Magnetic Fields

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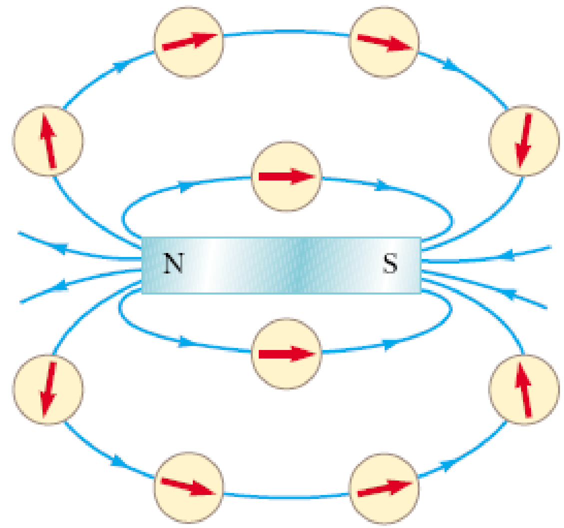
Applied Physics

Magnetic Fields and Forces



We can define a magnetic field B at some point in space in terms of the magnetic force $\mathbf{F_B}$ that the field exerts on a charged particle moving with a velocity v, which we call the test object.

For the time being, let us assume that no electric or gravitational fields are present at the location of the test object. Experiments on various charged particles moving in a magnetic field give the following results:

- The magnitude $\mathbf{F_B}$ of the magnetic force exerted on the particle is proportional to the charge **q** and to the speed **v** of the particle.

- The magnitude and direction of $\mathbf{F_B}$ depend on the **velocity** of the particle and on the magnitude and direction of the magnetic field **B**.

- When a charged particle moves parallel to the magnetic field vector, the magnetic force acting on the particle is **zero**.

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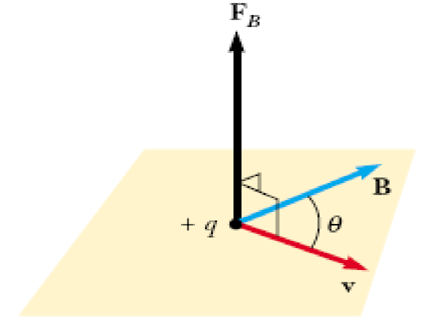
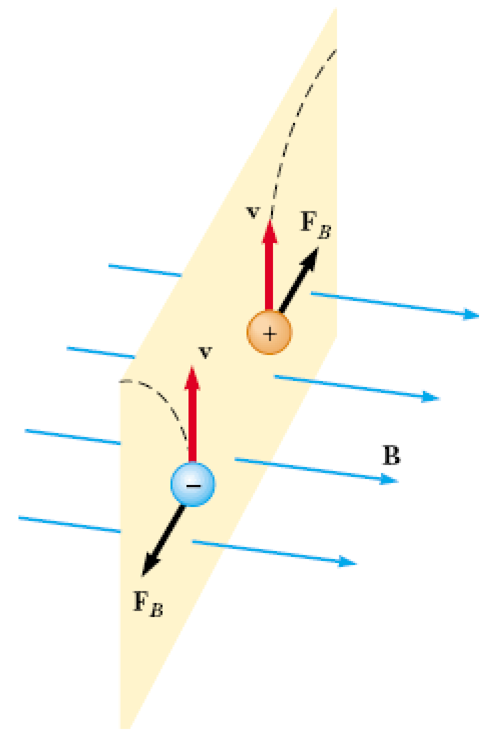
• When the particle's velocity vector makes any angle **θ≠0** with the magnetic field, the magnetic force acts in a direction perpendicular to both **v** and **B**; that is, $\mathbf{F_B}$ is perpendicular to the plane formed by **v** and **B**.

• The magnetic force exerted on a positive charge is in the direction opposite the direction of the magnetic force exerted on a negative charge moving in the same direction.

• The magnitude of the magnetic force exerted on the moving particle is proportional to **sinθ**, where **θ** is the angle the particle's velocity vector makes with the direction of **B**.





Magnitude of the magnetic force on a charged particle moving in a magnetic field

We can summarize these observations by writing the magnetic force in the form:

$$\mathbf{F}_B = q\mathbf{v} \times \mathbf{B}$$

$$F_B = |q| vB \sin\theta$$

where θ is the smaller angle between **v** and **B**. From this expression, we see that F is zero when **v** is parallel or antiparallel to **B** ($\theta = 0$ or $180°$) and maximum ($F_{B,\max} = |q|vB$) when **v** is perpendicular to **B** ($\theta = 90°$).

A magnetic field cannot change the speed of a particle

when a charged particle moves with a velocity **v** through a magnetic field, the field can alter the direction of the velocity vector but cannot change the speed or kinetic energy of the particle.

Differences between electric and magnetic forces

There are several important differences between electric and magnetic forces:

- The electric force acts along the direction of the electric field, whereas the magnetic force acts perpendicular to the magnetic field.
- The electric force acts on a charged particle regardless of whether the particle is moving, whereas the magnetic force acts on a charged particle only when the particle is in motion.
- The electric force does work in displacing a charged particle, whereas the magnetic force associated with a steady magnetic field does no work when a particle is displaced because the force is perpendicular to the displacement.

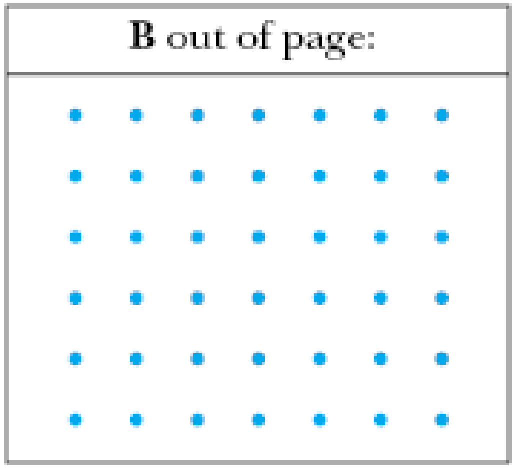
The SI unit of magnetic field is the newton per coulomb-meter per second, which is called the tesla (T):

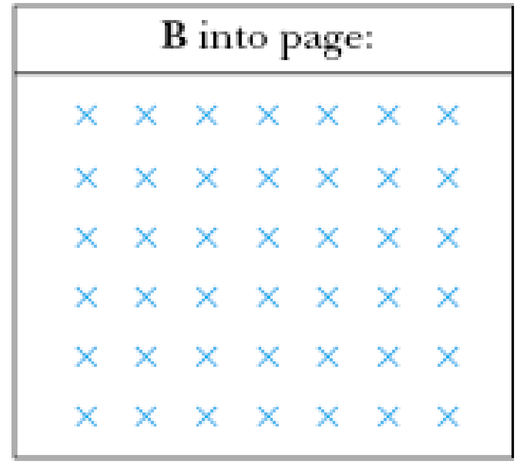
$$1\ \mathrm{T} = 1\ \frac{\mathrm{N}}{\mathrm{C \cdot m/s}}$$

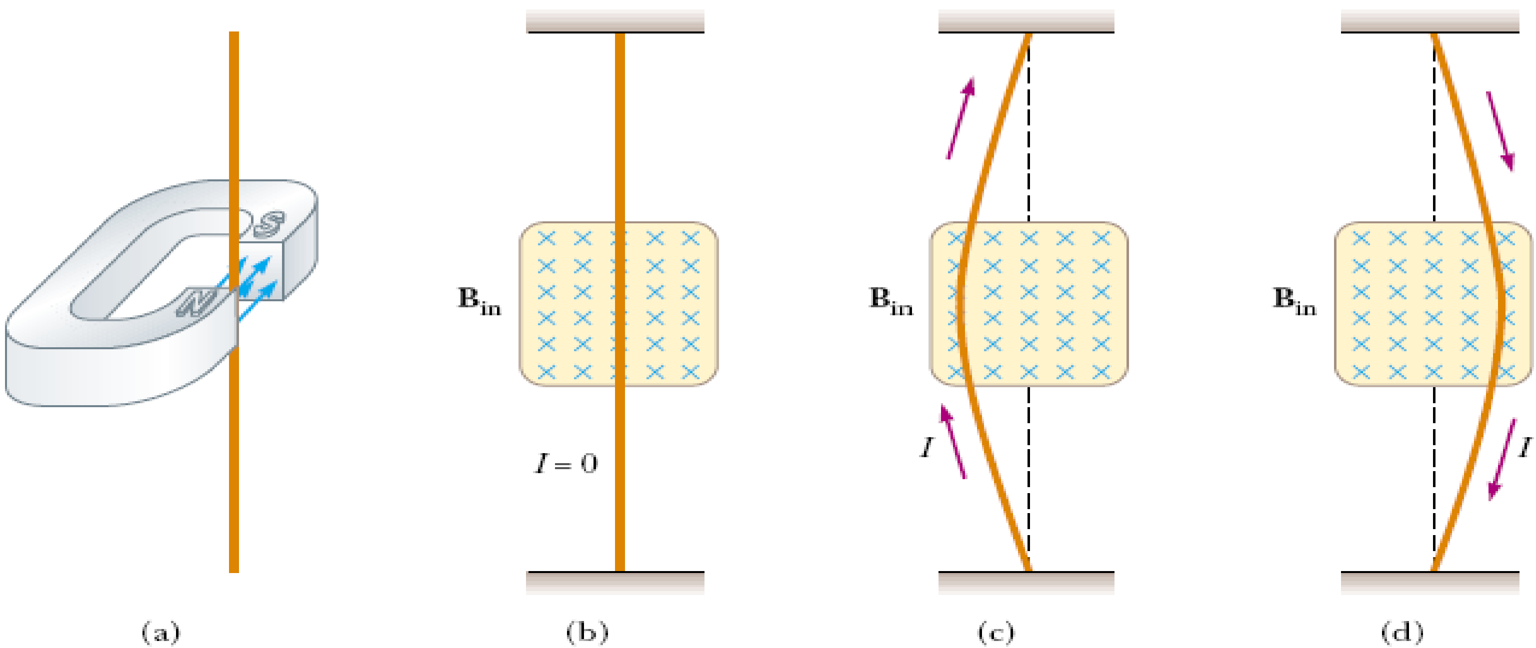
Because a coulomb per second is defined to be an ampere, we see that

$$1\ \mathrm{T} = 1\ \frac{\mathrm{N}}{\mathrm{A \cdot m}}$$

Magnetic Force Acting on a Current-Carrying Conductor







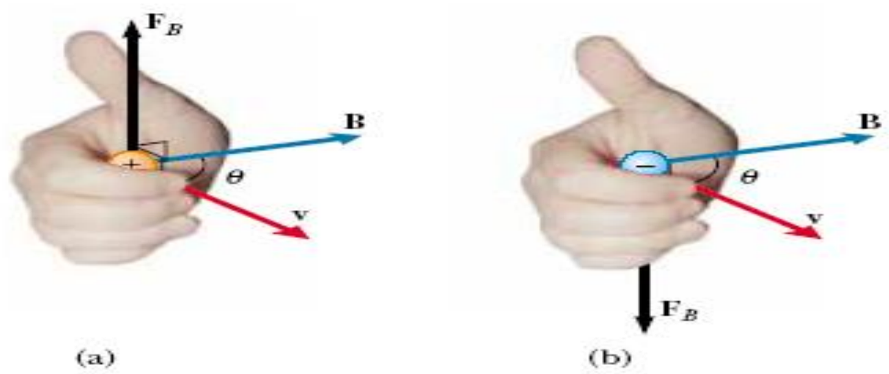
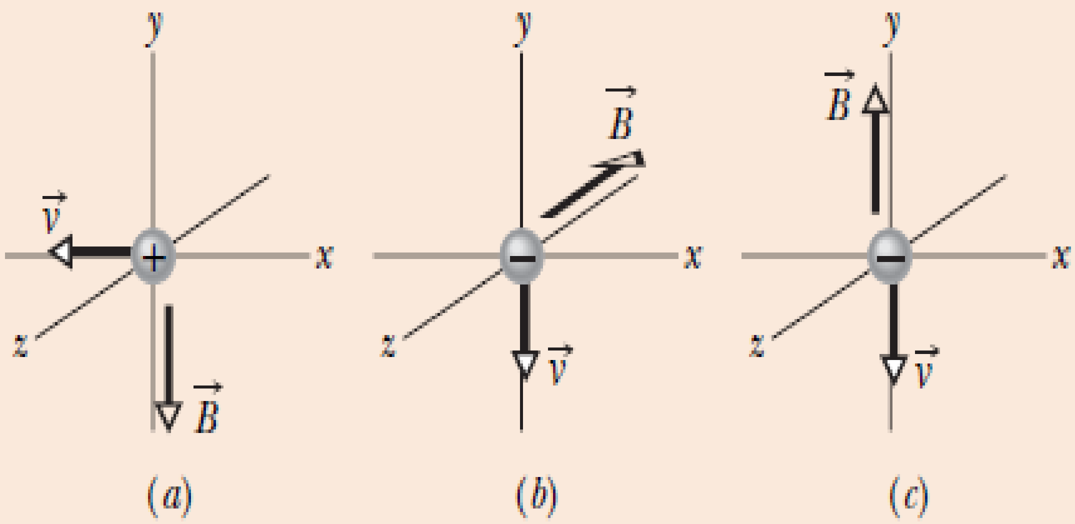


Figure 29.4 The right-hand rule for determining the direction of the magnetic force $\mathbf{F}_B = q\mathbf{v} \times \mathbf{B}$ acting on a particle with charge q moving with a velocity $\mathbf{v}$ in a magnetic field $\mathbf{B}$. The direction of $\mathbf{v} \times \mathbf{B}$ is the direction in which the thumb points. (a) If q is positive, $\mathbf{F}_B$ is upward. (b) If q is negative, $\mathbf{F}_B$ is downward, antiparallel to the direction in which the thumb points.

Fleming's Left Hand Rule:

The figure shows three situations in which a charged particle with velocity $\vec{v}$ travels through a uniform magnetic field $\vec{B}$. In each situation, what is the direction of the magnetic force $\vec{F}_B$ on the particle?



Example Problem

A uniform magnetic field $\vec{B}$, with magnitude 1.2 mT, is directed vertically upward throughout the volume of a laboratory chamber. A proton with kinetic energy 5.3 MeV enters the chamber, moving horizontally from south to north. What magnetic deflecting force acts on the proton as it enters the chamber? The proton mass is 1.67×10^{-27} kg. (Neglect Earth's magnetic field.)

KEY IDEAS

Because the proton is charged and moving through a magnetic field, a magnetic force $\vec{F}_B$ can act on it. Because the initial direction of the proton's velocity is not along a magnetic field line, $\vec{F}_B$ is not simply zero.

Magnitude: To find the magnitude of $\vec{F}_B$, we can use Eq. 28-3 ($F_B = |q|vB \sin \phi$) provided we first find the proton's speed v. We can find v from the given kinetic energy because $K = \frac{1}{2}mv^2$. Solving for v, we obtain

$$v = \sqrt{\frac{2K}{m}} = \sqrt{\frac{(2)(5.3\ \text{MeV})(1.60 \times 10^{-13}\ \text{J/MeV})}{1.67 \times 10^{-27}\ \text{kg}}}$$
$$= 3.2 \times 10^7\ \text{m/s}.$$

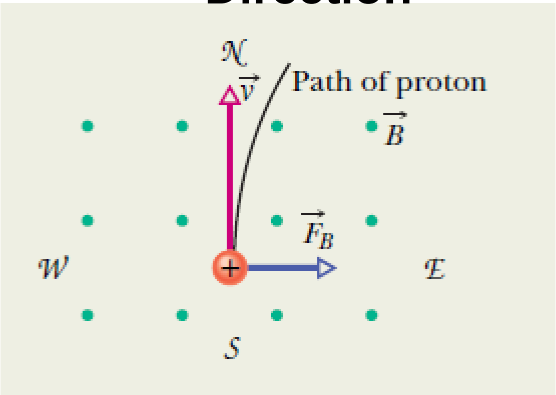
Equation 28-3 then yields

$$F_B = |q|vB \sin \phi$$
$$= (1.60 \times 10^{-19}\ \text{C})(3.2 \times 10^7\ \text{m/s}) \times (1.2 \times 10^{-3}\ \text{T})(\sin 90°)$$
$$= 6.1 \times 10^{-15}\ \text{N}. \qquad \text{(Answer)}$$

This may seem like a small force, but it acts on a particle of small mass, producing a large acceleration; namely,

$$a = \frac{F_B}{m} = \frac{6.1 \times 10^{-15}\ \text{N}}{1.67 \times 10^{-27}\ \text{kg}} = 3.7 \times 10^{12}\ \text{m/s}^2.$$

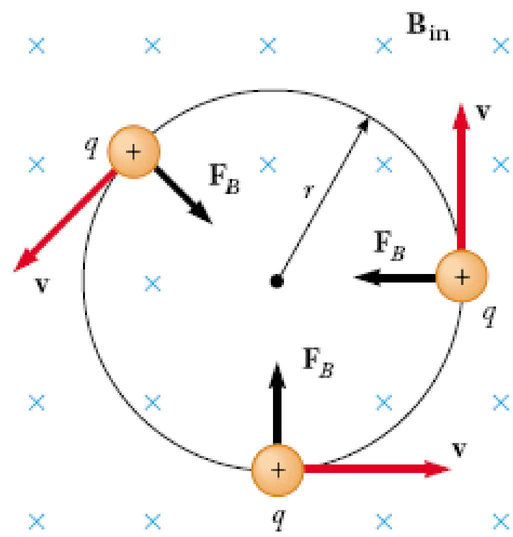
Direction



Key:
1 eV = 1.6×10^{-19} Joules

Motion of a Charged Particle in a Uniform Magnetic Field

consider the special case of a positively charged particle moving in a uniform magnetic field with the initial velocity vector of the particle perpendicular to the field.



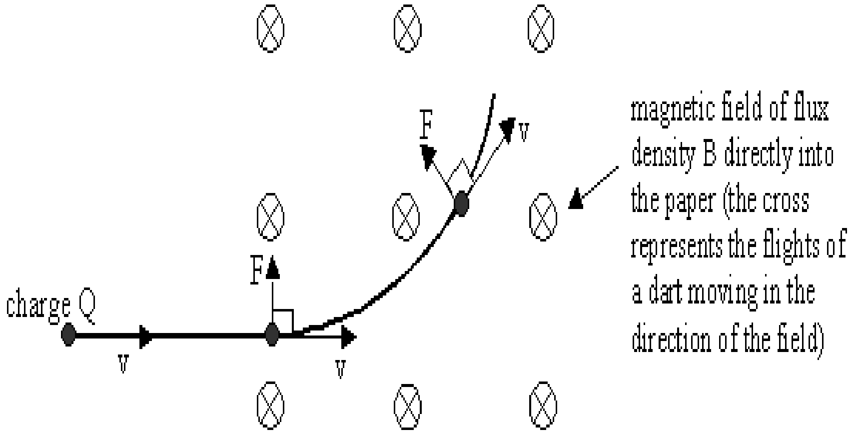
The particle moves in a circle because the magnetic force $\mathbf{F_B}$ is perpendicular to **v** and **B** and has a constant magnitude **qvB**.

The rotation is counterclockwise for a positive charge. If q were negative, the rotation would be clockwise.

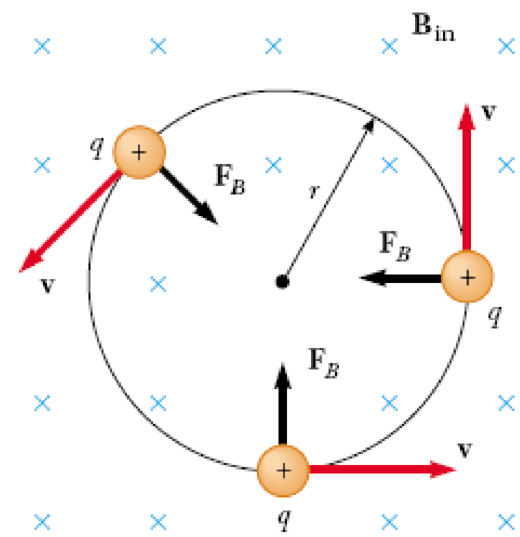
$$\sum F = ma_c$$

$$F_B = qvB = \frac{mv^2}{r}$$

$$r = \frac{mv}{qB}$$



That is, the radius of the path is proportional to the linear momentum **mv** of the particle and inversely proportional to the magnitude of the charge on the particle and to the magnitude of the magnetic field. The angular speed of the particle is,



$$\omega = \frac{v}{r} = \frac{qB}{m}$$

The period of the motion (the time interval the particle requires to complete one revolution) is equal to the circumference of the circle divided by the linear speed of the particle:

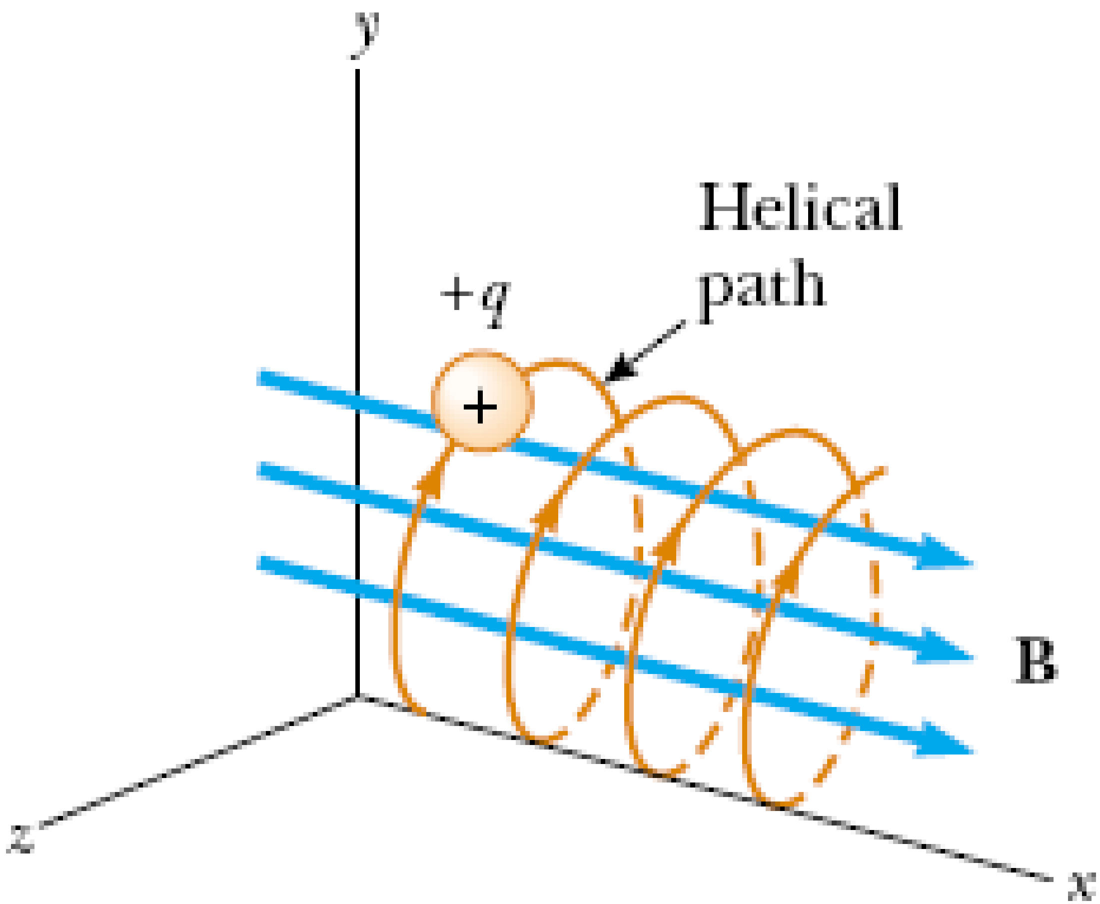
$$T = \frac{2\pi r}{v} = \frac{2\pi}{\omega} = \frac{2\pi m}{qB}$$

These results show that the angular speed of the particle and the period of the circular motion do not depend on the linear speed of the particle or on the radius of the orbit.
The angular speed . is often referred to as the cyclotron frequency because charged particles circulate at this angular frequency in the type of accelerator called a *cyclotron.*

Class Task:

- What will be the Kinetic Energy of a charged particle moving around a current carrying conductor?
- What will be the frequency of that charged particle?

If a charged particle moves in a uniform magnetic field with its velocity at some arbitrary angle with respect to B, its path is a helix.



Aurora Borealis (aurora means shine), it is seen over North & South Pole

Applications Involving: Charged Particles Moving in a Magnetic Field

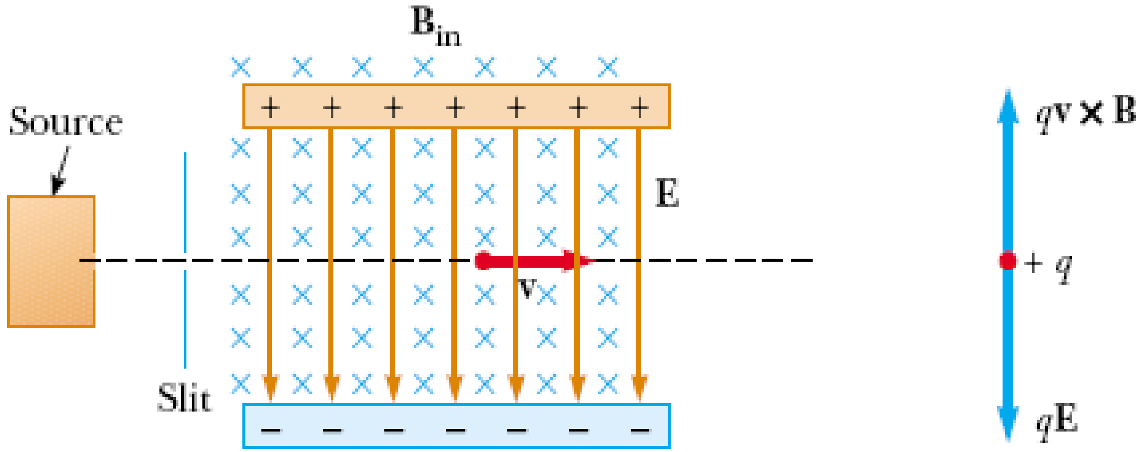
A charge moving with a velocity **v** in the presence of both an electric field **E** and a magnetic field **B** experiences both an electric force $q\mathbf{E}$ and a magnetic force $q\mathbf{v} \times \mathbf{B}$. The total force (called the Lorentz force) acting on the charge is

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$

Velocity Selector

$$qE = qvB$$

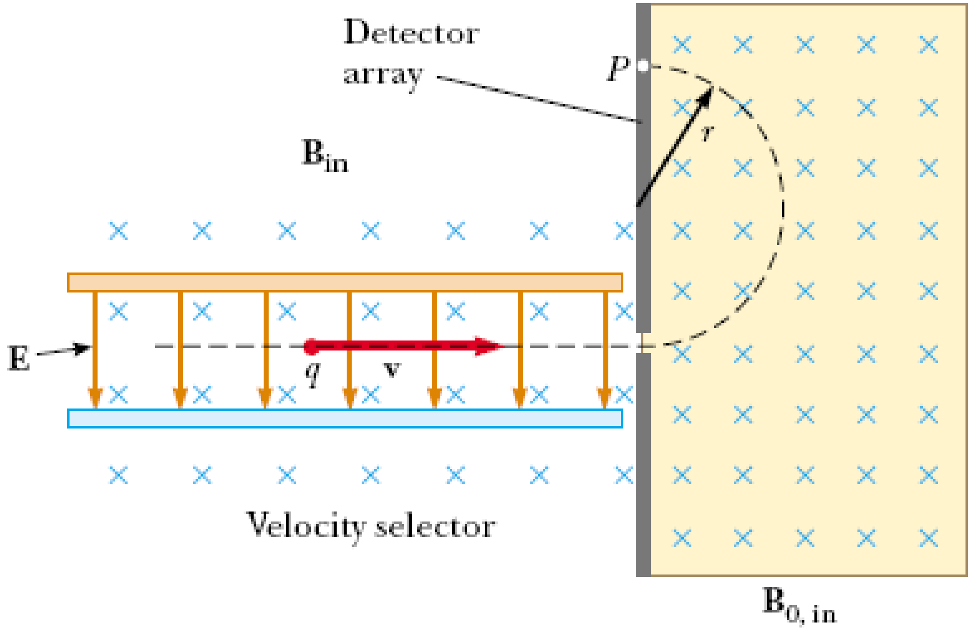
$$v = \frac{E}{B}$$



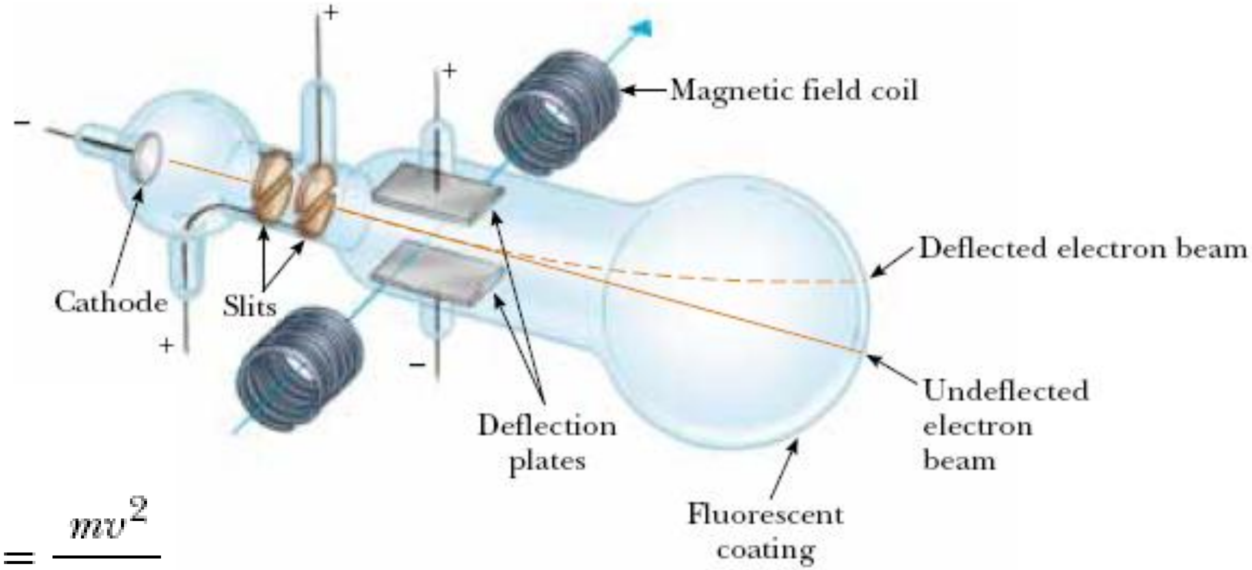
Only those particles having speed v pass undeflected through the mutually perpendicular electric and magnetic fields. The magnetic force exerted on particles moving at speeds greater than this, is stronger than the electric force, and the particles are deflected upward. Those moving at speeds less than this are deflected downward.

The Mass Spectrometer

A mass spectrometer separates ions according to their mass-to-charge ratio.
In one version of this device, known as the Bainbridge mass spectrometer, a beam of ions first passes through a velocity selector and then enters a second uniform magnetic field $\mathbf{B}_0$ that has the same direction as the magnetic field in the selector.



Upon entering the second magnetic field, the ions move in a semicircle of radius r before striking a detector array at P. If the ions are positively charged, the beam deflects upward. If the ions are negatively charged, the beam deflects downward.



$$\sum F = ma_c$$

$$F_B = qvB = \frac{mv^2}{r}$$

$$r = \frac{mv}{qB}$$

$$v = \frac{E}{B}$$

$$\frac{m}{q} = \frac{rB_0}{v}$$

$$\frac{m}{q} = \frac{rB_0 B}{E}$$

A variation of this technique was used by J. J. Thomson (1856–1940) in 1897 to measure the ratio *e/me for electrons.*

The Cyclotron

A cyclotron is a device that can accelerate charged particles to very high speeds. The energetic particles produced are used to bombard atomic nuclei and thereby produce nuclear reactions of interest to researchers.
A number of hospitals use cyclotron facilities to produce radioactive substances for diagnosis and treatment.

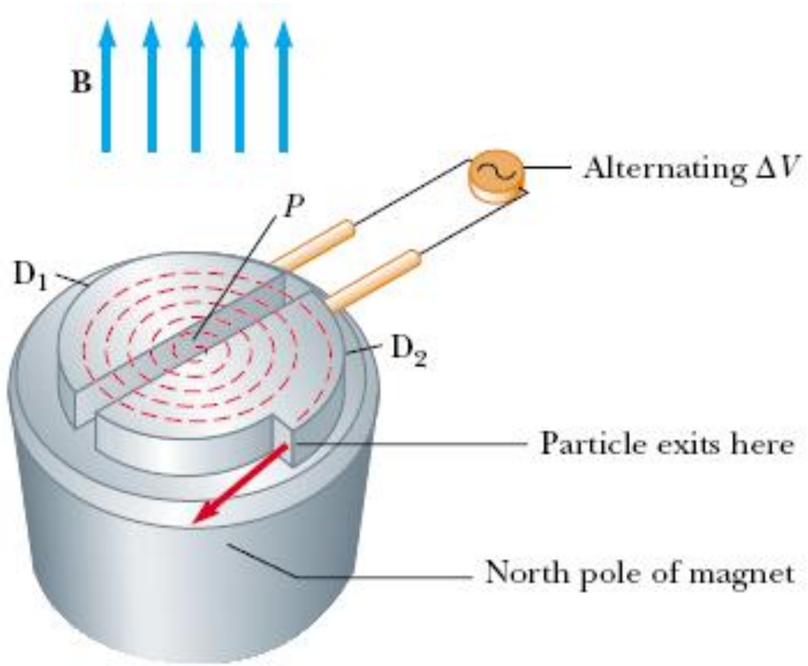
$$\sum F = ma_c$$

$$F_B = qvB = \frac{mv^2}{r}$$

$$r = \frac{mv}{qB}$$

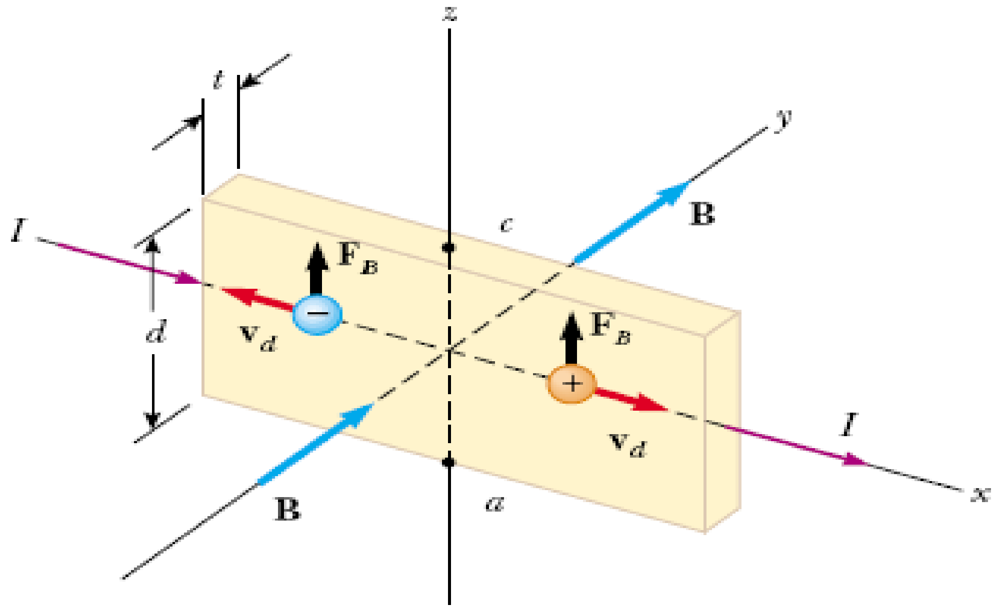
$$v = qBR/m$$

$$K = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$



The Hall Effect

When a current-carrying conductor is placed in a magnetic field, a potential difference is generated in a direction perpendicular to both the current and the magnetic field. This phenomenon, first observed by Edwin Hall (1855–1938) in 1879, is known as the *Hall effect*. It arises from the deflection of charge carriers to one side of the conductor as a result of the magnetic force they experience. The Hall effect gives information regarding the sign of the charge carriers and their density; it can also be used to measure the magnitude of magnetic fields.



GAUSS'S LAW IN MAGNETISM

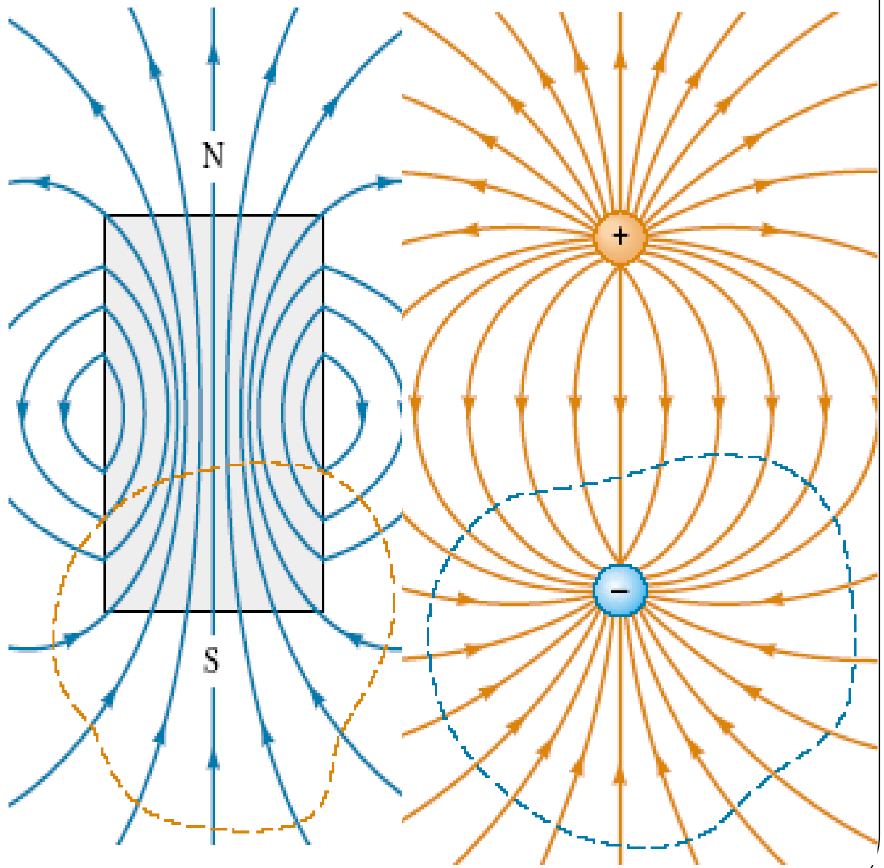
Gauss's law in magnetism states that

the net magnetic flux through any closed surface is always zero:

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

An isolated magnetic poles (monopoles) have never been detected and perhaps do not exist.

The magnetic field lines of a bar magnet form closed loops. Note that the net magnetic flux through the closed surface(dashed line) surrounding one of the poles (or any other closed surface) **is zero**. The electric field lines surrounding an electric dipole begin on the positive charge and terminate on the negative charge. The electric flux through a closed surface surrounding one of the charges is **not zero**.



Classification of Magnetic Substances

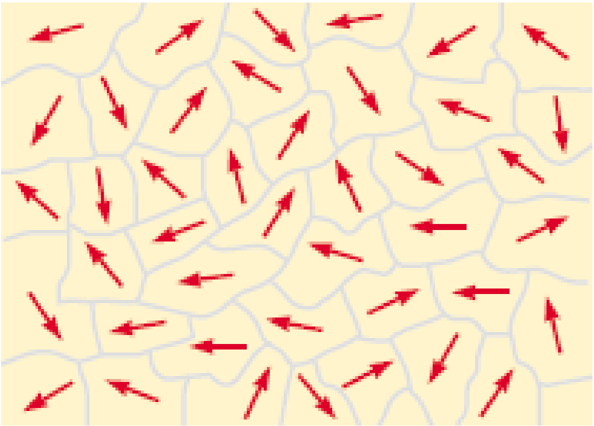
Substances can be classified as belonging to one of three categories, depending on their magnetic properties.
Paramagnetic and ferromagnetic materials are those made of atoms that have permanent magnetic moments.
Diamagnetic materials are those made of atoms that do not have permanent magnetic moments.

Substances may be classified in terms of how their magnetic permeability μ_m compares with μ_0 (the permeability of free space), as follows:

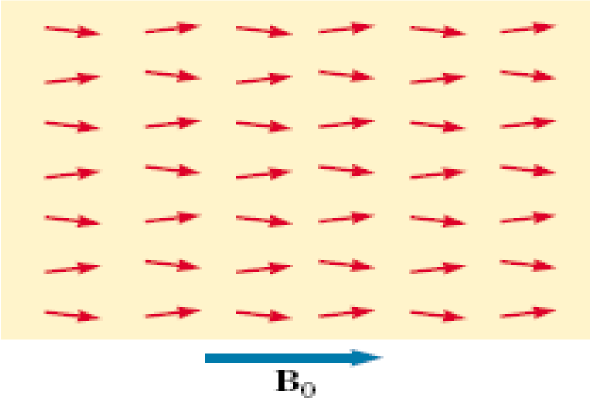
Paramagnetic	$\mu_m > \mu_0$
Diamagnetic	$\mu_m < \mu_0$

Because χ is very small for paramagnetic and diamagnetic substances (see Table 30.2), μ_m is nearly equal to μ_0 for these substances. For ferromagnetic substances, however, μ_m is typically several thousand times greater than μ_0 (meaning that χ is very great for ferromagnetic substances).

Ferromagnetism



A small number of crystalline substances in which the atoms have permanent magnetic moments exhibit strong magnetic effects called ferromagnetism.
Some examples of ferromagnetic substances are iron, cobalt, nickel, gadolinium, and dysprosium.
All ferromagnetic materials are made up of microscopic regions called **domains**, regions within which all magnetic moments are aligned.
These domains have volumes of about 10^12 to 108 m3 and contain 10^17 to 10^21 atoms. The boundaries between the various domains having different orientations are called **domain walls**.



Paramagnetism

Paramagnetic substances have a small but positive magnetic susceptibility ($0 < \chi \ll 1$) resulting from the presence of atoms (or ions) that have permanent magnetic moments. These moments interact only weakly with each other and are randomly oriented in the absence of an external magnetic field. When a paramagnetic substance is placed in an external magnetic field, its atomic moments tend to line up with the field. However, this alignment process must compete with thermal motion, which tends to randomize the magnetic moment orientations.

Diamagnetism

When an external magnetic field is applied to a diamagnetic substance, a weak magnetic moment is induced in the direction opposite the applied field. This causes diamagnetic substances to be weakly repelled by a magnet. Although diamagnetism is present in all matter, its effects are much smaller than those of paramagnetism or ferromagnetism, and are evident only when those other effects do not exist.

Q1. An electron that has velocity v = (2.0*10^6 m/s)i + (3.0*10^6 m/s)j moves with the uniform magnetic field (b =0.030t)I – (0.15t)j (a)Find the force on the electron due to magnetic field.(b)Repeat your calculation for proton having same velocity.

Q2. An alpha particle travel at velocity of magnitude 550m/s through uniform magnetic field of magnitude 0.045t (an alpha particle has the charge of + 3.2 * 10^-19C and mass of 6.6*10^-27 kg). the angle between v and B is 52 degree. What is the magnitude of (a)Force F b acting on the particle due to filed(b)Acceleration of particle due to Fb(c)Does the speed of particle increase, decrease or remain same.