HSST PHYSICS

MODULE 7 PART 4

Diamagnetism

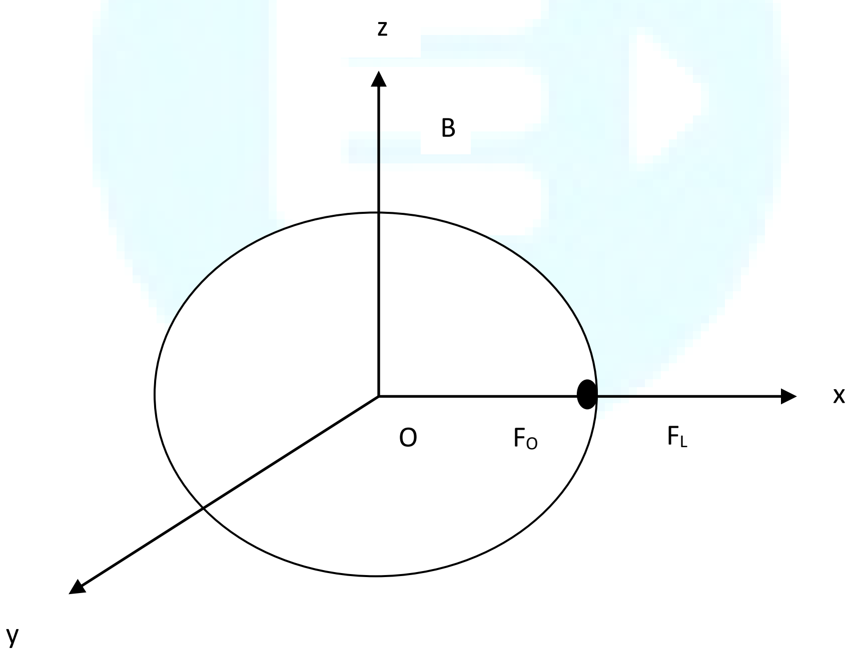
- Diamagnetism was discovered and named in September 1845 by Michael Faraday. This is the weakest form of magnetism that is displayed in the presence of an external magnetic field. The orbital motion of electrons changes due to the external magnetic field. This induced magnetic moment is extremely small and in a direction opposite to that of the applied field. When placed within a strong electromagnet, diamagnetic materials are attracted toward regions where the magnetic field is weak.
- Diamagnetism is found in all materials; however, because it is so weak it can only be observed in materials that do not exhibit other forms of magnetism. Diamagnetic substances are composed of atoms that have no net magnetic moments (i.e., all the orbital shells are filled and there are no unpaired electrons). However, when subjected to a field, a negative magnetization is produced and thus the susceptibility is negative.
- An exception to the 'weak' nature of diamagnetism occurs when a number of materials become superconducting. Superconductors are ideal diamagnets; when positioned in an external magnetic field, they expel the field lines from their interiors (depending on field intensity and temperature). Superconducting magnets are the foremost elements of most magnetic resonance imaging (MRI) systems and are among the most important applications of diamagnetism. Bismuth, which is used in guns, displays the strongest diamagnetism. Bismuth can be melted down and molded to efficiently capture any diamagnetic properties. Pyrolytic graphite is also an unusually strongly diamagnetic material that can be stably floated on a magnetic field.

Langevin's theory of Diamagnetism

Materials exhibit diamagnetism due to the fact that the effect of a magnetic field on the orbital motion of an electron is such as to produce a negative susceptibility.

Consider an electron which revolves around the nucleus with a frequency ω_0 as shown in figure below. If m is the mass of the electron, e is the charge and r is the radius of the electron orbit, the centripetal force on the electron due to the nucleus in the absence of an external field is given by,

$F_O = m\omega_0^2 r$…………..(1)



Now, let a magnetic field be applied along the z – axis. Then the magnetic Lorentz force acts on the electron and is directed away from the centre, given by

$F_L = -e\,(v \times b) = -eBr\omega$ since B is perpendicular to v.

The net inward force is then $F_O - eBr\omega = m\omega^2 r$

This is because due to the change in force, the angular frequency has changed from ω_0 to ω.

Substituting the value of F_O from eqn (1) and rearranging we get,

$$\omega^2 + \frac{eB}{m}\omega - \omega_0{}^2 = 0$$

$$\omega = \frac{-eB}{2m} + \sqrt{\left[\frac{eB}{2m}\right]^2 + \omega 0\ 2}$$

If $\omega_0 >> eB/2m$

$$\omega = \pm\ \omega_0 - \frac{eB}{2m}$$

$$= \pm\ \omega_0 - \omega_L$$

ω_L is the Larmor Precessional Frequency

In the absence of a magnetic field, the electron motion is spherically symmetric. When the field is applied, the plane of the orbit precesses about the field direction with Larmor frequency, which is smaller than the orbital motion ω_0.

This precessional motion of the orbit produces a current given by

I = Charge × Revolutions per unit time

$$= -e \times \frac{\omega L}{2\pi} = -\frac{Be}{4\pi m}^2$$

Magnetic moment due to this current loop is then

$\mu =$ current × area of the loop generated by precession $= \frac{-BZe^2}{4\pi M}\pi\rho^2$

$$= \frac{-BZe^2}{4m}\rho^2$$

Z is the number of electrons in the atom and ρ^2 is the mean square radius of the electrons from the field axis through the nucleus $= \frac{2}{3} r^2$ for spherically symmetric charge distribution.

$$\mu = \frac{-BZe^2}{6m} r^2$$

If N is the number of atoms per unit volume, the magnetization M = N μ

$$M = \frac{-NBZe^2}{6m} r^2$$

Since $B = \mu_0 H$, the diamagnetic susceptibility $\chi = \frac{M}{H} = \frac{-\mu_0 NZe^2}{6m} r^2$

This is the Langevin's equation for diamagnetic susceptibility.

The following conclusions can be made from the Langevin's equation;

1. The diamagnetic susceptibility is independent of temperature.
2. Outer electrons are the largest contributors to the diamagnetic susceptibility.
3. Diamagnetic susceptibility is proportional to the number of atoms per unit volume.