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Experiment 13

Diffusion in Solids, Liquids, and Gases

David Johnson

Notes for Instructors

Purpose

To estimate the relative diffusion rates for gases, liquids, and solids.

Method

Measure the time that it takes for molecular or atomic motion to occur over a certain distance for vanilla (vapor), propylene glycol in water (liquid), and Cu^{2+} in glass (solid).

Materials

Stopwatch or timer

Vanilla extract

Red food coloring (McCormick Red Food Color contains water, propylene glycol, FD&C red No. 40 and FD&C red No. 3)

Petri dish

Short pieces of 1/4-inch o.d. glass rod (a stirring rod)

Copper(II) chloride, $CuCl_2{\cdot}2H_2O$ (m.p. 435 °C)

Test tube

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Bunsen burner

Crucible tongs

Results

Estimates of the diffusion coefficient, *D*, in units of cm^2/s for a gas, liquid, and solid are 10^{-1}, 10^{-3}, and < 10^{-7} (at 500 °C), respectively. The estimate for the liquid state can be quite large and probably indicates that some mechanism of mixing in addition to diffusion is contributing to the molecular motion observed.

Diffusion in Solids, Liquids, and Gases

Purpose

To estimate the relative diffusion rates for gases, liquids, and solids.

Introduction

Diffusion is an important chemical and physical phenomenon that has a bearing on our daily lives. Diffusion of gases and other molecules across membranes in our bodies allows many biological processes to occur and thus keeps us alive by providing oxygen and energy sources to our cells. Paint dries because water or a solvent can diffuse to the surface and evaporate. Diffusion is one of the ways in which molecules move across large distances. Molecules can also move in other ways such as when a mechanical fan is used to draw fresh air into a room.

Perhaps one of the most interesting uses of diffusion is the enhancement of the color of gemstones such as rubies and sapphires. These two gemstones, which are important for manufacturing lasers, microcircuits, and even the glass plates above supermarket checkout scanners, are aluminum oxide with various metal oxides as impurities and can be synthetically prepared. Miners of sapphires and rubies have long known that the color of poor-quality stones can be enhanced by packing them in titanium and iron oxides (for blue color) or chromium oxide (for red color) and baking them at temperatures near 2050 °C, the melting point of the aluminum oxide crystal that makes up most of the stone. This procedure turns low-grade gems into colorful, high-quality stones. Similar procedures are used in making some types of stained glass.

The process of diffusion can depend on many factors. Some of these factors are temperature, pressure, the size and mass of the diffusing species, and the state of the material (whether it is a gas, liquid, or solid). All of these factors can affect the speed at which the two materials are intermixed, as well as the distance that one material can diffuse into another. Increasing the temperature increases the kinetic energy of atoms and molecules and can dramatically increase the rate of diffusion. Within a few hundred degrees of room temperature, the rate of diffusion of ions in solution doubles for every increase of 10 °C.

The velocity of a typical molecule near room temperature is very high - 100 to 1000 m/second. Yet it can take minutes, hours, or even years for molecules to diffuse a few centimeters. How can this be?

In a gas, collisions between molecules occur about every 10^{-7} m and cause the molecules to change directions. Therefore, a long and tortuous

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NOTE: This experiment was written by David Johnson, Department of Chemistry, University of Oregon, Eugene, OR 97403. We acknowledge helpful comments from Mark Ediger, Department of Chemistry, University of Wisconsin—Madison.

path must be followed in order to go 1 m in any particular direction.

Diffusion in a liquid is similar to diffusion in a gas except that the molecules are much closer together. They may travel only 10^{-10} m before a collision causes them to change direction. In addition, "cages" formed by surrounding molecules may trap the molecule in one place for many collisions. Thus, diffusion occurs at a slower rate. If some ink were dropped in a container of water, the molecules of the ink would undergo billions of collisions before they reached the edges of the container.

The atoms in the solid for the most part simply vibrate in a fixed position. This being the case, how can diffusion occur? The crystal structure of a solid has vacancies in it, whose concentration is governed by chemical equilibrium. (The concentration generally increases rapidly with increasing temperature.) The vacancies allow some atoms to diffuse through the solid, as shown in Figure 1.

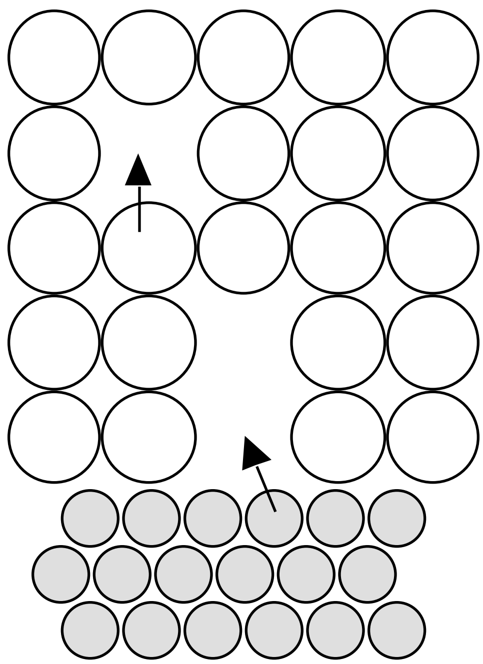

Figure 1. Solid diffusion. The atoms of one solid (open circles) can migrate into vacancies, allowing the atoms of the second solid (shaded circles) to diffuse into the first solid. If the atoms are small enough, they may be able to fill vacancies by migrating between the atoms of the first solid.

In this lab you will measure the time required for molecules, or atoms, to move over a certain distance in the gas, liquid, and solid phases. From this information you will be able to estimate the diffusion coefficient in each of these states. Mechanical mixing may occur during some measurements, and can lead to overestimates of the diffusion constant.

Warm-up Exercise

If you were to try to enhance the color of a sapphire by heat treatment (that is, by packing a piece of sapphire in titanium oxides and iron oxides and heating it to about 2000 °C), you would find that it takes 600 hours at this temperature for the color to diffuse 0.4 mm. Calculate the value of the diffusion coefficient, *D*, in units of cm^2/s.

Procedure

Wear eye protection.

Diffusion Between Two Gases

You will need to be in a group of four for this part of the experiment. Find an area of the lab where no one is working and where there are few or no drafts. Have each person stand in a line with 1 m between each person, as shown in Figure 2. The first person will open the bottle with vanilla and pour a few drops on a paper towel on the table or bench top.

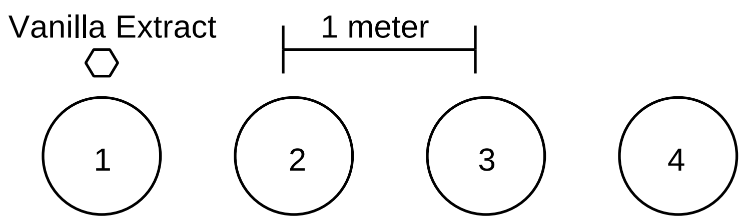

Figure 2. Arrangement of people (1–4) for the gaseous diffusion experiment.

Record the time required for each person (corresponding to a different distance) to smell the vanilla (Table 1). Discard the paper towel in a plastic bag when finished with a trial. Repeat the experiment twice more (after the odor has dissipated).

Table 1. Laboratory Data for Diffusion between Two Gases

Distance (m)	Trial 1 Time (seconds)	Trial 2 Time (seconds)	Trial 3 Time (seconds)
1			
2			
3			

Diffusion Between Two Liquids

You will need a Petri dish, a stopwatch, and the bulls-eye diagram in Figure 3. Fill the Petri dish with room temperature water and center it on the diagram. Wait at least several minutes for the water to stop moving. Put some food coloring (dissolved in an aqueous solution of propylene glycol) in a dropper. Holding the dropper upright, lower the end of the dropper under the surface of the water and inject a couple of drops of coloring in the center circle of the diagram. Start the stopwatch when the colored ring crosses the first circle. Record the time that the color crosses each of the next rings until you can no longer see the ring clearly (use Table 2, try to get four or five data points). The rings are 0.5 cm apart.

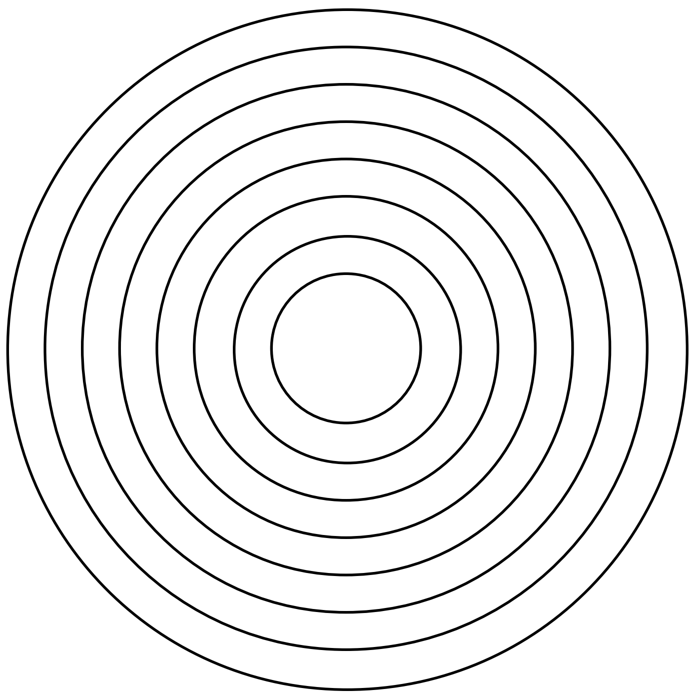

Figure 3. Bulls-eye for liquid diffusion experiment.

Table 2. Laboratory Data for Diffusion between Two Liquids

Distance (cm)	Trial 1 Time (seconds)	Trial 2 Time (seconds)	Trial 3 Time (seconds)
0.5			
1.0			
1.5			
2.0			

Rinse out the Petri dish and repeat the experiment twice.

Calculations

Calculate the average time for each of the distances in the gas and liquid diffusion experiments.

The diffusion coefficient, *D*, is proportional to velocity times distance or to (distance)^2 per time. *D* has the units square centimeters per second. Estimate *D* for both the gas and the liquid diffusion.

Diffusion in Solids

Partly fill a test tube with $CuCl_2 \cdot 2H_2O$. **CAUTION: Hydrogen chloride gas is produced when $CuCl_2 \cdot 2H_2O$ is heated. Do this experiment under a fume hood.**

Gently heat the test tube with a Bunsen burner. Adjust the heat to melt the copper chloride without spattering. You may be able to hear the $CuCl_2$ crackle as it starts to melt (m.p. 435 °C).

Obtain a glass rod that is a little longer than the height of the test tube. Put one end of the glass rod into the liquid copper chloride for at least 10 minutes. Record the actual time the glass is in contact with the melt. **CAUTION: Be careful of the molten copper chloride and the test tube. They are VERY HOT!**

Turn off the Bunsen burner. Remove the glass rod from the test tube and place on a flame-resistant surface for a few minutes to cool.

Rinse the glass rod in water and observe the color. If you wish to make the color more defined, heating the glass in the yellow (reducing) part of a Bunsen burner flame will turn the glass red. After the glass has cooled, carefully cut the glass so that you can see a cross-section of the rod. Try to observe how far into the glass the Cu^{2+} ions were able to travel. Estimate the value of *D* as before.