B13 · Electric and magnetic fields together

Completed notes

Add the electric and magnetic forces, and use the velocity selector v = E/B.

Slide 1 of 4 · Adding an electric and a magnetic force

Two forces act on the electron. Electric: F = **qE** (charge q, electric field E). Magnetic: F = **qvB** (speed v, magnetic field B).

Top plate +, so E points **down**. A negative charge is pushed **opposite** to E, so the electron is pushed up.

Right hand: up for a positive charge. **Reverse** it for the electron.

Opposite forces: **subtract**. The **larger** force sets the direction. Same way: add.

a = **Fnet ÷ m**. This is the acceleration at the instant of **entry**. Give size and **direction**.

Example. An electron ($e = 1.60 \times 10^{-19}$ C, $m = 9.11 \times 10^{-31}$ kg) moves at 3.50×10^{5} m/s to the right between plates with E = 520 N/C. The top plate is positive. A magnetic field of 2.50×10^{-3} T points into the page. What are the size and direction of the electron’s acceleration as it enters?

1. $F_e = qE = (1.60 \times 10^{-19})(520) = 8.32 \times 10^{-17}$ N. The top plate is positive, so E points down and the force on the electron is up.

2. $F_m = qvB = (1.60 \times 10^{-19})(3.50 \times 10^{5})(2.50 \times 10^{-3}) = 1.40 \times 10^{-16}$ N. The right hand gives up for a positive charge, so it is down for the electron.

3. The forces are opposite: $F_{net} = 1.40 \times 10^{-16} - 8.32 \times 10^{-17} = 5.68 \times 10^{-17}$ N, down (the larger force).

4. $a = F_{net}/m = (5.68 \times 10^{-17})/(9.11 \times 10^{-31}) = 6.23 \times 10^{13}$ m/s², down.

Try it. Same plates and electron, but the magnetic field now points out of the page. What are the size and direction of the electron’s acceleration as it enters?

1. The electric force is unchanged: 8.32×10^{-17} N, up.

2. With B out of the page the magnetic force reverses: it is now up for the electron.

3. Both point up, so they add: $F_{net} = 8.32 \times 10^{-17} + 1.40 \times 10^{-16} = 2.23 \times 10^{-16}$ N, up.

4. $a = (2.23 \times 10^{-16})/(9.11 \times 10^{-31}) = 2.45 \times 10^{14}$ m/s², up. It is larger than before because the forces now add.

Slide 2 of 4 · The velocity selector: v = E/B

A straight path means Fnet = **0**. The forces are equal in size and **opposite** in direction.

The bars | | mean **size only**: |qE| = **|qvB|**.

q is on both sides and **cancels**: E = vB, so v = **E/B**. Mass and charge are not in the equation.

Unit: 1 T = **1 N/(C·m/s)**, so N/C ÷ T is **m/s**. An alpha particle is a helium nucleus, charge **+3.20 × 10⁻¹⁹ C** (twice a proton).

Another speed changes the **magnetic** force but not the **electric** force. The larger force sets the bend.

A positive particle is pushed **with** E, a negative one **against** it. Reverse the right-hand-rule answer for negative charges.

Example. In crossed fields E = 1.20 × 10^{3} N/C (top plate positive, field down) and B = 3.00 × 10^{-3} T (into the page), the straight-through speed is 4.00 × 10^{5} m/s. An electron enters moving right at 5.00 × 10^{5} m/s. Does it bend up or down, and why?

1. The electric force is qE = (1.60 × 10^{-19})(1.20 × 10^{3}) = 1.92 × 10^{-16} N, up. It does not depend on speed.

2. The magnetic force is qvB = (1.60 × 10^{-19})(5.00 × 10^{5})(3.00 × 10^{-3}) = 2.40 × 10^{-16} N, down.

3. The magnetic force is larger, so the electron bends down.

Try it. A proton enters the same fields at 4.00 × 10^{5} m/s (top plate positive, B into the page, moving right). Does it pass straight through? What happens if it is replaced by an alpha particle at the same speed?

1. The field points down, so the electric force on the positive proton is down. The right hand (thumb right, fingers into the page) gives a magnetic force up. The forces are opposite.

2. The sizes cancel because v = E/B = (1.20 × 10^{3})/(3.00 × 10^{-3}) = 4.00 × 10^{5} m/s, so the proton passes straight through.

3. An alpha particle at the same speed also passes straight through: the charge cancels in qE = qvB and the mass does not appear.

Slide 3 of 4 · Method: how to solve a balance-of-forces problem

Step 1: **draw** the particle. One arrow per force: electric, magnetic or **weight**.

Step 2: Electric F = **qE**. Magnetic F = **qvB**. Sizes first. Then directions: plate signs, and the right hand reversed for a **negative** charge.

Step 3: straight path or steady speed: Fnet = **0**. The forces are equal and **opposite**.

Step 4: |qE| = **|qvB|**. The q **cancels**. Solve: v = **E/B**, E = **vB** or B = E/v.

Step 5: check. Arrows **opposite**? Does N/C ÷ T give **m/s**?

Example. An electron goes straight through crossed fields with $E = 1.20 \times 10^{3}$ N/C (top plate positive, field down) and $B = 3.00 \times 10^{-3}$ T (into the page). What is its speed? ($e = 1.60 \times 10^{-19}$ C)

1. Step 1: the electron moves right. E points down, so the electric force is up. The magnetic force is down. The arrows are opposite.

2. Step 2: electric force F = qE. Magnetic force F = qvB, where v is the unknown.

3. Step 3: the path is straight, so Fnet = 0 and the sizes are equal.

4. Step 4: qE = qvB, so $v = E/B = (1.20 \times 10^{3}) \div (3.00 \times 10^{-3}) = 4.00 \times 10^{5}$ m/s.

5. Step 5: $(1.60 \times 10^{-19})(1.20 \times 10^{3}) = 1.92 \times 10^{-16}$ N and $(1.60 \times 10^{-19})(4.00 \times 10^{5})(3.00 \times 10^{-3}) = 1.92 \times 10^{-16}$ N. They match, and N/C ÷ T is m/s.

Try it. NEW, for teacher review. An electron moves right at 5.00×10^{5} m/s and goes straight through plates with $E = 1.00 \times 10^{3}$ N/C (top plate positive, field down). What magnetic field strength and direction are needed? ($e = 1.60 \times 10^{-19}$ C)

1. Step 1: E points down, so the electric force on the electron is up. For the forces to balance, the magnetic force must be down.

2. Step 2 and 3: F = qE and F = qvB, and the path is straight, so Fnet = 0.

3. Step 4: qE = qvB, so $B = E/v = (1.00 \times 10^{3}) \div (5.00 \times 10^{5}) = 2.00 \times 10^{-3}$ T.

4. Direction: fingers into the page and thumb right make the palm face up, which is the force on a positive charge. For the electron the force is down, so B points into the page.

5. Step 5: $(1.60 \times 10^{-19})(1.00 \times 10^{3}) = 1.60 \times 10^{-16}$ N and $(1.60 \times 10^{-19})(5.00 \times 10^{5})(2.00 \times 10^{-3}) = 1.60 \times 10^{-16}$ N. They match.

Slide 4 of 4 · Choosing the tool

Find the **cue** first. Write its equation. Then use the numbers. Do not hunt for a formula that fits.

Straight path: Fnet = **0**. Circle: the **magnetic** force is the net force. Accelerated from rest through ΔV: energy gained is **qΔV**.

Cues: straight **v = E/B**; accelerated from rest **qΔV = ½mv²**; circle **qvB = mv²/r**; two forces **add Fe and Fm as vectors**.

Crossed fields: an **electric** and a **magnetic** field at right angles.

Two cues: one equation per cue, in **order**. Work backward from the **speed** if the end of the path gives it.

$v_\perp$ is the part of v at **right angles** to the field. At rest, or moving **along** the field: $v_\perp = 0$, so F = **0**.

Example. Three cases: (1) an electron is accelerated from rest through 400 V, then moves in a circle in a magnetic field; (2) a proton passes straight through plates and a magnetic field; (3) a positive ion moves along a magnetic field line. For each, write the first equation or statement you would use.

1. Case 1: $q\Delta V = \frac{1}{2}mv^2$ gives the speed, then $qvB = mv^2/r$ gives the radius.

2. Case 2: the path is straight, so the net force is zero and qE = qvB.

3. Case 3: the ion moves along the field, so $v_\perp = 0$ and the magnetic force is zero.

Try it. A proton ($m = 1.67 \times 10^{-27}$ kg) starts at rest, is accelerated through a potential difference, then enters crossed fields $E = 1.20 \times 10^{3}$ N/C and $B = 3.00 \times 10^{-3}$ T and goes straight through. What potential difference accelerated it?

1. Straight path: $v = E/B = (1.20 \times 10^{3})/(3.00 \times 10^{-3}) = 4.00 \times 10^{5}$ m/s.

2. Accelerator: $q\Delta V = \frac{1}{2}mv^2$, so $\Delta V = mv^2/(2q)$.

3. $\Delta V = (1.67 \times 10^{-27})(4.00 \times 10^{5})^2/[2(1.60 \times 10^{-19})] = 835$ V.

B13 · Worked practice

Electric and magnetic fields together | Questions 1-2 of 8

Constants from the Alberta Physics 30 data sheets: $k = 8.99 \times 10^{9}$ N·m²/C², $e = 1.60 \times 10^{-19}$ C, electron mass $m_e = 9.11 \times 10^{-31}$ kg, proton mass $m_p = 1.67 \times 10^{-27}$ kg, $g = 9.81$ m/s².

Easy · B13-N01. An electron moves at 4.0×10^{5} m/s through a magnetic field of 3.0×10^{-3} T and an electric field of 600 N/C. The two forces are in opposite directions. Find the size of the net force on the electron.

1. Givens: $q = 1.60 \times 10^{-19}$ C; $v = 4.0 \times 10^{5}$ m/s; $B = 3.0 \times 10^{-3}$ T; $E = 600$ N/C; forces opposite. Question: Fnet.

2. Magnetic: $qvB = 1.92 \times 10^{-16}$ N. Electric: $qE = 9.60 \times 10^{-17}$ N.

3. Subtract (opposite directions): 9.60×10^{-17} N, in the direction of the larger force, the magnetic one.

4. Answer: 9.60×10^{-17} N

Easy · B13-N02. A proton moves at 2.0×10^{5} m/s through a magnetic field of 0.0400 T. What electric field strength makes it go straight through? (N/C)

1. Givens: $v = 2.0 \times 10^{5}$ m/s; $B = 0.0400$ T. Question: E.

2. Straight through means $qE = qvB$, so $E = vB$.

3. $E = (2.0 \times 10^{5})(0.0400) = 8000$ N/C.

4. Answer: 8000 N/C

B13 · Worked practice

Electric and magnetic fields together | Questions 3-4 of 8

Easy · B13-N03. Does the speed that passes straight through a velocity selector change if the particle is an alpha particle (twice the charge of a proton) instead of a proton?

A. Yes, it doubles because the charge doubles
B. Yes, it halves because the mass is larger
C. Yes, it depends on the sign only
D. No, because v = E/B does not depend on the charge or mass

1. Givens: same fields; double charge. Question: does the selected speed change.

2. The charge cancels in qE = qvB. The selected speed is v = E/B for any charge or mass.

3. Answer: D. No, because v = E/B does not depend on the charge or mass

Medium · B13-N04. Fields E = 600 N/C and B = 1.50×10^{-3} T are at right angles in a velocity selector. What speed passes straight through?

1. Givens: E = 600 N/C; B = 1.50×10^{-3} T. Question: v.

2. v = E/B = 600 ÷ (1.50×10^{-3}) = 4.00×10^{5} m/s.

3. Answer: 4.00×10^{5} m/s

B13 · Worked practice

Electric and magnetic fields together | Questions 5-6 of 8

Medium · B13-N05. In a velocity selector the top plate is positive and the magnetic field points into the page. A proton moves right, slightly slower than E/B. Which way does it bend?

A. Up, toward the positive plate
B. Down, toward the negative plate
C. Into the page
D. Out of the page

1. Givens: top plate +; B into page; proton moving right with v < E/B. Question: direction it bends.

2. Electric force on a proton is from + to −: down. Magnetic force on a proton moving right in a field into the page is up (right-hand rule).

3. The magnetic force is proportional to v. A slower proton has a smaller magnetic force, so the downward electric force is larger: it bends down.

4. Answer: B. Down, toward the negative plate

Medium · B13-N06. Using the electron in the first question (net force 9.60×10^{-17} N), find the size of its acceleration at the instant it enters the fields. Use $m_e = 9.11 \times 10^{-31}$ kg.

1. Givens: $F_{net} = 9.60 \times 10^{-17}$ N; $m = 9.11 \times 10^{-31}$ kg. Question: a at entry.

2. $a = F/m = 1.05 \times 10^{14}$ m/s².

3. Answer: 1.05×10^{14} m/s²

B13 · Worked practice

Electric and magnetic fields together | Questions 7-8 of 8

Challenging · B13-N07. A velocity selector must pass particles at 2.5×10^5 m/s through a magnetic field of 0.0300 T. The electric field comes from plates 0.0200 m apart. What potential difference is needed?

1. Givens: $v = 2.5 \times 10^5$ m/s; $B = 0.0300$ T; $\Delta d = 0.0200$ m (the distance between the plates). Question: ΔV.

2. Straight through: $E = vB = 7500$ V/m.

3. $\Delta V = E\Delta d = (7500)(0.0200) = 150$ V.

4. Answer: 150 V

Challenging · B13-N08. Why do problems with both an electric and a magnetic field usually ask only for the acceleration at the instant of entry?

1. Givens: both fields act. Question: why the instant of entry.

2. The magnetic force depends on the velocity, and the velocity changes direction and size as the particle moves.

3. So the net force and acceleration keep changing; at the instant of entry the velocity is known, so we can find them.