Physics 115

General Physics II

Session 27

Magnetic fields and forces

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Lecture Schedule

12-May	Mon	23	DC Circuits & Meters	21.5-21.8
13-May	Tues	24	DC Circuits	21.5-21.8
15-May	Thurs	25	RC circuits	21.6-21.7
16-May	Fri	26	Circuits - Neurons	
19-May	Mon	27	Magnetism	22.1
20-May	Tues	28	Magnetic Force	22.2-22.5
22-May	Thurs	29	Magnetic Fields	22.6-22.7
22-May	Fri	30	Induced EMF, Applications	23.1-23.3
26-May	***holiday***		NO CLASS	
27-May	Tues	31	Energy, RL circuits	23.4-23.8
29-May	Thurs	32	Transformer	23.9-23.10
30-May	**Fri**		**EXAM 3 - Chapters 21,22,23**	
2-Jun	Mon	33	AC circuits	24.1-24.3
3-Jun	Tues	34	AC circuits	24.4-24.5
5-Jun	Thurs	35	Resonance, Applications	24.6
6-Jun	Fri	36	Last class - review	
June 9	**FINAL EXAM**		**2:30-4:20 p.m.**	**Comprehensive**
	Mon		**Monday, June 9, 2014**	

Today

Magnetic force on a moving charge

Last time

Electric current I = moving electric charges.

Ampere's experiment showed that a magnetic field exerts a force on a current → moving charges.

(The exact form of the force relation was not discovered until later in the 19th century.)

Experiments show the force is :

...Proportional to q, its speed v, and B

...Depends on the relative directions of **B** and the velocity **v** of the moving charge: proportional to sine of the angle between them

...perpendicular to both **v** and **B**.

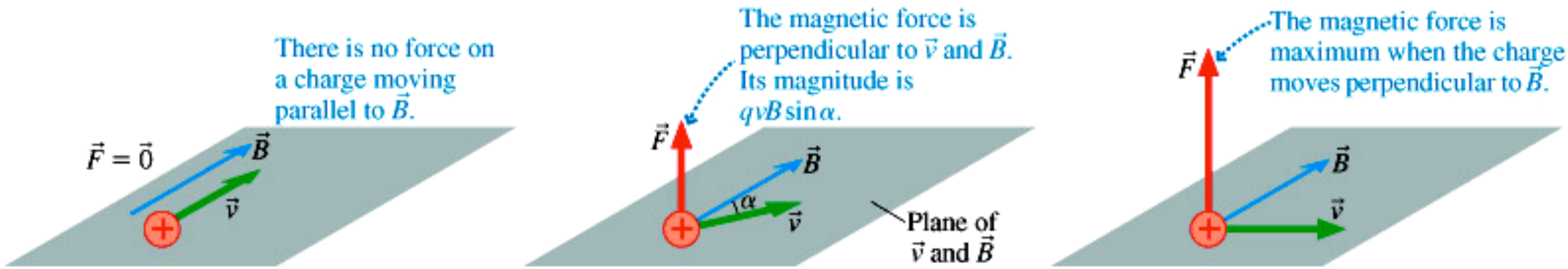
So, applying our usual procedure about proportionality:

$$F \propto qvB\sin\theta \Rightarrow F = q\left(\vec{v} \times \vec{B}\right)$$

Force on moving q:

$$\boxed{F = q\left(\vec{v} \times \vec{B}\right)}$$

Order matters! $\vec{v} \times \vec{B} = -\vec{B} \times \vec{v}$

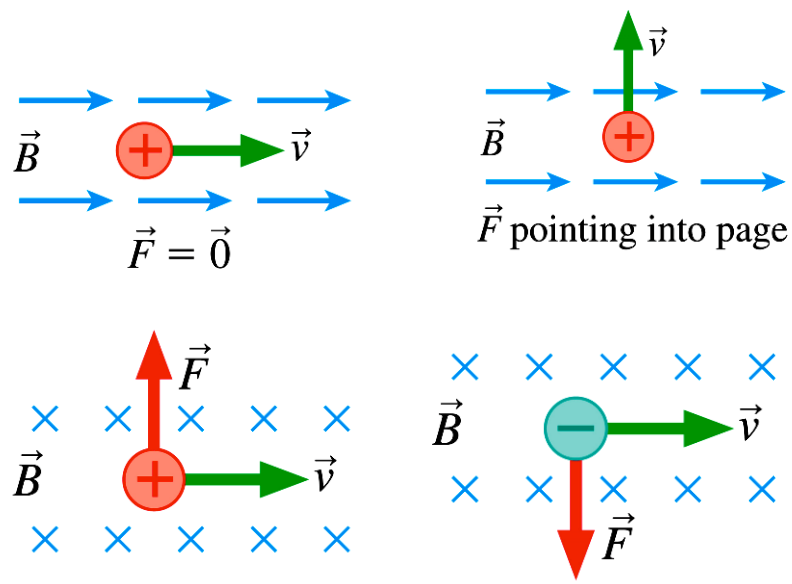


Magnetic Force on Moving Charges

Properties of the magnetic force:

$$\boxed{F = q\left(\vec{v} \times \vec{B}\right)}$$

1. Only moving charges experience the magnetic force. There is no magnetic force on a charge at rest (**v**=0) in a magnetic field.
2. There is no magnetic force on a charge moving parallel ($\theta=0^0$) or anti-parallel ($\theta=180^0$) to a magnetic field.
3. When there *is* a magnetic force, it is perpendicular to both **v** and **B**.
4. The force on a negative charge is in the direction *opposite* to **vxB**.
5. For a charge moving perpendicular to **B** ($\theta=90^0$) , the magnitude of the force is **F=|q|vB**.



Units for B fields

- Magnetic force on a charged particle: $F = qvB$
- Define field strength $B = F/qv$ (for v *perpendicular* to B)
  - Then units of B must be {N} / ({C}{m/s})
  - Notice denominator: {C}{m/s} = {C/s}{m}=ampere-meter
  - So units for B are N/(A•m): Special name assigned: tesla (T)
    - Named after Nikola Tesla (US, 1856-1943)
    - 1 T is a very intense B! Not handy for many applications
  - Obsolete CGS unit is still widely used: gauss (G)
    - One tesla = 10,000 gauss: 1 T = 10 kG

Examples:

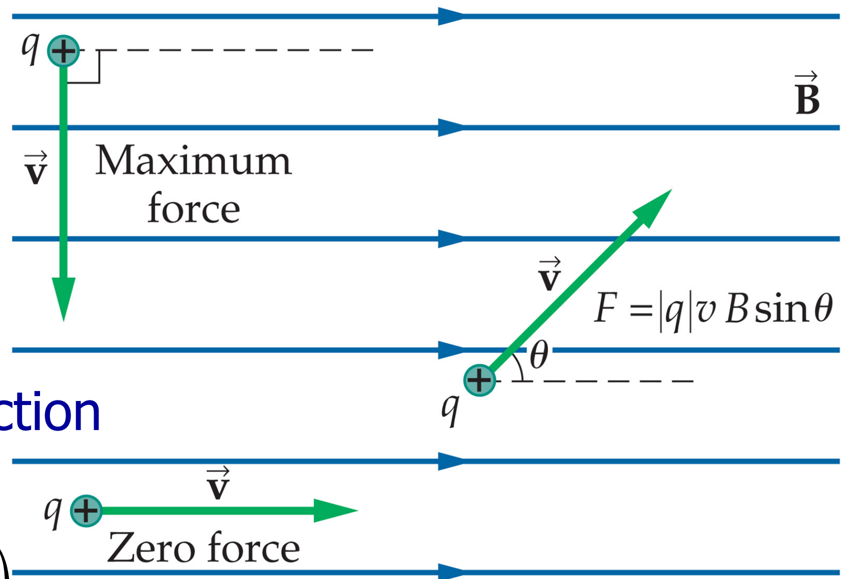
- earth's field ~ ½ G
- bar magnet ~ 100 G
- Medical imaging ~ 1.5 T

(>1 T fields require super-conducting magnets)

David Bowie (center) portrays Nikola Tesla in *The Prestige* (2006) (http://movies.yahoo.com/)

Example 1: charged particle in a B field

- Send a particle with q= 1 mC with speed v=200 m/s into a uniform B field of 0.03T, parallel to v
- Force on particle:
  - Force depends on particle's speed v and q, but *not* m
  - B force is always perpendicular to v
    - Force = 0 because B || v
- Motion of particle
  - Uniform motion
    - a = 0
    - v = constant
    - No change in speed or direction



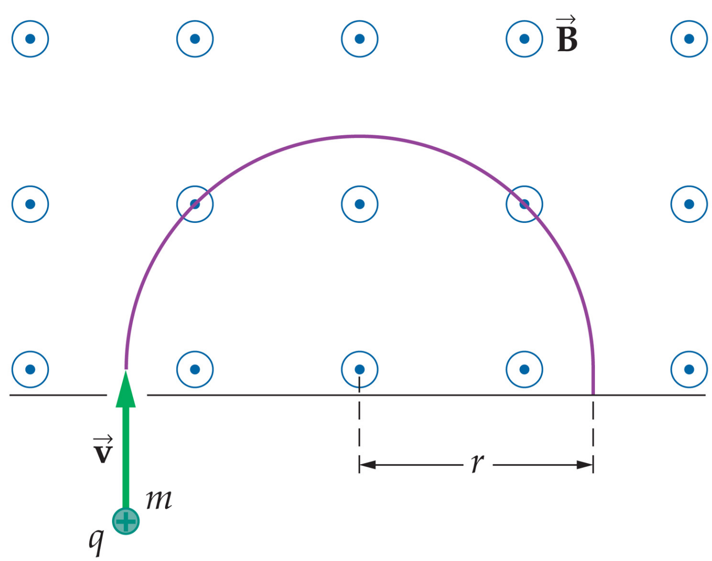
$$F = qvB\sin\theta$$
$$= (0.001C)(200m/s)(0.03T)(\sin(0^\circ) = 0)$$
$$= 0N$$

Example 2: charged particle in a B field

- Send a particle with q=1 mC with speed v=200 m/s into a uniform B field of 0.03T, now perpendicular to v
- Force on particle:
  - Force depends on particle's speed v and q, but not m
  - B force is always perpendicular to v

    IF NO OTHER FORCES, then

    - Path must be a circle: recall, circular motion → a __|__ v
      - F_B does not change speed, only direction



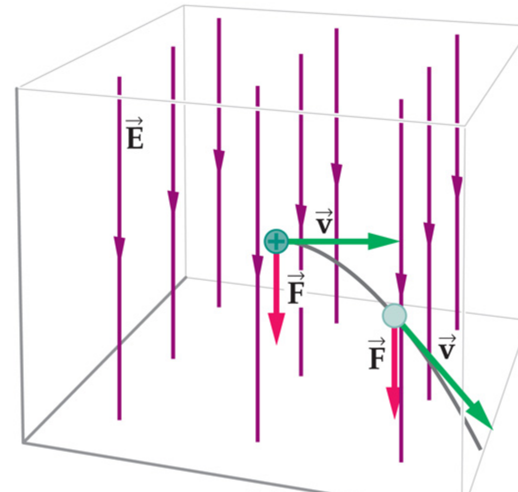
$$F = qvB\sin\theta$$

$$= (0.001C)(200m/s)(0.03T)(\sin(90^\circ))$$

$$= 0.006N$$

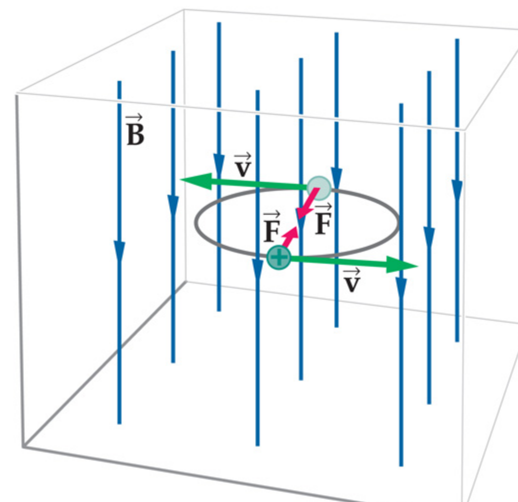
Comparing effects of E and B fields

- In an E field
  - Force is proportional to q
  - Force is always parallel to field direction
  - Force does not depend on speed
  - Force does not depend on mass
  - Force is never 0 unless q=0
  - Force always changes speed of particle
    - if v is initially perpendicular to field, E will gi
      it a parallel component



(a)

- In a B field
  - Force is proportional to q
  - Force is always perpendicular to field direction
  - Force does depend on speed
  - Force does not depend on mass
  - Force may be 0 even if q is not 0 (if **v** || **B**)
  - Force never changes speed of particle (always *perpendicular* to **v**)



(b)

Application: velocity selector

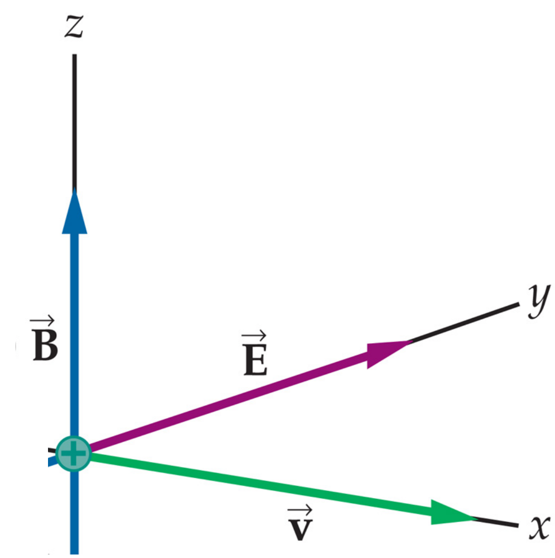
- If charged particle enters a region with both E and B, with B perpendicular to E
  - B force depends on q and speed : $|F_B| = qvB$
  - E force depends only on q: $|F_E| = qE$
- If we arrange so that directions of **v, E,** and **B** are **x, y, z**
  - Then for a + charge,
    - F_E is in +y direction
    - F_B is in –y direction
  - We can have net force =0 if $|F_E| = |F_B|$

  $qE = qvB \rightarrow v = E/B$

  Notice:

  - q cancels out: works for *any* q
  - Mass doesn't matter either
- Any particle with v=E/B has **a**=0
  - Travels in straight line at constant speed
  - All other v's are accelerated in y by E, deflected by B

  So this arrangement = VELOCITY SELECTOR



Quiz 17

- A charged particle moves in a magnetic field **B** (perpendicular to its initial velocity)
- Then the *same* particle moves in an electric field **E** (also perpendicular to its initial velocity)

Comparing the two, in **both** cases:

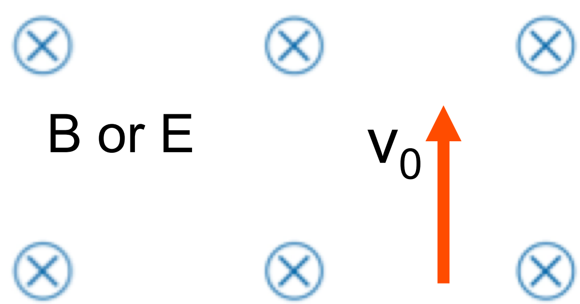
A. the particle is *accelerated*

B. the particle's *speed is unchanged*

C. the particle's *speed changes*

D. More than 1 of the above is true

E. None of the above are true



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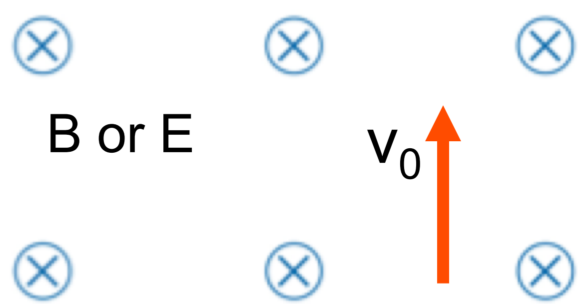


Application: mass spectrometer

- Mass spectrometer = device to measure the mass of ionized atoms (or to separate different mass groups)
- Method: linear acceleration in **E** + circular motion in **B**
  1. Ionize atoms so they all have the same net q
  2. Accelerate ions through a fixed E field, over a distance d
     - Force depends only on q, so all masses see the same F_E
     - Acceleration $a=F_E / m$, so a is inversely proportional to m
       - Heavier ions experience *smaller* a
       - Their final speed v is smaller after leaving acceleration zone
  3. Now send ions into a uniform B field, perpendicular to v
     - B force depends only on speed v (all have same q)
     - Faster ions experience bigger force, but $a_B=F/m$
       - Heavier ions experience smaller acceleration
         - » Circular path will have larger radius
         - » Use radius of path to identify mass

Mass Spec: how it works

1. Use heat or electron bombardment to ionize atoms
2. Use accelerator = uniform E field region to bring particles up to speed v_0
   - v_0 depends upon their mass: $a = F_E/m = qE/m$
3. Use velocity selector to get only atoms with $v_0=v$

$$E\Delta s = \Delta V$$
$$\Delta s = length\ of\ \ E\ region$$
$$q\Delta V = KE\ gained:$$
$$KE = \frac{1}{2}mv_0^2 \rightarrow v = \sqrt{\frac{2q\Delta V}{m}}$$

Then all ions have same q and v

In uniform B region:

F_B is perpendicular to v

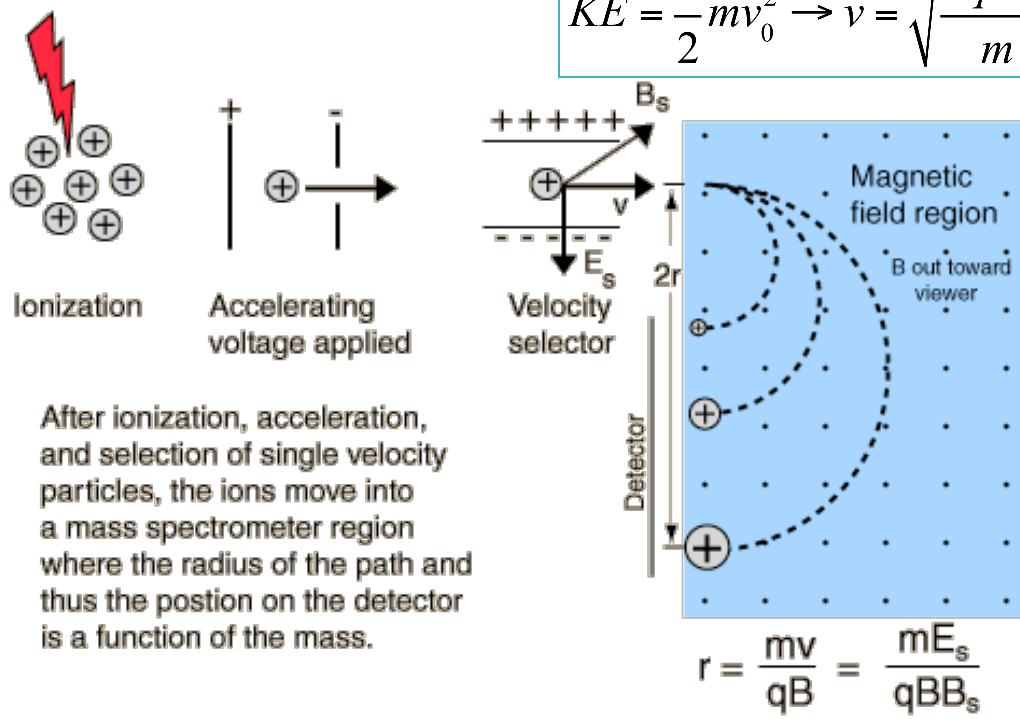
F_B acts like a central force

Recall from PHYS 114:

Circular path requires

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

$$F_C = qvB \Rightarrow r = \frac{mv}{qB}$$



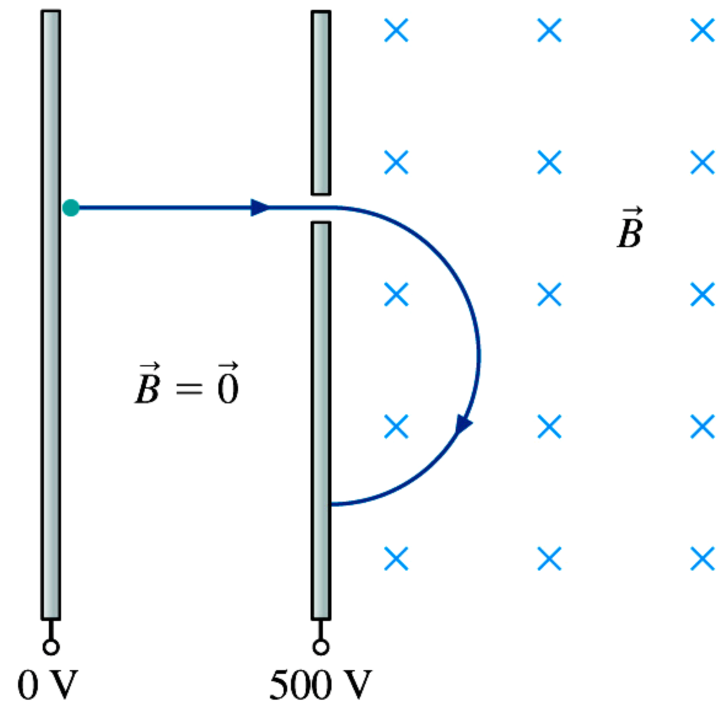
Example: The Radius of Motion in a mass spectrometer

An electron is accelerated from rest through a potential of 500 V, then injected into a uniform 1T magnetic field.

What is its speed?

What is the radius of its orbit?

Notice we are given accelerating V, so we can use conservation of energy:



$$Initially: KE + PE = 0$$

$$\tfrac{1}{2}mv^2 + (-e)\Delta V = 0 \rightarrow \tfrac{1}{2}mv^2 = e\,\Delta V$$

$$v = \sqrt{\frac{2\,e\,\Delta V}{m}} = \sqrt{\frac{2\left(1.6\times10^{-19}\ \text{C}\right)\left(500\ \text{V}\right)}{\left(9.1\times10^{-31}\ \text{kg}\right)}}$$

$$\text{Units: } \frac{\text{C V}}{\text{kg}} = \frac{\text{J}}{\text{kg}} = \frac{\text{N m}}{\text{kg}} = \frac{\text{kg m}^2}{\text{kg s}^2} = \frac{\text{m}^2}{\text{s}^2}$$

$$= 13.3\times10^{6}\ \text{m/s}$$

$$\boxed{r = \frac{mv}{qB} = \frac{\left(9.1\times10^{-31}\ \text{kg}\right)\left(1.33\times10^{7}\ \text{m/s}\right)}{\left(1.6\times10^{-19}C\right)1.0T} = 7.6\times10^{-5}m}$$

Not a practical orbit size!
$m_e = m_p/2000$

Application: separating *isotopes* of uranium

- Isotopes = varieties of an element with different atomic mass, due to different number of *neutrons* in nucleus
  - Same number of e's and protons: same atomic number
  - All chemical properties are identical: can't be separated by the wonders of chemistry! Need a physical method...

Example (from WW-II Manhattan project): mass specs at Berkeley

$$m\left({}^{235}U\right) = 3.90\times10^{-25}\,kg \text{ (usable as nuclear fuel)}$$

$$m\left({}^{238}U\right) = 3.95\times10^{-25}\,kg \text{ (99\% of natural U)}$$

For mass spec with entry $v = 1.05\times10^{5}\,m/s$, and $B = 0.75\text{T}$, what is d = distance between endpoints?

$$r_{235} = \frac{mv}{qB} = \frac{\left(3.90\times10^{-25}\,kg\right)\left(1.05\times10^{5}\,m/s\right)}{\left(1.6\times10^{-19}\,C\right)0.75T} = 34.1cm$$

$$r_{238} = \frac{\left(3.95\times10^{-25}\,kg\right)\left(1.05\times10^{5}\,m/s\right)}{\left(1.6\times10^{-19}\,C\right)0.75T} = 34.6cm$$

$$d = 2r = 1.0cm$$