will decay?

3. If you had 100 cubes of each color, how many of each colored cube would remain after one throw?

4. Construct a data table to show the number of throws compared to the remaining cubes of each color. Start with all the cubes of one color in a cup. Shake and roll them out on the lab table. The cube with a dot showing on top represents a decayed atom. For each shake, remove the decayed atoms and count the remaining radioactive atoms. When a colored cube turns dot up, replace it with a black cube. Continue until all cubes have decayed. Note: In this model, all colors will finally decay into the stable atoms represented by the black dice.

5. Repeat with each color of cube. Graph your results of amount remaining vs number of throws on the same graph using different colors for each set of data.

Developing and Using Scientific Ideas

1. Each cube has a half-life of a certain number of throws. Based on your knowledge of probability, what do you predict the half-life of each color to be?

2. How do the shapes of the graph from each color of cube compare?

3. How can you tell the half-life of each "radioactive element" from the graph?

4. The decay rate of a radioactive element is known as its activity. Based on the graph, which element would be more active? Explain your response.

Extending the Activity

Examine an AlkaSeltzer tablet before placing it in a glass of water. How can an AlkaSeltzer tablet simulate the process of radioactive decay and half-life? Now place the AlkaSeltzer tablet in water and observe the reaction. How is it like radioactive decay?

Learning Cycle 9
RADIOACTIVE DECAY
Concept Development

Problem

How can painted cubes or colored die be used to model a series of decays involving more than one daughter product?

Materials

Paper cup, 40 wooden cubes (or colored die): 10 red, 10 blue, 10 yellow, and 10 black

Procedure

In the previous activity, you modeled simple radioactive decay. There was one final daughter product that was a stable element, which showed no further decay. In this activity, you will model radioactive decay in which there are more than one resulting daughter products with the final product being the stable element. Your laboratory group should arbitrarily select a sequence for the order of the decay between colors of cubes. The last color must be black, but the first three colors can be in any order. Write down the sequence of decay.

1. Starting with the first color selected, place the 10 cubes of that color in the cup. Shake the cup, and then roll out the cubes on a table. Remove all of the cubes that have the black dot showing on the top. These cubes represent an element that has decayed into another element. Replace the removed cubes with cubes of the next color in your sequence.

2. Repeat step 1. Anytime a cube has a black dot on top, replace it with one of the next color in the sequence.

3. Record the number of the original color cubes remaining after each throw.

4. Continue to roll and replace the cubes until all cubes are black.

5. Record the total number of throws it took to get all black cubes.

6. Compare your total number of throws to other groups who used the same and different sequence of colored cubes.

Developing and Using Scientific Ideas

1. The *half-life* is defined as the amount of time to change half of the original material into new material. This material has a half-life of a certain number of throws. Approximately how many throws did it take to reduce your original color to half of the cubes?

2. If you started with 1000 cubes of your original color rather than the 10, what would you expect the half-life to be? Explain your response.

3. If you had started with a different first color, would you have had the same half-life for the original cubes? Explain your response.

4. If you put all 30 colored cubes (10 of each color) in the cup, shook them up, and poured them out on the table, how many decayed pieces would you expect to find? Explain your response.

5. How does the original mass (number) of the starting colored cubes compare to the final mass (number) of the black cubes?

6. What effect, if any, does the sequence of colored cubes have on the total number of throws it takes to get all to black cubes?

Extending the Activity

1. You now have gone through three different models of radioactive decay: M & Ms and Skittles, colored cubes or die with one daughter product, and colored cubes or die with more than one daughter product. Evaluate the effectiveness of these models and their limitations.

2. Students in a physical science class put 200 coins in a box. They shook the box and removed the coins that were "heads up." They continued to shake the coins and remove the ones showing heads. Eventually there were just a few coins left, and the simulation of radioactive decay was done. Based on your observations from this activity and the previous activity, evaluate the effectiveness of this model of radioactive decay.

3. Radioactive *isotopes*, elements with the same number of protons but different number of neutrons, are often used in medicine. Do you think these isotopes have a short or a long half-life? Explain. Research some of the uses of radioisotopes in medicine, and share your results with the class.

4. Most decay processes take a long time. Are there any large users of radioactive materials located where you live? How should radioactive wastes be stored? Consider both long and short-term storage.

Learning Cycle 9
NUCLEAR CHECKERS
Concept Development

Problem

How does an unstable Q-238 nucleus decay into a stable D-206 nucleus?

Materials

Decay checkerboard, 1 quarter, 1 dime, pennies or colored disks or colored beads, periodic table

Procedure

Most elements have stable isotopes. The nuclei of some isotopes, however, are unstable and disintegrate spontaneously (decay), emitting energetic particles. Most of the radioactive nuclei found in nature occur as products of the decay series of heavy nuclei (large atomic mass) into lighter nuclei. An unknown element, ${}^{238}_{92}Q$, is one such heavy nucleus that decays into a number of lighter nuclei (*daughter products*). The final daughter product of the series is a stable unknown isotope: ${}^{206}_{82}D$. In this activity, you will observe the decay of ${}^{238}_{92}Q$ by the emitting of smaller particles to a stable ${}^{206}_{82}D$ nucleus.

1. Obtain the graph paper that will be used as your decay checkerboard from your teacher. Label the long side "Atomic Mass Number" (A), which will be the y-axis. Number it from 202 to 238 (two numbers per square). Label the short side "Atomic Number" (Z), which will be the x-axis. Number it from 80 to 95 (one number per square). The checkerboard is actually a graph of the atomic mass number (A) vs atomic number (Z).

2. The ${}^{238}_{92}Q$ atom is represented by a quarter. Place a quarter on the appropriate location on the board. The nucleus is represented by the chemical symbol of a particular element with the mass number (A) as a left superscript and the atomic number (Z) as a left subscript: ${}^{A}_{Z}X$. The *atomic mass number* equals the number of nucleons (sum of protons and neutrons in a nucleus). The *atomic number* equals the number of protons.

3. A dime represents the final daughter product: ${}^{206}_{82}D$. Place a dime on the appropriate location on the board. Before going any further, check the placements of your ${}^{238}_{92}Q$ and ${}^{206}_{82}D$ nuclei with another group. Make any necessary adjustments.

4. The objective is for you to illustrate the decay process for ${}^{238}_{92}Q$ by tracing a path on the board that begins with the quarter (${}^{238}_{92}Q$) and ends with the dime (${}^{206}_{82}D$). You will trace your path with pennies (or colored disks or colored beads) to show all the resulting daughter products. You are restricted to two types of moves.

- An A-move allows you to move down two squares and then move to the left two squares.
- A B-move allows you to move to the right one square.

Your first two moves are an A-move followed by a B-move. Subsequent moves are at your discretion. You must end at the dime ($^{206}_{82}D$) and can only make A and B moves. A new daughter product is produced after each move. You must place a penny at the appropriate location on the board to indicate each new daughter product that is produced.

5. Record all daughter nuclei produced with their atomic masses and atomic numbers.

6. Compare your results with the results of other student groups.

Developing and Using Scientific Ideas

1. Use a copy of a periodic table to determine the two unknowns: $^{238}_{92}Q$ and $^{206}_{82}D$. What are the actual elements they represent?

2. How many daughter products were produced?

3. Use a copy of the periodic table to determine all the daughter products of the $^{238}_{92}Q$ decay series.

4. How many A-moves did you make? How many B-moves did you make?

5. What happens to the atomic mass of the nucleus for each A-move you make? What happens to the atomic mass of the nucleus for each B-move you make?

6. What happens to the atomic number of the nucleus for each A-move you make? What happens to the atomic number of the nucleus for each B-move you make?

7. An A-move always results in the production of a new daughter nucleus (as indicated by each penny on the board) and a particle. What is the "A" particle that is always produced during an A-move? Describe the particle in terms of the change in mass number and atomic number that has occurred.

8. A B-move always results in the production of a new daughter nucleus and a particle. What is the "B" particle that is always produced during a B-move? Describe the particle in terms of the change in mass number and atomic number that has occurred.

9. How does your decay series compare with the actual decay series for the parent nucleus? How are they similar? How are they different? This decay series is found in most physics textbooks.

Extending the Activity

In the Q-238 decay series you were limited to two types of moves: an A-move and a B-move that resulted in a new daughter nucleus and a particle. A third type of move, called a C-move, is possible for some nuclei. A C-move does not involve moving up or down the y axis or left or right along the x axis, since the number of protons or neutrons do not change. A C-move involves only a change in energy for the nucleus. In a C-move the parent nucleus emits energy. The result is that the daughter nucleus is the parent nucleus with less energy.

1. How could you model a C-move using the nuclear checkerboard? What modifications, if any, would have to be made to the board? Explain.

2. The elements with atomic numbers greater than 92 are known as the *transuranium* elements. Do these elements exist in nature? Investigate how these elements were created and the teams of scientists that were involved. How did these elements get their names?

3. Dmitri Mendeleev predicted the element technetium (atomic number 43), but no one could find it on the earth. Spend a little time with a physics reference book, an encyclopedia, or the Internet to find out why it was no where to be found. Report back to your class.

Learning Cycle 9
CONCEPT ENHANCER

Radioactive Decay

Radioactivity is the spontaneous emission of particles and energy from the nuclei of certain atoms. Are all atoms radioactive? No. But all atoms with atomic numbers over 83 are radioactive. So, too, are a few with lower atomic numbers. For example, technetium is radioactive and has an atomic number of 43. Many other elements have some radioactive isotopes. Examples include hydrogen-3 and carbon-14.

What do radioactive atoms do that other atoms do not? Radioactive atoms actually "spit" stuff out of the nucleus. They do this on their own with no help from outside forces. This process is called *radioactive decay.* When atoms decay, they may send out alpha particles, beta particles, gamma rays, or some combination.

Alpha Particles

When a nucleus emits an *alpha (α) particle* (which is a helium nucleus), the result is a decrease in atomic number of two and in atomic mass of 4 amu (atomic mass units), as illustrated in Figure 9.1. An alpha particle is relatively massive, has a charge of +2, and is slow moving. It has rather poor penetrating power. It could be stopped by a piece of paper, skin, or even 5 cm of air. Alpha particles inhaled or ingested, however, can do a great deal of damage to soft tissue. They can give off all their energy inside the body and have very damaging effects on the liver and spleen. In nuclear equations the symbol for an alpha particle is ${}^{4}_{2}He$.

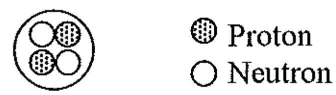

Figure 9.1

Beta Particles

Beta (β) particles are high-speed electrons that come out of the nucleus of an atom undergoing radioactive decay. How does this happen? It is believed that a neutron breaks down, sends out a negatively charged beta particle, and leaves a proton behind, as illustrated in Figure 9.2. When a beta particle leaves the nucleus, so does an antineutrino. A beta particle has a mass number of zero and a charge of −1. In nuclear equations the symbol for a beta particle is ${}^{0}_{-1}\beta$.

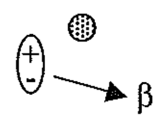

Figure 9.2

When a beta particle leaves the nucleus, the mass number does not change. As you have learned, a neutron (with a mass number of 1) changes into a proton (still having a mass number of 1 amu). The resulting beta particle has a mass number of zero, but the atomic number, or charge, does change. A new proton is then formed, causing the atomic number (change) to go up 1.

A beta particle has more penetrating power than an alpha particle does. A beta particle can penetrate several millimeters into solid material. Very heavy clothing or a sheet of aluminum that is several millimeters thick may stop beta particles.

Gamma Rays

When alpha particles and beta particles are released from a decaying nucleus, gamma rays may also be released. *Gamma rays (γ)* are a type of electromagnetic radiation (similar to X rays). They have no mass and no charge. Gamma rays have the greatest penetrating power. They are even able to penetrate several centimeters of lead. Because a gamma ray does not have a mass number or charge, its symbol in nuclear equations is $^{0}_{0}\gamma$. Sometimes the zeros are emitted. Even though the mass number and atomic number of the original nucleus do not change, the nucleus has a lower energy after the emission of the gamma ray than it did before.

Half-life and the Decay Process

Most radioactive elements go through a series of decays before turning into a stable element. Uranium-238 actually goes through 14 transmutations in the quest for stability. Each new product that is formed is called a *daughter product*. You modeled this process in the activities **IT'S DECAYING, RADIOACTIVE DECAY**, and **NUCLEAR CHECKERS.**

Does every atom in a radioactive sample decay at the same time? No. You saw this in the activities **IT'S DECAYING** and **RADIOACTIVE DECAY**. When you shook the M&Ms and rolled the cubes onto the lab table, some but not all of the M&Ms and cubes decayed. Radioactivity is a random event. The time it takes for half of the radioactive atoms in a sample to decay is called the *half-life* of the isotope. The half-life of cobalt-60 is 30 years. If you start with 2000 atoms of Co-60, sometime during the next 30 years approximately half (about 1000) of the atoms will decay into a different element. Co-60 typically decays by emitting beta particles and gamma rays, so will become an isotope of nickel. You modeled this decay in the activities **IT'S DECAYING** and **RADIOACTIVE DECAY**. In **IT'S DECAYING**, when an M&M had an M on top or a colored cube had a black dot on top, it had "decayed." You replaced it with a Skittle or a cube of a different color. In **RADIOACTIVE DECAY**, the resulting cubes of different colors represented new elements that also happened to be radioactive. Eventually all of the original cubes decayed into something new. The new elements also decayed according to their own half-life. If you kept rolling the cubes until they had all been replaced with black cubes, you modeled a complete decay series.

This model does not match exactly what happens in nature. In nature some of the original radioactive material will always remain and will not decay. This characteristic of the material allows us to use a dating technique called *carbon 14 dating* to determine the age of materials. Carbon 14 is used on materials that were once part of living things. The half-life of C-14 is 5730 years. By knowing the decrease in concentration of C-14 compared to the stable C-12 in a given material, the number of half-lives and the age of the material can be determined.

Now return to the sample of cobalt, which decayed from 2000 atoms to 1000 atoms in the first 30 years. During the next 30 years, half of the remaining half, or about 500 atoms, will decay. Likewise, in the next 30 years, half of that remaining half, or about 250 atoms, will decay. As you can see, half of the radioactive atoms will decay during the half-life no matter what the size of the sample.

In Part B of the activity **IT'S DECAYING**, you made a graph of remaining cubes compared to the number of throws for each set of colored cubes, as illustrated in Figure 9.3. Notice that each graph, called a *decay curve*, had the same basic shape.

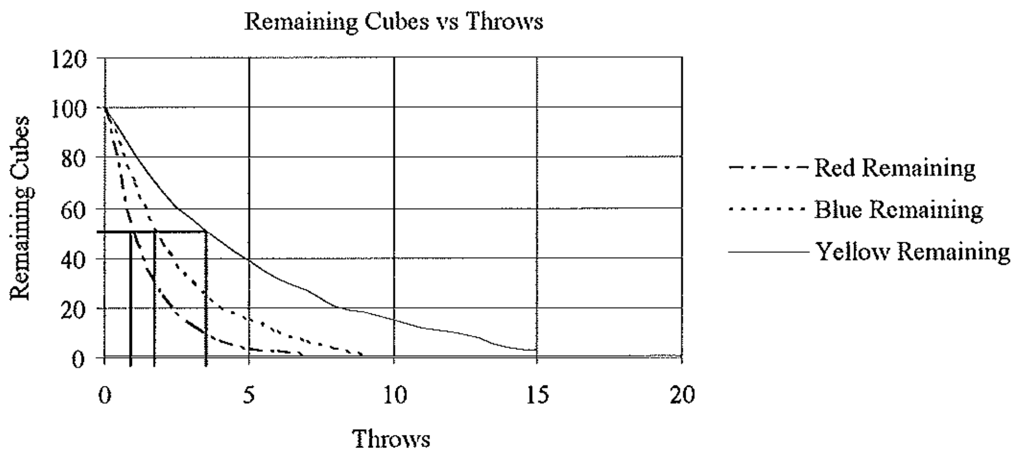

Figure 9.3

A graph of the remaining atoms vs number of half-lives can be used to determine the half-life of a particular isotope. Half of each of the samples is 50 cubes (or remaining atoms). A line drawn from half the sample over to the curve and then down to the horizontal axis will show the half-life of the sample. In this example, the red cubes have a half-life of one throw, the blue cubes of just about two throws, and the yellow cubes of almost four throws. This model is similar to the half-life of actual elements because each isotope has its own unique half-life. For example, the half-life of U-238 is 4.51 x 10^9 years, but the half-life of I-131 is 8.07 days. Most science reference books list the half-lives of various isotopes.

Conservation of Charge and Mass Number

When a nuclear reaction takes place, such as alpha or beta decay, both charge and mass number are conserved. It cannot be said that mass is conserved, because the reactants have just a little more mass than the products do. However, as illustrated in the activities **IT'S DECAYING** and **RADIOACTIVE DECAY**, the total number of candies or cubes remained the same after each shake or throw. Likewise, in the process of radioactive decay, atoms are not lost. They do not decay into nothing. They become different elements.

Reactants also have much more energy than the products. As early as the 1930s it was recognized that energy from atoms could be obtained in useful amounts. This energy as a resource has not yet been fully explored. Study the two simple equations shown below. The first equation shows the alpha decay of U-238. Notice that both mass number and charge are conserved (are the same on both sides of the equation). This is what you modeled with an "A-move" in the activity **NUCLEAR CHECKERS**. Notice also that the daughter product, ${}^{234}_{90}Th$, has a mass number that has decreased by four and an atomic number that has decreased by two.

$${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$
$${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}\beta$$

The second equation illustrates beta decay. Just like a "B-move" showed you, the atomic number has increased by one with no change in the mass number.

In gamma decay, neither the mass number nor the charge changes. The daughter nucleus is simply the parent nucleus with less energy. The equation below shows a thorium nucleus emitting a gamma ray. The asterisk indicates that $^{234}_{90}Th$ is in the excited state (higher energy levels). The nucleus will return to lower energy levels when a gamma ray is emitted.

$$^{234}_{90}Th^{*} \rightarrow {}^{234}_{90}Th + \gamma$$

In the activity **IS IT ALPHA, BETA, OR GAMMA?**, you will apply your understanding and use a *Geiger counter* to determine the type of radiation emitted by household products.

Learning Cycle 9
CONCEPTUAL PRACTICE

1. What is the mass number of an alpha particle? What is its charge? What symbol is used to represent an alpha particle in a nuclear equation?

2. What happens to the mass number of an isotope that decays by alpha decay? What happens to the atomic number of that nucleus?

3. What is the mass number of a beta particle? What is its charge? What symbol is used to represent a beta particle in a nuclear equation?

4. What happens to the mass number of an isotope that decays by beta decay? What happens to the atomic number of that nucleus?

5. Write a simple nuclear equation to show the alpha decay of plutonium-236.

6. How does the equation you wrote show the conservation of charge? How does it show conservation of mass number?

7. Write a simple nuclear equation to show the beta decay of carbon-14.

8. How does the equation you wrote show the conservation of charge? How does it show conservation of mass number?

9. What effect does the loss of a gamma ray have on a nucleus?

10. How much of a radioactive sample will decay after one half-life has passed? How much more will decay after the passing of another half-life?

11. The half-life of a radioactive source is approximately 3 days. You need 100 g of the material for a research project. You know the project will take you two weeks to finish. Will you order exactly 100 g of the material from the supply company? Why or why not?

12. Iodine-131 has a half-life of approximately 8 days. What part of the sample will still be radioactive after 40 days?

13. Use the remaining nuclei vs time graph in Figure 9.4 to determine the half-life of the isotope. Explain how you used the graph to find your answer.

14. Shelf life, which is similar to half-life, is used to describe the effectiveness of pharmaceuticals. Young children are often prescribed liquid antibiotics for ear infections. The prescription often contains a warning similar to this: Discard after 14 days. Why is it important to follow this warning?

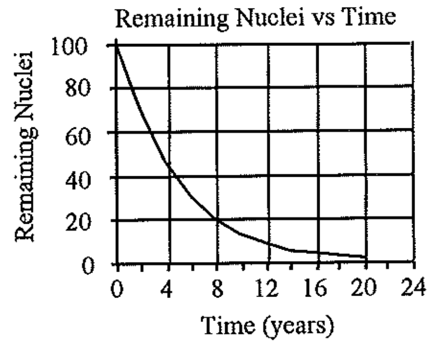

Figure 9.4

Learning Cycle 9

IS IT ALPHA, BETA, OR GAMMA?

Application

Problem

What radioactive particles do common consumer products emit?

Materials

Vernier Radiation Monitor; LabPro or other MBL interface; Logger Pro data collection software; Graphical Analysis or other graphing software (or Geiger counter and graph paper); common radioactive material; paper; sheet(s) of aluminum totaling 3–6 mm thick

Procedure

Several common consumer products contain radioactive material. These products emit a combination of alpha particles, beta particles, and gamma rays as they go through the decay process.

1. Devise a method with equipment available to you to determine what types of radiation an object emits. Your procedure must show that you are controlling variables and taking into account the level of background radiation.

2. Describe your procedure on paper. Conduct the experiment and collect the data in an organized data table.

Developing and Using Scientific Ideas

1. What type or types of radiation do you believe were emitted from the object you tested?

2. Use your data to support your conclusion.

Extending the Activity

1. Devise a procedure to test the effect of distance on the amount of radiation received by a Geiger counter. If you have enough time, carry out your activity and report back to the class.

2. What happens to the amount of radiation received by a Geiger counter as additional thin sheets of aluminum are placed between a radioactive source and the device? Devise a procedure that you could use to test your hypothesis.

3. As you read about radioactivity, you will find various ways of measuring the radiation that is produced and its effects on humans. Some terms you may encounter are Becquerel (Bq), Curie (Ci), Gray (Gy), Sievert (Sv), rem, Roentgens, and rad. Spend some time with a scientific dictionary or encyclopedia to find out how these different units are used.

4. Marie Curie was awarded the Nobel Prize (1903) in Physics for the co-discovery of radioactivity. She is known for her part in the discovery of the radioactive element radium. She was the first person to win two Nobel Prizes (the second in chemistry), and she also established a military radiotherapy service. Research the life of Marie Sklodowska Curie. Was she aware of the danger of working with radioactive materials? How did her work influence her activities later in life?

5. Radium salts were part of a mixture used to paint watch dials. Investigate why this mixture was used and what happened to the girls known as "the Radium Girls." What influences did this discovery have on conditions in the workplace? What substitutes are used today?