2019

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 2

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Free Response Question 3

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General Notes About 2019 AP Physics Scoring Guidelines

1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.

2. The requirements that have been established for the paragraph-length response in Physics 1 and Physics 2 can be found on AP Central at https://secure-media.collegeboard.org/digitalServices/pdf/ap/paragraph-length-response.pdf.

3. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded. One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.

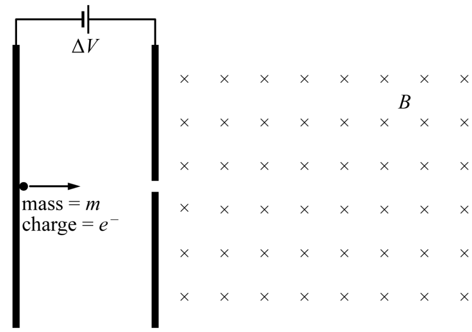
4. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth 1 point, and a student's solution embeds the application of that equation to the problem in other work, the point is still awarded. However, when students are asked to derive an expression, it is normally expected that they will begin by writing one or more fundamental equations, such as those given on the exam equation sheet. For a description of the use of such terms as "derive" and "calculate" on the exams, and what is expected for each, see "The Free-Response Sections — Student Presentation" in the *AP Physics; Physics C: Mechanics, Physics C: Electricity and Magnetism Course Description* or "Terms Defined" in the *AP Physics 1: Algebra-Based Course and Exam Description* and the *AP Physics 2: Algebra-Based Course and Exam Description*.

5. The scoring guidelines typically show numerical results using the value $g = 9.8 \text{ m/s}^2$, but the use of 10 m/s^2 is of course also acceptable. Solutions usually show numerical answers using both values when they are significantly different.

6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer. For example, suppose a solution requires subtracting two numbers that should have five significant figures and that differ starting with the fourth digit (e.g., 20.295 and 20.278). Rounding to three digits will lose the accuracy required to determine the difference in the numbers, and some credit may be lost.

Question 3

15 points



Two plates are set up with a potential difference V between them. A small sphere of mass m and charge $-e$ is placed at the left-hand plate, which has a negative charge, and is allowed to accelerate across the space between the plates and pass through a small opening. After passing through the small opening, the sphere enters a region in which there is a uniform magnetic field of magnitude B directed into the page, as shown above. Ignore gravitational effects. Express all algebraic answers in terms of V, m, e, B, and fundamental constants, as appropriate.

(a)

i. LO CHG-1.A.a, SP 7.A
1 point

What is the initial direction of the force on the sphere as it enters the magnetic field?

____ Into the page ____ Out of the page
____ Toward the top of the page ____ Toward the bottom of the page

For selecting “Toward the bottom of the page”		1 point

ii. LO CHG-1.B, SP 7.A
1 point

Describe the path taken by the sphere after it enters the magnetic field.

For describing a circular path for the sphere consistent with the selection from part (a)(i)		1 point
Example: The sphere will move in a circular path toward the bottom of the page.		

Question 3 (continued)

(b) LO CNV-1.E, SP 5.A, 5.E
2 points

Derive an expression for the speed of the sphere as it passes through the small opening.

For using a valid equation relating potential difference to kinetic energy of the sphere		1 point
$\Delta K = -\Delta U \therefore \frac{1}{2}mv^2 = -q\Delta V$		
$\frac{1}{2}mv^2 = eV$		
For the correct answer with supporting work		1 point
$v = \sqrt{\frac{2eV}{m}}$		

(c) LO CHG-1.C, SP 5.A, 5.E
3 points

Derive an expression for the radius of the path taken by the sphere as it moves through the magnetic field.

For an expression relating the magnetic force to the centripetal force		1 point
$\frac{mv^2}{r} = Bqv$		
For substituting the charge of the sphere into the above equation and solving for r		1 point
$\frac{mv}{r} = Be \therefore r = \frac{mv}{Be}$		
For substituting the answer from part (b)		1 point
$r = \frac{m}{Be}\sqrt{\frac{2eV}{m}} = \sqrt{\frac{2mV}{eB^2}}$		

An experiment is performed in which a beam of electrons is accelerated across the space between the plates and passes through the small opening. After passing through the opening, the electrons travel in a semicircular path and strike the right-hand plate. The potential difference between the plates is varied in regular increments, as shown in the table below. For each potential difference, the magnetic field is varied in order to cause the beam to strike the right-hand plate at a distance of 0.020 m from the opening.

Potential difference (V)	60	70	100	110	120	140
Magnetic field $\left(\text{T} \times 10^{-3}\right)$	2.62	2.78	3.39	3.54	3.78	3.99

Question 3 (continued)

(d) LO CHG-1.C, SP 4.C
1 point

Indicate below which quantities should be graphed to yield a straight line whose slope could be used to calculate a numerical value for the mass-to-charge ratio of an electron.

Vertical axis:____________
Horizontal axis:____________

Use the remaining columns in the table above, as needed, to record any quantities that you indicated that are not given. Label each column you use and include units.

$$r = \sqrt{\frac{2m_e V}{eB^2}} \quad \therefore \; B^2 = \frac{2m_e}{er^2} V$$

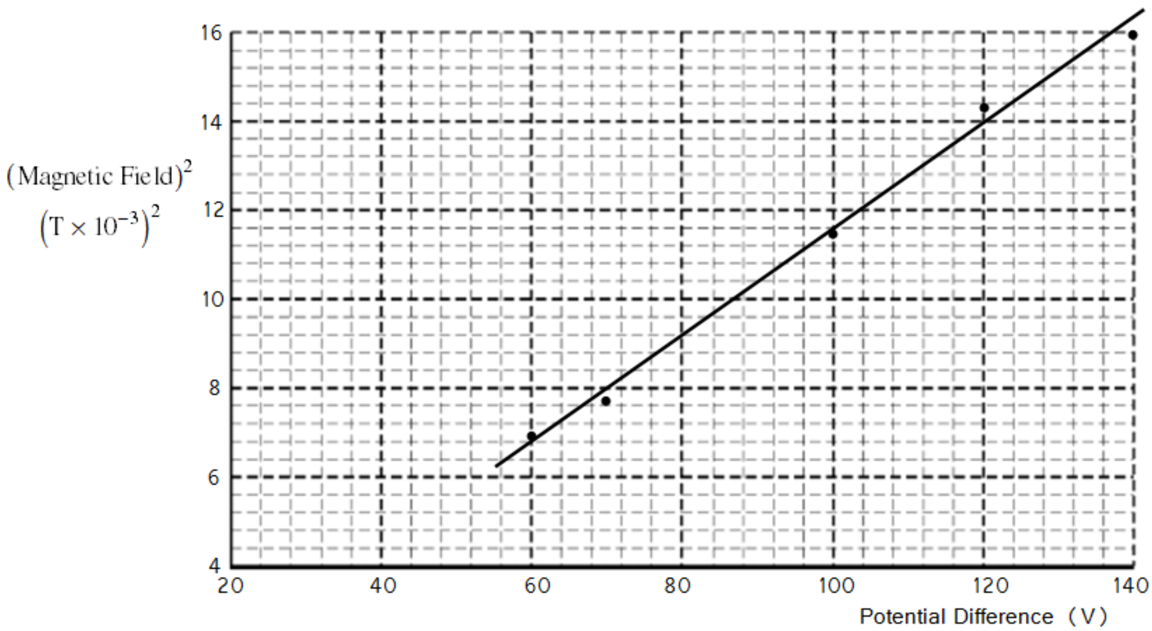
Potential difference (V)	60	70	100	110	120	140
Magnetic field $\left(\text{T} \times 10^{-3}\right)$	2.62	2.78	3.39	3.54	3.78	3.99
$(\text{Magnetic field})^2$ $\left(\text{T} \times 10^{-3}\right)^2$	6.86	7.73	11.5	12.5	14.3	15.9

For indicating axis choices with appropriate quantities to produce a straight line		1 point
Note: There are several possible choices.		

Question 3 (continued)

(e) LO CHG-1.C, SP 3.A, 4.C
4 points

On the graph below, plot the relationship determined in part (d). Clearly scale and label all axes, including units, if appropriate. Draw a straight line that best represents the data.



For correctly labeling both axes with quantities and units		1 point
For correctly scaling and labeling the axes so that the points use at least half the grid		1 point
For correctly plotting the data		1 point
For drawing a straight line that represents the data		1 point

(f) LO CHG-1.C, SP 4.D, 5.E
3 points

Using the straight line from part (e), determine the mass-to-charge ratio of an electron.

For correctly calculating the slope from the best-fit straight line and not from the data points unless the points fall on the best-fit line		1 point
$\text{slope} = \dfrac{14 - 9.2}{120 - 80} = 0.12\ \dfrac{(T \times 10^{-3})^2}{V} = 1.2 \times 10^{-7}\ T^2/V$		
For a correct expression relating the slope to the mass to charge ratio of an electron		1 point
$B^2 = \dfrac{2m_e}{er^2}V\ \therefore\ \text{slope} = \dfrac{2m_e}{er^2}\ \therefore\ \dfrac{m_e}{e} = \dfrac{r^2 \times \text{slope}}{2}$		
For substituting correct values into the above equation		1 point
$\dfrac{m_e}{e} = \dfrac{(0.01\ \text{m})^2 \times (1.2 \times 10^{-7}\ T^2/V)}{2} = 6.0 \times 10^{-12}\ \text{kg/C}$		

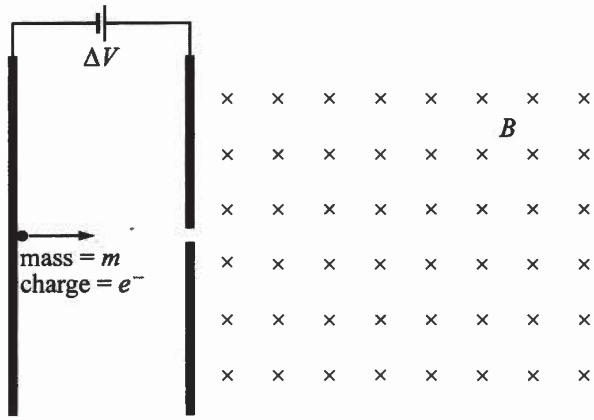
Question 3 (continued)

Learning Objectives

CHG-1.A.a: Calculate the magnitude and direction of the magnetic force of interaction between a moving charged particle of specified charge and velocity moving in a region of a uniform magnetic field.
CHG-1.B: Describe the path of different moving charged particles (i.e., of different type of charge or mass) in a uniform magnetic field.
CHG-1.C: Derive an expression for the radius of a circular path for a charged particle of specified characteristics moving in a specified magnetic field.
CNV-1.E: Calculate the work done or changes in kinetic energy (or changes in speed) of a charged particle when it is moved through some known potential difference.

Science Practices

3.A: Select and plot appropriate data.
4.C: Linearize data and/or determine a best-fit line or curve.
4.D: Select relevant features of a graph to describe a physical situation or solve problems.
5.A: Select an appropriate law, definition, or mathematical relationship or model to describe a physical situation.
5.E: Derive a symbolic expression from known quantities by selecting and following a logical algebraic pathway.
7.A: Make a scientific claim.



3. Two plates are set up with a potential difference V between them. A small sphere of mass m and charge $-e$ is placed at the left-hand plate, which has a negative charge, and is allowed to accelerate across the space between the plates and pass through a small opening. After passing through the small opening, the sphere enters a region in which there is a uniform magnetic field of magnitude B directed into the page, as shown above. Ignore gravitational effects. Express all algebraic answers in terms of V, m, e, B, and fundamental constants, as appropriate.

(a)

i. What is the initial direction of the force on the sphere as it enters the magnetic field?

____ Into the page ____ Out of the page

____ Toward the top of the page _X_ Toward the bottom of the page

ii. Describe the path taken by the sphere after it enters the magnetic field.

The sphere's path curves downward initially. While the sphere is in the region with the uniform magnetic field, the sphere travels in an arc that is part of a circle.

(b) Derive an expression for the speed of the sphere as it passes through the small opening.

$V = \frac{W}{q}$, $W = \Delta K$

$K = Vq$

$\frac{1}{2}mv^2 = Ve$

$\boxed{v = \sqrt{\frac{2Ve}{m}}}$

(c) Derive an expression for the radius of the path taken by the sphere as it moves through the magnetic field.

$F_{NET\ IN} = \frac{mv^2}{R}$

$qv \times B = \frac{mv^2}{R}$

$evB = \frac{mv^2}{R}$

$R = \frac{mv}{eB}$

$R = \frac{m\sqrt{\frac{2Ve}{m}}}{eB}$

$R = \frac{1}{B}\sqrt{\frac{2Vm}{e}}$

GO ON TO THE NEXT PAGE.

An experiment is performed in which a beam of electrons is accelerated across the space between the plates and passes through the small opening. After passing through the opening, the electrons travel in a semicircular path and strike the right-hand plate. The potential difference between the plates is varied in regular increments, as shown in the table below. For each potential difference, the magnetic field is varied in order to cause the beam to strike the right-hand plate at a distance of 0.020 m from the opening.

Potential difference (V)	60	70	100	110	120	140
Magnetic field $(T \times 10^{-3})$	2.62	2.78	3.39	3.54	3.78	3.99
(Magnetic field)^2 $(T^2 \times 10^{-6})$	6.86	7.73	11.5	12.5	14.3	15.9

$R^2 = \frac{2Vm}{B^2 e}$

$\frac{m}{e} = \frac{R^2 B^2}{2V}$

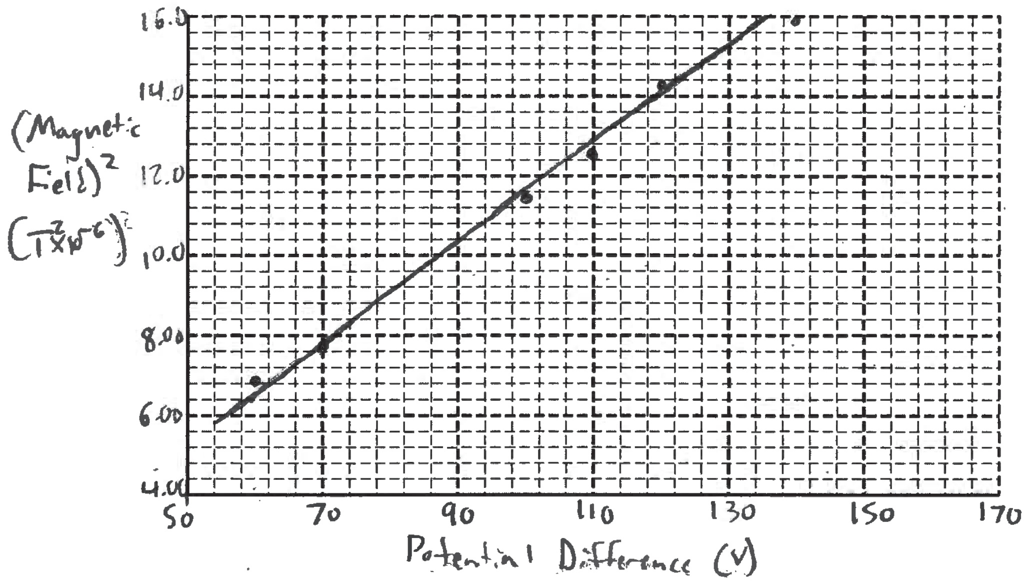
(d) Indicate below which quantities should be graphed to yield a straight line whose slope could be used to calculate a numerical value for the mass-to-charge ratio of an electron.

Vertical axis: (Magnetic field)^2 $(T^2 \times 10^{-6})$

Horizontal axis: Potential Difference (V)

Use the remaining columns in the table above, as needed, to record any quantities that you indicated that are not given. Label each column you use and include units.

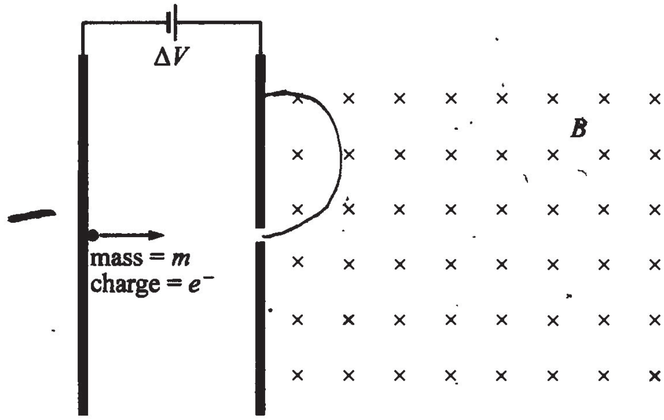
(e) On the graph below, plot the relationship determined in part (d). Clearly scale and label all axes, including units, if appropriate. Draw a straight line that best represents the data.



(f) Using the straight line from part (e), determine the mass-to-charge ratio of an electron.

$\text{slope} = \frac{14.8 \times 10^{-6}\, T^2 - 6.8 \times 10^{-6}\, T^2}{126\, V - 62\, V} = 1.3 \times 10^{-7}\, T^2/V$

$\frac{m}{e} = \frac{R^2}{2}(\text{slope}) = \frac{(.010\, m)^2}{2}(1.3 \times 10^{-7}\, T^2/V) = \boxed{6.5 \times 10^{-12}}$



3. Two plates are set up with a potential difference V between them. A small sphere of mass m and charge $-e$ is placed at the left-hand plate, which has a negative charge, and is allowed to accelerate across the space between the plates and pass through a small opening. After passing through the small opening, the sphere enters a region in which there is a uniform magnetic field of magnitude B directed into the page, as shown above. Ignore gravitational effects. Express all algebraic answers in terms of V, m, e, B, and fundamental constants, as appropriate.

(a)

i. What is the initial direction of the force on the sphere as it enters the magnetic field?

____ Into the page   ____ Out of the page

✓ Toward the top of the page   ____ Toward the bottom of the page

ii. Describe the path taken by the sphere after it enters the magnetic field.

It goes in a semi-circle ark up until it hits the plate

(b) Derive an expression for the speed of the sphere as it passes through the small opening.

$U_E = qV$
$U_E = K$
$qV = \frac{1}{2}mv^2$
$eV = \frac{1}{2}m_e v^2$ → $v = \sqrt{\frac{2eV}{m_e}}$

(c) Derive an expression for the radius of the path taken by the sphere as it moves through the magnetic field.

$\Sigma F = ma$
$\Sigma F = \frac{mv^2}{r}$
$qvB = \frac{mv^2}{r}$ → $qB = \frac{mv}{r}$
$r = \frac{mv}{qB}$

$r = \frac{m\left(\sqrt{\frac{2eV}{m_e}}\right)}{qB}$

GO ON TO THE NEXT PAGE.

An experiment is performed in which a beam of electrons is accelerated across the space between the plates and passes through the small opening. After passing through the opening, the electrons travel in a semicircular path and strike the right-hand plate. The potential difference between the plates is varied in regular increments, as shown in the table below. For each potential difference, the magnetic field is varied in order to cause the beam to strike the right-hand plate at a distance of 0.020 m from the opening. r=.01

Potential difference (V)	60	70	100	110	120	140
Magnetic field $(T \times 10^{-3})$	2.62	2.78	3.39	3.54	3.78	3.99
$\sqrt{\text{Potential difference}}$ (V)	7.75	8.37	10	10.49	10.95	11.83

(d) Indicate below which quantities should be graphed to yield a straight line whose slope could be used to calculate a numerical value for the mass-to-charge ratio of an electron.

$r = \frac{m}{q}\left(\frac{\sqrt{\frac{2eV}{m_e}}}{B}\right)$

Vertical axis: Magnetic field

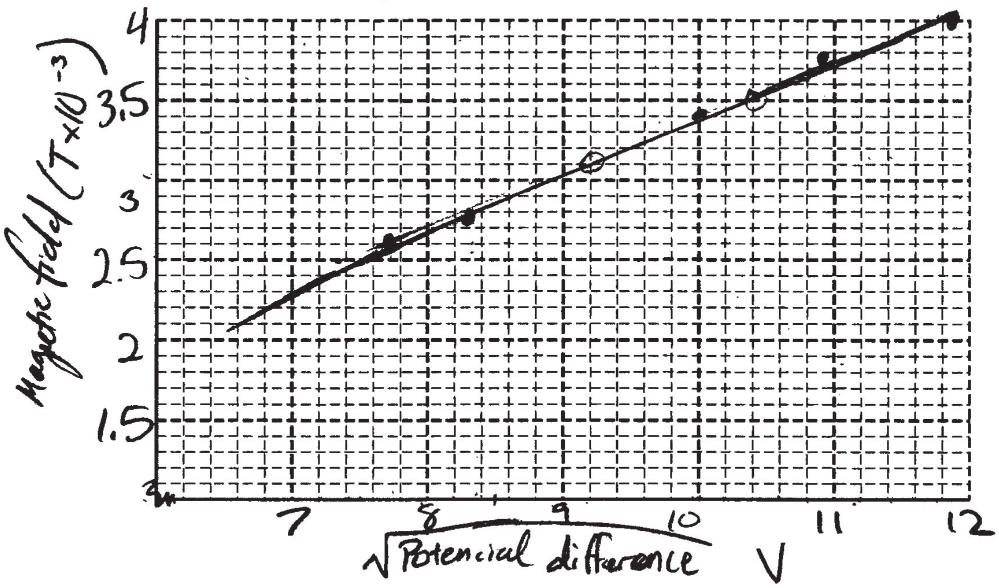
$r = \frac{m}{q}\frac{1}{B}\sqrt{\frac{2eV}{m_e}}$

Horizontal axis: $\sqrt{V}$

Use the remaining columns in the table above, as needed, to record any quantities that you indicated that are not given. Label each column you use and include units.

$B = \frac{m}{q}\frac{1}{r}\sqrt{V}$

(e) On the graph below, plot the relationship determined in part (d). Clearly scale and label all axes, including units, if appropriate. Draw a straight line that best represents the data.



(f) Using the straight line from part (e), determine the mass-to-charge ratio of an electron.

(10.4, 3.5) $\frac{B}{\sqrt{V}}$ 3.5 =

(9.2, 3.1)

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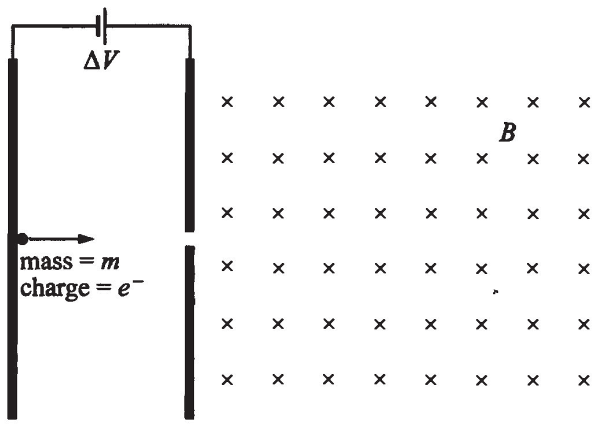


3. Two plates are set up with a potential difference V between them. A small sphere of mass m and charge $-e$ is placed at the left-hand plate, which has a negative charge, and is allowed to accelerate across the space between the plates and pass through a small opening. After passing through the small opening, the sphere enters a region in which there is a uniform magnetic field of magnitude B directed into the page, as shown above. Ignore gravitational effects. Express all algebraic answers in terms of V, m, e, B, and fundamental constants, as appropriate.

(a)

i. What is the initial direction of the force on the sphere as it enters the magnetic field?

____ Into the page ____ Out of the page

✓ Toward the top of the page ____ Toward the bottom of the page

ii. Describe the path taken by the sphere after it enters the magnetic field.

It is a circular path towards to top of the page

It travels in UCM

(b) Derive an expression for the speed of the sphere as it passes through the small opening.

$PE = \frac{kqq}{r} - \frac{kqq}{r} = \frac{1}{2}mv^2$

(c) Derive an expression for the radius of the path taken by the sphere as it moves through the magnetic field.

$qvB = \frac{1}{2}mv^2$

GO ON TO THE NEXT PAGE.

An experiment is performed in which a beam of electrons is accelerated across the space between the plates and passes through the small opening. After passing through the opening, the electrons travel in a semicircular path and strike the right-hand plate. The potential difference between the plates is varied in regular increments, as shown in the table below. For each potential difference, the magnetic field is varied in order to cause the beam to strike the right-hand plate at a distance of 0.020 m from the opening.

Potential difference (V)	60	70	100	110	120	140
Magnetic field $(T \times 10^{-3})$	2.62	2.78	3.39	3.54	3.78	3.99

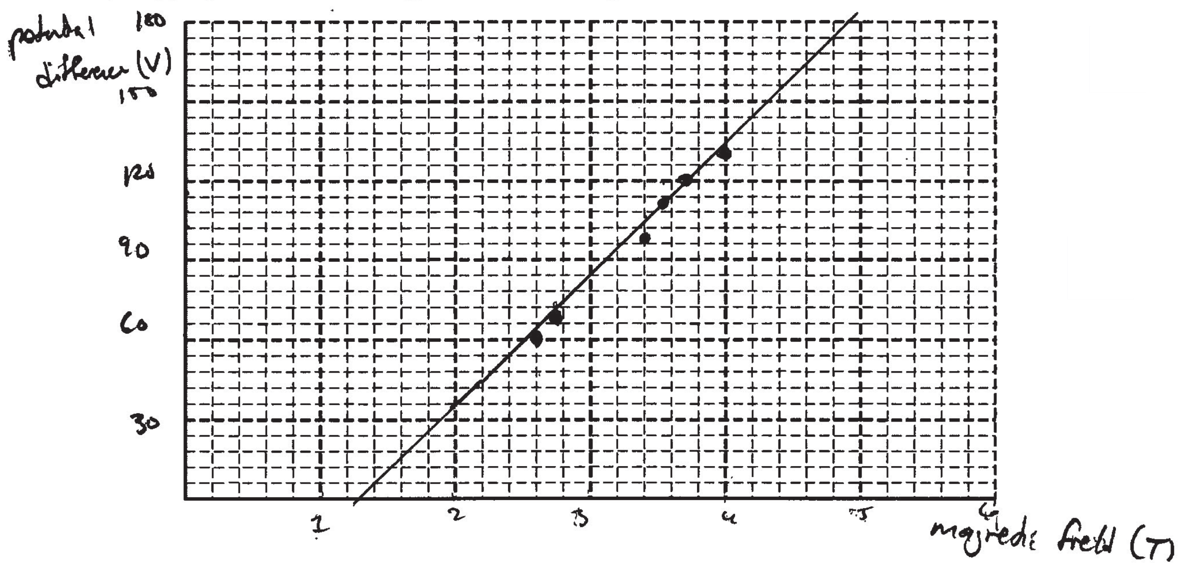
(d) Indicate below which quantities should be graphed to yield a straight line whose slope could be used to calculate a numerical value for the mass-to-charge ratio of an electron.

Vertical axis: Potential difference (V)

Horizontal axis: Magnetic field (T)

Use the remaining columns in the table above, as needed, to record any quantities that you indicated that are not given. Label each column you use and include units.

(e) On the graph below, plot the relationship determined in part (d). Clearly scale and label all axes, including units, if appropriate. Draw a straight line that best represents the data.



(f) Using the straight line from part (e), determine the mass-to-charge ratio of an electron.

take the slope of the line

$\frac{180}{5}$ · $\frac{90}{3}$

30

GO ON TO THE NEXT PAGE.

Question 3

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

The responses to this question were expected to demonstrate the following:

- Identify the magnitude and direction of forces on charged particles in both electric and magnetic fields
- Recognize that charged particles will move in circular motion when under the influence of magnetic forces
- Derive expressions utilizing concepts of Newton's laws and energy conservation
- Linearize data in order to extract physical quantities from experimental data
- Construct an appropriate graph using experimental data
- Utilize math skills, such as creating a best-fit model, and calculating a slope to extract desired quantities

Sample: E Q3 A
Score: 15

All parts of this response earned full credit. Part (a) has a correct selection and describes an appropriate path, so 2 points were earned. Part (b) uses a valid equation and has a correct answer with supporting work, so 2 points were earned. Part (c) sets the centripetal force equal to the magnetic force, makes the correct substitutions, and solves for r, so 3 points were earned. Part (d) indicates physical quantities that yield a straight line whose slope can be used to determine the mass-to-charge ratio, so 1 point was earned. Part (e) properly scales and labels the axes, correctly plots the data, and has an appropriate best-fit line, so 4 points were earned. Part (f) correctly calculates the slope, relates the slope to the mass-to-charge ratio, and correctly substitutes into the equation, so 3 points were earned.

Sample: E Q3 B
Score: 9

Part (a)(i) indicates an incorrect direction for the force, so no points were earned. Part (a)(ii) describes a circular path consistent with the direction of the force in part (a)(i), so 1 point was earned. Parts (b) earned full credit, 2 points. Part (c) sets the centripetal force equal to the magnetic force and solves for r but has both e and q in the final answer, so 2 points were earned. Part (d) indicates physical quantities that yield a straight line whose slope can be used to determine the mass-to-charge ratio, so 1 point was earned. Part (e) properly scales and labels the axes, correctly plots the data, and has an appropriate best-fit line, but has an incorrect unit on the horizontal axis, so 3 points were earned. Part (f) does not show a correct calculation of the slope and does not relate the slope to the mass-to-charge ratio, so no points were earned.

Sample: E Q3 C
Score: 4

Part (a)(i) indicates an incorrect direction for the force, so no points were earned. Part (a)(ii) describes a circular path consistent with the direction of the force in part (a)(i), so 1 point was earned. Part (b) uses an incorrect equation, so no points were earned. Part (c) incorrectly sets the magnetic force equal to kinetic energy, so no points were earned. Part (d) indicates physical quantities that do not yield a straight line, so no points were earned. Part (e) properly labels the axes, correctly plots the data, and has an appropriate best-fit line, but the scale does not use at least half the available grid, so 3 points were earned. Part (f) does not show a correct calculation of the slope and does not relate the slope to the mass-to-charge ratio, so no points were earned.