13.4 Changes of State

Connecting to Your World Familiar weather events can remind you that water exists on Earth as a liquid, a solid, and a vapor. A spring shower brings liquid raindrops and a winter blizzard delivers solid snowflakes. On a humid summer day, you may be uncomfortable because there is a high concentration of water vapor in the air. As water cycles through the atmosphere, the oceans, and Earth's crust, it undergoes repeated changes of state. In this section, you will learn what conditions can control the state of a substance.

Guide for Reading

Key Concepts

- When can sublimation occur?
- How are the conditions at which phases are in equilibrium represented on a phase diagram?

Vocabulary

sublimation
phase diagram
triple point

Reading Strategy

Predicting In your notebook, predict what causes ice cubes that are left in the freezer for a long time to get smaller.

Sublimation

If you hang wet laundry on a clothesline on a very cold day, the water in the clothes quickly freezes to ice. Eventually, however, the clothes become dry although the ice never thaws. The ice changes directly to water vapor without melting and passing through the liquid state. The change of a substance from a solid to a vapor without passing through the liquid state is called **sublimation.** Sublimation can occur because solids, like liquids, have a vapor pressure. **Sublimation occurs in solids with vapor pressures that exceed atmospheric pressure at or near room temperature.**

Iodine is another example of a substance that undergoes sublimation. This violet-black solid ordinarily changes into a purple vapor without passing through a liquid state. Notice in Figure 13.14 how dark crystals of iodine deposit on the underside of a watch glass placed on top of a beaker containing solid iodine that is being heated. The iodine vapor sublimes from iodine crystals in the bottom of the beaker and condenses to form crystals on the watch glass.

Sublimation has many useful applications. If freshly brewed coffee is frozen and the water vapor is removed with a vacuum pump, the result is freeze-dried coffee. Solid carbon dioxide (dry ice) is often used as a coolant for goods, such as ice cream, that must remain frozen during shipment. Dry ice has a low temperature of −78°C. Because it sublimes, it does not produce a liquid as ordinary ice does when it melts. Solid air fresheners contain a variety of substances that sublime at room temperature. Sublimation is also useful for separating substances. Organic chemists use sublimation to separate mixtures and to purify compounds.

Figure 13.14 When solid iodine is heated, the crystals sublime, going directly from the solid to the gaseous state. When the vapor cools, it goes directly from the gaseous to the solid state.

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 13.4
- **Core Teaching Resources,** Section 13.4 Review, Interpreting Graphics
- **Transparencies,** T148–T149
- **Laboratory Manual,** Lab 22
- **Laboratory Practicals,** 13-1

Technology

- **Interactive Textbook with ChemASAP,** Simulation 14, Assessment 13.4
- **Go Online,** Section 13.4

13.4

1 FOCUS

Objectives

13.4.1 Identify the conditions necessary for sublimation.
13.4.2 Describe how equilibrium conditions are represented in a phase diagram.

Guide for Reading

Build Vocabulary L2

Word Forms The word *sublimation* comes from the Latin word *sublimare*, meaning "to elevate." The meaning of *sublimare* was expanded by the Middle Ages to include "to refine" or purify. The process of sublimation can be used to remove impurities from a substance.

Reading Strategy L2

Use Prior Knowledge After students read this section, have them write a paragraph comparing sublimation to evaporation.

2 INSTRUCT

Connecting to Your World

Explain that rain is the condensation product of water vapor in the atmosphere. Ask students to describe the water cycle in terms of phase changes. *(They should focus on evaporation, condensation, and precipitation.)* Use the discussion to introduce sublimation.

Sublimation

Relate L2

The sublimation of iodine can be used to develop fingerprints found on paper. When iodine vapor is absorbed by fatty acids in sweat, the iodine imparts a yellow-brown color to the ridge pattern. Because the fingerprints tend to fade, they must be photographed or fixed with a reagent such as starch solution.

Quick LAB

Sublimation

L2

Objective After completing this activity, students will be able to:
- describe the process of sublimation.

Skills Focus Observing, inferring, predicting, communicating

Prep Time 15 minutes
Class Time 20 minutes

Safety Perform this activity in a well-ventilated room. Some people are allergic to substances in air fresheners.

Teaching Tips

- Students should not fill the shallow containers to the point where the sublimator floats, to prevent it from tipping over.
- If a colored air freshener is used, the condensed solid will be white.

Expected Outcome The heat from the hot water causes the air freshener to sublime. When the vapor reaches the cold surface of the upper cup, it condenses back into a solid.

Analyze and Conclude

1. the vaporization of a solid
2. At room temperature, there would be less sublimation; at the boiling point, there would be more sublimation.
3. When a substance sublimes in a mixture, other components remain as residue.

For Enrichment

L3

If you used a colored air freshener, ask students to explain why the condensed solid is white. *(The dye does not sublime and remains behind at the bottom of the sublimator.)*

Quick LAB

Sublimation

Purpose

To observe the sublimation of air freshener.

Materials

- small pieces of solid air freshener
- small shallow container
- 2 clear 8 oz plastic cups
- hot tap water
- ice
- 3 thick cardboard strips

Procedure

1. Place a few pieces of air freshener in one of the cups. **CAUTION** *Work in a well-ventilated room.*
2. Bend the cardboard strips and place them over the rim of the cup that has the air freshener pieces.
3. Place the second cup inside the first. The base of the second cup should not touch the air freshener. Adjust the cardboard as necessary. This assembly is your sublimator.
4. Fill the top cup with ice. Do not get any ice or water in the bottom cup.
5. Fill the shallow container about one-third full with hot tap water.
6. Carefully place your sublimator in the hot water. Observe what happens.

Analyze and Conclude

1. Define sublimation.
2. What do you think would happen if the water in the shallow container were at room temperature? If it were boiling?
3. Why is it possible to separate the substances in some mixtures by sublimation?

Interactive Textbook

Simulation 14 Predict the physical states present at different points on a phase diagram.

with ChemASAP

Phase Diagrams

The relationships among the solid, liquid, and vapor states (or phases) of a substance in a sealed container can be represented in a single graph. The graph is called a **phase diagram.** A phase diagram gives the conditions of temperature and pressure at which a substance exists as solid, liquid, and gas (vapor). **The conditions of pressure and temperature at which two phases exist in equilibrium are indicated on a phase diagram by a line separating the phases.**

Figure 13.15 shows the phase diagram for water. In each of the colored regions on the phase diagram, water is in a single phase. The curving line that separates water's vapor phase from its liquid phase are the equilibrium conditions for liquid and vapor. The line also illustrates how the vapor pressure of water varies with temperature. The other two curving lines give the conditions for equilibrium between liquid water and ice and between water vapor and ice. The point on the diagram at which all three curves meet is called the triple point. The **triple point** describes the only set of conditions at which all three phases can exist in equilibrium with one another. For water, the triple point is a temperature of 0.016°C and a pressure of 0.61 kPa (0.0060 atm). Figure 13.16 shows water at its triple point.

By referring to Figure 13.15, you can determine what happens if you melt ice or boil water at pressures less than 101.3 kPa. A decrease in pressure lowers the boiling point and raises the melting point. An increase in pressure will raise the boiling point and lower the melting point.

Checkpoint ***What are the variables that are plotted on a phase diagram?***

Go Online NSTA SciLinks

For: Links on Phase Diagrams
Visit: www.SciLinks.org
Web Code: cdn-1134

Go Online NSTA SciLinks

Download a worksheet on **Phase Diagrams** for students to complete, and find additional teacher support from NSTA SciLinks.

Differentiated Instruction

Less Proficient Readers

L1

The ability to interpret data in graphical format is fundamental to a course in chemistry. To reinforce this skill, have students compare the graph in Figure 13.9 to the graph in Figure 13.15. Ask students which line on the phase diagram corresponds to the curve for water in Figure 13.9. *(the line between liquid water and water vapor)*

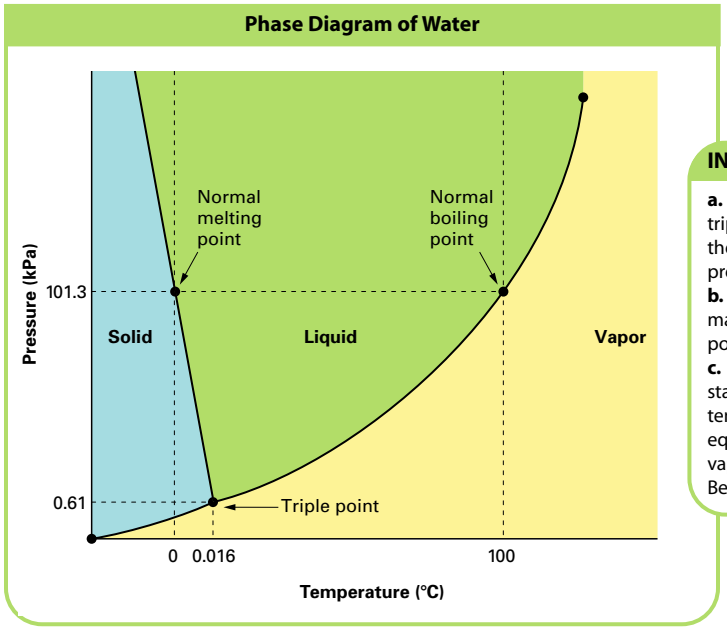

Figure 13.15 The phase diagram of water shows the relationship among pressure, temperature, and physical states of water.

INTERPRETING GRAPHS

a. Analyzing Data At the triple point of water, what are the values of temperature and pressure?
b. Inferring What states of matter are present at the triple point of water?
c. Analyzing Data Assuming standard pressure, at what temperature is there an equilibrium between water vapor and liquid water? Between liquid water and ice?

Look at Figure 13.15. Follow the equilibrium line between liquid water and water vapor to the triple point. Below the triple point, the vapor and liquid cannot exist in equilibrium. Increasing the pressure won't change the vapor to a liquid. The solid and the vapor are in equilibrium at temperatures below 0.016°C. With an increase in pressure, the vapor begins to behave more like a solid. For example, it is no longer easily compressed.

Figure 13.15 also illustrates how an increase in pressure affects the melting point of ice. For years, the accepted hypothesis for how ice skaters move along the ice was the following. The blades of the skates exert pressure, which lowers the melting point of the ice. The ice melts and a film of water forms under the blades of the skates. This film acts as a lubricant, enabling the skaters to glide gracefully over the ice. This hypothesis fails to explain why skiers also glide along very nicely on another solid form of water—snow. Wide skis exert much less pressure per unit area of snow than narrow skate blades exert on ice. Recent research shows that the surface of ice has a slippery, water-like surface layer that exists well below ice's melting point. Even ice that is at −129°C has this layer. A new hypothesis proposes that the liquid-like surface layer provides the lubrication needed for smooth skating and skiing.

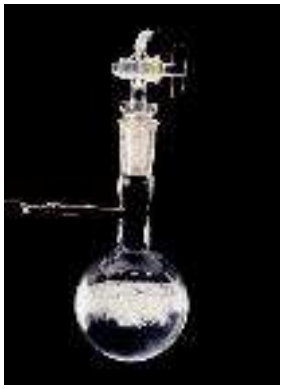

Figure 13.16 At the triple point, ice, liquid water, and water vapor can exist at equilibrium. Freezing, melting, boiling, and condensation can all occur at the same time, as shown in the flask.

Facts and Figures

Freeze-Dried Foods

Astronauts and backpackers use freeze-dried foods because they are lightweight and easily reconstituted by adding water. Freeze-dried foods don't require refrigeration because bacteria cannot multiply in the absence of moisture. The sublimation of ice at low pressure makes the process of freeze-drying possible. Food is frozen and placed in a chamber attached to a vacuum pump. Then the pressure in the chamber is lowered until the ice crystals sublime. Freeze-dried food tends to maintain its flavor because the substances in the food that impart flavor remain in the food as the ice sublimes.

Phase Diagrams

Interpreting Graphs L2

a. 0.016°C and 0.61 kPa
b. solid, liquid, and vapor
c. 100°C; 0°C

Enrichment Question L3

Show students the phase diagram for carbon on R18. Ask, **How many phases of carbon are shown in this diagram?** *(4)* **Which phases are in equilibrium at the two triple points?** *(diamond, graphite, and liquid carbon; graphite, liquid carbon, and carbon vapor)*

Use Visuals L1

Figure 13.15 Display the figure on an overhead projector. Explain that a phase diagram is a convenient way to summarize the conditions of temperature and pressure at which the solid, liquid, and gas phases of a substance are most stable. Point out that each line in the diagram represents the set of possible temperature-pressure values at which different phases are in dynamic equilibrium with one another. For example, in a closed system at 100°C and 101.3 kPa, liquid water is in dynamic equilibrium with water vapor. (Note that the *x*- and *y*-axes are not drawn to scale so that the triple point and normal boiling point can fit on the graph.) Ask, **At what temperature and pressure are the liquid, solid, and vapor phases of water in dynamic equilibrium?** *(0.016°C, 0.61 kPa)*

FYI

There is fourth phase of matter. This phase is called the plasma phase. In the plasma phase, matter consists of positive ions and free electrons. The plasma phase exists only at high temperatures. The glowing gas in a fluorescent lamp, the sun, and other stars are in the plasma phase.

Answers to...

Checkpoint pressure and temperature

Careers in Chemistry

Solid State Chemist

Go Online PHSchool.com

Have students research chemistry-related careers in the library or on the Internet. Students can then construct a table that describes the nature of the work, educational and training requirements, employment outlook, working conditions, and other necessary information.

3 ASSESS

Evaluate Understanding L2

List a series of temperature–pressure values on the board. Have students state which phase of water is most stable under each set of conditions.

Reteach L1

On the board, draw a stoppered, sidearm flask containing water and a chunk of ice. Note that the sidearm is connected to a vacuum pump. The diagram illustrates ice, liquid water, and water vapor in equilibrium. Have a student add an arrow and label to the diagram to represent a phase change. Continue until there are six arrows on the diagram.

Writing Activity

The substance is likely molecular because the bonds between ions are typically stronger than the attractions between molecules.

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 13.4.

with ChemASAP

Solid State Chemist

By now you are familiar with chemical reactions in aqueous solutions and the gaseous state. But did you know that chemical reactions can also take place in solids, without a liquid or a gas?

Reactions that take place in the solid state are extremely useful. These reactions occur during the manufacture of semiconductors for the electronics industry. The device that ignites the gas in a gas grill is made of a type of ceramic called a piezoelectric. This type of ceramic produces a voltage when subjected to mechanical pressure. There is a class of light-sensitive solids called photopolymers. These solids are used to make plates for printing presses that use dry inks instead of water-based inks. A solid-state reaction takes place in lenses that are designed to darken when exposed to light.

Solid state chemists often study crystal structures, superconductors, and semiconductors. They may also study the electrical, magnetic, and optical properties of solid compounds.

Solid state chemists often work at major universities, teaching and doing basic research. Corporations employ them to do pure research or to develop applications for new discoveries in this field. Companies in the petroleum, electronic, and computer industries are a few of the places a solid state chemist might be employed.

To work in this field usually requires an undergraduate or graduate degree in chemistry or chemical engineering. Courses studied include chemistry, physics, and mathematics.

Go Online PHSchool.com

For: Careers in Chemistry
Visit: www.PHSchool.com
Web Code: cdb-1134

13.4 Section Assessment

21. Key Concept What properties must a solid have to undergo sublimation?
22. Key Concept What do the curved lines on a phase diagram represent?
23. Describe one practical use of sublimation.
24. What does the triple point on a phase diagram describe?
25. Using Figure 13.15, estimate the boiling point of water at a pressure of 50 kPa.

Connecting Concepts

Types of Bonding Would you expect a substance that sublimates at or near room temperature to be a molecular substance or an ionic substance? Use what you learned about bonding in Chapters 7 and 8 to explain your answer.

Interactive Textbook

Assessment 13.4 Test yourself on the concepts in Section 13.4.

with ChemASAP

Section 13.4 Assessment

21. Sublimation occurs in solids that have vapor pressures that exceed atmospheric pressure at or near room temperature.
22. The lines show the conditions of temperature and pressure at which two phases exist in equilibrium.
23. freeze-dried coffee, dry ice as a coolant, air fresheners, separating mixtures, and purifying substances
24. The triple point describes the only set of conditions at which three phases can exist in equilibrium.
25. about 60°C

Thin Films

A thin film consists of layers of atoms deposited on a surface at a uniform depth of 10^{-9} m to 10^{-6} m. Engineers can produce thin films with specific electrical properties by varying the element deposited and the thickness of the deposit. **Interpreting** ***Thin films are sometimes referred to as super crystals. What does this imply about their structure?***

Semiconductor microchips Thin films of conducting materials, insulating materials, and semiconducting materials are layered and then etched to make a chip that contains thousands of microcircuits.

Smart windows Layers of transparent thin films, sandwiched between glass, change tint when electrically charged. The original tint returns when the electrical charge is removed.

CDs and DVDs The reflective surface of CDs are bands of thin films that carry digital information as notches on the surface of the film. DVDs increase information storage by using two or more thin-film layers.

PDAs The display of a PDA contains thousands of liquid crystals attached to transparent, thin-film transistors (TFT). Images are produced as each TFT sends a charge to its linked liquid crystal.

Computer monitors Using thin-film transistors and a liquid-crystal display, flatscreen monitors provide sharp images, save space, and are about 60% more efficient than cathode ray monitors.

Thin Films

L3

Purpose

This feature builds on the discussion of crystal structure in Section 13.3.

Background

New research in thin films has centered on the development of single-crystal substrates. A substrate is an underlying template that lines up the atoms of a crystalline thin film grown on it, similar to a waffle iron that confers a grid pattern on batter poured into it while hot. A substrate must have a crystalline structure that matches that of the thin film and that aligns the film's structure so that electrons or light can be conducted through the film. Single-crystal MgO is used with barium titanate as a substrate for optical modulators and switches; with yttrium-barium-copper oxides (YBCO) for superconducting thin films; and with other oxides as a substrate for optical waveguide films. These new substrates are useful because of the important applications of devices made using the thin films that are grown on the substrates. High-temperature superconducting films are currently being developed for a variety of electronic devices such as magnetic sensors for medical, geological, and industrial applications; microwave components for radar and communication technologies; and ultrafast switches, interconnects, and current leads.

Answers to...

Interpreting A thin film is composed of a single crystal.