# UNIT 12

# Kinetics and Nuclear Chemistry

## Rates of Reaction

## Unit Overview

In this unit, students will learn about chemical kinetics and nuclear chemistry; both these topics share the concept of half-life. The text and video introduce the basics of collision theory, and show how increasing the number of productive collisions speeds up reactions. Understanding chemical kinetics is vital to maximizing the efficiency of industrial chemical production and to understanding the regulation of biochemical reactions.

In the latter half of this unit, students will learn about the early groundbreaking research in radiation and nuclear chemistry. They should understand the basic types of radiation and be able to explain the nuclear reactions that produce them. After learning about fission and fusion, students should be able to explain how nuclear weapons and nuclear power plants operate. The material in this unit will give them a deeper awareness of important issues such as nuclear waste disposal and nuclear weapons proliferation.

### Learning Objectives and Applicable Standards

Participants should be able to:

1. Describe the different factors that influence the rate of a chemical reaction, referencing the basics of collision theory.
2. Explain what a rate law is and what kind of data one needs to determine what the rate law for a reaction is.
3. Read and understand a potential energy diagram, define activation energy, and explain how higher temperatures and catalysts speed up a reaction.
4. Explain reaction mechanisms and rate-limiting steps.
5. Trace the history of the discovery of radioactivity.
6. Describe the different types of radioactive decay and write balanced nuclear equations.
7. Explain the concept of half-life and describe the process of radiometric dating.
8. Relate the history of the discovery of nuclear fission and fusion, and explain how these reactions produce nuclear explosions and nuclear power.

### Key Concepts and People

1. **Collision Theory:** Molecules must collide in order to react**.** Collision theory underlies the study of chemical kinetics. To react, molecules must collide in certain ways. Reactions proceed faster when productive collisions occur more often.

2. **Potential Energy/Reaction Coordinate Diagrams:** These diagrams show whether a reaction is endothermic or exothermic and the activation energy of the reaction.

3. **Reaction Mechanisms:** Reactions usually happen in a series of simpler reactions**.** This series of steps is called the "reaction mechanism," and the slowest step determines the rate of the overall reaction.

4. **Catalysts:** Catalysts speed up chemical reactions without themselves being changed by the chemical reaction. They increase the reaction rate by providing an alternate mechanism with lower activation energy.

5. **The Discovery of Radioactivity:** Wilhelm Röntgen, Henri Becquerel, and Marie and Pierre Curie pioneered research in radioactivity. Together these scientists discovered radioactivity and described its properties. Different modes of decay produce particles with different energies and properties.

6. **Radiation:** Radioactive material decays in a predictable way. Radioactive substances have half-lives. Because the decay is predictable, scientists can use radiometric dating to determine the age of ancient material.

7. **Nuclear Fission:** Lisa Meitner and Otto Hahn discovered nuclear fission**.** The discovery of fission leads to the development of nuclear chain reactions, nuclear bombs, and nuclear power plants.

## Video

From an instantaneous explosion to the slow rusting of iron, the rates at which different chemical reactions proceed can vary tremendously depending on several factors, including temperature and concentration. Sometimes, like with the rotting of food, chemists want to slow down reaction rates. But often, the goal is to speed them up—and one way to do this is to use a catalyst. In this video, we will learn about catalysts and how using them can lead to cheaper, more effective, and more sustainable drug production processes. We will also discover how the rates of some reactions, like nuclear decay, are unchangeable, and how scientists take advantage of this, using PET scans to reveal the presence of disease.

## VIDEO CONTENT

### Host Introduction
### "Chemical Reactions"

Dr. Wilton Virgo, assistant professor at Wellesley College, demonstrates the basics of chemical reactions. He rides bumper cars at an amusement park to explain that chemical reactions happen when molecules collide, and that increasing the concentrations will increase the chances of a reaction happening. He then rides a rollercoaster to discuss activation energy—the energy needed to make a given reaction "go."

### Laboratory Demonstration
### "Activation Energy"

Harvard University Lecture Demonstrator Daniel Rosenberg demonstrates activation energy by mixing hydrogen and chlorine gases in a test tube stopped by a cork. He keeps a dark cloth over the tube because light can provide the activation energy needed to make the reaction happen. By shining lights with different energy levels on the tube, he discovers what it will take to make the reaction happen and to shoot the cork across the room.

### Host Science Explanation
### "Catalysts"

Dr. Wilton Virgo is on a train in the amusement park and talks about how the train is like a catalyst because it is providing an alternative pathway that will take him from one side of the park to another in a shorter amount of time. Dr. Virgo expands on the analogy by explaining that at each stop, the train empties and is available to take more passengers back to the other side of the park. A catalyst acts in the same manner – it changes during a reaction, but once the reaction is over, the catalyst returns to its original state and can be used in subsequent reactions.

### Laboratory Demonstration
### "Elephant's Toothpaste"

Daniel Rosenberg demonstrates a catalyst in action using potassium iodide to catalyze the decomposition of hydrogen peroxide. He then does the same reaction but mixes in dish soap to create some visually interesting results.

### Current Chemistry Research
### "Molecular Architects"

At Boston College, Professor Amir Hoveyda and his team have developed a set of catalysts that may provide a new blueprint for how we approach catalyst development for years to come. This segment provides an interesting definition of what a catalyst is by discussing what they are looking for and what they have discovered.

### History of Chemistry
### "Nuclear Decay"

Wilton Virgo explains that the rates of some chemical reactions are unchangeable: the most common example of reactions that cannot be slowed down or speeded up are nuclear or radioactive decay. Scientist Marie Curie coined the term "radioactivity" to describe the steady emission of rays she observed in uranium and thorium. Along with her husband Pierre, Curie accurately proposed what was a revolutionary idea for its time—that this behavior was the result of something happening inside the atom.

### Real World Application
### "PET SCANS"

At Massachusetts General Hospital, radioactivity and half-lives play a crucial role in performing PET (Positron Emission Tomography) scans. PET scans are a crucial tool in detecting diseases at an early stage and can also be used by doctors to target their treatment in more specific and effective ways.

## Unit Text

### Content Overview

The first half of this unit introduces chemical kinetics. The basics of collision theory and rate laws are discussed first, followed by the effects of concentration, temperature, and catalysts on reaction rate. The second half of the unit covers nuclear chemistry and begins with a brief history of the discovery of radioactivity. The next sections describe basic types of radiation and nuclear equations, followed by nuclear stability, the strong force, and half-lives. The final sections discuss fission, fusion, nuclear weapons, and nuclear power plants.

### Sidebar Content

1. **Rate Laws:** This sidebar shows how an equation (a rate law) represents the rate of a chemical reaction in terms of reactant concentrations.

2. **The Arrhenius Equation:** Collision frequency, temperature, and activation energy all appear in this equation for the rate constant.

3. **Nuclear Stability:** There are four fundamental forces of nature: gravity, electromagnetism, the strong force, and the weak force. The strong force holds protons together in a nucleus, while the repelling forces of the positive charges are constantly trying to force protons apart from one another. However, the strong force holds the protons together and binds neutrons to protons and other neutrons.

4. **Decay Chains and Radon:** This explains nuclear decay chains and how uranium-238 leads to radon gas in houses.

## Interactives

### Historical Timeline of Chemistry

This interactive illustrates how different discoveries build upon, disprove, or reinforce previous theories. This not only reinforces basic chemistry concepts, but also emphasizes the nature of science. Scientists mentioned in this unit are listed on the timeline.

### Control a Haber-Bosch Ammonia Plant Interactive

In this simulation, students try to maximize the efficiency of an ammonia plant. Students will be able to watch the interaction of $H_2$ and $N_2$ molecules and see the effect of concentration and temperature on reaction rate. They will also be able to choose from three catalysts to increase the plant's productivity. Please note that a lesson plan and student worksheet are available online with this interactive.

## During the Session

### Before Facilitating this Unit

The kinetics activity provided below gives students a good introduction to some of the factors that influence reaction rates. The cornstarch demo reinforces the basics of collision theory in a dramatic way, and the hydrogen peroxide demo goes hand in hand with the text's discussion of catalysis.

The second half of the unit text covers nuclear chemistry, and because hands-on activities with radioactive material are not safe, the teacher will need to rely on simulations such as the half-life activity below. Many simulations for radioactive decay, radiometric dating, and fission chain reactions are also available online. (See References and Additional Resources.)

### Tips and Suggestions

1. **The rate law is not derived from the net chemical equation.** Some students assume that all reactants in the equation can affect the rate, or that the coefficients in the equation determine the rate law. Rate laws can only be determined experimentally.

2. **Individual nuclei decay at random.** Many students at this level have had some exposure to the concept of half-life, and mistakenly believe that small numbers of nuclei will behave like large numbers. Emphasize that the decay of each individual nucleus is completely unpredictable, and only large numbers of nuclei behave predictably.

### Starting the Session: Checking Prior Thinking

You might assign students a short writing assignment based on the following questions, and then spend some time discussing prior thinking. This will help elicit prior thinking and misconceptions.

1. What chemical reactions happen very slowly? Very quickly? Why do you think the rates are different?
2. Why might someone want to speed up a chemical reaction? Why might someone want to slow down a chemical reaction?
3. How do you think changing the rate of a reaction could be changed? What factors might influence reaction rates?
4. What do you think of when you hear the word "radioactivity"?
5. What are some uses of radioactive materials and radiation?
6. How is it possible that radiation can be both a cause of and a treatment for cancer?

### Before Watching the Video

Students should be given the following questions to consider while watching:

1. What is activation energy?
2. What role does a catalyst play in the "elephant's toothpaste" reaction?
3. What is radioactivity?
4. What does the term half-life mean?

### Watch the Video

### After Watching the Video

Use these additional questions as follow-up, either as a group discussion or as short writing assignments.

1. What is a catalyst? How do catalysts work?
2. Provide some examples of how catalysts can be useful.
3. What role does radioactivity play in PET scans at Massachusetts General Hospital?

# Group Learning Activities

## Kinetics

### Objective

Students will control the rate of the reaction between Alka-Selzter tablets and water to make the top of a film canister pop off after exactly 30 seconds.

### Materials
Each group of students will require:
- A film canister
- Some Alka-Seltzer tablets
- Water (cold and hot)

### Procedure
When Alka-Seltzer dissolves in water, it produces $CO_2$ gas. You will perform this reaction inside a closed film canister. Your task is to control the rate of this reaction so that the top of the canister pops off after exactly 30 seconds. Try adjusting the amount of Alka-Seltzer, the size of the Alka-Seltzer pieces, and the temperature of the water.

### Discussion Questions
The following questions can help students reflect on this exercise. If possible, have students record their responses to the questions in a journal and spend some time discussing as a class.

1. What effect did the amount of Alka-Seltzer have on the reaction rate? Why?
2. What effect did the size of the Alka-Seltzer pieces have on the reaction rate? Why?
3. What effect did the temperature of the water have on the reaction rate? Why?

### Hazards
Goggles should be worn at all times to protect students from lids and bubbling Alka-Seltzer.

### Disposal
Water and Alka-Seltzer may be poured down drain. Unused tablets may be stored for later use or disposed in trash.

## Half-Life

### Objective
Students will simulate nuclear decay and graph the data in order to gain an understanding of half-life.

### Materials
- One coin per student

### Procedure
Start with the entire class standing up; each standing student represents a radioactive nucleus. Have all students flip their coins once. If a student gets heads, he/she remains standing (the nucleus doesn't decay); if a student gets tails, the student sits (the nucleus decays). Record the number of standing students in a table on the board. Have the remaining students flip their coins one more time. Those that get tails must sit. Record the number of standing students. Repeat this cycle until all students are seated. Each round of coin flipping represents one half-life. Graph

the data from the table. To get a smoother graph, you will probably need to repeat the procedure a few times and take an average of the data.

### Discussion Questions

The following questions can help students reflect on this exercise. If possible, have students record their responses to the questions in a journal and spend some time discussing as a class.

1. The data from this experiment probably did not create a perfectly smooth graph, where exactly half the sample decays after each half-life. If you started with 10 grams of a real radioactive element, however, the graph would look almost perfectly smooth. Why is there a difference?

2. What determined the half-life of the element in this simulation?

3. What determines the half-life of actual radioactive elements?

4. After each half-life, the amount of a radioactive element decreases by half. Will the element ever decay completely, if the amount just keeps getting cut in half?

### Hazards

There is no increased risk of harm in this activity.

### Disposal

There are no special disposal considerations.

# In-Class Chemical Demonstrations

## Reaction Rate and Surface Area

### Objective

This demonstration shows that surface area can affect the rate of a reaction.

### List of Materials

- Cornstarch
- Bunsen burner
- Drinking straw

### Procedure

1. Show that a small pile of cornstarch will not catch fire when the surface is burned with a Bunsen burner.

2. Place some cornstarch in a drinking straw. From the side and from below, blow the cornstarch into the Bunsen burner flame; it will burn rapidly in a fireball.

### Discussion

These questions can help guide a discussion.

1. What is the difference between the pile of cornstarch and when the cornstarch is blown?

2. Why does the blown cornstarch catch on fire, but the pile of cornstarch does not?

### Hazards

Make sure you blow the cornstarch away from people and flammable materials.

### Disposal

There are no special disposal considerations.

## Catalysis

### Objective

This demonstration shows that yeast serves as a catalyst to the decomposition of hydrogen peroxide. The hydrogen peroxide decomposes slowly in the following reaction:

$H_2O_2(aq)$ ® $H_2O(l) + O_2(g)$

### List of Materials

- 3% hydrogen peroxide solution
- Large beaker
- Dry yeast

### Procedure

1. Pour about 50 mL of 3% hydrogen peroxide solution into a large beaker.

2. Sprinkle some dry yeast into the beaker; the catalase enzyme in the yeast speeds up the decomposition, and the mixture will rapidly foam up.

3. Light a wooden splint and blow it out, leaving the end smoldering. Put the burning end into the gas inside the beaker to show that the splint burns faster in the oxygen produced.

### Discussion

These questions can help guide a discussion.

1. Before the yeast is added, is any reaction occurring?

2. Why does the yeast cause the reaction to speed up?

3. Hydrogen peroxide is used in first aid to clean cuts and scrapes. When it comes in contact with damaged skin, it foams up just like the demonstration. Why?

### Hazards

It is good lab practice to review a chemical's Material Safety Data Sheet (MSDS) before working with any chemical. Follow instructions on the MSDS and encourage students to review them. Wear proper protective gear at all times: chemical splash goggles, chemical-resistant apron, and gloves.

Hydrogen peroxide: Many substances will cause hydrogen peroxide to decompose into water and oxygen gas. It deserves the science teacher's special handling and storage attention. Substance is severely corrosive to skin, eyes, and respiratory tract; very strong oxidant. Dangerous fire and explosion risk. Do not heat this substance. While a 3% solution of hydrogen peroxide is very weak, it is still an oxidizer and a skin and eye irritant.

### Disposal

Check local regulations for proper disposal of hydrogen peroxide.

## Going Deeper (In-Class Discussion or Reflection)

Instructors should allow up to 30 minutes for discussion at the end of the session, or students can use the time to reflect on one or more of these questions in journals.

1. Find real-life examples of reaction rates being influenced by concentration, surface area, temperature, and catalysts.
2. Radiocarbon dating is not accurate when applied to objects that are very young or very old. Explain.
3. A fission chain reaction is fastest when the fissile material is in a spherical shape. If the material is pounded into a flat sheet, the chain reaction will slow down and possibly stop. Explain.
4. After each half-life, the amount of the radioactive substance decreases by half. Will the substance ever completely disappear?
5. Some of the scientists working on the Manhattan Project felt a lot of guilt for having worked on creating a weapon of mass destruction. Others felt proud of their role in bringing World War II to an end. Do you think that working on the Manhattan Project was morally right?
6. Why does refrigeration of food prevent spoilage?
7. Thermodynamics actually predicts that diamonds are less stable than graphite, and therefore should turn into graphite readily. Does this happen as predicted? Why or why not?
8. Suppose you have two gas phase molecules, A and B. They react to form product AB by colliding into one another. Based on your understanding of gas behavior, think about a

way in which you could improve the probability of molecule A colliding with molecule B in a closed reaction container.

9. Suppose you have two molecules, C and D. Like molecules A and B in example 3, they can form a product, CD, by colliding into one another. Molecule C, however, is a large, complicated molecule; the product CD forms only when molecule D hits one specific spot on molecule C. How can you improve the probability of this reaction occurring? How is this the same or different from your answers to the previous question?

## Before the Next Unit

Students should read the Unit 12 text if they haven't already done so. They may be assigned one or more reading assignments from the list below, or if you choose to have them use the course materials outside of class, they can watch the Unit 13 video and/or read the Unit 13 text as an assignment before the next session.

## References and Additional Resources

"Marie Curie and The Science of Radioactivity." The American Institute of Physics -- Physics Publications and Resources. http://www.aip.org/history/curie/ (accessed August 10, 2012).

*The Day After Trinity*. DVD. Directed by Jon Else. Chatsworth, CA: Image Entertainment, 2002.

"NOVA | Island of Stability." PBS: Public Broadcasting Service. http://www.pbs.org/wgbh/nova/physics/stability-elements.html (accessed August 10, 2012).

Phet Interactive Simulations. "Alpha Decay." University of Colorado at Boulder. Accessed August 29, 2013. http://phet.colorado.edu/en/simulation/alpha-decay

Phet Interactive Simulations. "Beta Decay." University of Colorado at Boulder. Accessed August 29, 2013. http://phet.colorado.edu/en/simulation/beta-decay

Phet Interactive Simulations. "Nuclear Fission." University of Colorado at Boulder. Accessed August 29, 2013. http://phet.colorado.edu/en/simulation/nuclear-fission

Phet Interactive Simulations. "Radioactive Dating Game." University of Colorado at Boulder. Accessed August 29, 2013. http://phet.colorado.edu/en/simulation/radioactive-dating-game

## For Professional Development

In addition to watching the videos, reading the text, and going through the activities listed in the course guide, participants taking this course for professional development should read the following papers and answer the corresponding reflection questions. Participants should then complete the accompanying professional development assignments.

## Further Reading and Reflection Questions

Kolomuc, Ali and Sehar Tekin. "Chemistry Teachers' Misconceptions Concerning Concept of Chemical Reaction Rate." *Eurasian Journal of Physics and Chemistry Education.* 3:2 (2011): 84-101. Accessed August 29, 2013. http://eurasianjournals.com/index.php/ejpce/article/viewFile/686/394

1. Were you surprised by the results of this study? Why or why not?

2. Have you held any of the same misconceptions as the teachers in this study? If so, which ones? How did you overcome these misconceptions? Have any of your students held the same misconceptions uncovered by this study? Which ones? How have you addressed those in the past?

3. What are some strategies you could employ to help address the misconceptions uncovered by this study?

Viola, V. E. "Teaching Nuclear Science: A Cosmological Approach." *Journal of Chemical Education.* 71: 10 (1994): 840-844. Accessed August 29, 2013. http://depa.fquim.unam.mx/amyd/archivero/nucleosin2_20646.pdf

1. What are some of the benefits and challenges of presenting nuclear chemistry in the context of cosmology for high school audiences?

2. How could you use the ideas presented in this paper and adapt them to teach nuclear chemistry at a high school level?

## Professional Development Assignments

1. After reading the papers above and reflecting on the questions presented develop a lesson plan designed to teach material presented in this unit.

2. Using a group activity or classroom demonstration presented in this course guide, show how you would implement it into your classroom. Where would it fit into your curriculum or standards? Would you change the demonstration or activity in any way? How would you assess student learning?