Chapter 31 Quantum Mechanics and Atomic Physics

Chapter Introduction

The idea that all matter is composed of atoms is fundamental to our modern view of the world. It has given us a firm basis for understanding the properties of solid, liquids, and gases. This understanding has led to a host of useful devices, one of the most famous being the laser. The laser beams arise because atoms generate light as they undergo transitions from a higher to a lower atomic energy level. Our venture into the atomic world begins with the concept of the nuclear atom and continues with the Bohr model of the hydrogen atom. This model introduces many basic atomic features, including the notions of discrete energy states and quantum numbers. We will see, however, that quantum mechanics has displaced the Bohr model and provides a more complete description of the atom. Following an overview of quantum mechanics, the Pauli exclusion principle will be discussed. This principle is important for explaining how electrons are arranged in complex atoms and how the elements are ordered in the periodic table. We will then apply our knowledge of atomic structure to describe how X-rays and laser light are produced.
Basic Terms

Nuclear atom

The idea of nuclear atom originated in 1911, as a result of experiments by Ernest Rutherford, in which alpha particles were scattered by a thin metal foil. The phrase "nuclear atom" refers to the fact that an atom consists of a small, positively charged nucleus surrounded at relatively large distance by a number of electrons, whose total negative charge equals the positive nuclear charge when the atom is electrically neutral.

Line spectrum

A line spectrum is a series of discrete electromagnetic wavelengths emitted by the atoms of a low-pressure gas that is subjected to a sufficiently high potential difference. Certain groups of discrete wavelengths are referred to as "series." The line spectrum of atomic hydrogen includes, among others, the Lyman series, the Balmer series, and the Paschen series of wavelength.

Bohr model (atom)

The Bohr model applies to atoms or ions that have only a single electron orbiting a nucleus containing Z protons. This model assumes that the electron exists in circular orbits that are called stationary orbits, because the electron does not radiate electromagnetic waves while in them. According to this model, a photon is emitted only when an electron changes from a higher energy orbit (level) to a lower one. The model also assumes that the orbital angular momentum $L_n$ of the electron can only have values that are integer multiples of Plank's constant divided by $2\pi$. 
\[ L_n = n(h/2\pi); \quad n = 1, 2, 3, \ldots \] With the assumption above, it can be shown that the \( n \)th Bohr orbit has a radius (in meters) of \( r_n = (5.29 \times 10^{-11} \text{ m}) (n^2/Z) \) and that the total energy associated with this orbit is \( E_n = -(13.6 \text{ eV}) (Z^2/n^2) \).

**Ionization energy**

The ionization energy is the energy needed to remove an electron completely from an atom. The Bohr model predicts that the wavelengths comprising the line spectrum emitted by a hydrogen atom are given by Equation 31.2.

**Quantum number**

Because the various electron orbits and the associated energies have only discrete values, one uses integer numbers to identify each orbit and its corresponding energy. Such integer number is called a quantum number. Quantum mechanics describes the hydrogen atom in terms of four quantum numbers: (1) the principal quantum number \( n \), which can have the integer values \( n = 1, 2, 3, \ldots \); (2) the orbital quantum number \( l \), which can have values \( l = 0, 1, 2, \ldots, (n-1) \); (3) the magnetic quantum number \( m_l \), which can have positive and negative integer values \( m_l = -l, \ldots, -2, -1, 0, +1, +2, \ldots, +l \), and (4) the spin quantum number \( m_s \), which can be either \( m_s = +\frac{1}{2} \) or \( m_s = -\frac{1}{2} \). According to quantum mechanics, an electron does not reside in a circular orbit but, rather, has some probability of being found at various distances from the nucleus.

**Electron spin**

The spin quantum number is an intrinsic property of an electron and is also called spin angular momentum. Loosely speaking, one can view the electron as spinning while it orbits the nucleus, analogous to the way the
Earth spins as it moves around the sun. The electron spin has two possible values:

\[ m_s = \pm \frac{1}{2} \]

**Pauli exclusion principle**

The Pauli exclusion principle states that no two electrons in an atom can have the same set of values for the four quantum numbers \( n, l, m_l, \) and \( m_s \). This principle determines the way in which the electrons in multiple-electron atoms are distributed into shells and subshells. The arrangement of the periodic table of the elements is related to the exclusion principle.

**X-ray**

X-rays are electromagnetic waves emitted when high-energy electrons strike a metal target contained within an evacuated glass tube. The emitted X-ray spectrum of wavelengths consists of sharp "peaks" or "lines", called **characteristic X-rays**, superimposed on a broad continuous range of wavelengths called **Bremsstrahlung**. The minimum wavelength, or cutoff wavelength, of the Bremsstrahlung is determined by the kinetic energy of the electron striking the metal target in the X-ray tube.