States of Matter
Part I. The Three Common States: Solid, Liquid and Gas

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Abstract

There are three basic states of matter that can be identified: solid, liquid, and gas. Solids, being compact with very restricted movement, have definite shapes and volumes; liquids, with less compact makeup have definite volumes, take the shape of the containers; and gases, composed of loose particles, have volumes and shapes that depend on the container. This paper is in two parts. A short description of the common states (solid, liquid and gas) is described in Part I. This is followed by a general observation of three additional states (plasma, Bose-Einstein Condensate, and Fermionic Condensate) in Part II.

Keywords: *Ionic solids, liquid crystals, London forces, metallic solids, molecular solids, network solids, quasicrystals***.**

Introduction

This paper is in two parts. The common or usual states of matter: solid, liquid and gas or vapor[1], are mentioned in Part I; and the three additional states: plasma, Bose-Einstein condensate (BEC), and Fermionic condensate are described in Part II.

Solid formation occurs when the attraction between individual particles (atoms or molecules) is greater than the particle energy (mainly kinetic energy or heat) causing them to move apart. The particles are locked in positions near each other, so that solids have defined shapes and volumes. The particles of solids are still in motion, but they remain fixed in place and only vibrations take place.

Liquids are formed when the particle energy is increased and the rigid solid structure breaks down. Liquid particles can slide past one another and collide with other particles, but they remain close to each other. Thus liquids can 'flow' to take the container shape but they cannot be readily compressed. Therefore liquids have defined volumes but undefined shapes.

Gases are formed when energy exceeds attraction between molecules. Particles move quickly and freely in all directions spreading out everywhere within the container. Gases can be compressed easily and they have undefined shapes.

It is well known that heating will cause substances to change state - state conversion, in accordance with their enthalpies of fusion ΔH_f or vaporization ΔH_v, or latent heats of fusion and vaporization. For example, ice will be converted to water (fusion) and thence to vapor (vaporization). What happens if a gas is super-heated to very high temperatures? What happens if it is cooled to near absolute zero temperatures? Such curiosity led to the discoveries of plasma in 1879; Bose-Einstein condensate (BEC) in 1995; and to the first observation of the Fermionic condensate in 2003.

Plasmas are hot ionized gases. High energy of plasmas causes stripping of electrons from individual atoms forming a gas of charged ions. The center of stars such as the sun is the most common place that plasmas can be found. The Sun is a 1.5 million kilometer ball of plasma, heated by nuclear fusion. But plasma exists in many ordinary things also, such as neon lights and fluorescence lights.

Bose-Einstein Condensates (BEC) are super cooled materials that exist at temperatures close to absolute zero. In this state all atoms jump into a single quantum-mechanical state, forming a giant super atom.

[1] The gas state of a substance that is a liquid or solid at normal temperatures and pressures (101.3 kPa).

The Fermionic Condensates are superfluid phases formed by fermions at near absolute zero temperatures. The formation is analogous to electrons in a superconductor.

This paper is based on the technical reports submitted by the student[2] of semester 1/2004, as part of the requirement for general chemistry CT 1101, Faculty of Science and Technology, Assumption University. It is a short description of the common and additional states of matter.

The Common States of Matter

The relative compactness of the three common states, made up of particles of atoms, molecules or ions is shown in figure 1. The solid state is most densely packed and the movement of the component particles is extremely restricted. Thus solids have definite shapes and volumes. The liquid state is less compact and the component particles can move within certain constraints. Liquids have definite volumes but they take the shape of the containers. The gas state particles are separated and are free to move. Gases take the shapes and volumes of the containers.

The Solid State

Basically there are two categories of solids: *amorphous solids* with no defined shape and *crystalline solids* with a well-defined structure. Amorphous solids can be like carbon black or linked as in plastics. Solids may also be composed of a jumble of molecules (super-cooled liquids) as in glass.

In the crystalline solids particles are pulled into a rigid, organized structure of repeating patterns called a *crystal lattice*. Depending on the particles, the crystal lattice may be of different shapes (Chemtutor LLC. 2004). Figure 2 is a microscopic illustration of solid structure and figure 3 demonstrates a crystal structure.

Four major types of solids may be identified (Malone, 2001). *Ionic solids* like sodium chloride NaCl (s) whose crystal lattice consists of ions, which are connected to their neighbors by electrical attraction. *Molecular solids*, such as ice $H_2O(s)$ or sugar $C_{12}H_{22}O_{11}(s)$ whose crystal lattices contain molecules held by intermolecular forces. *Network solids* like diamond, graphite and *Buckministerfullerene* formed by covalently held atoms throughout the whole solid. Such crystals are among the hardest materials. For example diamond is the hardest known natural substance. And *metallic solids* held by metallic bonds where the core of nuclei and inner-electrons are enveloped by a cloud of valance electrons. All crystalline solids have characteristic angles *(cleavage angles)* and can be cleaved easily along lines defined by the aligning of atoms or molecules of the crystal.

Quasicrystals, a novel form of solid with molecular structure resembling Penrose tiles[3], first made in 1984, became a major focus of materials research (Nelson 1986).

The common point about solids is that the position of atoms or molecules is fixed. They are attached to one another and have no independent translational linear motion. Solids can have vibration and rotation molecular energies only. Lattice particles are barely moving. Thus solids are incompressible (Dummies 2004).

The Liquid State

Order in the particles (atoms, ions, molecules) of any substance depends on the forces of attraction and repulsion between them. For molecular particles these are *intermolecular forces*[4]. They are caused by the attraction or repulsion of electrical charges between molecules. There are three types of intermolecular forces: *London forces* caused by *instantaneous dipole – induced dipole attractions*; *dipole-dipole attractions; and*

[2] Complete member listing is in the acknowledgement section, placed in part II of this paper.

[3] In the 1970's Roger Penrose (famous for collaborating on *singularities* with Stephen W. Hawkins) found that only two geometric shapes, put together in jigsaw-puzzle fashion, can cover a flat surface in patterns that never repeat themselves. The shapes, called *Penrose tiles*, were initially considered a curiosity unrelated to natural phenomena. *Singularities* = objects so crushed by their own weight that they become infinitely dense, like *black holes*

[4] Weak electrical interactions between molecules that are not as strong as chemical bonds

hydrogen bonding. In London forces, random movement of bond electrons produces a lopsided balance by chance and creates a dipole for an instant (instantaneous dipole). This induces a dipole in its neighbor (induced dipole), and the two dipoles attract each other.

Liquids and also solids have high densities, minimal thermal expansion and fixed volumes. They are essentially incompressible. To explain these properties three postulates of the *kinetic theory of gases* (see below under gas state) have to be modified; namely, the particles are attracted to each other by intermolecular forces and are held close together; their volume is not negligible; the particle motion is restricted.

Molecules of liquids are less tightly arranged than those of solids but more closely than those of gases. Hence unlike solids, liquids have no long-range order, but their molecules interact via their intermolecular forces. This induces some order with respect to neighboring molecules. Every molecule in a liquid has the same number of nearest neighbors, and is equally spaced from one another. Molecules further removed are randomly placed. Thus liquids have short-range order that exists only for a few molecule lengths. A microscopic illustration of a liquid is shown in Fig. 4.

Certain liquids have a certain degree of long-range order that is less than in a solid. Such liquids are known as *liquid crystals.* They contain long rod-like molecules. In appropriate temperature ranges they become aligned parallel to each other to create a long-range order. But unlike molecules in a solid, molecules in a liquid crystal can still slide (flow) past one another. The arrangement of the molecules determines the optical properties. For example some liquid crystals appear opaque when their molecules have one alignment and transparent when they are differently aligned. These are the LCDs (Liquid Crystal Displays) used in digital equipment, like watches and calculators.

The intermolecular forces determine the physical properties of liquids, such as its boiling point, freezing point, and surface tension. These in turn influence behavior under different temperatures, pressures and on contact with other substances.

Boiling Point

The boiling point of a liquid is the temperature at which molecules escape from the liquid phase and change into the gaseous state. It is the temperature at which liquid and gas are in equilibrium. Boiling starts when bubbles of vapor form within the liquid. These bubbles rise to the top of the liquid and release the gaseous molecules to the atmosphere above the liquid's surface. 2.260 kJ (540 calories) of heat is required to evaporate 1 gram of water at 100 C (212° F) at sea level. The boiling point depends on atmospheric pressure. Boiling points are raised by dissolved substances. This is a *colligative property*, a property that depends only on the *number* of particles and not on the *nature* of particles.

Freezing Point

The freezing point of a substance is the temperature at which the liquid state changes into the solid state. The molecules of the liquid change into a more ordered structure as the liquid freezes. It is accompanied by a decrease in entropy, $\Delta S < 0$. The melting point of a substance, the point at which it changes from a solid to a liquid, is identical with its freezing point, where it changes from liquid to solid. Freezing points are lowered by dissolved substances. This is also a colligative property.

Viscosity

The degree of resistance to flow is shown by the viscosity of a liquid. Flow makes a liquid take the shape of the container that holds it. Oils contain large *convoluted molecules* that catch on one another. This gives them a high viscosity, much higher than water. But the polarity of the water molecules causes them to attract one another and make water more viscous than a non-polar liquid, such as propane. Fig. 5 shows a viscous liquid.

Surface Tension

Liquids behave as if there is a delicate skin on their surface. This property is called surface tension. In rain droplets water molecules are held together by surface tension, which acts like a thin balloon. Water-strider bugs can walk across water surfaces because of surface tension. Fig. 6, shows heavy objects floating on a liquid.

Capillary Action

Water will climb up a cloth if the edge touches a puddle, and it will climb up a capillary glass tube that is dipped in water. The water climbs because the water molecules are more attracted to the cloth or glass, than they are to each other (MSN Encarta 2003a). This is capillary action.

The Gas State

Fig. 7 is a microscopic illustration of carbon dioxide CO_2 gas structure. It is apparent that the gas molecules are separated more than in liquids. There is almost no interaction among the individual molecules. Hence gases move freely and expand to fill any sized or any shaped container. Because of this, one mole of any gas under STP (standard temperature and pressure) has a constant volume of 22.4 L (the molar volume of any gas at STP).

Gases are compressible and have low densities. They mix thoroughly, fill a container uniformly, and exert uniform pressure on all sides of a container. These properties are explained by the *kinetic theory*, which states that gases are made up of very small particles that are widely spaced and have negligible volume. The particles move rapidly and undergo *elastic collisions* with each other and with container walls giving rise to gas pressure; but they do not have electrical interactions. The gas temperature is related to the average kinetic energy of the gas particles (Malone, 2001).

The theory also allows understanding of the gas laws, such as *Graham's law* of diffusion, which says gas diffusion rates are inversely related to the square root of its molar mass; *Boyle's law*, which says the pressure and volume of a given mass of gas are inversely related at constant temperature; *Charles's law* that says at constant pressure gas volume is directly related to its temperature; *Gay-Lussac's law* that says gas pressure and gas temperature are directly related at constant pressure; *Avogardo's law* that says gas volume and moles of gas are directly related at constant temperature and pressure; and *Dalton's law* that says the total gas pressure is the sum of the partial pressures of component gases.

The chemical structure of gases varies greatly and the properties of gases vary widely. Some gases are transparent, some have strong smell, some dissolve in water, and some react violently with almost any substance; while other gases have opposite properties.

Increased pressures or decreased temperatures force gas atoms or molecules closer together. When the gas molecules are near enough, the weak intermolecular forces of attraction become effective, a short-range order is introduced and a liquid is formed. Similarly, when liquid molecules are moved closer, the same forces turn the liquid into a solid.

Color

Some gases have characteristic colors. Fluorine gas is green, chlorine is yellow-green, and nitrogen dioxide is red-brown. But most gases are colorless.

Odor

Many gases, including nitrogen, oxygen, and hydrogen, are odorless. Ammonia has a sharp pungent odor. Fuel gases such as methane, propane, and butane are odorless. Therefore a sulfur compound with intense smell is added to fuel gases to ensure early detection for gas leakage.

Solubility

Some gases such as carbon dioxide dissolve well in water. Many others including nitrogen, hydrogen, and oxygen, are only slightly soluble in water. The solubility of any gas decreases with increasing temperature.

Chemical Reactivity

Some gases are reactive while others are inert. The chemical reactivity of gases varies widely. Oxygen, chlorine, and fluorine are extremely reactive gases. Fluorine will react with almost any other substance; even water and glass will burn in a fluorine atmosphere. But the *noble* or *inert gases* are inert. Neon does not react at all.

.Structure

Gas particles are the smallest units (atoms or molecules) into which a gas can be divided without changing its chemical properties. The noble gases, such as neon and helium, are made up of individual atoms. Some elements in the gas state, such as hydrogen H_2, oxygen O_2, and nitrogen N_2 are composed of diatomic molecules. Other gases like carbon dioxide CO_2, methane CH_4, and ammonia NH_3 are compounds and exist as molecules. (MSN Encarta 2003b). Part II follows**.**

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Solid **Liquid** **Gas**

Fig. 1. The three common states of matter

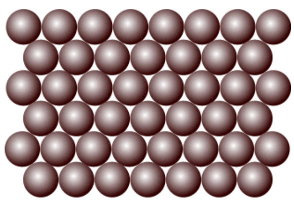

Fig. 2. Microscopic illustration of solid

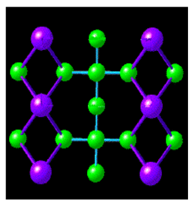

Fig. 3. Simplified crystal structure

Fig. 4. Microscopic illustration of liquid

Fig. 5. Solid in a viscous liquid

Fig. 6. Surface tension floats heavy solids

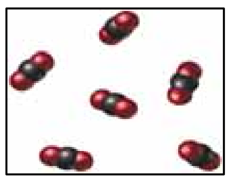

Fig. 7. Microscopic illustration of gas