The Kinetic-Molecular Theory of Gases

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CHAPTER 1

The Kinetic-Molecular Theory of Gases

Lesson Objectives

- Describe kinetic energy as it applies to molecules.
- Explain how kinetic energy is related to the mass and velocity of a particle.
- Describe the nature of elastic collisions and the implications for matter at the molecular level.
- Describe the origins and assumptions of the kinetic-molecular theory, and use this model to describe the nature of matter at the molecular level.
- Describe ideal behavior as it applies to a gas.

Lesson Vocabulary

- **kinetic energy**: The energy associated with motion.
- **elastic collision**: A collision in which momentum is conserved.
- **kinetic-molecular theory**: Describes the molecular behavior of an ideal gas.
- **ideal gas**: Gases that conform to the kinetic-molecular theory.

Check Your Understanding

- What are the similarities and differences between different states of matter?

Introduction

Ice, water, and steam appear quite differently to the eye. If you were to look at these three states of matter on the molecular level, you would see that the arrangement of molecules is very different here as well. However, solids and liquids have definite volumes, unlike gases which tend to take on the shape of their container. In this lesson, you will learn about the unique behavior of gas particles on a molecular level and the basis for kinetic molecular theory.

States of Matter - A Microscopic View

If we see matter at the macroscopic level, we can easily tell whether it is solid, liquid, or gas. In **Figure** 1.1, we see a green chlorine gas-liquid equilibrium. The various states of matter can largely be explained by studying interactions between particles that occur at the microscopic level. **Figure** 1.2 shows how the three states of matter differ on the molecular level.

FIGURE 1.1
Chlorine gas.

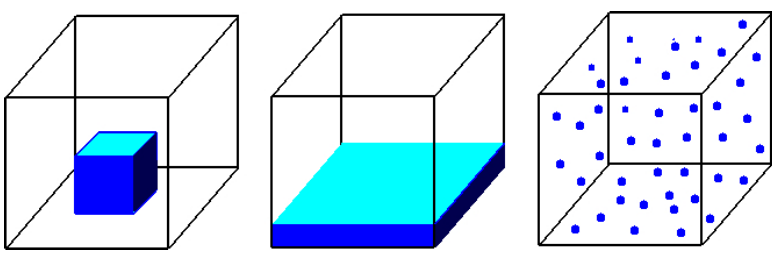

FIGURE 1.2
In this image, we see how atoms of argon interact in the solid, liquid, and gas phases.

As we saw in our chapter on the mole, matter is ultimately composed of particles. We cannot "see" individual molecules, but we can see the effects exerted by the structure of each molecule on the behavior of the bulk material. What accounts for the very different properties exhibited by the same substance when it exists in different phases of matter? The sizes and properties of individual atoms and molecules do not change when a substance changes phase. Rather, it is the interactions between particles that are changing.

Liquids and Solids

As shown in **Figure** 1.2, each state of matter looks quite different at the molecular level. In the case of liquids and solids, the distances between particles are negligible relative to the size of each particle; they are essentially in direct contact with one another. In liquids, particles are free to move and exchange neighbors, resulting in the properties of a fluid. In solids, they are rigidly fixed in space and held tightly to neighboring particles.

Gases

The story is quite different for gases. Gases take the shape of their container, and they are relatively easy to compress. There are fewer gas particles per unit volume than for the same substance in the liquid or solid form. In fact, the liquid form of a given material is generally several hundred times more dense than the gas form at normal pressures. Despite the large amounts of empty space, a sample of a gas contains many particles moving around, colliding and imparting force on their surroundings. For example, in a one mole sample of gas at 0°C and 1 atm of pressure, each cubic centimeter contains roughly 2.7×10^{19} molecules. Each molecule participates in several billion collisions every second, moving only about 10-100 nanometers between collisions. Additionally, these gas particles move at very high speeds. For example, at 25°C, the average speed of hydrogen molecules in a sample of hydrogen gas is 1960 m/s.

These are just some of the differences we see when we look at the molecular level and study the different states for a particular chemical species. The following simulation illustrates how particles behave over time in the liquid, solid, and gas states: http://phet.colorado.edu/en/simulation/states-of-matter .

In this simulation, you can watch different types of molecules form a solid, liquid, or gas. Add or remove heat to watch the phase change. Change the temperature or volume of a container and see a pressure-temperature diagram respond in real time.

One of the concepts shown by this animation is that particles are constantly moving and vibrating. This is an important assumption that we make when we study matter at the molecular level. Anything that is moving and has mass also possesses some amount of **kinetic energy**, or the energy of motion. Kinetic energy increases as the molecular mass increases and as the velocity of the particle increases.

Another thing we can see in this animation is that particles are constantly colliding with one another. One assumption that we make when talking about collisions between gas particles is that they are completely elastic collisions. In an **elastic collision**, momentum is conserved, which means that none of the kinetic energy of the colliding particles is lost in some other form (such as the emission of light). This makes sense, because if energy were lost in collisions, the speeds of the particles would gradually decrease over time, and eventually everything would condense down into a solid form.

The Kinetic-Molecular Theory of Gases

Some of the observations and assumptions we just made about particle behavior at the molecular level were proposed in independent works by August Kroning (1856) and Rudolf Clausius's 1857 work titled "the theory of moving molecules." This work became the foundation of the **kinetic-molecular theory** of gases. The kinetic-molecular theory of gases makes the following assumptions:

1. Gases are comprised of large numbers of particles that are in continuous, random motion and travel in straight lines.
2. The volume of gas particles in a sample is extremely small compared to the total volume occupied by the gas.
3. Attractive and repulsive forces between gas molecules are negligible.
4. Energy can be transferred between molecules during collisions. Collisions are completely elastic.
5. The average kinetic energy of the molecules is proportional to the temperature of the sample.
6. Gases that conform to these assumptions are called **ideal gases**.

By applying these principles to gases, it is possible to show that the properties of gases on the macroscopic level are a direct result of the behavior of molecules on the microscopic level.

Lesson Summary

- Differences between solids, liquids, and gases depend upon the interactions between the individual particles.

- Kinetic energy is directly proportional to the mass and velocity of a particle; that is, as mass and/or velocity increase, so does the kinetic energy.
- The kinetic-molecular theory describes the behavior of an ideal gas.
- Assumptions of the kinetic-molecular theory include the following:
  - Gas particles are in constant, random motion.
  - The volume of gas particles is negligible in comparison to the volume of the container.
  - There are no attractive forces between gas particles.
  - Collisions of gas particles are elastic, so no energy is lost.
  - The speed of a gas particle is directly proportional to the temperature of the system.

Lesson Review Questions

1. What do we mean when we say molecular view of matter? Can you draw a diagram to describe what particles might look like at the molecular level for solids, liquids, and gases?
2. What is kinetic energy? Does kinetic energy increase or decrease as particle speed increases?
3. Describe what is meant by an elastic collision. What would happen to particles over time if most collisions were not elastic?
4. Summarize the major points of the kinetic-molecular theory.
5. How are ideal gases and the kinetic-molecular theory related?
6. Determine whether or not the following gases would be ideal; that is, do they fit the points of kinetic-molecular theory?
   a. As a gas is heated, its particles start to move more slowly.
   b. When one gas particle bumps into another, no energy is lost.
   c. The gas particles follow predictable, circular paths within a container.

Further Reading / Supplemental Links

- Brenner, H. C. (1992). The kinetic molecular theory and the weighing of gas samples. Journal of Chemical Education, 69(7), 558-null. doi: 10.1021/ed069p558
- Hildebrand, J. H. (1963). An introduction to molecular kinetic theory - Selected topics in modern chemistry The University of California, Berkeley. New York: Reinhold Pub. Corp.
- Timm, J. A. (1935). The kinetic-molecular theory and its relation to heat phenomena. Journal of Chemical Education, 12(1), 31-null. doi: 10.1021/ed012p31
- TedEd "The Invisible Properties of Gases": http://www.youtube.com/watch?v=EHxdVtygP1g

Points to Consider

- One of the assumptions of the kinetic-molecular theory is that collisions between particles are elastic –that momentum is conserved. Can you think of collisions you have witnessed in your everyday life that are completely elastic? Are collisions that you typically see elastic or not? Give examples.

References

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2. Courtesy of NASA. http://exploration.grc.nasa.gov/education/rocket/state.html . Public Domain