2.6: Early Models of the Hydrogen Atom

Ernest Rutherford had proposed a model of atoms based on the α-particle scattering experiments of Hans Geiger and Ernest Marsden. In these experiments helium nuclei (α-particles) were shot at thin gold metal foils. Most of the particles were not scattered; they passed unchanged through the thin metal foil. Some of the few that were scattered were scattered in the backward direction; i.e. they recoiled. This backward scattering requires that the foil contain heavy particles. When an α-particle hits one of these heavy particles it simply recoils backward, just like a ball thrown at a brick wall. Since most of the α-particles don't get scattered, the heavy particles (the nuclei of the atoms) must occupy only a very small region of the total space of the atom. Most of the space must be empty or occupied by very low-mass particles. These low-mass particles are the electrons that surround the nucleus.

There are some basic problems with the Rutherford model. The Coulomb force that exists between oppositely charge particles means that a positive nucleus and negative electrons should attract each other, and the atom should collapse. To prevent the collapse, the electron was postulated to be orbiting the positive nucleus. The Coulomb force is used to change the direction of the velocity, just as a string pulls a ball in a circular orbit around your head or the gravitational force holds the moon in orbit around the Earth.

But this analogy has a problem too. An electron going around in a circle is constantly being accelerated because its velocity vector is changing. A charged particle that is being accelerated emits radiation. This property is essentially how a radio transmitter works. A power supply drives electrons up and down a wire and thus transmits energy (electromagnetic radiation) that your radio receiver picks up. The radio then plays the music for you that is encoded in the waveform of the radiated energy.

If the orbiting electron is generating radiation, it is losing energy. If an orbiting particle loses energy, the radius of the orbit decreases. To **conserve angular momentum**, the frequency of the orbiting electron increases. The frequency increases continuously as the electron collapses toward the nucleus. Since the frequency of the rotating electron and the frequency of the radiation that is emitted are the same, both change continuously to produce a continuous spectrum and not the observed discrete lines. Furthermore, if one calculates how long it takes for this collapse to occur, one finds that it takes about 10^{-11} seconds. This means that nothing in the world based on the structure of atoms could exist for longer than about 10^{-11} seconds. Clearly something is terribly wrong with this classical picture, which means that something was missing at that time from the known laws of physics.

Niels Bohr approached this problem by proposing that we simply must invent new physical laws since experimental observations are inconsistent with the known physical laws. Bohr therefore proposed in 1913 that

1. The electron could orbit the nucleus in a stationary state without collapsing.
2. These orbits have discrete energies and radiation is emitted at a discrete frequency when the electron makes a transition from one orbit to another.
3. The energy difference between the orbits is proportional to the frequency of radiation emitted

$$E_f - E_i = \Delta E_{fi} = h\nu \tag{2.6.1}$$

where the constant of proportionality, h, is Planck's constant. Note that $E_f - E_i$ is the difference between energy levels and $h\nu$ is the energy of the emitted photon.

4. The angular momentum, M, of the orbiting electron is a positive integer multiple of $h/2\pi$, which often is written as $\hbar$ and called h-bar.

$$M = n\hbar \tag{2.6.2}$$

- where $n = 1, 2, 3, \dots$

Bohr's revolutionary proposal was taken seriously because with these ideas, he could derive Rydberg's formula and calculate a value for the Rydberg constant, which up to this point had only been obtained empirically by fitting the Rydberg equation to the luminescence data.

Example 2.6.1

Make four sketches to illustrate Bohr's four propositions