MOLECULAR MOTION
Science Key Concepts Series: Chemistry/Physics

FOR USE IN: Chemistry/Physics Grades 9-14
EDUCATIONAL ADVISOR: Dr. O. Roger Anderson, Columbia University, Professor Natural Sciences, Teachers College; and Senior Research Scientist, Lamont-Doherty Earth Observatory

EDUCATIONAL OBJECTIVES

To help the student understand these key concepts about molecular motion:
- characteristic molecular properties of the states of matter
- the kinetic theory of solids, liquids and gases
- the smoke cell and Brownian motion
- diffusion in gases and liquids
- changes of state and the energy transfers which accompany them.

BACKGROUND INFORMATION

Matter can exist in three states - solid, liquid, and gas. In a solid the species, whether it is the ions of an ionic solid or the molecules of a molecular solid, are packed tightly together with only vibrational movement as the species move against each other in position. This is potential energy - energy of position. Potential energy is stored in ionic compounds in the bonds between the positive and negative ions that are attracted to each other. (Oppositely charged species attract each other.) The oppositely charged ions in an ionic solid form a crystalline structure. In a molecular solid, forces of attraction exist between molecules that are called intermolecular attractions. However small the attraction is, it still relies on a force of attraction between areas of positive and negative charge on the molecules.
In liquids, the species are farther apart than in a solid, but not as far apart as in a gas. Liquids can flow and they assume the shape of the container up to the volume of the liquid. Since liquids can flow, there are more possibilities for movement between the molecules, whether it is molecules in the liquid state or ions produced from melting an ionic solid.
Gases are made up mostly of empty space, so the species are far apart. The species could be molecules or gaseous ions produced from an ionic solid. The species occupy all parts of any volume they are confined to as they diffuse into a space and spread out, whether it is in a stoppered bottle or the atmosphere. Because the particles are far apart, they can also be compressed into a smaller space by exerting pressure on the gas. If they are compressed enough, forces of attraction can result in the gas changing to a liquid. Pressure and a lower temperature might be necessary for the gas to form a liquid and ultimately a solid.
The particles of a gas are in constant motion with the particles colliding with each other and also the walls of a container. The gaseous species do not exert any attractive or repulsive forces on one another between collisions. If two molecules are compared, one that is heavier than another, the heavier molecule will move slower than the lighter molecule. Therefore, there is an inverse relationship between the weight of a molecule and the speed with which it moves. Energy of motion is kinetic energy and its value can be calculated from the mass of a molecule and the velocity of the molecule.
The process of diffusion is one of movement. This is illustrated as gas molecules diffuse such as a perfume sprayed into the air and the perfume molecules move from an initial higher concentration to a lower concentration as they occupy the space into which they have been sprayed. As they spread out, they collide with air molecules.
Without the interference of other molecules, they would be able to diffuse more quickly. If the temperature was increased, the molecules would also be able to move more quickly. A higher temperature would affect the velocity of the molecules and therefore the kinetic energy, or energy of motion, of the molecules. A similar process of diffusion could also occur as an ionic solid dissolved in water and ions were produced in solution.
If some of the ions had colour, movement of the ions as they dissolved could be observed as they spread out in the water. As before, the process could be speeded up if the solution was heated.

The video contains the following key concepts. To play only concepts 2 or 3, simply fast-forward to its title.

	min: sec
1. Brownian Motion	4:40
2. Diffusion	5:05
2. Changes of State	4:24

The concepts are illustrated with imaginative demonstrations, which are too dangerous costly, or complicated to be done in the classroom. Computer animation, graphics, positioned captions, and live photography, clarify and provide context for the concepts.

Brownian Motion

Properties of the three states of matter
Solids, liquids and gases represent three states of matter. They have characteristic properties.
An introduction to molecular theory
The arrangement and motion of molecules in the three states of matter.
Evidence for the particle theory - Brownian motion
The behaviour of smoke particles observed through a microscope provides evidence for the random movement of molecules in the air. This effect was discovered in the 1820s, by Robert Brown, who observed a comparable movement of pollen grains suspended in water.

Diffusion

The diffusion of gases in air
Diffusion is illustrated by the behaviour of bromine vapour in an air-filled gas jar. It can be simply explained in term of the molecular model of gases.
Gaseous diffusion in a vacuum

Bromine vapour diffuses much faster in a vacuum, when there are no molecular collisions between the air and bromine.

Comparing the rates of diffusion of gases

Gases diffuse at different rates. Nitrogen dioxide molecules diffuse faster than bromine molecules, which are heavier. We can also compare the rates of diffusion of colourless gases such as ammonia and hydrogen chloride. When these gases meet, they form a white smoke of ammonium chloride, marking the distance each has diffused.

Diffusion In liquids

Diffusion also occurs in liquids. The rate of diffusion of one liquid in another increases as the temperature rises.

Changes of State

Energy transfer during melting

We can use simple molecular theory to interpret the change of state which occurs during melting. A simple demonstration shows that an energy transfer accompanies this change of state.

Energy transfer during evaporation

The molecular theory also explains what happens during evaporation. Here again, a substance absorbs energy, as it undergoes a change of state. A simple demonstration shows that some liquids take more energy from their surroundings than others when they evaporate.

Condensation

Cooling a gas produces a liquid. If air is cooled using liquid nitrogen, we get liquid air. Cooling carbon dioxide gas with the same coolant produces solid carbon dioxide. This changes directly from solid to gas when it warms up.

AFTER SHOWING THE VIDEO

Brownian Motion

This motion can be observed as gas molecules collide with other gas molecules or as solid particles move through liquid. The motion tells us that both gases and liquids can move, though gases have more possibilities for movement than liquids. This can be observed in a movie theatre where the light comes out of the projector through the movement of dust particles as they bump against air molecules. Albert Einstein used the observations of Robert Brown to propose that molecular movement can exist on a microscopic scale.

Movement of Bromine

At room temperature bromine exists as a liquid. It is dark red in colour. When bromine is transferred from one container to another closed container, evaporation of liquid bromine can be observed as bromine gas fills the new container. The equation for this reaction is:

$$Br_2(1) \Leftrightarrow Br_2\ (g)$$

As long as the container is closed, both evaporation of liquid bromine to gas and condensation of gaseous bromine to liquid will take place. The process of evaporation can take place more quickly if there are only bromine molecules present and no other molecules such as air. This is because the presence of other molecules interferes with the movement.

Small and Large Molecules

Small and large molecules refers to the mass of the molecules. Ammonia, NH_3, molecules have a molecular mass of 17.0 grams per 1 mole of molecules. Hydrogen chloride, HCl, molecules have a mass of 35.5 grams per 1 mole of molecules. One mole of molecules is 6.02×10^{23} molecules, a very big number. The lighter weight ammonia molecules can travel at a faster speed than the heavier hydrogen chloride molecules. Therefore, there is an inverse relationship between weight and speed. It makes sense that heavier molecules would not be able to travel as fast as lighter weightier molecules. The reaction between the two molecules is:

$$HCl\ (g) + NH_3\ (9) \rightarrow NH_4\ Cl\ (s)$$

Even though a white cloud is observed in the video and it looks like smoke, it is actually solid ammonium chloride, NH_4 Cl. A white ring of the solid forms in the tube.

The relationship between the speed of HCl compared to NH_3 is equal to the square root of 35.5 divided by 17.0 or 1.45. This basically means that ammonia could travel 1.45 times as fast as hydrogen chloride. If a tube 1 meter in length was used with ammonia at one end and hydrogen chloride at the other end, the distance ammonia travels could be represented as x and for hydrogen chloride, its distance would be 1 meter - x

Setting up a proportion: $$\frac{x}{-x} = \frac{1.45}{1}$$

Solving the proportion, x = 0.593 m. or 59.3 cm. This means that ammonia would travel 59.3 cm from its end and hydrogen chloride would travel 40.7 cm (l -x). The ammonia traveled faster and moved a greater distance. Verification that ammonia is a base and hydrochloric acid is an acid was illustrated using litmus paper. Red litmus paper turns blue in base and blue litmus paper turns red in acid.

Diffusion of Crystalline Potassium Permanganate

The equation for the dissolving of potassium permanganate, KM_nO_4, in water and the formation of a solution (aq) is:

$$KM_nO_4\ (s) \rightarrow K^+\ (aq) + M_nO_4\ (aq)$$

Though aqueous potassium ions, K^+, are colourless, aqueous permanganate ions, M_nO_4 ions are purple. The diffusion of the purple ions can be observed in the video because of the ability of liquids to flow and move. As the temperature is increased, molecules of water can travel at a greater velocity and the ions can diffuse faster.

Melting and Evaporation

The process of a solid substance melting to form a liquid and the liquid evaporating to form a gas, requires heat energy from the surroundings. This is observed in the video when the temperature in the surroundings decreases as the ice melts. The surroundings get colder (the temperature goes down) and the loss of heat energy by the surroundings is gained by the solid and used to melt the solid. Additional heating of the liquid results in evaporation of the liquid to form a gas. This is represented by:

$$H_2O\ (s) \rightarrow H_2O\ (l) \rightarrow H_2O\ (g)$$

Evaporation of Different Liquids

Liquids evaporate at different rates. The rate of evaporation depends on the strength of the intermolecular forces that hold the liquid together. If the forces are stronger, the liquid does not evaporate as fast as another liquid with weaker forces of attraction between the molecules.

Freezing and Deposition

Liquid nitrogen (boiling point = -196°C) is cold enough that air trapped inside of a balloon will solidify, or freeze when the balloon filled with air is submerged into the liquid nitrogen. The equation is:

$$\text{Air (g)} \rightarrow \text{Air (l)}$$

However, a balloon filled with carbon dioxide gas behaves differently. When the balloon is submerged into liquid nitrogen, solid carbon dioxide forms, not the liquid. The equation is:

$$C0_2\text{ (g)} \rightarrow C0_2\text{ (s)}$$

This process is known as deposition, the depositing of solid.

There were several questions addressed in the video that were not answered.

1. Why does a solid melt when it gets warm enough?
   Heating a solid overcomes the potential energy that exists between the particles of the solid. When the attractive forces have been overcome, a liquid is formed that can move. It now has more kinetic energy.
2. Which substance takes the most energy from its surroundings: water, ethanol, or ether?
   There are stronger intermolecular forces between water molecules than there are between ethanol or ether molecules. The weakest intermolecular forces exist between ether, followed by ethanol, and then water molecules, It requires more energy from the surroundings for water, with its strong intermolecular forces, to evaporate than it does for the other two substances.

EXPLORING AND INVESTIGATING

1. Measure the amount of heat energy involved in the melting of an ice cube of a specific weight. Design a procedure to do this experiment. Heat energy is calculated using the following: Temperature change x Mass of ice x Specific heat of ice .
2. Design an experiment to observe the difference in the evaporation rates of ethanol and water.
3. Record your observations as alka seltzer dissolves in cold water and hot water. Explain your observations.

Caution: observe all safety regulations of your school when doing experiments in the laboratory. Check with the appropriate officer in your school before doing these experiments.

Guide written by

Dr. Julie Ealy and James Ealy, Teachers College, Columbia University

The Science Key Concepts Series consists of 16 videos:
<u>for Biology</u>: Cells and Tissues, Cellular Energy and Metabolism, Energy Transfer & Biogeochemical Cycles, Homeostasis, Sensory Responses and Tropisms
<u>for Physics</u>: Electricity and Magnetism, The Electromagnetic Spectrum, Force and Motion, Molecular Motion, Waves
<u>for Chemistry:</u> Applied Chemistry, Electrochemistry, Radioactivity, Reactions and Energy Changes, Reactivity of Elements, Uses of Natural Resources

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MARLIN MOTION PICTURES LTD.
211 Watline Avenue
Mississauga ON L4Z 1P3
Phone: 905-890-1500 or 1-800-865-7617
Fax: 905-890-6550 or 1-800-203-8786
Email: info@marlineducation.com
Website: www.marlineducation.com