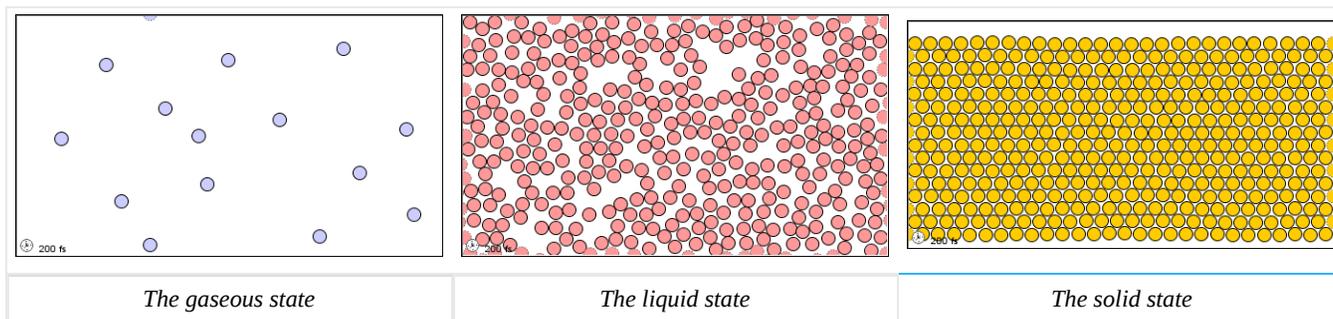


2.2: Macroscopic Properties and Microscopic Models

As a simple example of how the macroscopic properties of a substance can be explained on a microscopic level, consider the liquid mercury. Macroscopically, mercury at ordinary temperatures is a silvery **liquid** which can be poured much like water—rather unusual for a metal. Mercury is also the heaviest known liquid. Its density is 13.6 g cm^{-3} , as compared with only 1.0 g cm^{-3} for water. When cooled below -38.9°C mercury solidifies and behaves very much like more familiar **solid** metals such as copper and iron. Mercury frozen around the end of a wooden stick can be used to hammer nails, as long as it is kept sufficiently cold. Solid mercury has a density of 14.1 g cm^{-3} slightly greater than that of the liquid.

When mercury is heated, it remains a liquid until quite a high temperature, finally boiling at 356.6°C to give an invisible vapor. Even at low concentrations gaseous mercury is extremely toxic if breathed into the lungs. It has been responsible for many cases of human poisoning. In other respects mercury vapor behaves much like any other **gas**. It is easily compressible. Even when quite modest pressures are applied, the volume decreases noticeably. Mercury vapor is also much less dense than the liquid or the solid. At 400°C and ordinary pressures, its density is $3.6 \times 10^{-3} \text{ g cm}^{-3}$ about one four-thousandth that of solid or liquid mercury.

Three states of Matter



A modern chemist would interpret these macroscopic properties in terms of a microscopic model involving atoms of mercury. As shown in the following figure, the atoms may be thought of as small, hard spheres. Like billiard balls they can move around and bounce off one another. In solid mercury the centers of adjacent atoms are separated by only 300 pm ($300 \times 10^{-12} \text{ m}$ or 3.00 \AA). Although each atom can move around a little, the others surround it so closely that it cannot escape its allotted position. Hence the solid is rigid. Very few atoms move out of position even when it strikes a nail. As temperature increases, the atoms vibrate more violently, and eventually the solid melts. In liquid mercury, the regular, geometrically rigid structure is gone and the atoms are free to move about, but they are still rather close together and difficult to separate. This ability of the atoms to move past each other accounts for the fact that liquid mercury can flow and take the shape of its container. Note that the structure of the liquid is not as compact as that of the solid; a few gaps are present. These gaps explain why liquid mercury is less dense than the solid.

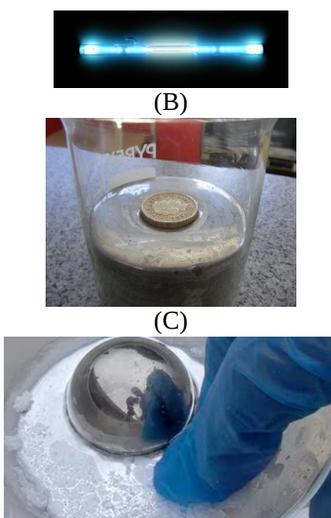


Figure 2.2.1: Macroscopic view of the element mercury: (A) in the gaseous state (above 356.6°C); (B) as a liquid (between -38.9 and 356.6°C) and (C) in solid form (below -38.9°C)

In gaseous mercury, also called mercury vapor, the atoms are very much farther apart than in the liquid and they move around quite freely and rapidly. Since there are very few atoms per unit volume, the density is considerably lower than for the liquid and solid. By moving rapidly in all directions, the atoms of mercury (or any other gas for that matter) are able to fill any container in which they are placed. When the atoms hit a wall of the container, they bounce off. This constant bombardment by atoms on the sub-microscopic level accounts for the pressure exerted by the gas on the macroscopic level. The gas can be easily compressed because there is plenty of open space between the atoms. Reducing the volume merely reduces that empty space. The liquid and the solid are not nearly so easy to compress because there is little or no empty space between the atoms.

You may have noticed that although our sub-microscopic model can explain many of the properties of solid, liquid, and gaseous mercury, it cannot explain all of them. Mercury's silvery color and why the vapor is poisonous remain a mystery, for example. There are two approaches to such a situation. We might discard the idea of atoms in favor of a different theory that can explain more macroscopic properties. On the other hand it may be reasonable to extend the atomic theory so that it can account for more facts. The second approach has been followed by chemists. In the current section on [Atoms, Molecules and Chemical Reactions](#) as well as [Using Chemical Equations in Calculations](#) we shall discuss in more detail those facts that require only a simple atomic theory for their interpretation. Many of the subsequent sections will describe extensions of the atomic theory that allow interpretations of far more observations.

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