3.2: Hydrogen - The Simplest Atom

Hydrogen, **H**, is the element with atomic number 1. Most hydrogen atoms consist of a single proton forming the nucleus with 1 electron per hydrogen atom. Recall from Section 2.12 and Figure 2.6 that elemental hydrogen exists as molecules with 2 H atoms, chemical formula H2, in which the 2 H atoms are joined together by a *covalent bond* consisting of 2 shared electrons. Molecules consisting of 2 atoms so joined are called **diatomic** molecules. As will be seen, several important elements among the first 20 elements are gases that consist of diatomic molecules in their elemental forms.

Showing Electrons in Atomic Symbols and Molecular Formulas

In discussing chemical behavior related to atomic structure, it is particularly useful to have a means of showing the electrons in the atoms (more specifically, the less strongly held outer shell electrons). This is done with **Lewis symbols** (named after G. N. Lewis) also called **electron-dot symbols**. The Lewis symbol of the hydrogen at

$$\mathbf{H\cdot}$$

Figure 3.1.

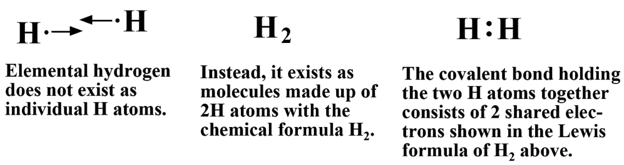

Figure 3.1. Elemental hydrogen exists as molecules each of which contains two H atoms.

Properties and Uses of Elemental Hydrogen

Pure elemental H2 under normal conditions is a colorless, odorless gas that has the lowest density of any pure substance. Liquified H2 boils at a very cold -253˚C and solidifies at -259˚ C. Hydrogen gas is widely used in the chemical industry to react chemically with a large number of substances. It burns readily with a large release of energy and mixtures of hydrogen with oxygen or air are extremely explosive. The chemical reaction for elemental hydrogen burning with oxygen (O2) in air is

$$2\,H_2 + O_2 \rightarrow 2\,H_2O + \text{energy} \tag{3.2.1}$$

The product of this reaction is water. Used as a fuel, elemental hydrogen is a very green element because when it is burned or otherwise reacted to provide energy, the reaction product is simply water, H2O. Furthermore, given a source of electrical energy, elemental hydrogen and elemental oxygen can be produced at two separate electrodes by passing a direct current through water in which an appropriate salt has been dissolved to make the water electrically conducting:

$2H2O \xrightarrow[\text{current}]{\text{Electrical}} 2H2 + O2$ (3.2.2)

So elemental hydrogen generated by the application of electrical energy to water provides a source of energy that can be moved from one place to another and utilized to produce electricity in fuel cells (see below) or for other beneficial purposes such as the synthesis of ammonia essential as a source of plant fertilizer nitrogen. The production of elemental hydrogen by electrolysis may be regarded as a green process because it does not require any reagents other than water. Furthermore, the electrolysis byproduct oxygen is harmless and has many uses whereas hydrogen made by the reaction of steam with carbon-containing compounds (see below) consumes fossil fuel and generates CO, which in some cases is burned producing greenhouse gas carbon dioxide. The main disadvantage of the electrolysis process for H2 generation is the relatively low efficiency by which the electricity is used in the process and improvements are needed in this area.

Elemental hydrogen is widely used for chemical synthesis and other industrial applications. Its preparation by electrolysis of water was mentioned above. It is now most commonly prepared from methane, CH4, the main ingredient of natural gas, by **steam reforming** at high temperatures and pressures:

$CH4 + H2O \xrightarrow[\text{30 atm P}]{\text{800°C T}} CO + 3H2$ (3.2.3)

Hydrogen is used to manufacture a number of chemicals. Two of the most abundantly produced chemicals that require hydrogen for synthesis are ammonia, NH_3, and methanol (methyl alcohol, CH_3OH). The latter is generated by the reaction between carbon monoxide and hydrogen:

$$CO + 2\,H_2 \rightarrow CH_3OH \tag{3.2.2}$$

Methanol used to be made by heating wood in the absence of air and condensing methanol from the vapor given off, a process known as destructive distillation. Generation of so-called wood alcohol made by this relatively green process from biomass has the potential to supply at least a fraction of the methanol now needed, thus reducing the consumption of natural gas.

Methanol has some important fuel uses. During the 1930s it was used instead of gasoline to run internal combustion engines to power a significant fraction of automobiles in France before Middle Eastern oil fields became such an abundant source of petroleum. At present it is blended with gasoline as an oxygenated additive; engines using this blended fuel produce less pollutant carbon monoxide. Now the most common use of methanol as a fuel is to break it down to elemental hydrogen and carbon dioxide to produce hydrogen used in fuel cells.

In addition to its uses in making ammonia and methanol, hydrogen is added chemically to hydrocarbon molecules in some fractions of gasoline to upgrade the fuel value of gasoline. Hydrogen can be added directly to coal or reacted with carbon monoxide to produce synthetic petroleum. It is also combined with unsaturated vegetable oils to make margarine and other hydrogenated fats and oils. This application is controversial and becoming less common because of suspected adverse long-term health effects of these products commonly called trans fats.

Hydrogen in Fuel Cells

Fuel cells, discussed further in Chapter 15, are devices that enable hydrogen to “burn” at around room temperature and to produce electricity directly without going through some sort of internal combustion engine and electricity generator. A fuel cell (Figure 3.2) consists of two electrically conducting electrodes, an anode and a cathode that are contacted with elemental H2 and O2, respectively. As shown in the diagram, at the anode H2 loses electrons (it is said to be oxidized) to produce H+ ion. At the cathode O2 gains electrons (it is said to be reduced) and reacts with H+ ions to produce water, H2O. The H+ ions required for the reaction at the cathode are those generated at the anode and they migrate to the cathode through a solid membrane permeable to protons (the H+ ion is a proton). The net reaction is

$$2\,H_2 + O_2 \rightarrow 2\,H_2O + \text{electricalenergy} \tag{3.2.3}$$

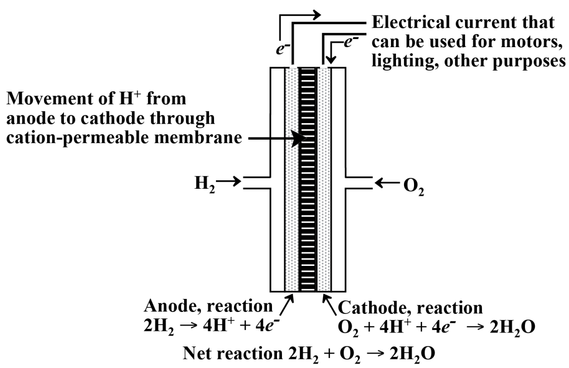

Figure 3.2. Cross-sectional diagram of a fuel cell in which elemental hydrogen can be reacted with elemental oxygen to produce electricity directly with water as the only chemical product.