3.10 Physics: Fields (Gravitational, Electric, Magnetic)

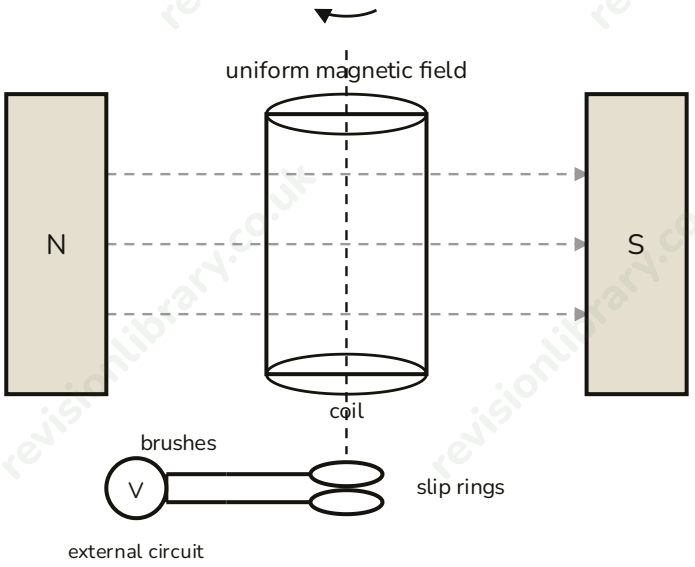
AQA 7408 · Calculator allowed · about 120 minutes · Write-in edition

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 A simple a.c. generator consists of a rectangular coil of 300 turns, each of area 1.10 x 10^{-2} m^2, rotating at a constant angular frequency of 300 rad/s in a uniform magnetic field of flux density 0.0750 T. You are given: the EMF induced by a rotating coil, EMF = B*A*N*ω*sin(ω*t).



(a) Calculate the peak EMF generated by the coil. **(2)**

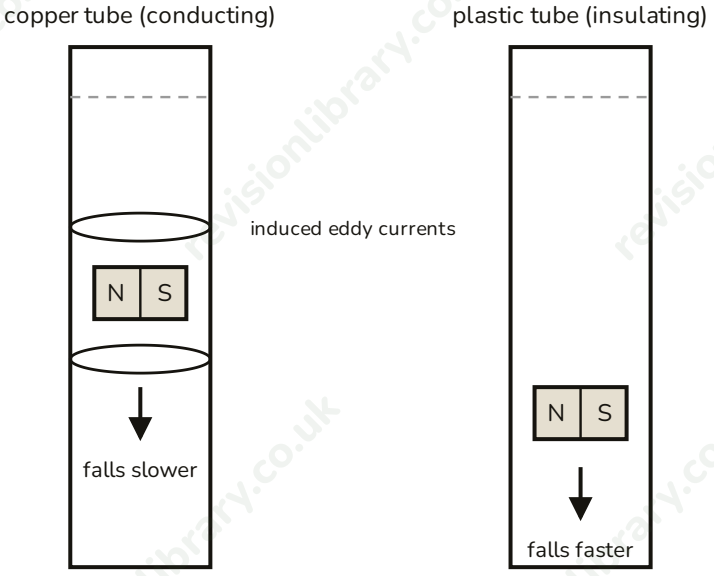
(b) Calculate the frequency of rotation of the coil, in Hz. **(2)**

(c) Describe how the induced EMF varies with time over one complete rotation of the coil, and explain, in terms of the rate of change of flux linkage, why the EMF is zero at certain points in the rotation. **(3)**

(Total for Question 1 is 7 marks)

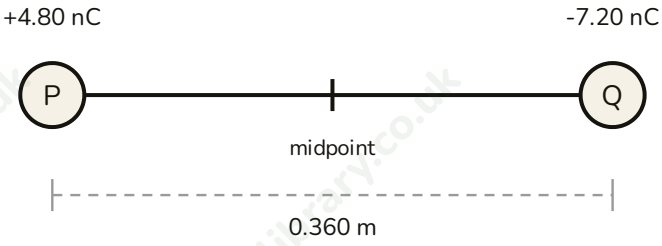
2 A student drops a strong bar magnet, from rest, down through a long vertical tube. In one trial the tube is made of a conducting metal such as copper; in a second, otherwise identical, trial the tube is made of an insulating plastic. The magnet takes noticeably longer to fall through the copper tube than through the plastic tube, even though it is dropped from the same height each time and air resistance can be ignored in both cases.

Explain, in terms of Faraday's law and Lenz's law, why the magnet falls with a smaller acceleration in the copper tube than in the plastic tube, and explain what happens to the gravitational potential energy the magnet loses as it falls through the copper tube.



(Total for Question 2 is 6 marks)

3 Two small charged spheres, P and Q, are fixed 0.360 m apart in a vacuum. Sphere P carries a charge of +4.80 x 10^{-9} C and sphere Q carries a charge of -7.20 x 10^{-9} C. You are given $1/(4*\pi*epsilon0) = 8.99 \times 10^9$ N m^2 C^{-2}, so that the force between two point charges is $F = Q1*Q2/(4*\pi*epsilon0*r^2)$ and the electric field due to a point charge is $E = Q/(4*\pi*epsilon0*r^2)$.



(a) Calculate the magnitude of the electrostatic force between P and Q, and state whether the force is attractive or repulsive. **(3)**

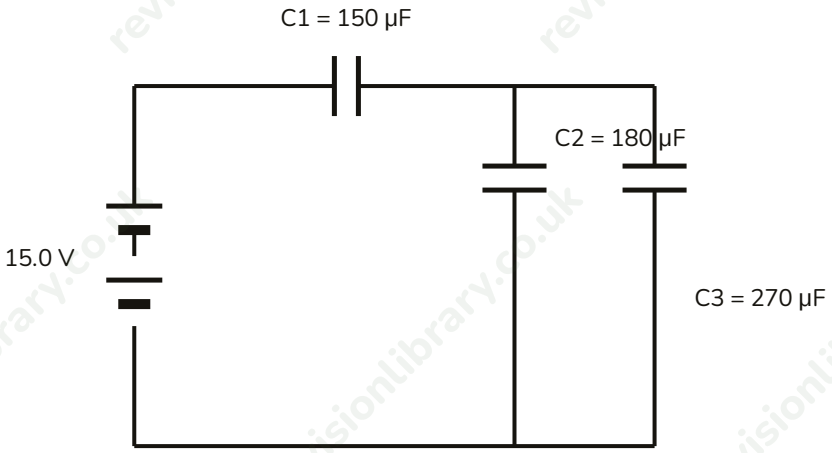
(b) Calculate the electric field strength due to P alone at the location of Q. **(2)**

(c) A small test charge is placed at the midpoint between P and Q, 0.180 m from each sphere. Given that the field due to P and the field due to Q both point in the same direction at this point (from P towards Q), calculate the magnitude of the resultant electric field at the midpoint. **(4)**

(d) State the direction of the resultant electric field at the midpoint. **(1)**

(Total for Question 3 is 10 marks)

4 In the circuit shown, a capacitor C1 of capacitance 150 uF is connected in series with a parallel combination of two capacitors, C2 = 180 uF and C3 = 270 uF. The combination is connected to a 15.0 V d.c. supply and allowed to charge fully.



(a) Calculate the combined capacitance of C2 and C3 in parallel. **(1)**

(b) Calculate the total capacitance of the circuit. **(3)**

(c) Calculate the total charge supplied by the 15.0 V source when the capacitor network is fully charged. **(2)**

(d) Calculate the potential difference across C1. **(2)**

(e) Calculate the total energy stored in the fully charged capacitor network. **(3)**

(Total for Question 4 is 11 marks)

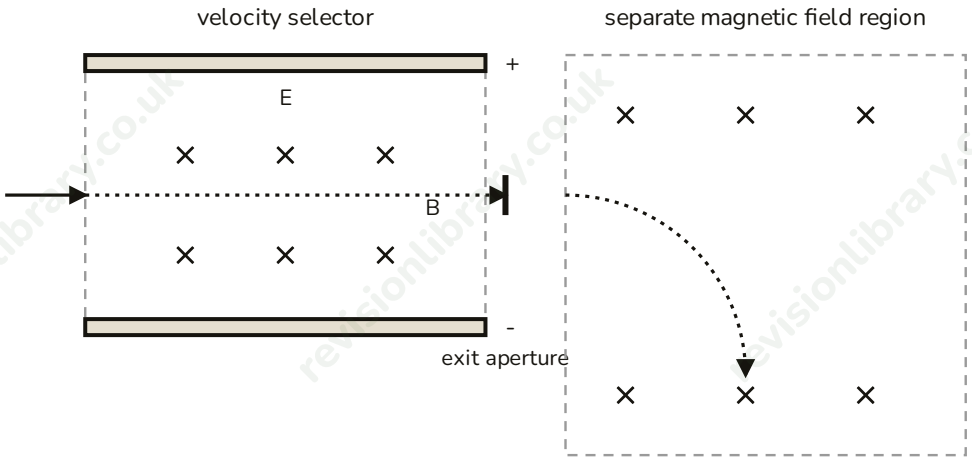
5 A step-down transformer converts a 230 V a.c. mains supply to a 12.0 V supply for a low-voltage lighting system. The primary coil has 4600 turns. You are given the ideal transformer equation Vs/Vp = Ns/Np.

(a) Calculate the number of turns needed on the secondary coil, assuming the transformer is ideal. **(2)**

(b) In practice this transformer is only 92.0% efficient. When the secondary current is 8.00 A, calculate the primary current, assuming Vp and Vs are unchanged. **(4)**

(Total for Question 5 is 6 marks)

6 A velocity selector consists of a region where a uniform electric field and a uniform magnetic field act at right angles to each other and to the velocity of charged particles passing through. A beam of ions passes through undeviated when the electric force and the magnetic force on each ion are equal and opposite. The electric field strength is 6.00×10^4 V/m and the magnetic flux density in the selector is 0.120 T.



(a) Show that the speed of ions that pass through the selector undeviated is given by $v = E/B$, and calculate this speed for the values given. **(3)**

(b) Ions leaving the selector then enter a separate uniform magnetic field of flux density 0.350 T, directed perpendicular to their velocity, where they follow a circular path of radius 4.20×10^{-2} m. Calculate the specific charge (charge-to-mass ratio, q/m) of the ions. **(3)**

(c) Suggest why, in practice, it can be difficult to obtain a truly uniform electric field over the whole region through which the ions travel in the velocity selector, and state one consequence of this for the beam of ions leaving the selector. **(2)**

(Total for Question 6 is 8 marks)

7 A meteoroid of mass 2.50×10^3 kg travels from deep space towards the Earth. Treat the Earth as an isolated uniform sphere (ignore the Sun and Moon), take the gravitational potential at infinity to be zero, and use $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, M(Earth) = 5.97×10^{24} kg, R(Earth) = 6.37×10^6 m. You are given: gravitational potential $V = -GM/r$, and escape velocity $v = \sqrt{2GM/r}$.

(a) Calculate the gravitational potential at the Earth's surface. **(2)**

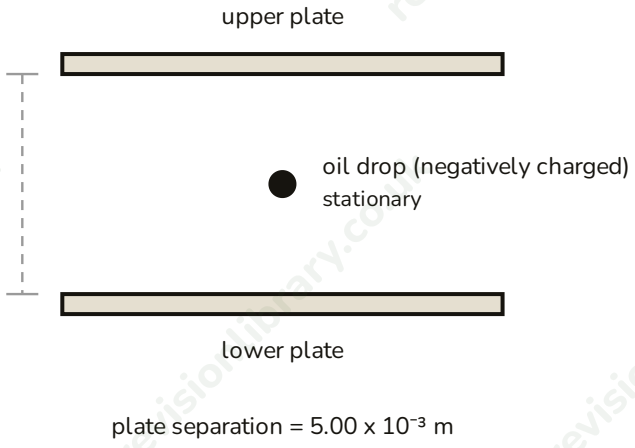
(b) Calculate the minimum kinetic energy the meteoroid would need at the Earth's surface so that it could, in principle, escape to infinity (ignore atmospheric resistance). **(3)**

(c) Show that the escape velocity from the Earth's surface is about 1.12×10^4 m/s. **(3)**

(d) The meteoroid actually approaches the Earth with a speed of 1.60×10^4 m/s while still very far away (effectively at infinity). Using conservation of energy, and ignoring atmospheric drag, calculate its speed just above the atmosphere, at a distance R from the Earth's centre. **(4)**

(Total for Question 7 is 12 marks)

8 A small charged oil drop of mass 9.80 x 10^{-15} kg carries a charge of -3.20 x 10^{-19} C. The drop is held stationary between two horizontal parallel plates separated by a distance of 5.00 x 10^{-3} m, in a Millikan-type experiment. Take g = 9.81 N kg^{-1}.



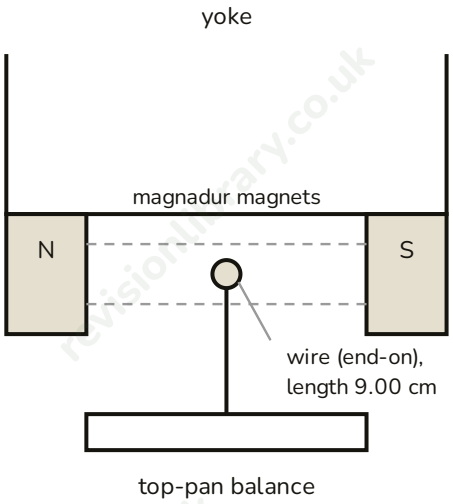
(a) Show that the electric field strength required to hold the drop stationary is about 3.00 x 10^{5} N/C. **(3)**

(b) Calculate the potential difference between the plates needed to produce this field. **(2)**

(c) State which plate, upper or lower, must be at the higher potential, explaining your reasoning. **(2)**

(Total for Question 8 is 7 marks)

9 REQUIRED PRACTICAL. A student determines the magnetic flux density between the poles of a strong magnet using a current balance. A straight horizontal wire of length 9.00 x 10^{-2} m is placed at right angles to the magnetic field, resting on a support connected to a top-pan balance. You are given F = B*I*L for a wire at right angles to a uniform field. Take g = 9.81 N kg^{-1}.



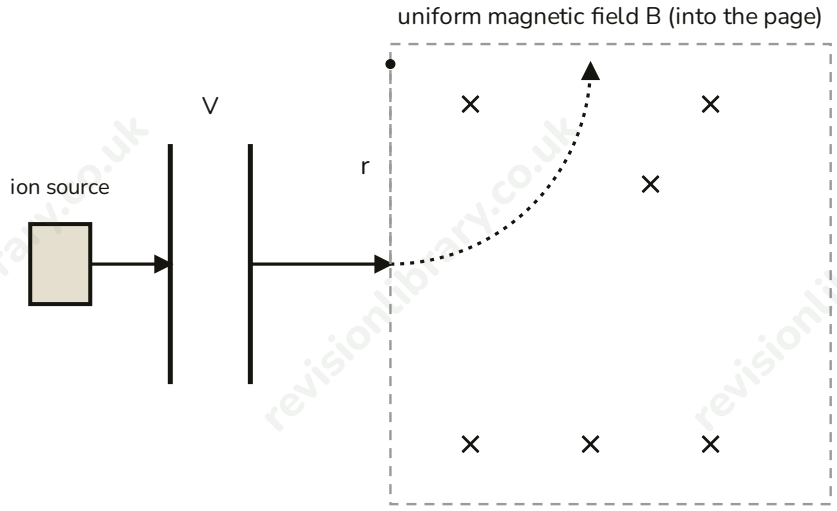
(a) With no current flowing, the balance reads 152.40 g. When a current of 3.50 A flows through the wire, the balance reading changes to 152.87 g. Calculate the magnetic force on the wire corresponding to this change in balance reading. **(3)**

(b) Calculate the magnetic flux density between the poles of the magnet. **(2)**

(c) The student repeats the experiment for a range of currents and plots a graph of force F (y-axis) against current I (x-axis). Explain how this graph gives a more reliable value of B than using a single pair of readings. **(3)**

(Total for Question 9 is 8 marks)

10 In a simple mass spectrometer, singly ionised carbon-12 ions (charge $+1.60 \times 10^{-19}$ C, mass 1.99×10^{-26} kg) are accelerated from rest through a potential difference of 2.00×10^{3} V and then enter a region of uniform magnetic flux density 0.450 T, directed at right angles to their velocity. You are given: work done accelerating the ion, $q*V = (1/2)*m*v^2$, and the condition for circular motion in the magnetic field, $B*q*v = m*v^2/r$.



(a) Calculate the speed of the carbon-12 ions as they enter the magnetic field. **(3)**

(b) Calculate the radius of the circular path followed by the carbon-12 ions in the magnetic field. **(3)**

(c) A singly ionised carbon-13 ion (same charge, mass 2.16×10^{-26} kg) is accelerated through the same potential difference and enters the same magnetic field. Without recalculating the speed and radius from scratch, state and explain whether the radius of its circular path would be greater than, less than, or equal to that of the carbon-12 ion. **(3)**

(Total for Question 10 is 9 marks)

Mark scheme · 3.10 Physics: Fields (Gravitational, Electric, Magnetic)

Question 1

(a) substitutes into EMF0 = B*A*N*ω **M1**

(a) EMF0 = 74.3 V (awrt 3 sf) **A1**

(a) Answer: EMF0 = 74.3 V

(b) uses f = ω/(2*π) **M1**

(b) f = 47.7 Hz (awrt 3 sf) **A1**

(b) Answer: f = 47.7 Hz

(c) states the EMF varies sinusoidally with time, reaching peak values of about +74.3 V and -74.3 V, with period T = 2*π/ω = 0.0209 s **B1**

(c) states the EMF is zero twice per rotation, at the instants when the flux linkage through the coil is at a maximum or a minimum (a turning point of the flux linkage) **B1**

(c) explains that at these instants the rate of change of flux linkage is (momentarily) zero, and since the induced EMF is proportional to the rate of change of flux linkage, the EMF is also zero at these instants **B1**

(c) Answer: The EMF varies sinusoidally with time (period 0.0209 s, peak ±74.3 V) and is zero twice per rotation, when the flux linkage is at a maximum or minimum, because the rate of change of flux linkage is momentarily zero at those instants.

Question 2

Level 1 Makes only basic, largely isolated statements, for example simply asserting that a current is induced or that energy is 'lost' as heat, with little or no correct use of Faraday's law or Lenz's law and no clear chain of reasoning linking cause to effect. **1-2**

Level 2 Correctly identifies that the moving magnet causes a changing magnetic flux which induces eddy currents in the copper tube (Faraday), and that Lenz's law means these currents oppose the motion, producing a retarding force. The explanation of the energy transfer to heat is present but the reasoning chain (flux change, induced EMF, induced current, retarding force, reduced acceleration, energy dissipation) has gaps, is not fully sequenced, or contains minor errors. May not fully explain the plastic-tube case. **3-4**

Level 3 Gives a complete, correctly sequenced explanation: the falling magnet causes a changing flux linkage through the copper tube's wall, which by Faraday's law induces an EMF and hence eddy currents in the conducting tube; by Lenz's law these induced currents create a magnetic field that opposes the change producing them, so they exert an upward (retarding) force on the magnet, reducing its acceleration below g. Correctly explains that the magnet's lost gravitational potential energy is transferred, via the induced current, into heat (resistive/Joule heating) dissipated in the resistance of the tube. Correctly contrasts this with the plastic tube, where no closed conducting path exists, so no eddy currents (and hence no retarding force) are induced and the magnet falls with acceleration g. Uses correct scientific terminology throughout. **5-6**

Indicative content:

- As the magnet falls, the magnetic flux linking any circular path within the wall of the copper tube changes with time.
- By Faraday's law, a changing flux linkage induces an EMF in the conducting tube.
- Because the copper tube forms continuous closed conducting loops, this induced EMF drives circulating (eddy) currents in the tube wall.
- By Lenz's law, the induced current acts in the direction that opposes the change that produced it, i.e. it opposes the relative motion between the magnet and the tube.
- This opposition means the eddy currents' magnetic field exerts a retarding (upward) force on the falling magnet.
- The net downward force on the magnet is therefore less than its weight, so its acceleration is less than g (and, given enough tube length, it approaches a constant terminal velocity).
- In the plastic tube there is no continuous conducting path, so no eddy currents (and therefore no retarding force) can be induced, and the magnet falls freely with acceleration g.
- By conservation of energy, the gravitational potential energy the magnet loses in the copper tube is transferred into electrical energy by the induced current, which is then dissipated as heat due to the resistance of the tube wall (rather than being converted entirely into kinetic energy, as in the plastic tube).

Question 3

(a) correctly substitutes into F = Q1*Q2/(4*π*epsilon0*r^2) **M1**

(a) F = 2.40 x 10^{-6} N (awrt 3 sf) **A1**

(a) states the force is attractive, since P and Q carry opposite-sign charges **B1**

(a) Answer: F = 2.40 x 10^{-6} N, attractive

(b) correctly substitutes into E = Q(P)/(4*π*epsilon0*r^2) **M1**

(b) E = 333 N C^{-1} (awrt 3 sf), allow 3.33 x 10^2 N/C **A1**

(b) Answer: E = 333 N C^{-1}

(c) calculates the field due to P at the midpoint: E_P = 1.33 x 10^3 N/C **M1**

(c) calculates the field due to Q at the midpoint: E_Q = 2.00 x 10^3 N/C **M1**

(c) both individual values correct to 3 sf (allow ecf on method) **A1**

(c) adds the two fields (since they act in the same direction) to give E_total = 3.33 x 10^3 N/C (awrt) **A1**

(c) Answer: E_total = 3.33 x 10^3 N C^{-1}

(d) states the field points from P towards Q **B1**

(d) Answer: From P towards Q

Question 4

(a) C23 = C2 + C3 = 450 uF **B1**

(a) Answer: C23 = 450 uF

(b) uses 1/C(total) = 1/C1 + 1/C23 **M1**

(b) correctly substitutes C1 = 150 uF and their C23 = 450 uF **A1**

(b) C(total) = 112.5 uF (awrt), allow ecf **A1**

(b) Answer: C(total) = 112.5 uF

(c) uses Q = C(total) x V **M1**

(c) Q = 1.69 x 10^{-3} C (awrt, allow 1.69 mC), allow ecf **A1**

(c) Answer: Q = 1.69 x 10^{-3} C

(d) uses V1 = Q/C1, using the total charge from part (c) (charge is the same through both series elements) **M1**

(d) V1 = 11.3 V (awrt), allow ecf **A1**

(d) Answer: V1 = 11.3 V

(e) uses W = (1/2)*C(total)*V^2 **M1**

(e) correctly substitutes C(total) = 112.5 uF and V = 15.0 V **A1**

(e) W = 1.27 x 10^{-2} J (awrt, allow 12.7 mJ), allow ecf **A1**

(e) Answer: W = 1.27 x 10^{-2} J

Question 5

(a) uses Ns = Np*(Vs/Vp) **M1**

(a) Ns = 240 turns **A1**

(a) Answer: Ns = 240 turns

(b) calculates output power: P(out) = Vs*Is = 96.0 W **M1**

(b) uses efficiency = P(out)/P(in) to find P(in) = P(out)/0.920 **M1**

(b) P(in) = 104 W (awrt) **A1**

(b) Ip = P(in)/Vp = 0.454 A (awrt), allow ecf **A1**

(b) Answer: Ip = 0.454 A

Question 6

(a) equates the electric force q*E to the magnetic force q*v*B for an undeviated ion **M1**

(a) correctly cancels q and rearranges to v = E/B **A1**

(a) v = 5.00 x 10^5 m/s **A1**

(a) Answer: v = 5.00 x 10^5 m/s

(b) uses r = m*v/(q*B), rearranged to q/m = v/(r*B) **M1**

(b) correctly substitutes v = 5.00 x 10^5 m/s (from part (a)), r = 4.20 x 10^{-2} m and B = 0.350 T **A1**

(b) q/m = 3.40 x 10^7 C/kg (awrt), allow ecf **A1**

(b) Answer: q/m = 3.40 x 10^7 C kg^{-1}

(c) identifies that the field lines spread out (fringing/edge effects) near the edges of the parallel plates, so the field is not perfectly uniform close to the plate edges **B1**

(c) states a suitable consequence, e.g. ions travelling near the edges experience a slightly different force balance and are not perfectly velocity-selected, so the emerging beam has a small spread of speeds rather than being purely monochromatic **B1**

(c) Answer: Fringing (edge) effects mean the field is weaker or less uniform near the plate edges; ions passing close to the edges are not perfectly velocity-selected, so the emerging beam has a small spread of speeds.

Question 7

(a) substitutes correctly into V = -GM/R **M1**

(a) V = -6.25 x 10^7 J kg^{-1} (awrt 3 sf), correct sign and unit **A1**

(a) Answer: V = -6.25 x 10^7 J kg^{-1}

(b) recognises that total mechanical energy per unit mass must be at least zero for escape: KE_{min} = -m*V(surface) **M1**

(b) substitutes m = 2.50 x 10^3 kg and their V from part (a) **A1**

(b) KE_{min} = 1.56 x 10^{11} J (awrt 3 sf), allow ecf **A1**

(b) Answer: KE_{min} = 1.56 x 10^{11} J

(c) quotes and uses v = $\sqrt{2GM/R}$ **M1**

(c) correct substitution of GM and R **A1**

(c) evaluates to v = 1.12 x 10^4 m/s (cao), matching the value given **A1**

(c) Answer: v = 1.12 x 10^4 m/s

(d) states energy conservation per unit mass: (1/2)*v_∞^2 + 0 = (1/2)*v_R^2 + (-GM/R) **M1**

(d) correctly rearranges to $v_R = \sqrt{v_\infty^2 + 2GM/R}$, equivalently $v_R = \sqrt{v_\infty^2 + v_{esc}^2}$ **M1**

(d) correctly substitutes v_∞ = 1.60 x 10^4 m/s and 2GM/R (or their v_{esc} from part (c)) **A1**

(d) v_R = 1.95 x 10^4 m/s (awrt 3 sf), allow ecf **A1**

(d) Answer: v_R = 1.95 x 10^4 m/s

Question 8

(a) states the equilibrium condition q*E = m*g **B1**

(a) rearranges to E = m*g/q and substitutes the given values **M1**

(a) E = 3.00 x 10^5 N/C (cao), matching the given value **A1**

(a) Answer: E = 3.00 x 10^5 N C^{-1}

(b) uses V = E*d **M1**

(b) V = 1.50 x 10^3 V (awrt, accept 1500 V), allow ecf **A1**

(b) Answer: V = 1.50 x 10^3 V

(c) recognises that, for a negative charge, the electric force is opposite to the field direction, so the field must point downward for the force on the drop to act upward **B1**

(c) states the upper plate must be at the higher potential, since field lines point from high to low potential **B1**

(c) Answer: The upper plate is at the higher potential.

Question 9

(a) finds the change in mass reading: delta m = 152.87 - 152.40 = 0.47 g = 4.70 x 10^{-4} kg **M1**

(a) uses F = delta m * g **M1**

(a) F = 4.61 x 10^{-3} N (awrt 3 sf) **A1**

(a) Answer: F = 4.61 x 10^{-3} N

(b) uses B = F/(I*L) **M1**

(b) B = 1.46 x 10^{-2} T (awrt, allow 14.6 mT), allow ecf **A1**

(b) Answer: B = 1.46 x 10^{-2} T

(c) states the graph should be a straight line through the origin, with gradient equal to B*L **B1**

(c) states B is found from B = gradient/L **B1**

(c) explains that using the gradient of a line of best fit through several data points averages out random errors, giving a more reliable value than relying on a single (potentially anomalous) measurement **B1**

(c) Answer: Plot F against I; the gradient equals B*L, so B = gradient/L. Using a line of best fit through many points reduces the effect of random error compared with a single reading.

Question 10

(a) uses q*V = (1/2)*m*v^2 **M1**

(a) correctly rearranges to v = $\sqrt{2*q*V/m}$ **A1**

(a) v = 1.79 x 10^5 m/s (awrt 3 sf) **A1**

(a) Answer: v = 1.79 x 10^5 m/s

(b) uses r = m*v/(B*q) **M1**

(b) correctly substitutes m, their v from part (a), B and q **A1**

(b) r = 4.96 x 10^{-2} m (awrt), allow ecf **A1**

(b) Answer: r = 4.96 x 10^{-2} m

(c) recognises from q*V = (1/2)*m*v^2 that v is proportional to $1/\sqrt{m}$, so the more massive carbon-13 ion has a smaller speed **M1**

(c) recognises from r = m*v/(B*q) that, since v is proportional to $1/\sqrt{m}$, r is proportional to $m/\sqrt{m} = \sqrt{m}$ **M1**

(c) concludes the carbon-13 ion has a greater mass, so $\sqrt{m}$ is greater, so its radius is greater than that of the carbon-12 ion **A1**

(c) Answer: The carbon-13 ion has a greater radius than the carbon-12 ion.