Velocity selectors and particle identification solutions

Electromagnetism 3 Analysing volcanic gas samples

Matching answers and examiner-style commentary

OCR A H556 | A-level physics | Module 6 | 36 marks

Specification points covered

6.3.2(a–c) Magnetic orbits and velocity selection using crossed fields.

6.2.3(a), 6.2.1(d) Uniform electric fields and electric force.

All ion masses, charge states and detector criteria needed are supplied.

Use $e = 1.60 \times 10^{-19}$ C and $1\ u = 1.66 \times 10^{-27}$ kg. Treat the supplied isotope masses as exact multiples of u.

1 Read the two-stage instrument

A laboratory investigates noble gases from a volcanic monitoring site. Its source supplies a range of ion speeds. A selector prepares a known-speed beam, then a separate magnetic analyser sorts the transmitted ions by their paths.

The selector plates have gap d = 12.0 mm. The upper plate is at $+V_s$ and the lower plate is at 0 V. A uniform field $B_s = 0.0800$ T is perpendicular to the page; its direction is to be found. The required selected speed is 6.00×10^4 m s^{-1}.

In the analyser, $B_a = 0.200$ T points out of the page. The ions enter to the right and are positively charged. Neglect fringing, collisions and interactions between ions. Unless changed, use these baseline settings.

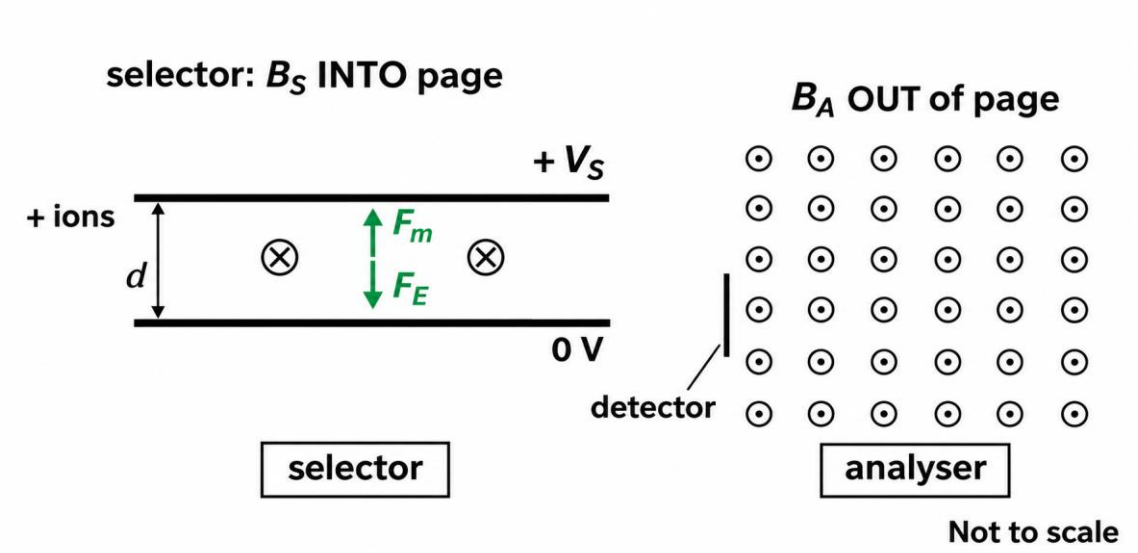


Figure 1 Selector and separate analyser

1(a) Which stage is intended to transmit a straight beam at one selected speed, and which stage changes the direction of that transmitted beam? **[1 mark]**

The crossed-field selector transmits a straight beam at one speed. The separate magnetic analyser changes the transmitted ions' direction.

Marking guidance 1: both stages identified correctly.

1(b) In the analyser, an ion follows a semicircle and returns to the entry-side detector plane. Its detector is x below the entry aperture. Express the orbit radius in terms of x. **[1 mark]**

The entry and detector are opposite ends of a diameter, so $x = 2r$ and $r = x/2$.

Marking guidance 1: $r = x/2$.

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2 Balance the selector forces

2(a) State the electric force direction on a positive ion between the selector plates. **[1 mark]**

The electric field points from the upper plate at higher potential towards the lower plate: downwards. The force on a positive ion is also downwards.

Marking guidance 1: downwards.

2(b) Choose the direction of B_s, into or out of the page, that lets the magnetic force oppose the electric force. Justify your choice. **[2 marks]**

B_s must point into the page. For a positive ion moving right, this gives an upward magnetic force by the force-direction rule.

An upward magnetic force can balance the downward electric force.

Marking guidance 1: into page. 1: correct magnetic-force direction and opposition.

2(c) Derive $v = E/B_s$ for an undeflected ion. Explain why the selected speed is independent of ion mass and charge magnitude. **[2 marks]**

For straight motion the transverse resultant is zero, so the force magnitudes are equal: $|q|E = B_s|q|v$.

Cancel the same non-zero $|q|$ and rearrange: $v = E/B_s$. Mass does not appear, and charge magnitude cancels.

Marking guidance 1: force balance. 1: cancellation/result and independence explained.

2(d) At the chosen field directions, state the initial deflection of a positive ion travelling (i) faster and (ii) slower than the selected speed. Explain. **[2 marks]**

The electric force $|q|E$ is fixed while the magnetic force $B_s|q|v$ increases with speed.

Faster: the upward magnetic force is larger, so the initial deflection is up. Slower: the downward electric force is larger, so the initial deflection is down.

Marking guidance 1: faster/up with force comparison. 1: slower/down with force comparison.

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3 Set and test the selector

3(a) Calculate the required electric field strength and plate p.d. for the baseline selected speed. **[2 marks]**

Step 1 The magnetic field and required speed set the balancing electric field.

$E = B_s v = (0.0800)(6.00 \times 10^4) = 4.80 \times 10^3$ V m^{-1}.

Step 2 Use the physical plate gap in metres.

$V_s = Ed = (4.80 \times 10^3)(0.0120) = 57.6$ V.

Marking guidance 1: 4.80×10^3 V m^{-1}. 1: 57.6 V.

3(b) Keep the same plate p.d. and gap but select 4.00×10^4 m s^{-1}. Find the required B_s magnitude. **[1 mark]**

The plate settings keep E at 4.80×10^3 V m^{-1}.

$B_s = E/v = (4.80 \times 10^3)/(4.00 \times 10^4) = 0.120$ T.

Marking guidance 1: 0.120 T.

3(c) Relative to the baseline settings, both E and B_s increase by a factor of 1.50. What happens to the selected speed? **[1 mark]**

The ratio E/B_s is unchanged, so the selected speed stays at 6.00×10^4 m s^{-1}.

Marking guidance 1: unchanged, with ratio reasoning.

3(d) A negative ion travels right at the baseline selected speed. Explain why it can also pass straight through the selector at the same plate and field settings. **[2 marks]**

Changing the charge sign reverses both forces: electric force is now up and magnetic force down.

Their magnitudes remain equal at $v = E/B_s$, so the transverse resultant is still zero. This does not mean it will follow the positive-ion path in the separate analyser.

Marking guidance 1: both forces reverse. 1: equal magnitudes/zero resultant at the same speed.

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4 Interpret the magnetic analyser

4(a) For the baseline selected speed, calculate the analyser radii for singly charged ions of masses 20u and 22u. **[2 marks]**

Use $r = mv/(B_a e)$; the selector has already fixed the same speed for both ion types.

$m_{20} = 20(1.66 \times 10^{-27}) = 3.32 \times 10^{-26}$ kg.

$r_{20} = [(3.32 \times 10^{-26})(6.00 \times 10^{4})]/[(0.200)(1.60 \times 10^{-19})] = 0.06225$ m.

$m_{22} = 3.652 \times 10^{-26}$ kg; $r_{22} = 0.068475$ m.

Marking guidance 1: 0.0623 m for 20u. 1: 0.0685 m for 22u.

4(b) Find their detector distances below the entry aperture and the separation of the two peaks. **[2 marks]**

Each detector distance is a diameter, not a radius.

$x_{20} = 2r_{20} = 0.12450$ m = 124.50 mm; $x_{22} = 0.13695$ m = 136.95 mm.

Peak separation = 136.95 − 124.50 = 12.45 mm.

Marking guidance 1: both detector distances from 2r. 1: separation about 12.5 mm.

4(c) A further singly charged positive ion is detected 130.7 mm below entry. Infer its mass in kg and in u. **[3 marks]**

Step 1 Convert the detector distance to the physical orbit radius.

$r = x/2 = 0.1307/2 = 0.06535$ m.

Step 2 Rearrange the orbit relationship to find mass.

$m = B_a e r/v = [(0.200)(1.60 \times 10^{-19})(0.06535)]/(6.00 \times 10^{4}) = 3.4853 \times 10^{-26}$ kg.

Step 3 Divide by the supplied atomic mass unit.

$m/u = (3.4853 \times 10^{-26})/(1.66 \times 10^{-27}) = 20.996 \approx 21.0$. The supplied model therefore suggests about 21u.

Marking guidance 1: x/2 and valid mass relationship. 1: about 3.49×10^{-26} kg. 1: about 21.0u.

4(d) Could an ion with twice the mass and twice the charge magnitude follow the same analyser path at the same selected speed? Explain. **[1 mark]**

Yes. The path radius depends on $m/|q|$ at fixed v and B_a; doubling both leaves that ratio and the radius unchanged.

Marking guidance 1: yes with m/|q| reasoning.

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5 Read a detector scan

Table 1 is a baseline scan. Peak positions are rounded readings, not isotope mass data.

Table 1

Peak	Distance below entry / mm
A	124.5
B	130.7
C	136.9

5(a) Assign the 20u and 22u singly charged ions to peaks in Table 1. **[1 mark]**

At these settings, 20u corresponds to 124.5 mm and 22u to 136.9 mm, so they are peaks A and C respectively.

Marking guidance 1: 20u → A and 22u → C.

5(b) The selector is reset to transmit a speed 10% greater, while B_a is unchanged. Predict the new detector positions for the 20u and 22u ions. **[1 mark]**

At fixed m, charge and B_a, x = 2r is proportional to speed.

$x_{20,new} = 1.10(124.50) = 136.95$ mm; $x_{22,new} = 1.10(136.95) = 150.645$ mm ≈ 150.6 mm.

Marking guidance 1: both positions, about 137.0 and 150.6 mm.

5(c) The source accelerating voltage changes, but the selector settings remain at baseline. Assume the source still supplies ions at the selected speed. Must the detector peaks shift simply because of that voltage change? Explain. **[2 marks]**

No. The unchanged selector still transmits only ions at $v = E/B_s = 6.00 \times 10^4$ m s^{-1}.

For a given m and charge, the unchanged analyser field therefore gives the same radius and peak position. The number transmitted may change if the speed distribution changes.

Marking guidance 1: selected speed unchanged. 1: peak position unchanged, with correct selector/analyser reasoning.

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6 Choose a resolving setting

6(a) The laboratory can use B_a = 0.180 T or 0.300 T. At the baseline selected speed, calculate the 20u–22u detector separation for each setting. **[2 marks]**

At fixed speed, separation is inversely proportional to B_a. Start from 12.45 mm at 0.200 T.

At 0.180 T: $\Delta x = 12.45(0.200/0.180) = 13.83$ mm.

At 0.300 T: $\Delta x = 12.45(0.200/0.300) = 8.30$ mm.

Marking guidance 1 each: correct separations.

6(b) For each of those fields, calculate the larger detector distance, for the 22u ion. The detector extends 160 mm below entry. **[2 marks]**

At 0.180 T: $x_{22} = 136.95(0.200/0.180) = 152.17$ mm.

At 0.300 T: $x_{22} = 136.95(0.200/0.300) = 91.30$ mm.

Both are within 160 mm. The larger orbit is the one that tests the available span.

Marking guidance 1 each: distances about 152 and 91.3 mm.

6(c) A supplied detector criterion requires separation of at least 12.0 mm and both peaks within its 160 mm span. Choose an analyser field and justify against both conditions. **[1 mark]**

Choose 0.180 T: separation is 13.83 mm, above 12.0 mm, and the farther peak is at 152.17 mm, within 160 mm. The 0.300 T setting fails the separation criterion.

Marking guidance 1: correct choice explicitly supported by both constraints.

6(d) In a separate experiment the selector is removed. These singly charged ions instead accelerate from rest through the same p.d. before entering the analyser. Find r_{22}/r_{20}, and compare it with the fixed-speed ratio. **[2 marks]**

At fixed accelerating p.d., $\frac{1}{2}mv^2 = eU$ and $r = mv/(B_a e)$, giving $r = \sqrt{(2mU/e)}/B_a$.

Thus $r_{22}/r_{20} = \sqrt{(22/20)} = 1.049$.

With the selector fixing speed, the ratio is 22/20 = 1.10. Different operating conditions give different mass dependence.

Marking guidance 1: fixed-p.d. ratio about 1.049 with valid reasoning. 1: fixed-speed ratio 1.10 and explicit contrast.

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6(e) Correct both errors: “The selector works because the electric and magnetic fields cancel. Its selected speed tells us which isotope is present.” **[2 marks]**

The electric and magnetic forces are equal and opposite at the selected speed; E and B are different quantities with different units and do not cancel.

The selected speed is independent of mass. Identification requires the analyser path plus known charge and field, not the selector speed alone.

Marking guidance 1: equal forces, not equal/cancelling fields. 1: speed alone does not identify mass/isotope.

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