Cosmic Chemistry: An Elemental Question

Atoms, Elements, and Isotopes

STUDENT TEXT

An **atom** is the basic structure from which all matter is composed, in the same manner as a brick is the basic structure from which a wall is built. Although atoms are too small to be seen with our eyes, scientists have long had indirect evidence for the existence of atoms. We can now use the world's most powerful scanning tunneling microscopes to "see" the magnified images of atoms and to study surface reaction sites on an atom-by-atom basis.

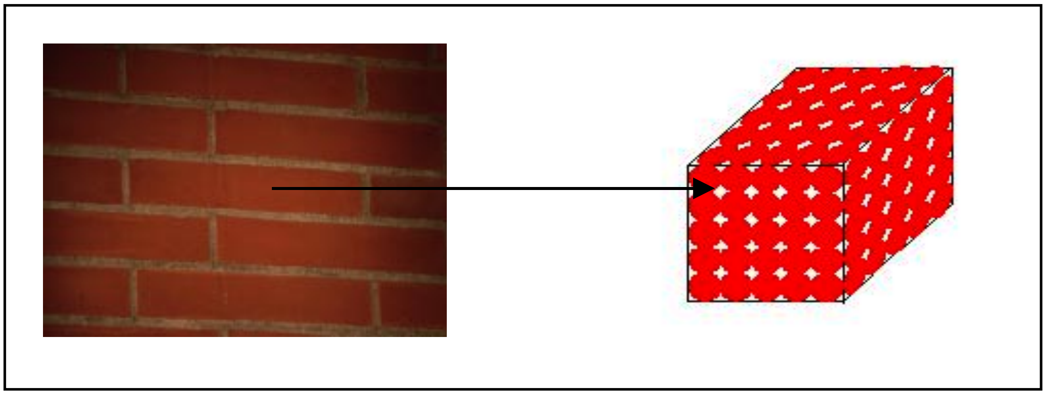

Figure 1: Just as a brick is basic to the structure of a wall, an atom is basic to the structure of matter.

Atoms are made of small particles called **protons**, **neutrons**, and **electrons**. Each of these particles is described in terms of measurable properties, including **mass** and **charge**. Mass is the amount of matter that an object contains. The proton and neutron have roughly the same mass and have approximately one thousand times the mass of the electron. A proton has a mass of $1.6726231 \times 10^{-27}$kg and has a charge of +1. A neutron has a mass of $1.6749286 \times 10^{-27}$kg, but does not have an electric charge. The electron's mass, $9.1093897 \times 10^{-31}$kg, is much smaller than either a neutron or proton. It has a charge of –1. This means that the proton and electron have equal but opposite electrical charges.

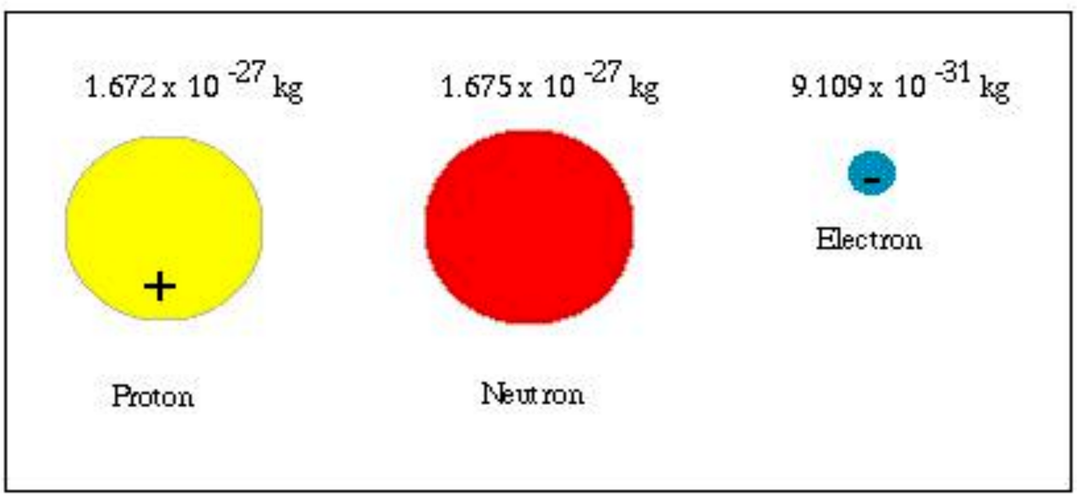

Figure 2: Model of Proton, Neutron, and Electron

If the proton and neutron were enlarged, and each had the approximate mass of a hippopotamus, the electron, enlarged to the same scale, would have less mass than an owl.

Figure 3: Comparison of Masses

In an atom, the protons and neutrons clump together in the center and are called the **nucleus**. Because the protons are positively charged, the nucleus has a positive electric charge. The electrons of the atom move rapidly around the nucleus. If we attempt to detect an electron in an atom, we might find evidence of it located almost anywhere around the nucleus. However, if we repeat this experiment many times, it will be found that the electron is much more likely to be located in certain regions of space surrounding the nucleus than in other regions of space. We might think that the electron is rapidly moving around the nucleus and our experiment "catches" the electron as an instantaneous "snapshot" of it in motion. The probability of finding the electron in any region of space can then be described by a cloud that rapidly thins out as one goes farther from the nucleus. The density of the cloud at any point is the probability of finding the electron at that point.

Most of an atom is empty space. The nucleus of the atom contains almost all of the mass of the atom. A greatly enlarged atom might look like a marble (the nucleus) inside an empty football stadium (the **electron probability cloud**).

Figure 4: Electron Probability Cloud Around a Nucleus

The attractive electric force between the positively-charged protons in the nucleus and the negatively-charged electrons around the nucleus holds the atom together. Atoms containing the same number of protons and electrons have no net charge. Atoms that have extra electrons or are missing electrons have a net electrical charge and are called **ions**. Ions can interact with other ions due to the electrical attraction between opposite charges.

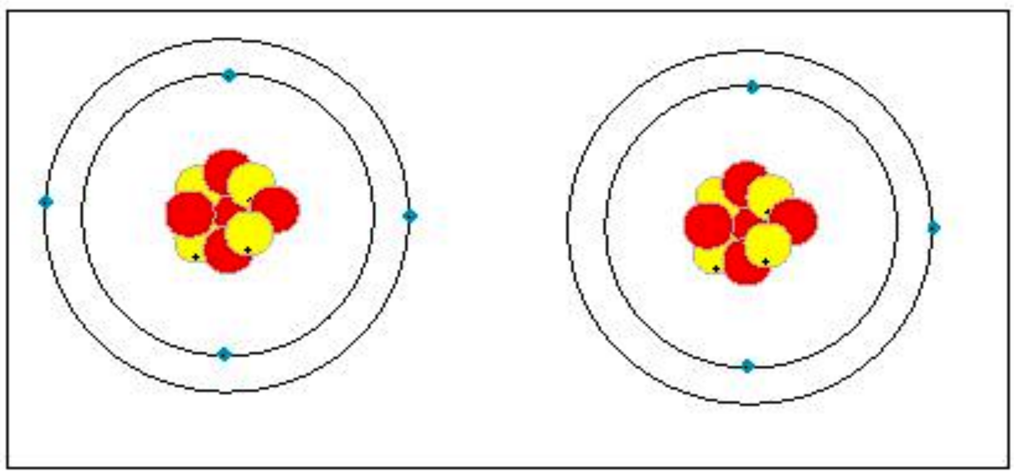

Figure 5: Diagram Comparing a Beryllium Atom and a Positively-Charged Beryllium Ion

Atoms interact with other atoms by sharing or transferring electrons that are farthest from the nucleus. These electrons are sometimes called **valence electrons**. These outer electrons determine the chemical properties of the element, such as how readily it interacts with other elements and the allowable ratios for its combinations with other substances.

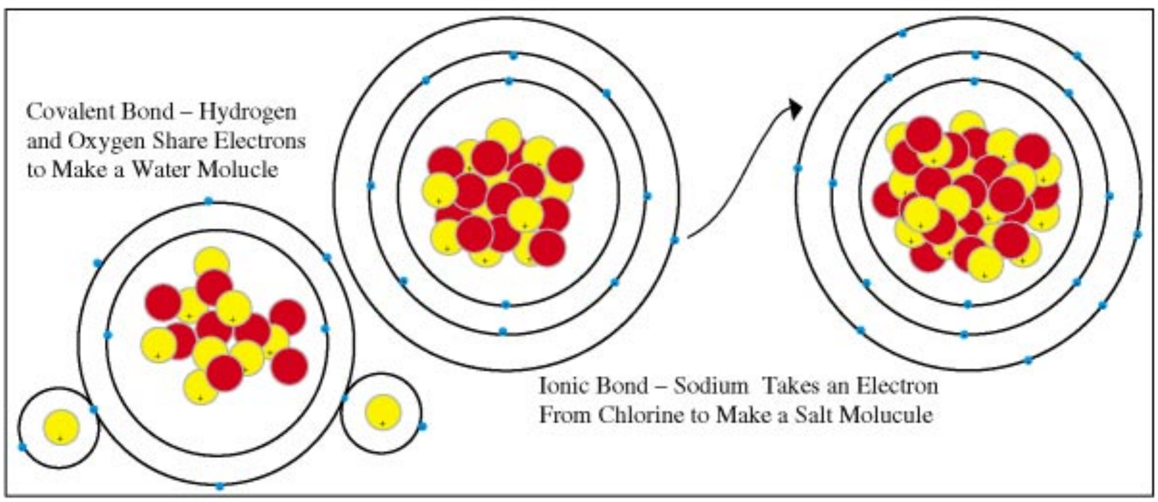

Figure 6: Model of Covalent and Ionic Bonds

An **element** is a substance made up of a single type of atom. It can't be broken into simpler components by chemical processes. There are 92 naturally occurring elements. They may be solids, liquids, or gases.

Modern Periodic Table of the Elements

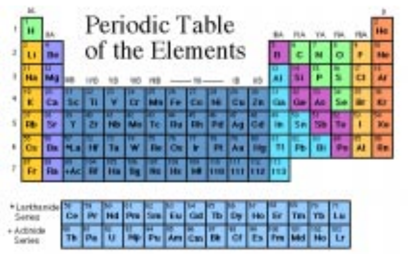

Figure 7: Modern Periodic Table

The elements are distributed unevenly, with some much more common than others. The ten most abundant elements on earth make up more than 99% of our planet.

Element	Symbol	Relative % of Earth's Mass
Oxygen	O	46.6
Silicon	Si	27.7
Aluminum	Al	8.1
Iron	Fe	5.0
Calcium	Ca	3.6
Sodium	Na	2.8
Potassium	K	2.6
Magnesium	Mg	2.1
Titanium	Ti	0.4
Hydrogen	H	0.1

Figure 8: The Ten Most Abundant Elements

A bar of gold can be shaved into gold dust, and still be recognizable as gold.

Figure 9

Gold is one example of an element.

How fine can the dust become and still be considered gold?

Figure 10

The smallest particle that would still have the properties associated with gold is an atom. To get an idea of how small an atom is, consider that a small gold coin may contain over 20,000,000,000,000,000,000,000 atoms.

Figure 11

The mass of an atom or particle is expressed in atomic mass units or amus. One atomic mass unit is a very small amount of mass. An **amu** is $^{1}/_{12}$ the mass of one atom of ^{12}C, or about 1.66 x 10^{-27} kg.

Atomic mass values for elements are almost never an integer. The only exception is carbon, whose mass was used as a standard reference. The mass of a ^{12}C carbon atom is specified as exactly 12. The mass of an atom of another element is the ratio of its mass to the mass of a carbon atom. Even the masses of protons, neutrons, and electrons are ratios of their mass to carbon. These ratios are not integers. Since atoms are made of various numbers of these particles, it is unlikely that the mass of an atom other than carbon would add up to exactly a whole number.

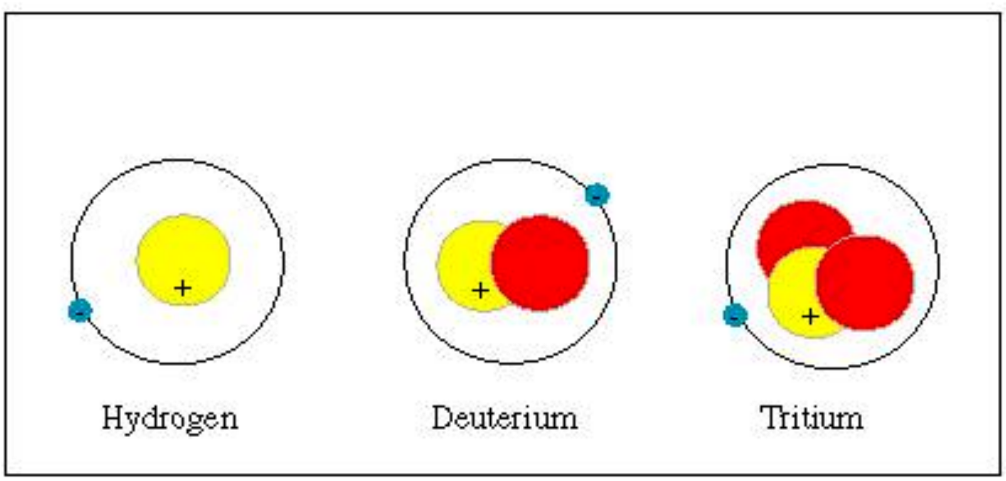

Figure 12: Diagram Comparing Hydrogen, Deuterium, and Tritium Atoms

When an element has atoms that differ in the number of neutrons in the nuclei, these atoms are called different isotopes of the element. All isotopes of one element have identical chemical properties. This means it is difficult to separate isotopes from each other by chemical processes. However, the physical properties of the isotopes, such as their masses, boiling points, and freezing points, are different. Isotopes can be most easily separated from each other using physical processes.

Most atoms of the element hydrogen contain only one proton in their nuclei. Each of these atoms has a mass of 1.008 amu. There exist atoms of hydrogen that have either one or two neutrons in the nucleus in addition to the single proton. These are called deuterium or tritium, having masses of 2.014 amu and 3.016 amu respectively. Deuterium and tritium are isotopes of hydrogen. An atom of deuterium has two particles in its nucleus, and tritium has three. Since atoms of both deuterium and tritium have only one proton in their nuclei, they only have one electron. They behave, chemically, like other hydrogen atoms.

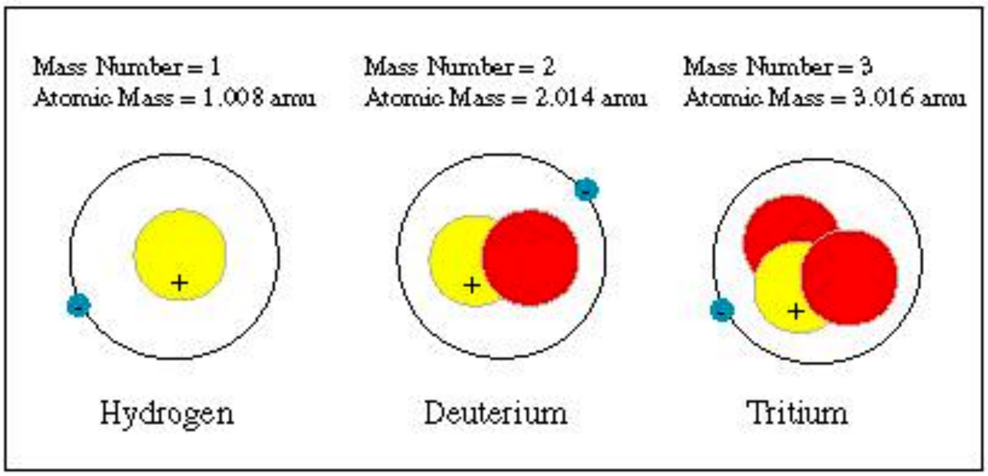

Figure 13: Mass Number and Atomic Mass of Hydrogen, Deuterium, and Tritium Atoms

The sum of the number of protons and neutrons in the nucleus of an atom is called that element's **mass number**. This is not the same as the element's mass. Since different isotopes of an element contain different numbers of neutrons in the nuclei of their atoms, isotopes of the same element will have different atomic masses. This was shown above for the three isotopes of hydrogen. The symbol for an isotope is the symbol for the element followed by the mass number. Hydrogen is symbolized as H1, while deuterium is symbolized as H2.

What would we call an atom that had three particles in its nucleus, like tritium, but two were protons and one was a neutron? This would be an uncommon isotope of a different element, helium (He3). Because there were two protons in this nucleus, there would also be two electrons in the probability cloud around it. Since it is the outer electrons that determine the chemical properties of an atom, this would be a different kind of atom than hydrogen. The presence of two rather than one electron would cause it to have distinctive chemical properties. Thus, this must be a different element, and it is named helium. The most common isotope of helium (He4) has two protons and two neutrons in the nucleus of each atom.

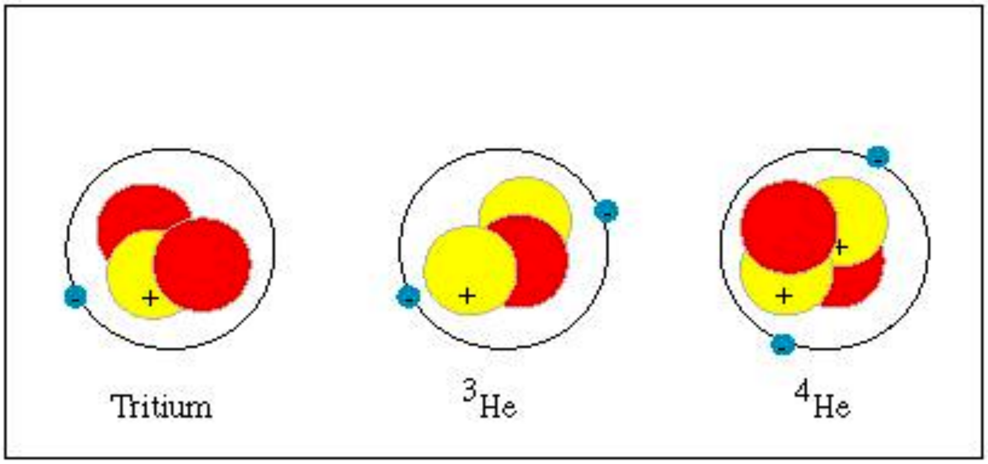

Figure 14: Diagram of Tritium, ^{3}He, and ^{4}He Atoms

To distinguish between elements, we often refer to their **atomic numbers**. The atomic number is the number of protons in the nucleus of an atom of that element (which is equal to the number of electrons around that atom's nucleus). Hydrogen's atomic number is 1, while helium's atomic number is 2. Gold has an atomic number of 79, which means it has 79 protons in its nucleus. The modern periodic table of the elements shows the different elements arranged in increasing order of atomic number.

There are 92 elements found in nature and several more exotic, manmade elements. Based on their chemical and physical properties, scientists have invented a tool to show relationships among these elements. It is known as the periodic table of the elements.

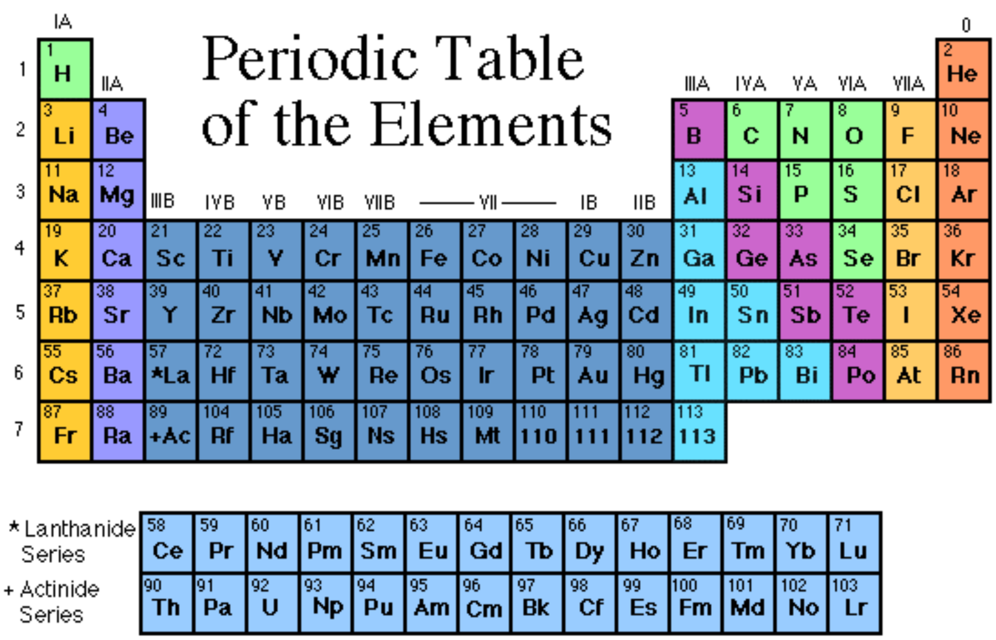

Figure 15: Periodic Table of the Elements, Los Alamos National Laboratories

Observations show that the same elements exist throughout the known universe. We organize information about the elements in the form of a periodic table. The elements and their interactions are studied in all disciplines of science, as chemicals form the basis of life science, physical science, and earth and space science. As the American Association for the Advancement of Science wrote in *2061, Science for All Americans*, "All humans should participate in the pleasure of coming to know their universe better."