V25.0109: General Chemistry I: Honors

Notes for Lecture 1

Let us begin our study of chemisty with a simple question:

What is chemistry?

Chemistry is about structure: Specifically, it is the study of the stable structures or *chemical bonding patterns* that can be formed by bringing atoms into specific spatial arrangements. The term "structure" can also refer to the beautiful *supramolecular* structures that are possible when molecules are brought together into large assemblies.

Chemistry is also about transformation. Specifically, it is the study of the transformations of substances into other substances caused by the interactions of atoms and molecules to form new molecules by the forming, breaking and reforming of *chemical bonds*.

What exactly is meant by a *chemical bond* will be defined more precisely later in the course and next semester.

While the above definition encompasses much of chemistry, it falls short of conveying the full breadth of the subject. Chemistry is also the study and prediction of the properties of substances and the rationalization of these properties from the microscopic detailed motions of individual constituent atoms/molecules that result from the forces between them.

Note that both of these aspects refer to a connection between microscopic dynamics and macroscopic observable phenomena.

I. WHEN DID CHEMICAL PROCESSES START TO OCCUR?

To answer this question, we need to know something about the origin of organized aggregates of particles, such as atoms and molecules.

Current astronomical data and cosmological models place the present age of the universe somewhere between 10 and 20 billion years. Best current estimates place the age at around 13.7±0.2 billion years old. During the first 10^{-6} seconds after the so called "big bang," the average temperature was roughly 10^{12}-10^{13} degrees (scale is irrelevant at these high temperatures), far too hot for aggregated structures, such as molecules, atoms, atomic nuclei, or even nuclear constituent particles, such as protons and neutrons to exist. The universe was essentially a dense, expanding ball consisting of elementary particles. Among these were the basic constituents of everyday matter, the electron, and two species of subnuclear particles, called the "up" and "down" *quarks*. The monikers "up" and "down" are merely labels that allow us to distinguish them is different particles rather than any kind of directional attribute. Among many interesting properties of these particles, the electron carries an *electric charge* (which we will discuss in more detail in a later lecture) of -1 in some units. The up and down quarks have fractional electric charges of +2/3 and -1/3, respectively. Remeber that particles with like charges tend to repel each other, while particles with opposite charges tend to attract each other.

According to our model, as the universe expanded, it cooled, a phenomenon we will encounter again later in the course. Thus, after the first 10^{-6} seconds, the temperature had dropped to approximately 10^{10} degrees, cool enough for aggregates of quarks to form. The force holding them together is not the charge-charge attraction/repulsion alluded to above, but rather a force, known as the "strong" force, which dominates at these high temperatures. The specific combinations involving the up and down quarks are:

$$\begin{aligned} 2\text{ up} + 1\text{ down} &= 1\text{ proton} \\ 2u + 1d &\longrightarrow 1\,p \\ \text{charge}: \quad 2 \times \frac{2}{3} - \frac{1}{3} &= 1 \end{aligned}$$

$$\begin{aligned} 1\text{ up} + 2\text{ down} &= 1\text{ neutron} \\ 1u + 2d &\longrightarrow 1n \\ \text{charge}: \quad \frac{2}{3} - 2 \times \frac{1}{3} &= 0 \end{aligned}$$

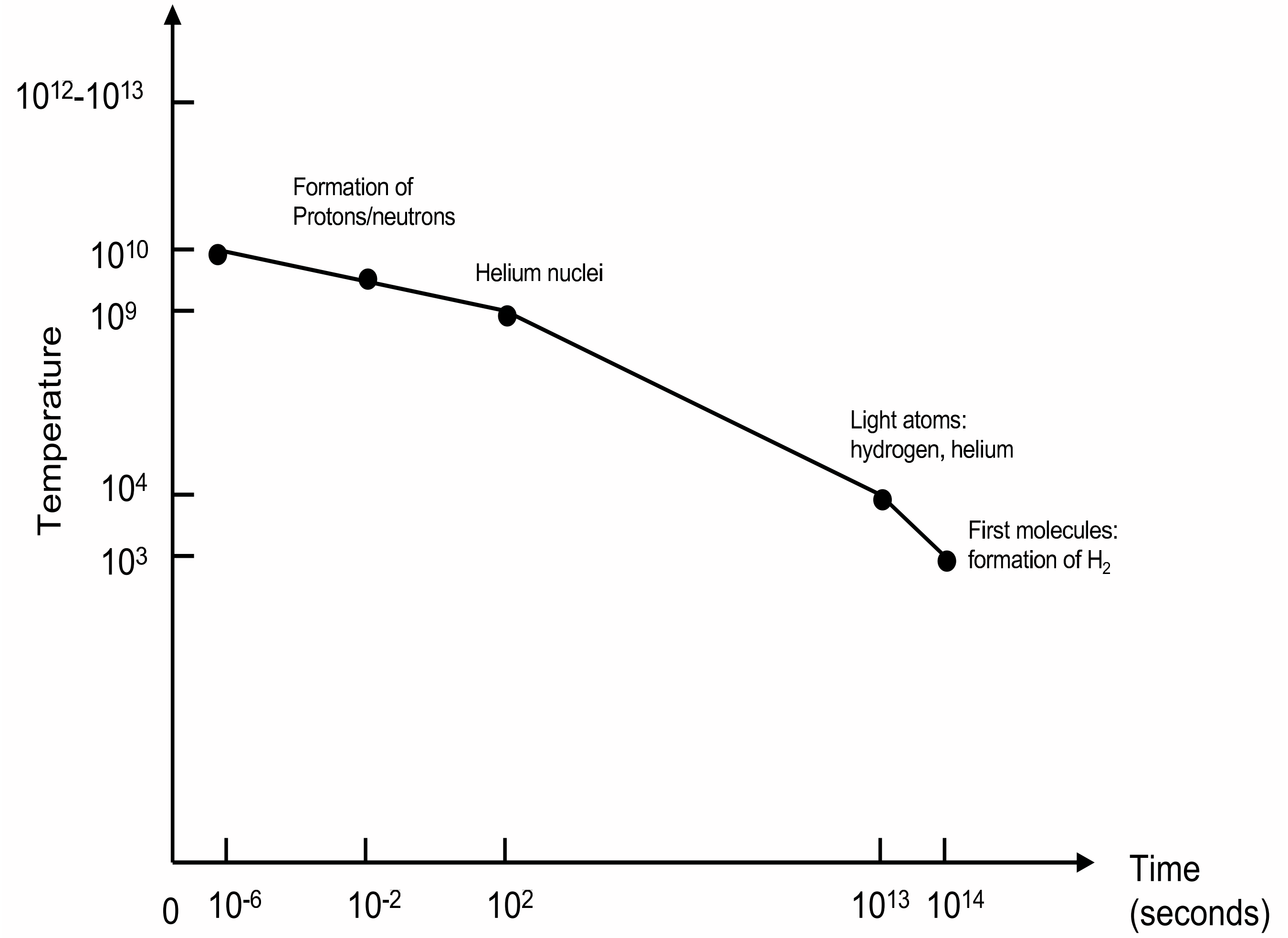
that is, the familiar particles that comprise atomic nuclei are actually, themselves, built up from smaller constituents.

The proton, itself, is also a hydrogen nucleus. After about 100 sec, when the temperature had dropped to just under 10^9 degrees, helium nuclei, the next lightest nuclear species, started to form in small amounts. The helium nucleus consists of 2 protons and 2 neutrons, or a total of 12 quarks. Both the hydrogen and helium nuclei, being composed of protons and neutrons, are positively charged particles. As such, they could have attract the negatively charged electrons by means of the attraction of opposite charges. However, the temperature was still too high for this.

It was only after 10^{13} seconds or 300,000 years after the big bang, when the temperature was on the order of 10^4 degrees, that electrons could remain bound to the positively charged nuclei by the electrostatic attraction. Only hydrogen and helium atoms were produced at this time, which, as we now see, contain considerable substructure. The hydrogen atom, consists of 1 proton and 1 electron (charge neutral), which is actually 4 particles in total, if we count the quark constituents of the proton. The helium atom, which contains 2 protons, 2 neutrons and 2 electrons, sums to 14 elementary particles. Of course, under normal, everyday conditions, the substructure of the nucleus is essentially invisible, and, thus, the atom can be viewed simply as a positively charged nuclear core surrounded by negatively charged electrons.

Atoms are generally comprised of a compact nuclear core (made up of specific numbers of protons and neutrons) surrounded by enough electrons to yield a charge-neutral aggregate. Today, some 116 different kinds of atoms have either been discovered as naturally occurring or produced in the laboratory and two others are postulated to exist. We refer to this set as the set of *elements*. The complete set of elements is arranged in a table in the front cover of the book. This table is known as the *periodic table*, which we will discuss in more detail in the next several lectures.

Not until 1-3 million years after the big bang were temperatures cool enough (on the order of 10^3 degrees) for the simplest molecule, H_2 to form. This is when the chemistry that is familiar to us today started to occur, with the simple reaction $H+H \rightarrow H_2$. Several tens of millions of years would yet be required for star formation, where, it is believed, heavier elements were synthesized and released in energetic bursts. Several billion years would be required for the formation of planets/solar systems and for the kind of chemistry required for life processes. The timeline below summarizes these milestones in the evolution of the universe.



II. WHY DOES CHEMISTRY OCCUR?

What is the precise nature of chemical processes and what drives them will be the questions we endeavor to touch upon in this and next semester. The answer to why chemistry occurs lies in the fact that at normal energy/temperature scales, the so called “electromagnetic” force, which is responsible for the charge-charge interactions described above, dominates. Electrostatic forces are responsible for the structure and dynamical behavior of atoms and molecules. The modern-day quantum theory of these interactions (which will be introduced next semester) can, in principle, predict the properties of atoms, molecules and aggregations of these into macroscopic matter. However, exact solutions of the theory for nearly all systems is intractable, and it becomes necessary to construct models and approximations.

This brings up the importance of the interplay between theory and experiment. Without theory, science would be just a vast catalogue of experimental results bearing no relation to each other and having no apparent rationalization. Theoretical analysis gives a deeper understanding of experimental findings by providing interpretation, connection to other experimental results, and prediction of experimental outcomes. However, theoretical predictions or hypotheses must be subject to vigorous experimental scrutiny before they can become statements of *scientific law* or accepted *theories.* Likewise, without experiment, science would be just a collection of untestable hypotheses. Even when a theoretical hypothesis become scientific law, if enough experimental evidence emerges that contradicts the statement, it might be necessary to ammend or discard that law in favor of another. There have only been a few instances of this in the history of science, and these have often resulted in scientific revolutions (e.g., Galileo's planetary model, Newton's laws of classical mechanics, the quantum theory, and Einstein's special and general relativity theories).