Diffusion and Effusion

Key Term

Graham’s law of effusion

The constant motion of gas molecules causes them to spread out to fill any container in which they are placed. The gradual mixing of two or more gases due to their spontaneous, random motion is known as diffusion, illustrated in Figure 4.1. Effusion is the process whereby the molecules of a gas confined in a container randomly pass through a tiny opening in the container. In this section, you will learn how effusion can be used to estimate the molar mass of a gas.

**Main idea**

The rates of effusion and diffusion for gases depend on the velocities of their molecules.

The rates of effusion and diffusion depend on the relative velocities of gas molecules. The velocity of a gas varies inversely with the square root of its molar mass. Lighter molecules move faster than heavier molecules at the same temperature.

Recall that the average kinetic energy of the molecules in any gas depends only on the temperature and equals $\frac{1}{2}mv^2$. For two different gases, A and B, at the same temperature, the following relationship is true:

$$\frac{1}{2}M_Av_A^2 = \frac{1}{2}M_Bv_B^2$$

**FIGURE 4.1**

Diffusion  When a bottle of perfume is opened, some of its molecules diffuse into the air and mix with the molecules of the air. At the same time, molecules from the air, such as nitrogen and oxygen, diffuse into the bottle and mix with the gaseous scent molecules.

**CRITICAL THINKING**

Deduce As diffusion occurs, what would you expect to see happen to the different molecules in the figure at the right?
From the equation relating the kinetic energy of two different gases at the same conditions, one can derive an equation relating the rates of effusion of two gases with their molecular mass. This equation is shown below.

\[
\frac{\text{rate of effusion of } A}{\text{rate of effusion of } B} = \sqrt{\frac{M_B}{M_A}}
\]

In the mid-1800s, the Scottish chemist Thomas Graham studied the effusion and diffusion of gases. The above equation is a mathematical statement of some of Graham’s discoveries. It describes the rates of effusion. It can also be used to find the molar mass of an unknown gas. **Graham’s law of effusion** states that the rates of effusion of gases at the same temperature and pressure are inversely proportional to the square roots of their molar masses.

Quick LAB DIFFUSION

**QUESTION**
Do different gases diffuse at different rates?

**PROCEDURE**
Record all of your results in a data table.

1. Outdoors or in a room separate from the one in which you will carry out the rest of the investigation, pour approximately 10 mL of the household ammonia into one of the 250 mL beakers, and cover it with a watch glass. Pour roughly the same amount of perfume or cologne into the second beaker. Cover it with a watch glass also.

2. Take the two samples you just prepared into a large, draft-free room. Place the samples about 12 to 15 ft apart and at the same height. Position someone as the observer midway between the two beakers. Remove both watch glass covers at the same time.

3. Note whether the observer smells the ammonia or the perfume first. Record how long this takes. Also, record how long it takes the vapor of the other substance to reach the observer. Air the room after you have finished.

**DISCUSSION**

1. What do the times that the two vapors took to reach the observer show about the two gases?

2. What factors other than molecular mass (which determines diffusion rate) could affect how quickly the observer smells each vapor?

**MATERIALS**
- household ammonia
- perfume or cologne
- two 250 mL beakers
- two watch glasses
- 10 mL graduated cylinder
- clock or watch with second hand

**SAFETY**
Wear safety goggles and an apron.

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Graham's Law of Effusion

Sample Problem J  Compare the rates of effusion of hydrogen and oxygen at the same temperature and pressure.

1. **ANALYZE**
   - **Given:** identities of two gases, H₂ and O₂
   - **Unknown:** relative rates of effusion

2. **PLAN**
   - molar mass ratio → ratio of rates of effusion
   - The ratio of the rates of effusion of two gases at the same temperature and pressure can be found from Graham's Law.
     \[
     \frac{\text{rate of effusion of } A}{\text{rate of effusion of } B} = \frac{\sqrt{M_B}}{\sqrt{M_A}}
     \]

3. **SOLVE**
   - \[
   \frac{\text{rate of effusion of } H_2}{\text{rate of effusion of } O_2} = \frac{\sqrt{M_{O_2}}}{\sqrt{M_{H_2}}} = \frac{\sqrt{32.00 \text{ g/mol}}}{\sqrt{2.02 \text{ g/mol}}} = \frac{\sqrt{32.00 \text{ g/mol}}}{\sqrt{2.02 \text{ g/mol}}} = 3.98
   \]
   - Hydrogen effuses 3.98 times faster than oxygen.

4. **CHECK YOUR WORK**
   - The result is correctly reported to three significant figures. It is also approximately equivalent to an estimated value of 4, calculated as \(\sqrt{32}/\sqrt{2}\).

**Practice**  Answers in Appendix E

1. Compare the rate of effusion of carbon dioxide with that of hydrogen chloride at the same temperature and pressure.

2. A sample of hydrogen effuses through a porous container about 9 times faster than an unknown gas. Estimate the molar mass of the unknown gas.

3. If a molecule of neon gas travels at an average of 400. m/s at a given temperature, estimate the average speed of a molecule of butane gas, C₄H₁₀, at the same temperature.

**SECTION 4 FORMATIVE ASSESSMENT**

**Reviewing Main Ideas**
1. Compare diffusion with effusion.
2. State Graham's law of effusion.
3. Estimate the molar mass of a gas that effuses at 1.6 times the effusion rate of carbon dioxide.
4. Determine the molecular mass ratio of two gases whose rates of effusion have a ratio of 16 : 1.

5. List the following gases in order of increasing average molecular velocity at 25°C: H₂O, He, HCl, BrF₅, and NO₂.

**Critical Thinking**
6. **ANALYZING INFORMATION** An unknown gas effuses at one-half the speed of oxygen. What is the molar mass of the unknown? The gas is known to be either HBr or HI. Which gas is it?