Chapter 1

Atomic Physics

Day – 1

1. The Nuclear Atom

Before we can further progress in relating the energy levels of an atom to its internal structure, we need to have better idea of what the inside of an atom is like. We know that atoms are much smaller than the wavelengths of visible light, so there is no hope of actually seeing an atom using than light. But we can still describe how the mass and electric charges are distributed throughout the volume of the atom.

Here‟s where things stood in 1910. J.J. Thomson had discovered the electron and measured its charge – to – mass ratio (*e/m*) in 1897; and by 1909, Millikan had completed his first measurements of the electron charge ^{-}e. These and other experiments showed that almost all the mass of an atom had to be associated with the positive charge, not with the electrons. It was also known that the overall size of atoms is of the order of 10^{-10} m and that all atoms except hydrogen contain more than one electron. What was not known was how the mass and charge were distributed within the atom. Thomson had proposed a model in which the atom consisted of a sphere of positive charge, of the order of 10^{-10}m in diameter, with the electrons embedded in it like raisins in a more or less spherical muffin.

Rutherford‟s experimental setup is shown schematically in figure. A radioactive substance at the left emits alpha particles. Thick lead screens stop all particles except those in a narrow beam defined by small holes. The beam then passes through a target consisting of a thin gold, silver, or copper foil and strikes screens coated with zinc sulfide, similar in principal to the screen of TV picture tube. A momentary flash, or scintillation, can be seen on the screen whenever it is struck by an alpha particle. Rutherford and his students counted the numbers of particles deflected through various angles.

Think of the atoms of the target material as being packed together like marbles in a box. An alpha particle can pass through a thin sheet of metal foil, so the alpha particle must be able actually to pass through the interiors of atoms. The total electric charge of the atom is zero, so outside the atom there is little force on the alpha particle. Within the atom there are electrical forces caused by the electrons and by the positive charge. But the mass of an alpha particle is about 7300 times that of an electron. Momentum considerations shown that the alpha particle can be scattered only a very small amount by its interaction with the much lighter electrons. It‟s like throwing a pebble through a swarm of mosquitoes; the mosquitoes don‟t deflect the pebble very much. Only interactions with the positive charge, which is tied to almost all of mass of the atom, can deflect the alpha particle appreciably.

Back to the drawing board! Suppose the positive charge, instead of being distributed through a sphere with atomic dimensions (of the order of 10^{-10}m), is all concentrated in a much smaller space. Then it would act like a point charge down to much smaller distances. The maximum electric field repelling the alpha particle would be much larger, and the amazing large – angle scattering would be possible. Rutherford called this concentration of positive charge the nucleus. He again computed the numbers of particles expected to be scattered through various angles. Within the accuracy of his experiments, the computed and measured results agreed, down to distance of the order of 10^{-14}m. His experiments therefore established that the atom does have a nucleus, a very small, very dense structure, no larger than10^{-14}m in diameter. The nucleus occupies only about 10^{-12} of the total volume of the atom or less, but it contains all the positive charge and at least 99.95% of the total mass of the atom.

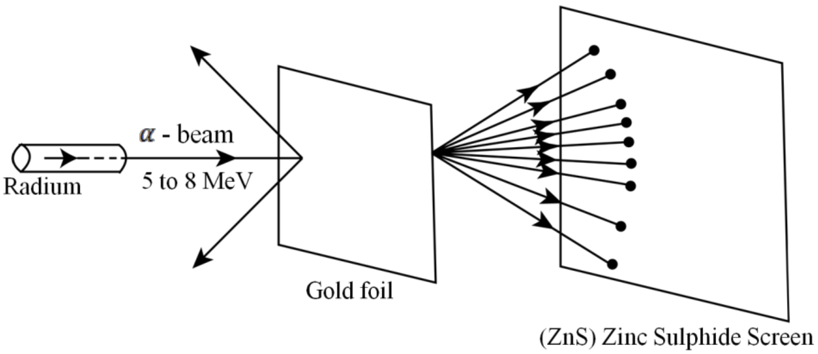
1.1 The Bohr Model

At the same time (1913) that Bohr established the relationship between spectral wavelength and energy levels, he also proposed a model of the hydrogen atom. He developed his ideas while working in Rutherford‟s laboratory. Using this model, now known as the Bohr model, he was able to calculate the energy levels of hydrogen and obtain agreement with values determined from spectra.

Rutherford‟s discovery electrons at relatively large distance (~10^{-10}m) away from the very small (~10^{-14}m), positively charged nucleus despite their electrostatic attraction? Rutherford suggested that perhaps the electrons revolve in orbits about the nucleus, just as the planets revolve around the sun.

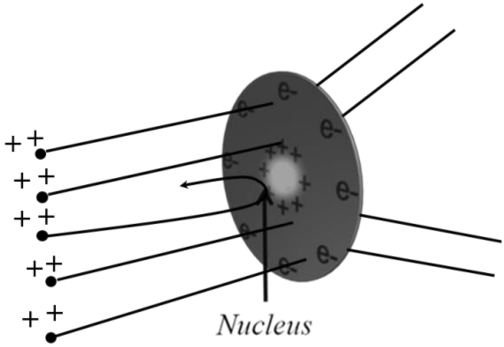
But according to classical electromagnetic theory, any accelerating electric charge (either oscillating or revolving) radiates electromagnetic waves. An example is radiation from an oscillating point charge, shown in figure. The energy of an orbiting electron should therefore decrease continuously, its orbit should becomes smaller and smaller, and it should spiral rapidly into the nucleus. Even worse, according to classical theory the frequency of the electromagnetic waves emitted should equal the frequency of revolution. As the electrons radiated energy, their angular speeds would change continuously, and they would emit a continuous spectrum (a mixture of all frequencies), not the line spectrum actually observed.

1.2 Rutherford Scattering



1.3 Observation

1. Most of the α particles either undeflected or deflected through small angles of the order $1^0 \rightarrow$ will be nucleous diameter = 10^{-12} cm, very few deflected through angles as large as $90^0 \rightarrow$ space of electrons dia = 10^{-10} meter.



1.4 Impact Parameter (b)

The closest distance of approach between the beam particle and scattered.

$$b = \frac{z_1 z_2 e^2}{8\pi\varepsilon_0 K}\cot\frac{\theta}{2}$$

z_1 = atomic number of beam particle
z_2 = atomic number of target material
θ = change in direction of velocity.

1.5 Number of particles scattered per unit area

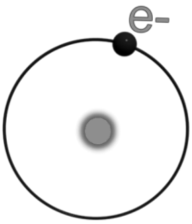
$$\mathrm{N}(\theta) = \frac{Nint}{16}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{z_1^2 z_2^2}{r^2 K^2 \sin\frac{4\theta}{2}}$$

Here n = number of atoms per unit volume
t = thickness of target foil
θ = scattering angle

1.6 Bohr' Model

Assumptions

1. Orbits in which are elliptical not circular.



2. Electron revolves in orbits whose angular momentum will be as

$$mvr = n\frac{h}{2\pi} \qquad \text{Here } n = 1, 2, 3 \ldots\ldots$$

Here n is principal quantum number
H is plank‟s constant.

3. Centripetal force will be provided by coulomb‟s force between positive charge nucleous and electron.

$$\frac{1}{4\pi\varepsilon_0}\frac{e(ze)}{r^2} = \frac{mv^2}{r}$$

1.7 Radius of nth Bohr's orbit

$$= n\frac{h}{2\pi} \quad \Rightarrow \quad v = \frac{nh}{2\pi mr}$$

mvr

$$\frac{ze^2}{4\pi\varepsilon_0 r^2} = \frac{mv^2}{r}$$

$$\frac{ze^2}{4\pi\varepsilon_0 mr} = \frac{n^2h}{4\pi^2m^2r^2}$$

$$r_n = \frac{n^2h^2\varepsilon_0}{\pi mze^2} \quad \Rightarrow \quad \mathbf{r_n = 0.53\frac{n^2}{z}} \text{ Å}$$

$$\Rightarrow \quad r_n \propto \frac{n^2}{z}$$

1.8 Velocity of electron in nth Bohr's orbit

$$v = \frac{nh}{2\pi mr} = \frac{nh\pi mze^2}{2\pi mn^2h^2\varepsilon_0}$$

$$v_n = \frac{ze^2}{2nh\varepsilon_0} \quad \Rightarrow \quad \mathbf{v_n = 2.2\times 10^6\frac{z}{n}\ meter/sec}$$

$$\Rightarrow \quad v_n \propto \frac{z}{n}$$

Also $\quad v_n \approx \left(\frac{c}{137}\right)\left(\frac{z}{n}\right)$

1.9 Kinetic energy of electron in nth Bohr's orbit

$$K_n = \frac{1}{2}mv_n{}^2$$

$$= \frac{1}{2}m\ \frac{z^2e^4}{4n^2h^2\varepsilon_0^2}$$

$$\mathbf{K_n = \frac{1}{8}\left(\frac{me^4}{h^2\varepsilon_0^2}\right)\frac{z^2}{n^2}} \quad \Rightarrow \quad K_n \propto \frac{z^2}{n^2}$$

1.10 Potential energy of electron in nth Bohrs orbit

$$U_n = \frac{1}{4\pi\varepsilon_0}\frac{(-e)(ze)}{r}$$

$$= -\frac{ze^2}{4\pi\varepsilon_0 r}$$

$$= -\frac{ze^2\pi mze^2}{4\pi\varepsilon_0 n^2h^2\varepsilon_0}$$

$$\mathbf{U_n = -\frac{1}{4}\left(\frac{me^4}{h^2\varepsilon_0^2}\right)\left(\frac{z^2}{n^2}\right)}$$

1.11 Total energy of electron in nth Bohr's orbit

$$\text{T.E.} = E_n = K_n + U_n$$

$$E_n = \frac{1}{8}\left(\frac{me^4}{h^2\varepsilon_0^2}\right)\frac{z^2}{n^2} - \frac{1}{4}\left(\frac{me^4}{h^2\varepsilon_0^2}\right)\left(\frac{z^2}{n^2}\right)$$

$$\mathbf{E_n = -\frac{1}{8}\left(\frac{me^4}{h^2\varepsilon_0^2}\right)\frac{z^2}{n^2}}$$

$$E_n \propto \frac{z^2}{n^2}$$

Also $E_n = -13.6\,\frac{z^2}{n^2}\ eV$

Here $\mathbf{K_n} = |\mathbf{E_n}| = \left|\frac{\mathbf{U_n}}{\mathbf{z}}\right|$

Rydbery constant : $|E_n| = \frac{me^4}{8h^2\varepsilon_0^2}\,\frac{z^2}{n^2}$

$$= Rhc\left(\frac{\mathbf{z^2}}{\mathbf{n^2}}\right)$$

$\Rightarrow \quad Rhc = \frac{me^4}{8h^2\varepsilon_0^2}$

$$\mathbf{R} = \frac{\boldsymbol{me^4}}{\boldsymbol{8h^3\varepsilon_0^2 c}} \Rightarrow R = 1.0973 \times 10^7\ \text{met}^{-1}$$

$$\mathbf{Rhc = 13.6\ eV}$$

1.12 Ionisation Energy

Energy required to remove an electron from atom.

For H – atom minimum energy required to ionise the atom will be +13.6 eV.

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