<u>Atoms and Atomic Physics</u>

Atoms and Molecules:

• An <u>atom</u> is the smallest unit of a chemical element. That is, it is the smallest piece that still displays the chemical properties of that element. There are 92 naturally occurring chemical elements.

• Elements are indicated by chemical symbols which are usually just abbreviations of their names.
Examples: <u>H</u>ydrogen H, <u>He</u>lium He, .., <u>O</u>xygen O, .., Iron (Latin: *<u>Fe</u>rrum*) Fe, ..., <u>U</u>ranium U.

• A <u>molecule</u> consists of two or more atoms bound together (by electrical forces).
Examples: Molecular hydrogen H_2, Water H_2O, Methane CH_4 , ..., Chlorophyll, DNA,...

• Atoms of different elements (as determined by chemical interactions) also differ in their <u>masses</u>.
They can be arranged by mass in a numerical order and numbered 1, 2 , 3 ,..., 92, with hydrogen atoms (#1) being the lightest and uranium atoms (#92) the heaviest. (See below.)

• Atoms and molecules move almost independently when in a <u>gaseous</u> state. At higher densities and/or lower temperatures, short range electrical forces can cause the material to assume the forms we call <u>liquid</u> or <u>solid</u>. In crystals atoms or molecules are arranged in regular repeating patterns; in amorphous solids they are not.

Atomic Structure:

• The positively-charged <u>nucleus</u> of an atom occupies a central location. It contains at least 99.95% of the atom's mass. (It is made up of one of more nucleons, namely protons and neutrons. See below.)

• Negatively-charged <u>electrons</u> surround the nucleus, bound to the nucleus by the electrical attraction between positive and negative charges. They can be thought of as "orbiting" the nucleus under the influence of this electric force much as planets orbit the sun under the influence of gravity.

• Individual electrons all have the same negative charge -e which is taken to be the "unit" of charge.

• The positive <u>nuclear</u> charge is +Ze, where Z is an integer (Z = 1, 2, 3,....). It is called the <u>Atomic Number</u>.
(Note that increasing atomic number "happens" to correspond to increasing atomic mass.)

• A normal atom is charge <u>neutral</u>, containing a nucleus of charge +Ze and Z electrons each of charge -e.
(An atom from which one or more electrons has been removed is called an <u>ion</u> and will be positively charged. Negative ions, with an excess electron, are also possible.)

Electrons, Radiation, and Chemistry:

• One must add energy to the motion of an electron to move it to a higher energy (*i.e.*, larger) orbit. If one removes energy, the electron must move closer to the nucleus. This energy can be in the form of electromagnetic radiation ("light") or it can be associated with collisions with other atoms.

• Only certain orbits are "allowed" to an electron. Consequently, only certain discrete amounts of energy can be absorbed or emitted as an electron moves from one "orbit" to another. This is why a gas emits or absorbs light only at certain discrete frequencies or wavelengths (*cf.* "spectral lines").

• The orbital structures (spacings, energies) are the same for all atoms of a given element (with slight differences among isotopes), but different for the atoms of different elements. Hence the wavelengths at which atoms absorb and emit radiation are different for the atoms of different elements. (That is why each element - or molecule- has its own unique spectral "fingerprint".)

• The <u>chemistry</u> of an atom, namely what other atoms it will or will not combine with to form molecules, the strength of those attachments, *etc.*, is determined by electrical interactions between the electrons and (to a lesser extent) the nuclei of the atoms involved. Chemical properties are essentially determined by the number of electrons (= Z) and the arrangement of their orbits.

Atomic Physics:

Atomic physics deals with the structure of atoms and particularly with motions of the electrons in atoms. The principal force involved is the electric force. This includes both the force of attraction or repulsion between electrical charges and the magnetic forces that arise from motions of charges (electrical currents).

The electrical interactions between atoms and other atoms is generally the province of chemistry. Interactions with electromagnetic radiation (emission and absorption) are studied *via* spectroscopy.

Nuclei and Nuclear Physics

- The nucleus of an atom contains nucleons - positively charged protons and uncharged neutrons.
- Protons have a charge equal to that of an electron, but of opposite (positive) sign.
- Each chemical element is characterized by a unique atomic number Z: This is equal to (i) the number of protons in the nucleus, (ii) the positive charge of the nucleus, (iii) the number of electrons in the neutral atom, and (iv) the mass-ranking of the atom, with Z = 1 (hydrogen) being the lightest.
- The proton mass is about 1836 times that of an electron; a neutron has 1837 times the electron mass.
- The nucleus of an atom of a given chemical element Z will contain a number, N, of neutrons which can usually have one of several different values for a given Z. Atoms of different N but common Z are called isotopes of the element Z.
- The atomic weight A is equal to the nucleon number, the sum of proton and neutron numbers:

$$A = Z + N$$

Nomenclature: A given isotope of an element is represented by the chemical symbol for the element with the atomic weigh affixed as a superscript. For example

$$^{1}H \qquad ^{2}H \qquad \text{and} \qquad ^{3}H$$

represent the three isotopes of hydrogen. All contain one proton (Z = 1 or it wouldn't be hydrogen!) but these three isotopes contain zero, one, and two neutrons, respectively. The atomic number Z is sometimes included as a subscript but usually not since the chemical symbol implies the Z-value. The isotopes of hydrogen (Z = 1) have the smallest atomic masses. At the opposite extreme we have uranium with Z = 92; its principal isotopes are ^{235}U ^{236}U and ^{238}U

Nuclear Reactions

Nuclear processes are those which involve changes in the nucleus of an atom. In chemical reactions the numbers of atoms of a given element do not change; the atoms are just combined with other atoms in various ways to change the numbers of different kinds of molecules. In nuclear reactions, on the other hand, it is usually the case that the atomic nuclei of one chemical element are changed into nuclei of another. Sometimes this happens spontaneously, as in the radioactive decay of tritium (the heaviest isotope of hydrogen) to the lightest isotope of helium:

$$^{3}H \rightarrow {}^{3}He + e^{-} + \nu$$

What has happened here is that one of the neutrons has changed into a proton. The e^- is an ejected electron, the ν is the chargeless and almost-massless neutrino. Again, in a chemical reaction the number of atoms of a given element does not change; it is the same on both sides of the equation. In nuclear reactions the number of nucleons (3 in the above example) and the net electrical charge (+1) do not change. (Nucleon number can change if matter encounters antimatter and annihilation occurs, or if matter-antimatter nucleon pairs are created by radiation. This generally requires very extreme conditions.)

Spontaneously occurring nuclear reactions are generally fission reactions where a nucleus breaks up into two or more lighter species. Spontaneous fission reactions are characterized by a half-life; the average time a nucleus lives before it comes apart. Sometimes fission reactions can be induced or triggered by collision with a high energy photon (gamma ray), another nucleus, or by absorption of a neutron. (The last triggers the uranium or plutonium fission in nuclear reactors or in “atomic” bombs.)

Fusion reactions occur when two lighter nuclei combine to form a heavier nucleus. These generally require high densities and temperatures to occur. For this reason we often speak of “thermonuclear” fusion. One of the simplest fusion reactions is involved in powering the Sun:

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{-} + \nu$$

The heavy isotope of hydrogen (“deuterium”) so produced can then combine (think “hydrogen bomb”) with another proton to make a light isotope of helium and a gamma (γ) ray . That reaction is, symbolically

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$$