Past-paper walk-through

Electric Fields ▪ 10.3

eXercise

Questions in this set

- 2024 Q4
- 2023 Q4
- 2022 Q3
- 2019 Q1
- 2018 Q1
- 2017 Q4
- 2016 Q3
- 2015 Q4

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 4

2024 ▪ Q4

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$. - Particle 2 has mass $\frac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(a) **Calculate** the ratio $\frac{K_2}{K_1}$.

Question 4

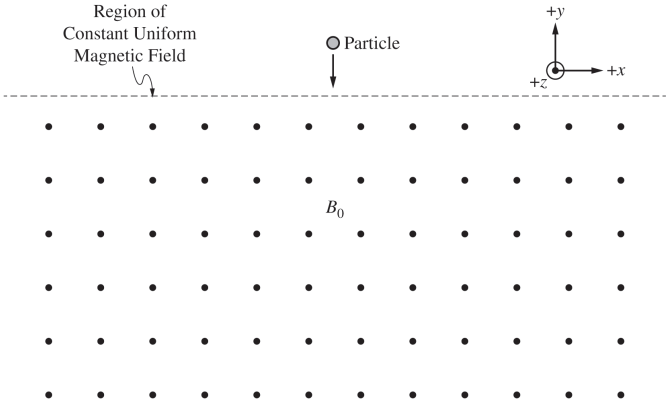

Figure 2

Question 4

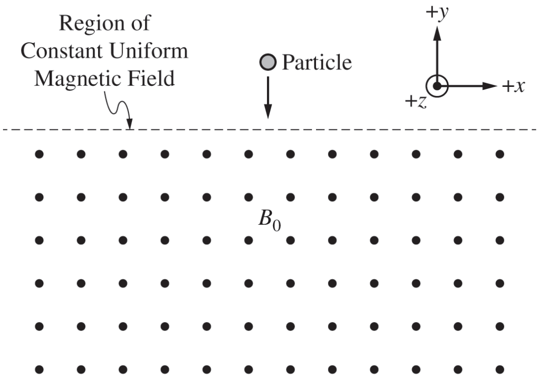

Figure 1

Question 4

2024 ▪ Q4

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$. - Particle 2 has mass $\frac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(b)(i) [Figure 1: A diagram showing a "Region of Constant Uniform Magnetic Field" as a grid of dots (indicating a field directed out of the page, in the $+z$-direction) bounded above by a dashed horizontal line. Above the region, a "Particle" (circle with

Question 4

dot) is shown with a downward arrow into the region. A small coordinate axis in the upper right shows $+y$ up, $+x$ right, and $+z$ out of the page (toward viewer). The field magnitude is labeled B_0 within the dotted region.]

After exiting the device, the particles enter a large region of constant uniform magnetic field of magnitude B_0 that is directed in the $+z$-direction (out of the page), as shown in Figure 1. Each particle is moving in the $-y$-direction when entering the region, and each particle is moving in the $+y$-direction when exiting the region.

Determine an expression for the speed of Particle 2 in the region. Express your answer in terms of M, K_2, and physical constants, as appropriate.

(b)(ii) **Derive** an expression for the horizontal distance Δx between the locations where Particle 2 enters and leaves the region. Express your answer in terms of M, Q, K_2, B_0, and physical constants, as appropriate.

Question 4

2024 ▪ Q4

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$. - Particle 2 has mass $\frac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(c) [Figure 2: The same diagram as Figure 1 — a "Region of Constant Uniform Magnetic Field" shown as a grid of dots bounded above by a dashed horizontal line, with a "Particle" (circle with dot) above the region and a downward arrow into it, and

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the coordinate axis ($+y$ up, $+x$ right, $+z$ out of page) shown in the upper right, field magnitude B_0 labeled within the region. This copy is provided blank for the student to sketch on.]

On the following diagram in Figure 2, **sketch** and clearly **label** the paths of **both** particles 1 and 2 in the region.

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2024 ▪ Q4

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass M and negative charge $-Q$. - Particle 2 has mass $\dfrac{M}{2}$ and positive charge $+2Q$.

In separate trials, a device is used to accelerate each particle in the $-y$-direction from rest through a potential difference of absolute value $|\Delta V|$. The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the $-y$-direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies K_1 and K_2, respectively.

(d) A uniform electric field is added to the region such that Particle 1 of negative charge $-Q$ travels with constant speed in a straight line through the region. **Determine** the direction of the electric field.

Solution 4

(a) Mark scheme

- $K_2/K_1 = 2$. Derivation: for a charged particle released from rest and accelerated through a potential difference ΔV, energy conservation ($E_0 = E_f$, $\Delta U + \Delta K = 0$) gives $-\Delta U_E = \Delta K$, i.e. the final kinetic energy equals $|q\Delta V|$. Particle 1 (charge $-Q$): $K_1 = |-Q\Delta V| = Q\Delta V$. Particle 2 (charge $+2Q$, same ΔV): $K_2 = |+2Q\Delta V| = 2Q\Delta V$. Ratio: $\dfrac{K_2}{K_1} = \dfrac{2Q\Delta V}{Q\Delta V} = 2$. Scoring: 1 pt for indicating the final kinetic energy of a particle equals $|q\Delta V|$ (explicit absolute-value notation not required); 1 pt for the correct ratio $K_2/K_1 = 2$.

Solution 4

(b)(i) Mark scheme

- $v = 2\sqrt{\dfrac{K_2}{M}}$. Derivation: kinetic energy $K = \frac{1}{2}mv^2$. Particle 2 has mass $M/2$, so $K_2 = \frac{1}{2}\left(\dfrac{M}{2}\right)v^2$. Solving for v: $v = 2\sqrt{K_2/M}$. Scoring: 1 pt for a correct expression for the speed of Particle 2 in terms of K_2 and M.

Solution 4

(b)(ii) Mark scheme

- $\Delta x = \dfrac{\sqrt{K_2 M}}{QB_0}$. Derivation: Newton's second law with the magnetic force gives $\vec{a}_c = \dfrac{q\vec{v} \times \vec{B}}{m}$, so for circular motion $\dfrac{v^2}{r} = \dfrac{qvB}{m}$, i.e. $r = \dfrac{mv}{qB}$. Substituting Particle 2's mass $(M/2)$, charge magnitude $(2Q)$, speed from part (b)(i) $\left(v = 2\sqrt{K_2/M}\right)$, and field B_0: $r = \dfrac{(M/2)\left(2\sqrt{K_2/M}\right)}{2QB_0} = \dfrac{\sqrt{K_2 M}}{2QB_0}$. The horizontal distance Δx between where the particle enters and leaves the field region equals the diameter of the semicircular path: $\Delta x = 2r = \dfrac{\sqrt{K_2 M}}{QB_0}$. Scoring: 1 pt for substituting the

Solution 4

magnetic-force expression into a Newton's-second-law equation for circular motion; 1 pt for correctly substituting Particle 2's mass, charge, and speed (from (b)(i)) into the resulting radius expression; 1 pt for indicating $\Delta x = 2r$.

Solution 4

(c) Mark scheme

- Sketch (both particles enter moving straight down into the field region and curve back out): Particle 1's path is a semicircular arc that is concave up and curves to the right, with a LARGER radius of curvature. Particle 2's path is a semicircular arc that is concave up and curves to the left — the opposite direction from Particle 1 (consistent with its opposite-sign charge) — with a SMALLER radius of curvature than Particle 1's path (consistent with Particle 2's smaller mass and larger charge magnitude giving a smaller $r = mv/qB$). Scoring: 1 pt for a path for Particle 1 that is concave up and to the right; 1 pt for a path for Particle 2 that is concave up and in the opposite direction from Particle 1; 1 pt for Particle 1's path having a larger radius of curvature than Particle 2's path.

Solution 4

(d) Mark scheme

- The electric field must point in the $+x$-direction. Reasoning: Particle 1 carries charge $-Q$ and must travel in a straight line at constant speed through the region, so the electric force $q\vec{E}$ must exactly cancel the magnetic force on it at every instant; given the curving direction of Particle 1's path shown in part (c) (curving to the right, i.e. toward $+x$, under the magnetic force), the needed electric force — and hence, since the charge is negative, the field direction — works out to $+x$. (Any direction consistent with the student's own path for Particle 1 in part (c) also earns credit.) Scoring: 1 pt for indicating either that the electric field is directed in the $+x$-direction, or a direction consistent with the path drawn for Particle 1 in part (c).

Question 4

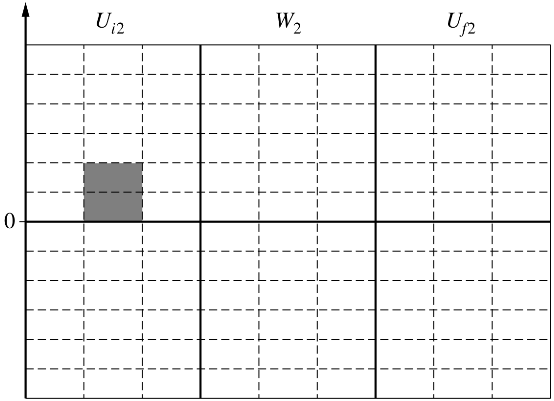
2023 ▪ Q4

(10 points, suggested time 20 minutes)
Particles A and B each have positive charge $+Q$ and are held fixed at two vertices of an equilateral triangle of side d, as shown. Point P is located equidistant from each vertex of the triangle.
[Figure: An equilateral triangle with vertices labeled; Particle A at one vertex and Particle B at another vertex, each carrying charge $+Q$, with side length d between them; Point P is located at the position equidistant from all three vertices (the centroid), including the unoccupied bottom-right vertex referenced in the discussion below.]
Students Y and Z discuss the electric field and the electric potential at Point P after a third charged particle is placed in the bottom-right vertex. The students make the following statements.

Question 4

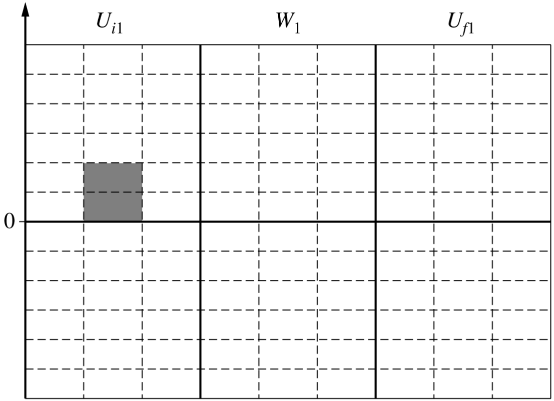
Student Y: "If a particle with positive charge $+2Q$ is placed at the bottom-right vertex, the magnitude of the electric field will be zero at Point P."
Student Z: "To make the value of the electric potential zero at Point P, a particle with negative charge $-Q$ should be placed at the bottom-right vertex."
(a) In a coherent, paragraph-length response, evaluate the accuracy of each student's statement. If any aspect of either student's statement is inaccurate, explain how to correct the student's statement. Support your evaluations using appropriate physics principles.

Question 4



Scenario 2

Question 4



Scenario 1

Question 4

Question 4

2023 ▪ Q4

(10 points, suggested time 20 minutes)
Particles A and B each have positive charge $+Q$ and are held fixed at two vertices of an equilateral triangle of side d, as shown. Point P is located equidistant from each vertex of the triangle.
[Figure: An equilateral triangle with vertices labeled; Particle A at one vertex and Particle B at another vertex, each carrying charge $+Q$, with side length d between them; Point P is located at the position equidistant from all three vertices (the centroid), including the unoccupied bottom-right vertex referenced in the discussion below.]
Students Y and Z discuss the electric field and the electric potential at Point P after a third charged particle is placed in the bottom-right vertex. The students make the following statements.
Student Y: "If a particle with positive charge $+2Q$ is placed at the bottom-right vertex, the magnitude of the electric field will be zero at Point P."

Question 4

Student Z: "To make the value of the electric potential zero at Point P, a particle with negative charge $-Q$ should be placed at the bottom-right vertex."

(b)(i) Particles A and B are once again held in place at two vertices of the equilateral triangle. The students want to represent the electric potential energy of a system of particles that is brought very far away to the bottom-right vertex. Scenarios 1 and 2 are considered.

In Scenario 1, a third particle with positive charge $+Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following chart that represents the electric potential energy U_{i1} of the system consisting of all three particles when the third particle with positive charge is very far away from the other particles.

In the grid provided, complete the bar chart.

Question 4

- Draw a bar to represent the work W_1 required to move the third particle with positive charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f1} of the system consisting of all three particles when the third particle with positive charge is held in place at the bottom-right vertex.

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.
[Chart: A bar chart grid with three labeled columns: U_{i1}, W_1, U_{f1}, and a horizontal "0" baseline. A bar is already shown under column U_{i1} (a small positive bar above the 0 line), representing the initial potential energy of the two-particle system when the third particle is very far away. Scenario 1 title below the chart.]
(b)(ii) In Scenario 2, a particle with negative charge $-Q$ is moved from very far away to the bottom-right vertex and then held in place. A bar is shown on the following

Question 4

chart that represents the electric potential energy U_{i2} of the system consisting of all three particles when the particle with negative charge is very far away from the other particles.

In the grid provided, complete the bar chart.

- Draw a bar to represent the work W_2 required to move the particle with negative charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f2} of the system consisting of all three particles when the particle with negative charge is held in place at the bottom-right vertex.

Question 4

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a "0" in that column.
[Chart: A bar chart grid with three labeled columns: U_{i2}, W_2, U_{f2}, and a horizontal "0" baseline. A bar is already shown under column U_{i2} (a small positive bar above the 0 line), representing the initial potential energy of the two-particle system when the negative particle is very far away. Scenario 2 title below the chart.]

Solution 4

(a) Mark scheme

- Student Y is incorrect: before the third particle is placed at the bottom-right vertex, the electric field from particles A and B at Point P points down and to the right. The electric field from a positively charged particle placed at the bottom-right vertex would point up and to the left. Evaluating Student Y correctly requires recognizing the VECTOR nature of electric field (Point 1: vector-nature evaluation). The third particle needs charge $+Q$, not $+2Q$, to have the correct magnitude to cancel the field to zero at Point P (Point 2: stating the third particle must be $+Q$ for zero field at P, OR stating what resultant field magnitude a $+2Q$ particle would actually produce at P). Student Z is incorrect: before the third particle is placed, the electric potential at Point P is positive;

Solution 4

because P is equidistant from all three particles, the potential at P is proportional to the TOTAL charge of the system (Point 3: scalar-nature evaluation of electric potential). Zero potential at P requires the third particle to have charge $-2Q$ (so the total system charge is zero), not $-Q$ (Point 4: correctly stating the required charge is $-2Q$). Point 5 (holistic): the paragraph response is logical, relevant, internally consistent, and follows the paragraph-response requirements (addresses both students' claims with physics-based justification).

Solution 4

(b)(i) Mark scheme

- Bar chart for Scenario 1 (third particle $+Q$ brought from infinity to the bottom-right vertex): draw U_{i1} as a small POSITIVE bar (the electric PE of the A–B pair only, since the third particle is infinitely far away and does not yet interact — take this as the baseline unit, e.g. $+1$ unit) (this bar is given/shaded on the chart). Draw W_1 (work done bringing the $+$Q particle in) as a positive bar equal to twice U_{i1} (Point 1: W_1 positive). Draw U_{f1} as a positive bar equal to $3U_{i1}$ (Point 2: $U_{f1} = 3U_{i1}$), consistent with energy conservation $U_{i1} + W_1 = U_{f1}$ (Point 3: bars satisfy $U_{i1} + W_1 = U_{f1}$, i.e. U_{f1} is the tallest bar, W_1 is the middle bar at twice U_{i1}'s height, all three bars positive).

Solution 4

(b)(ii) Mark scheme

- Bar chart for Scenario 2 (third particle $-Q$ brought from infinity to the bottom-right vertex): U_{i2} is the same given/shaded positive bar as U_{i1} (PE of the A–B pair only, unchanged by which charge is later brought in). Draw U_{f2} as a NEGATIVE bar equal in magnitude to U_{i2}, i.e. $U_{f2} = -U_{i2}$ (Point 1). Draw W_2 (work done bringing the $-Q$ particle in) as a NEGATIVE bar equal to $-2U_{i2}$, so that energy conservation $U_{i2} + W_2 = U_{f2}$ holds (Point 2: W_2 negative and consistent with $U_{i2} + W_2 = U_{f2}$, i.e. U_{f2} is a shallow negative bar of the same magnitude as U_{i2}, and W_2 is a deeper negative bar of twice that magnitude).

Question 3

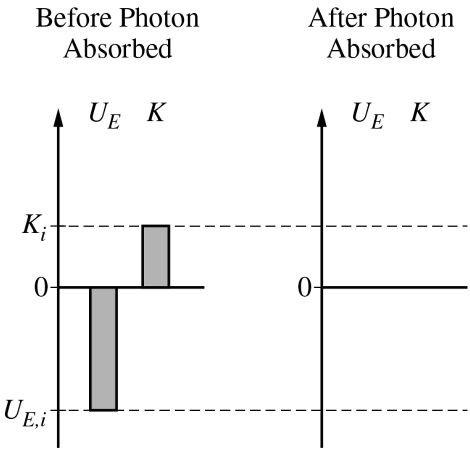
2022 ▪ Q3

[Diagram: A circle representing the electron's circular orbit of radius r around a stationary proton at the center. The electron, labeled with a minus sign, is on the circle at upper left, with an arrow pointing along the circle indicating its direction of motion; a line labeled r connects the electron to the central proton, labeled with a plus sign. Note: Figure not drawn to scale.]

A hydrogen atom can be modeled as an electron in a circular orbit of radius r about a stationary proton, as shown above. The gravitational force between the proton and electron is negligible compared to the electrostatic force between them.

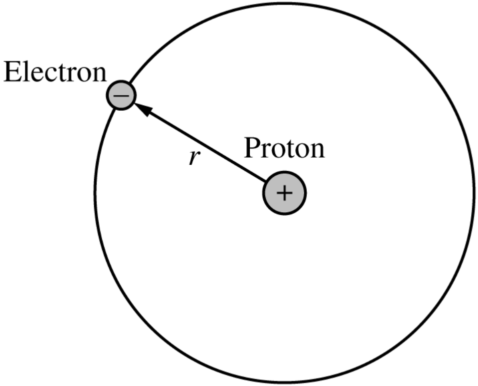
(a) Derive an equation for the speed v of the electron in terms of r and physical constants, as appropriate.

Question 3



Before Photon Absorbed
After Photon Absorbed
U_E
K
U_E
K
K_i
0
$U_{E,i}$
0

Question 3



Note: Figure not drawn to scale.

Question 3

2022 ▪ Q3

[Diagram: A circle representing the electron's circular orbit of radius r around a stationary proton at the center. The electron, labeled with a minus sign, is on the circle at upper left, with an arrow pointing along the circle indicating its direction of motion; a line labeled r connects the electron to the central proton, labeled with a plus sign. Note: Figure not drawn to scale.]

A hydrogen atom can be modeled as an electron in a circular orbit of radius r about a stationary proton, as shown above. The gravitational force between the proton and electron is negligible compared to the electrostatic force between them.

(b) Derive an equation for the total energy of the atom in terms of r and physical constants, as appropriate.

Question 3

2022 ▪ Q3

[Diagram: A circle representing the electron's circular orbit of radius r around a stationary proton at the center. The electron, labeled with a minus sign, is on the circle at upper left, with an arrow pointing along the circle indicating its direction of motion; a line labeled r connects the electron to the central proton, labeled with a plus sign. Note: Figure not drawn to scale.]

A hydrogen atom can be modeled as an electron in a circular orbit of radius r about a stationary proton, as shown above. The gravitational force between the proton and electron is negligible compared to the electrostatic force between them.

(c) When the hydrogen atom absorbs a photon, the electron moves to an orbit with a larger radius and the total energy of the atom increases. Is your equation for the energy derived in part (b) consistent with this description of the model of a hydrogen atom absorbing a photon? Explain why the equation is or is not consistent.

Question 3

2022 ▪ Q3

[Diagram: A circle representing the electron's circular orbit of radius *r* around a stationary proton at the center. The electron, labeled with a minus sign, is on the circle at upper left, with an arrow pointing along the circle indicating its direction of motion; a line labeled *r* connects the electron to the central proton, labeled with a plus sign. Note: Figure not drawn to scale.]

A hydrogen atom can be modeled as an electron in a circular orbit of radius *r* about a stationary proton, as shown above. The gravitational force between the proton and electron is negligible compared to the electrostatic force between them.

(d)(i) Experiments show that a hydrogen atom can absorb a photon of frequency 3.2×10^{15} Hz.

Calculate the energy of a photon with this frequency.

(d)(ii) A student claims that when a hydrogen atom absorbs a photon at this frequency, the energy could be converted into mass, adding an electron to the atom.

Question 3

Calculate the amount of energy needed to create a particle with the mass of an electron and determine whether or not there is sufficient energy gained by the atom to add another electron.

(d)(iii) [Diagram: Two bar charts side by side, titled "Before Photon Absorbed" and "After Photon Absorbed." Each chart has a vertical axis with two bars labeled U_E and K. In the left ("Before") chart, a dashed horizontal line marks a positive level K_i and a dashed horizontal line below zero marks a negative level $U_{E,i}$; the U_E bar extends from 0 down to $U_{E,i}$ (negative), and the K bar extends from 0 up to K_i (positive). The right ("After") chart shows only the zero line, with both bars blank for the student to draw.] The left bar chart in the figure above is complete and represents the initial electric potential energy $U_{E,i}$ of the atom and the initial kinetic energy K_i of the electron before the photon is absorbed. In the space provided on the right, draw a bar chart to

Question 3

represent a possible final electric potential energy of the atom and final kinetic energy of the electron.

Solution 3

(a) Mark scheme

- (1 point) Set the electrostatic (Coulomb) force equal to the net (centripetal) force on the electron: $\Sigma F = ma \Rightarrow F_E = F_C \Rightarrow \frac{kq^2}{r^2} = \frac{mv^2}{r}$ (an incorrect mass label is still acceptable for this point). (1 point) Use these expressions, with mass and charge consistently referring to the electron (m_e, e; q_e/q_p notation also acceptable), to solve for speed: $\frac{ke^2}{r^2} = \frac{m_e v^2}{r} \Rightarrow v^2 = \frac{ke^2}{m_e r} \Rightarrow v = \sqrt{\frac{ke^2}{m_e r}}$.

Solution 3

(b) Mark scheme

- (1 point) Electric potential energy, using charges consistent with part (a): $U = -\dfrac{ke^2}{r}$. (1 point) Kinetic energy of the electron, substituting the speed from part (a) to eliminate v: $K = \frac{1}{2}m_e v^2 = \frac{1}{2}m_e\left(\dfrac{ke^2}{m_e r}\right) = \frac{1}{2}\dfrac{ke^2}{r}$. (1 point) Indicate the total energy of the atom is the sum of potential and kinetic energy: $E = U + K = -\dfrac{ke^2}{r} + \frac{1}{2}\dfrac{ke^2}{r} = -\dfrac{ke^2}{2r}$.

Solution 3

(c) Mark scheme

- (1 point) Correctly indicate that the equation from part (b), $E = -\dfrac{ke^2}{2r}$, is consistent with the given description, with an explanation that references that equation. (1 point) Correctly address the functional dependence: as the orbital radius r increases, E becomes less negative — i.e. the total energy increases — which matches the description that absorbing a photon increases both the orbit radius and the atom's total energy. Model response: "The equation from part (b) indicates that as the radius increases, the total energy of the atom becomes less negative, which is an increase in the total energy. This is consistent with the given description of the atom absorbing a photon."

Solution 3

(d)(i)

Mark scheme

- $E = hf = (6.63 \times 10^{-34}\ \mathsf{J \cdot s})(3.2 \times 10^{15}\ \mathsf{Hz}) = 2.12 \times 10^{-18}\ \mathsf{J}$.

Solution 3

(d)(ii)

Mark scheme

- (1 point) Mass-energy of an electron: $E = mc^2 = (9.11 \times 10^{-31}$ kg$)(3.00 \times 10^8$ m/s$)^2 = 8.20 \times 10^{-14}$ J. (1 point) Compare this to the photon energy from part (d)(i) (2.12×10^{-18} J), in matching units (J to J, or eV to eV), and correctly conclude the photon energy is negligible compared to the electron's mass-energy — so there is NOT enough energy to create a new electron (the student's claim is incorrect). An answer consistent with the student's own (d)(i)/(d)(ii) numbers also earns this point.

Solution 3

(d)(iii)

Mark scheme

- On the "After Photon Absorbed" bar chart relative to "Before": (1 point) the electric potential energy bar U_E is drawn smaller in magnitude but still negative (shorter than $U_{E,i}$, still below zero). (1 point) the kinetic energy bar K is drawn smaller in magnitude but still positive (shorter than K_i, still above zero). This reflects that as r increases, both $|U| = ke^2/r$ and $K = \frac{1}{2}ke^2/r$ decrease in magnitude while U stays negative and K stays positive.

Question 1

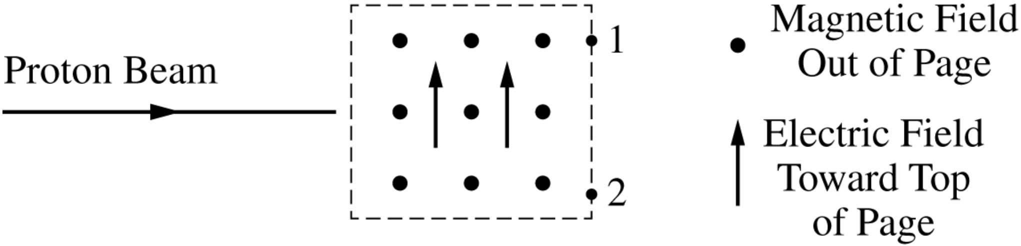
2019 ▪ Q1

The figure above shows a particle with positive charge $+Q$ traveling with a constant speed v_0 to the right and in the plane of the page. The particle is approaching a region, shown by the dashed box, that contains a constant uniform field. The effects of gravity are negligible.
[Figure: A diagram labeled "Region of Field" shows a dashed square box on the right. To the left, a dot labeled "Particle" with "$+Q$" beneath it has an arrow labeled v_0 pointing right toward the box.]
(a)(i) On the figure below, draw a possible path of the particle in the region if the region contains only an electric field directed toward the bottom of the page.
[Figure labeled "Electric Field": a dashed square box on the right; to the left, a dot with an arrow pointing right toward the box.]

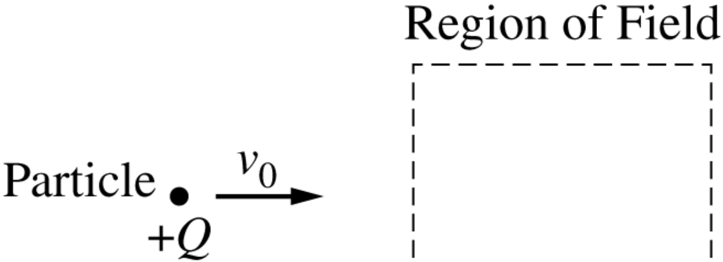
Question 1

(a)(ii) On the figure below, draw a possible path of the particle in the region if the region contains only a magnetic field directed out of the page.
[Figure labeled “Magnetic Field”: a dashed square box on the right; to the left, a dot with an arrow pointing right toward the box.]
(a)(iii) For which of the previous situations is the motion more similar to that of a projectile in only a gravitational field near Earth’s surface, and why?

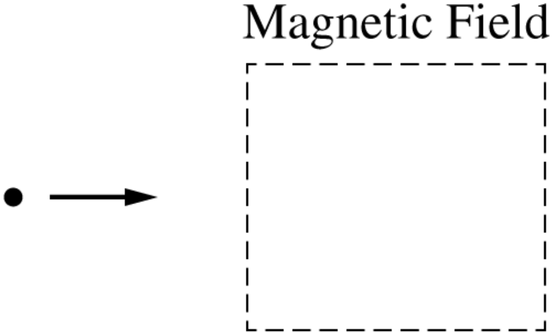
Question 1


Proton Beam
1
2
Magnetic Field
Out of Page
Electric Field
Toward Top
of Page

Question 1



Question 1



Question 1

2019 ▪ Q1

The figure above shows a particle with positive charge $+Q$ traveling with a constant speed v_0 to the right and in the plane of the page. The particle is approaching a region, shown by the dashed box, that contains a constant uniform field. The effects of gravity are negligible.

[Figure: A diagram labeled "Region of Field" shows a dashed square box on the right. To the left, a dot labeled "Particle" with "$+Q$" beneath it has an arrow labeled v_0 pointing right toward the box.]

(b) Another region of space contains an electric field directed toward the top of the page and a magnetic field directed out of the page. Both fields are constant and uniform. A horizontal beam of protons with a variety of speeds enters the region, as shown above. Protons exit the region at a variety of locations, including points 1 and 2 shown on the figure. In a coherent, paragraph-length response, explain why some

Question 1

protons exit the region at point 1 and others exit at point 2. Use physics principles to explain your reasoning.

[Figure: “Proton Beam” with an arrow entering a dashed square box from the left. Inside the box, rows of dots (field out of page) with two upward arrows in the middle (electric field direction inside region); the right edge of the box has two exit points marked “1” (upper) and “2” (lower). To the right of the box, a legend shows a dot labeled “Magnetic Field Out of Page” and an upward arrow labeled “Electric Field Toward Top of Page”.]

Solution 1

(a)(i)

Mark scheme

- The particle's path is a curved (parabola-like) trajectory: it starts moving horizontally to the right with no leftward velocity component, then deflects toward the bottom of the page and reaches an edge of the region — analogous to projectile motion, since the electric force $\vec{F} = q\vec{E}$ on the positive charge is constant and directed toward the bottom of the page. Points: 1 pt for a curved path that is initially horizontal and does not have a component of velocity toward the left; 1 pt for a path that deflects toward the bottom of the page and reaches an edge of the region.

Solution 1

(a)(ii) Mark scheme

- For the positive charge moving right through a field directed out of the page, the magnetic force $\vec{F} = q\vec{v} \times \vec{B}$ initially points toward the bottom of the page and continuously changes direction (always perpendicular to velocity), curving the particle along a circular arc that deflects toward the bottom of the page and exits through an edge of the region, without completing more than a semicircle. Points: 1 pt for a curved path that is initially horizontal, is not more than a semicircle, and reaches an edge of the region; 1 pt for a path that deflects toward the bottom of the page.

Solution 1

(a)(iii)

Mark scheme

- The motion in the electric-field case (part (a)(i)) is more similar to projectile motion near Earth's surface, because the electric force (and thus acceleration) on the particle is constant in magnitude and direction — always directed toward the bottom of the page — just as gravity produces a constant downward acceleration on a projectile; both produce a parabolic path. (The magnetic force, by contrast, continually changes direction since it depends on velocity, so it does not give this parabolic analogy.)

Solution 1

(b) Mark scheme

- In this region the electric force on a proton ($F_E = qE$, directed toward the top of the page, since E points that way) and the magnetic force ($F_B = qvB$, directed toward the bottom of the page for a proton moving right through a field out of the page) initially act in opposite directions. F_E does not depend on the proton's speed, but F_B increases with speed. For one particular speed the two forces balance and the proton passes through undeflected; a slower proton has a smaller magnetic force than electric force, so the net force is upward and it deflects upward, exiting at point 1; a faster proton has a larger magnetic force, so the net force is downward and it deflects downward, exiting at point 2. Thus slower protons exit the region at point 1 and faster protons exit at point 2, because the

Solution 1

different net force (sum of the two field forces) produces different paths. Scoring (1 pt each): (1) initially the electric and magnetic forces act in opposite directions; (2) the magnetic force is affected by speed but the electric force is not; (3) different paths occur as a result of the addition (sum) of the forces; (4) slower protons exit higher at point 1 and faster protons exit lower at point 2; (5) a logical, relevant, internally consistent paragraph-length argument that addresses the question using physics principles.

Question 1

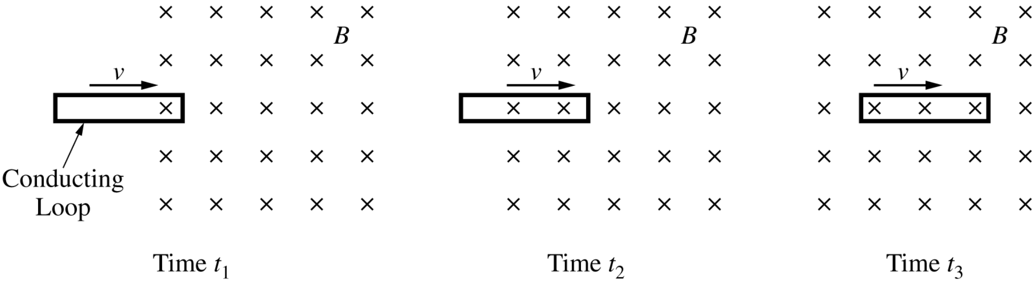
2018 ▪ Q1

The figures above show a rectangular conducting loop at three instants in time. The loop moves at a constant speed v into and through a region of constant, uniform magnetic field B directed into the page. The magnetic field is zero outside the region. [Three diagrams, each showing a grid of "$\times$" symbols (magnetic field B into the page) with a rectangular conducting loop moving to the right with velocity v. "Time t_1": the loop is entering the field region from the left, with its right edge just inside the field and its left edge outside the field (only partially inside the $\times$'s). "Time t_2": the loop is fully inside the field region, entirely surrounded by $\times$'s. "Time t_3": the loop is exiting the field region on the right side, with its left edge inside the field ($\times$'s) and its right edge outside the field (no $\times$'s). Label "Conducting Loop" points to the rectangle at Time t_1.]

Question 1

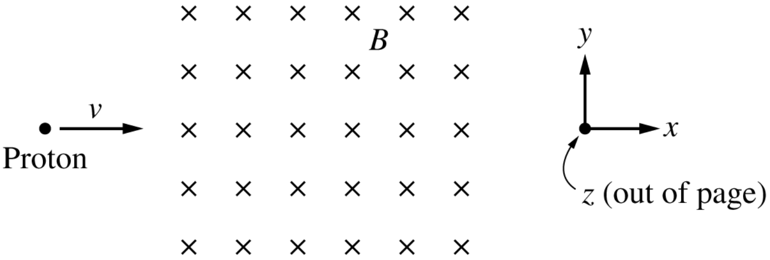
(a) In a coherent paragraph-length response, compare the magnitude and direction of the current at times t_1, t_2, and t_3. Include an explanation of why there is or is not a current and the direction of the current if one is present. Use fundamental physics concepts and principles in your explanation.

Question 1

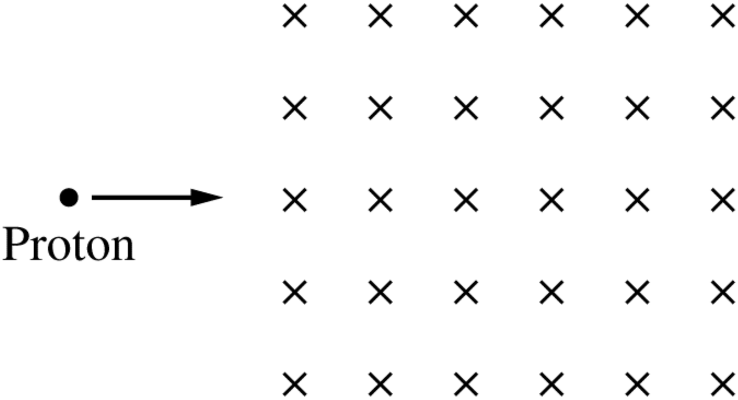


Question 1

of gravity are negligible.



Question 1



Question 1

2018 ▪ Q1

The figures above show a rectangular conducting loop at three instants in time. The loop moves at a constant speed v into and through a region of constant, uniform magnetic field B directed into the page. The magnetic field is zero outside the region.

[Three diagrams, each showing a grid of "$\times$" symbols (magnetic field B into the page) with a rectangular conducting loop moving to the right with velocity v. "Time t_1": the loop is entering the field region from the left, with its right edge just inside the field and its left edge outside the field (only partially inside the $\times$'s). "Time t_2": the loop is fully inside the field region, entirely surrounded by $\times$'s. "Time t_3": the loop is exiting the field region on the right side, with its left edge inside the field ($\times$'s) and its right edge outside the field (no $\times$'s). Label "Conducting Loop" points to the rectangle at Time t_1.]

Question 1

(b)(i) The loop is removed. A proton traveling to the right in the plane of the page, as shown below, then enters the region of magnetic field with a speed $v = 3.0 \times 10^5$ m/s. The magnitude of the field is 0.030 T. The effects of gravity are negligible.
[Diagram: a grid of "$\times$" symbols representing magnetic field B into the page. A proton (labeled "Proton") enters from the left moving to the right with velocity v into the field region. A separate coordinate-axis diagram alongside shows x (to the right), y (upward), and z (out of the page).]
Calculate the magnitude of the force on the proton as it enters the field.
(b)(ii) On the figure below, sketch a possible path of the proton as it travels through the magnetic field. Clearly label the path P1.
[Diagram: a grid of "$\times$" symbols (field into the page) with a proton entering from the left moving to the right, labeled "Proton", with velocity v arrow.]

Question 1

(b)(iii) A second proton now enters the magnetic field at the same point and from the same direction but at a greater speed than the first proton. On the figure above, draw the path of the second proton as it travels through the field. Clearly label the path P2.
(b)(iv) Next an electric field is applied in the same region as the magnetic field, such that there is no net force on the first proton as it enters the region. Calculate the magnitude and indicate the direction of the electric field relative to the coordinate system shown in part (b).

Solution 1

(a) Mark scheme

- At t_1 and t_2 the loop is still entering the field region (only part of the loop's area is inside the field), so the flux through the loop is changing at the same constant rate at both instants (loop moves at constant speed v into a uniform field B) — the induced current has equal, nonzero magnitude at t_1 and t_2, and flows in the same direction. By t_3 the loop is entirely inside the field, so the enclosed flux is no longer changing, and there is no current. Current flows only when the flux through the loop is changing — equivalently, only the loop side that is within the field (cutting field lines) has moving charge carriers experiencing an unbalanced magnetic force ($\vec{F} = q\vec{v} \times \vec{B}$) driving current around the loop; the other side is field-free. By Lenz's law (the induced current opposes the increasing into-the-page

Solution 1

flux) or by direct force analysis on the charge carriers in each segment, the induced current flows counter-clockwise. Once the loop is fully inside the field (at t_3), the net EMF around the loop is zero and no current flows. [Scoring: 1 pt equal nonzero same-direction current at t1,t2; 1 pt no current at t3; 1 pt current depends on changing flux/force on charges; 1 pt correct counter-clockwise direction with flux-opposing or force-on-charge-carrier explanation; 1 pt coherent on-topic paragraph structure.]

Solution 1

(b)(i)

Mark scheme

- $F = qvB = (1.6 \times 10^{-19}\ \mathsf{C})(3.0 \times 10^{5}\ \mathsf{m/s})(0.030\ \mathsf{T}) = 1.4 \times 10^{-15}\ \mathsf{N}$.

Solution 1

(b)(ii)

Mark scheme

- The proton follows a circular arc, curving upward (+y direction) from the entry point — consistent with the magnetic force $\vec{F} = q\vec{v} \times \vec{B}$ on a positive charge moving in $+x$ through a field into the page ($-z$), which points in $+y$. Credit requires the arc to be no more than a semicircle and to reach (exit through) the edge of the field region; a path greater than a semicircle, or one that doesn't reach the field's edge, earns no credit.

Solution 1

(b)(iii)

Mark scheme

- Path P2 is a circular arc with a larger radius of curvature than P1 (from $r = mv/(qB)$: greater speed gives a larger radius for the same charge, mass, and field), curving in the same direction (upward) as P1, consistent with the P1 answer in (b)(ii).

Solution 1

(b)(iv)

Mark scheme

- For zero net force, the electric force must exactly cancel the magnetic force on the proton: $qE = qvB \Rightarrow E = vB = (3.0 \times 10^5 \text{ m/s})(0.030 \text{ T}) = 9000 \text{ N/C}$. Direction: the electric field must point opposite to the magnetic force direction used in (b)(ii) — since the magnetic force on the proton (moving in $+x$ through B into the page) points in $+y$ (consistent with the upward-curving path), the electric field must point in the $-y$ direction (toward the bottom of the page), so the electric force on the positive proton ($q\vec{E}$) points in $-y$ and cancels the magnetic force.

Question 4

2017 ▪ Q4

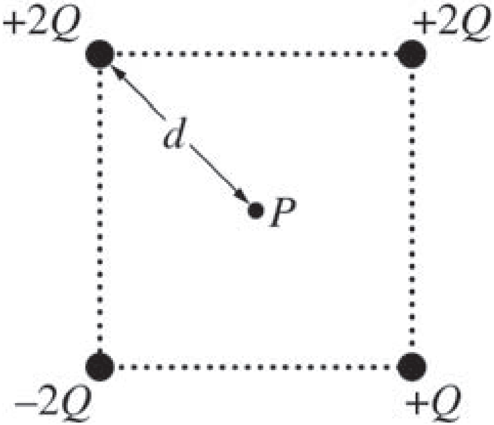
[Figure: A square with a charged object at each corner: top-left corner $+2Q$, top-right corner $+Q$, bottom-left corner $-2Q$, bottom-right corner $+2Q$. Point P is at the center of the square, with a dotted line segment of length d drawn from the top-left corner ($+2Q$) to point P.]

The figure above represents four objects, with charges as shown, that are held in place at the corners of a square. Point P is at the center of the square, a distance d from each of the objects. Express all algebraic answers to the following in terms of Q, d, and physical constants.

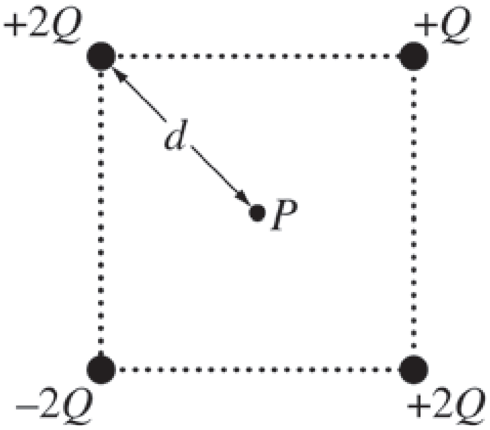
(a) On the dot below, draw an arrow that represents the direction of the net electric force exerted on the object with charge $+Q$ by the other three objects.

[Figure: A dot labeled $+Q$ at the intersection of a horizontal dashed line and a vertical dashed line, for the student to draw a force-direction arrow from the dot.]

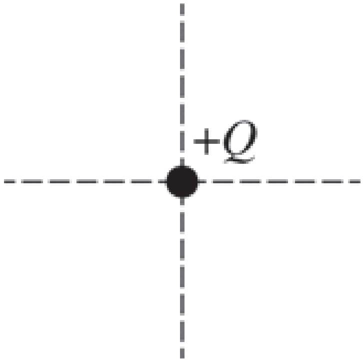
Question 4



Question 4



Question 4



Question 4

2017 ▪ Q4

[Figure: A square with a charged object at each corner: top-left corner $+2Q$, top-right corner $+Q$, bottom-left corner $-2Q$, bottom-right corner $+2Q$. Point *P* is at the center of the square, with a dotted line segment of length *d* drawn from the top-left corner ($+2Q$) to point *P*.]

The figure above represents four objects, with charges as shown, that are held in place at the corners of a square. Point *P* is at the center of the square, a distance *d* from each of the objects. Express all algebraic answers to the following in terms of *Q*, *d*, and physical constants.

(b)(i) Calculate the magnitude of the electric field at point *P* due to all four objects. On the dot below, draw an arrow to indicate the direction of the net field at point *P*. [Figure, left "Draw Arrow": A dot labeled *P* at the intersection of a horizontal dashed line and a vertical dashed line, for the student to draw a field-direction arrow from the dot. Right "Calculate Electric Field": blank space for the calculation.]

(b)(ii) Calculate the electric potential at point *P* due to all four objects.

Question 4

2017 ▪ Q4

[Figure: A square with a charged object at each corner: top-left corner $+2Q$, top-right corner $+Q$, bottom-left corner $-2Q$, bottom-right corner $+2Q$. Point P is at the center of the square, with a dotted line segment of length d drawn from the top-left corner ($+2Q$) to point P.]

The figure above represents four objects, with charges as shown, that are held in place at the corners of a square. Point P is at the center of the square, a distance d from each of the objects. Express all algebraic answers to the following in terms of Q, d, and physical constants.

(c) In a coherent, paragraph-length response, briefly describe the meaning of electric potential energy and explain qualitatively how electric potential energy can be related to work. Also explain qualitatively how the electric potential energy of the four-object system would change if the $+Q$ and $+2Q$ objects on the right side of the square now switch positions as shown in the figure below. Support your explanation using appropriate physics principles.

Question 4

[Figure: A square with a charged object at each corner, showing the swapped configuration: top-left corner $+2Q$, top-right corner $+2Q$, bottom-left corner $-2Q$, bottom-right corner $+Q$. Point P is at the center of the square, with a dotted line segment of length d drawn from the top-left corner ($+2Q$) to point P.]

Solution 4

(a)

Mark scheme

- Draw an arrow from the $+Q$ object pointing outward, along a diagonal of the square, directed away from the object with charge $-2Q$, with no other arrows drawn. 1 pt total.

Solution 4

(b)(i) Mark scheme

- Find the net electric field at point P (center of the square) due to all four charges. 3 points:
- 1 pt for correctly determining the magnitudes of the field from the individual objects: the fields from the two $+2Q$ objects cancel (may be implicit or explicit in the calculation); for the $-2Q$ object, $E = 2kQ/d^2$; for the $+Q$ object, $E = kQ/d^2$ (where d is the distance from each charge to P).
- 1 pt for correctly adding the individual fields: $E = 3kQ/d^2$.
- 1 pt for showing the correct direction on the diagram: along a diagonal of the square, toward the object with charge $-2Q$.

Solution 4

(b)(ii)

Mark scheme

- Show a correct scalar potential summation at point P:
- $V = (k/d)(+2Q + Q + 2Q - 2Q) = 3kQ/d$.
- 1 pt for showing this correct scalar summation. A final numeric answer is not required, but no credit is given if an incorrect final answer is included.

Solution 4

(c) Mark scheme

- Paragraph-length response on electric potential energy and how it changes when the $+Q$ and $+2Q$ objects on the right side of the square swap positions. 5 points, 1 each for:
- 1) Indicating that electric potential energy is the energy stored in a configuration of charged objects.
- 2) Indicating that the change in potential energy equals the work done by an external force to create a particular configuration.

Solution 4

- 1 Indicating that moving the $+2Q$ object results in an increase in energy, and moving the $+Q$ object results in a decrease in energy — i.e., showing understanding that moving charges of the same sign closer together increases the energy and/or moving charges of opposite sign closer together decreases the energy, with some support such as $U = kqQ/r$ or a description of doing work against/with the forces.
- 4) Indicating that the net result is an increase in energy, with some explanation.
- 5) Giving a logical, relevant, and internally consistent response that addresses the required argument/question and follows the published paragraph-length-response guidelines.

Question 3

2016 ▪ Q3

[Figure: two identical spheres X and Y shown as dots inside a large outer circle, with concentric-style closed curves (isolines of electric potential) drawn around each sphere, the two families of isolines merging into a single outer boundary. Sphere X is on the left, sphere Y is on the right (labeled $\bullet Y$). Around Y there are three nested circles; three labeled points lie on these circles moving outward from Y: point C (innermost, closest to Y), point B (middle), and point A (outermost, on the outer boundary). Around X there are also nested closed curves. The outermost curve encloses both X and Y and is the single outermost isoline shown.]

The dots in the figure above represent two identical spheres, X and Y, that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere Y is positive. The lines are isolines of electric potential, also in the

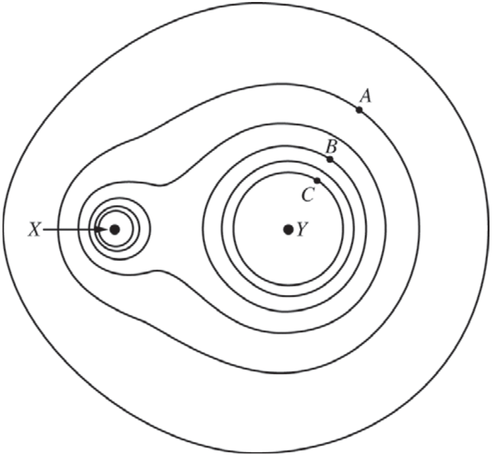
Question 3

plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

(a) Indicate the values of the potentials, including the signs, at the labeled points A and B.

Potential at point A ______________ Potential at point B ______________

Question 3



Question 3

2016 ▪ Q3

[Figure: two identical spheres X and Y shown as dots inside a large outer circle, with concentric-style closed curves (isolines of electric potential) drawn around each sphere, the two families of isolines merging into a single outer boundary. Sphere X is on the left, sphere Y is on the right (labeled $\bullet Y$). Around Y there are three nested circles; three labeled points lie on these circles moving outward from Y: point C (innermost, closest to Y), point B (middle), and point A (outermost, on the outer boundary). Around X there are also nested closed curves. The outermost curve encloses both X and Y and is the single outermost isoline shown.]

The dots in the figure above represent two identical spheres, X and Y, that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere Y is positive. The lines are isolines of electric potential, also in the plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

Question 3

(b)(i) How do the magnitudes and the signs of the charges of the spheres compare? Explain your answer in terms of the isolines of electric potential shown.

(b)(ii) The spheres at points X and Y have masses in the same ratio as the magnitudes of their charges. The isolines of gravitational potential for the spheres have shapes similar to those of the isolines shown. Explain why the two sets of isolines have similar shapes.

Question 3

2016 ▪ Q3

[Figure: two identical spheres X and Y shown as dots inside a large outer circle, with concentric-style closed curves (isolines of electric potential) drawn around each sphere, the two families of isolines merging into a single outer boundary. Sphere X is on the left, sphere Y is on the right (labeled $\bullet Y$). Around Y there are three nested circles; three labeled points lie on these circles moving outward from Y: point C (innermost, closest to Y), point B (middle), and point A (outermost, on the outer boundary). Around X there are also nested closed curves. The outermost curve encloses both X and Y and is the single outermost isoline shown.]

The dots in the figure above represent two identical spheres, X and Y, that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere Y is positive. The lines are isolines of electric potential, also in the plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

Question 3

(c) Let the potentials at the three labeled points be V_A, V_B, and V_C. A proton with charge $+q$ and mass m is released from rest at point B.
Based on your answer to part (b)(ii), briefly describe one similarity and one difference between the electric and gravitational forces exerted on the proton by the system of the two spheres. The similarity and difference you describe must not be ones that generally apply to all forces.

Question 3

2016 ▪ Q3

[Figure: two identical spheres X and Y shown as dots inside a large outer circle, with concentric-style closed curves (isolines of electric potential) drawn around each sphere, the two families of isolines merging into a single outer boundary. Sphere X is on the left, sphere Y is on the right (labeled $\bullet Y$). Around Y there are three nested circles; three labeled points lie on these circles moving outward from Y: point C (innermost, closest to Y), point B (middle), and point A (outermost, on the outer boundary). Around X there are also nested closed curves. The outermost curve encloses both X and Y and is the single outermost isoline shown.]

The dots in the figure above represent two identical spheres, X and Y, that are fixed in place with their centers in the plane of the page. Both spheres are charged, and the charge on sphere Y is positive. The lines are isolines of electric potential, also in the plane of the page, with a potential difference of 10 V between each set of adjacent lines. The absolute value of the electric potential of the outermost line is 50 V.

Question 3

(d)(i) At some time after being released from rest at point B, the proton has moved through a potential difference of magnitude 20 V.
Determine the change in electric potential energy of the proton-spheres system when the proton has moved through the 20 V potential difference. Express your answer symbolically in terms of q, V_A, V_B, V_C, and physical constants, as appropriate.
(d)(ii) As it moved through the 20 V potential difference, the proton was displaced a distance d by the electric force. Determine a symbolic expression for the total work done on the proton by the electric field in terms of the average magnitude E_{avg} of the electric field over that distance.
(d)(iii) Two students are discussing how and why the kinetic energy of the proton would change after it is released.

Question 3

- Student 1 says that if the system is defined as the proton and the spheres, the increase in the proton's kinetic energy is due to a change in the system's potential energy as the proton moves through the 20 V potential difference.
- Student 2 says that if the system is defined as only the proton, the kinetic energy of the proton increases because positive work is done on the proton by the electric field as the proton moves through the 20 V potential difference.

Discuss each student's claims, explaining why each is correct or incorrect.

Solution 3

(a) Mark scheme

- Potential at point A has magnitude 60 V; potential at point B has magnitude 80 V (units not required). Both potentials must carry the SAME sign as each other (either both positive or both negative, consistent with the actual isoline diagram) — this follows from part (b)(i)'s result that the two spheres carry same-sign charge, so no equipotential surface between them is ever at zero and the potential never changes sign across the region. A correct answer states V_A = 60 V and V_B = 80 V with matching (not opposite) signs on the two values — either both written as explicitly positive or both with no negative sign, or both explicitly negative, whichever matches the diagram's isoline pattern.

Solution 3

(b)(i) Mark scheme

- Sphere Y carries a greater magnitude of charge than sphere X: the nearest equipotential line of the same value is farther from Y than it is from X, which indicates Y produces a given potential value over a larger distance, i.e., Y has the larger charge magnitude. The two spheres X and Y must have the SAME sign of charge: the isolines show no zero-potential line anywhere between the spheres, meaning the potentials produced by the two charges never cancel between them — this is only possible if both charges are the same sign (equivalently: the electric field vectors, which are perpendicular to the equipotentials, show a pattern consistent with two same-sign sources). Full credit needs (1) correctly comparing

Solution 3

the charge magnitudes of X and Y with a valid isoline-based explanation and (2) correctly identifying that X and Y are the same sign with a valid explanation.

Solution 3

(b)(ii) Mark scheme

- Gravitational potential and electric potential both fall off with distance in the same mathematical ($1/r$) way, and both depend directly on the strength of their respective source (mass for gravity, charge for electricity). Since the masses of the two spheres are given to be in the same ratio as the magnitudes of their charges, the relative 'strength' of each sphere as a gravitational source matches its relative strength as an electric source. Because the sources have the same relative strengths and the same $1/r$ potential dependence on distance, the resulting isoline patterns (shapes) for gravitational potential match those for electric potential.

Solution 3

(c) Mark scheme

- Similarity (not true of all forces): both the electric force and the gravitational force between the proton and the sphere system have the same inverse-square (1/r^2) dependence on distance. Difference (not true of all forces): the proton has the same sign of charge as the two spheres (established in part (b)(i)), so the electric force on the proton is repulsive; gravity, however, is always attractive. Therefore the electric and gravitational forces on the proton point in opposite directions (an alternative acceptable difference: the two forces differ in magnitude for these objects). Full credit needs one valid non-generic similarity and one valid non-generic difference.

Solution 3

(d)(i)

Mark scheme

- $\Delta U\_E = q\Delta V$. The proton moves from point B toward point A through the 20 V potential difference, so $\Delta V = V\_A - V\_B$ (given as 20 V in magnitude). Symbolically: $\Delta U = q(V\_A - V\_B)$. Full credit needs (1) an attempt to apply $\Delta U\_E = q\Delta V$ using the given symbolic variables and (2) arriving at the correct symbolic result $\Delta U = q(V\_A - V\_B)$ — using numeric values for the potentials instead of symbols earns no credit for this part.

Solution 3

(d)(ii)

Mark scheme

- Work done by the electric field: $W = F\_avg \cdot d$, where the average force on the proton is $F\_avg = qE\_avg$. So $W = qE\_avg \cdot d$. (Equivalently, using energy: $W = -\Delta U\_E = q\Delta V$, and since $\Delta V = E\_avg \cdot d$ over the displacement, this again gives $W = qE\_avg \cdot d$.) Full credit needs (1) a correct expression for work — $W = Fd$ or $-\Delta U\_E = q\Delta V$ — and (2) a correct expression for F or ΔV in terms of E_avg — $F\_avg = qE\_avg$ or $\Delta V = E\_avg\ d$ (full credit is also awarded for directly writing the correct combined expression $W = qE\_avg\ d$).

Solution 3

(d)(iii) Mark scheme

- Both students are correct. Student 1 is correct: when the system is defined as the proton together with the two spheres, no external forces act on this system, so by conservation of energy the total energy of the system is constant — the increase in the proton's kinetic energy is exactly matched by a decrease in the system's electric potential energy; energy is simply transferred from one form (potential) to another (kinetic) within the system. Student 2 is correct: when the system is defined as only the proton, the two charged spheres (and their electric field) are external to the system, so the electric field does positive work on the proton as it moves through the potential difference, and by the work-energy theorem this positive external work increases the proton's kinetic energy. Full credit needs (1)

Solution 3

indicating Student 1 is correct with a valid discussion of energy transfer within the combined system due to conservation of energy, and (2) indicating Student 2 is correct with a valid discussion that an external force (the spheres' electric field) does positive work on the proton, changing its kinetic energy.

Question 4

2015 ▪ Q4

[Figure: A diagram showing an "Electron Source" (small filled square) at the top, above two horizontal parallel plates (shown as pairs of horizontal line segments with a gap between the left and right portions, indicating a hole at the center of each plate). The top plate and bottom plate are separated by distance d (marked with a vertical double-headed arrow on the left). An electron travels straight down through the hole in the top plate with velocity v_0 (arrow pointing down, at the top plate's central gap), continues down through the gap between the plates, and exits through the hole in the bottom plate with velocity v_f (arrow pointing down, at the bottom plate's central gap). Note: Figure not drawn to scale.]

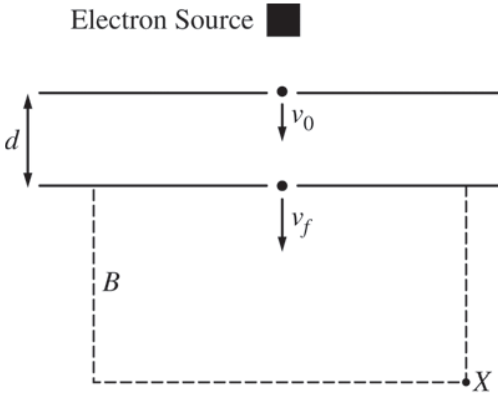
The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \mathrm{m}^2$, separated by a distance $d = 0.010$ m. Each plate has a hole at its center through which electrons can pass. High velocity

Question 4

electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6$ m/s, take 1.49 ns to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6$ m/s.

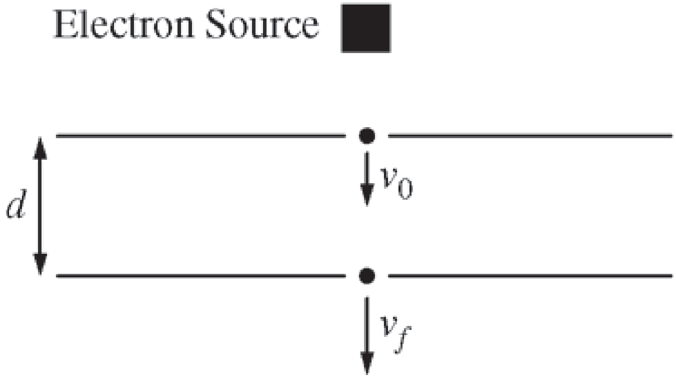
(a) Which of the plates, top or bottom, is negatively charged? Support your answer with a reference to the direction of the electric field between the plates.

Question 4



Note: Figure not drawn to scale.

Question 4



Note: Figure not drawn to scale.

Question 4

2015 ▪ Q4

[Figure: A diagram showing an "Electron Source" (small filled square) at the top, above two horizontal parallel plates (shown as pairs of horizontal line segments with a gap between the left and right portions, indicating a hole at the center of each plate). The top plate and bottom plate are separated by distance d (marked with a vertical double-headed arrow on the left). An electron travels straight down through the hole in the top plate with velocity v_0 (arrow pointing down, at the top plate's central gap), continues down through the gap between the plates, and exits through the hole in the bottom plate with velocity v_f (arrow pointing down, at the bottom plate's central gap). Note: Figure not drawn to scale.]

The apparatus shown in the figure above consists of two oppositely charged parallel conducting plates, each with area $A = 0.25\ \text{m}^2$, separated by a distance $d = 0.010$ m. Each plate has a hole at its center through which electrons can pass. High velocity electrons produced by an electron source enter the top plate with speed $v_0 = 5.40 \times 10^6$ m/s, take 1.49 ns to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6$ m/s.

Question 4

(b) Calculate the magnitude of the electric field between the plates.

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Question 4

(c) Calculate the magnitude of the charge on each plate.

Question 4

2015 ▪ Q4

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Question 4

(d)(i) The electrons leave the bottom plate and enter the region inside the dashed box shown below, which contains a uniform magnetic field of magnitude B that is perpendicular to the page. The electrons then leave the magnetic field at point X.
[Figure: Same electron-source/parallel-plate diagram as above (Electron Source square, top plate, electron traveling down at v_0, bottom plate, electron traveling down at v_f), but now below the bottom plate is a dashed-line box labeled B on its left edge, representing a region of uniform magnetic field perpendicular to the page. The bottom-right corner of the dashed box is labeled point X. Note: Figure not drawn to scale.]
On the figure above, sketch the path of the electrons from the bottom plate to point X. Explain why the path has the shape that you sketched.
(d)(ii) Indicate whether the magnetic field is directed into the page or out of the page. Briefly explain your choice.

Solution 4

(a) Mark scheme

- The top plate is negative. The electron speeds up as it travels from the top plate to the bottom plate ($v_f > v_0$: 8.02×10^6 m/s at exit vs. 5.40×10^6 m/s at entry), so the net electric force on it points downward, in its direction of motion. (1) Relate this force direction to the field direction: since the electron's charge is negative, the field must point opposite to the force on it, i.e. upward, from the bottom plate toward the top plate. (2) Relate the field direction to the plate charges: field lines point away from positive charge and toward negative charge, so a field pointing from the bottom plate toward the top plate means the bottom plate is positive and the top plate is negative. No credit for stating 'the top plate

Solution 4

is negative' without this two-step explanation (force-to-field, then field-to-charge-sign).

Solution 4

(b) Mark scheme

- Two equally-creditable 4-step derivations, both arriving at $E = 10{,}000$ N/C. KINEMATIC ROUTE: (1) find the electron's acceleration between the plates, $a = (v_f - v_i)/t$; (2) apply Newton's second law for the force needed, $F = ma = m(v_f - v_i)/t$; (3) set the electric force equal to this, $eE = F$; (4) solve for E and substitute: $E = \dfrac{m(v_f - v_i)}{et} = \dfrac{(9.11 \times 10^{-31}\ \text{kg})(8.02 \times 10^{6} - 5.40 \times 10^{6}\ \text{m/s})}{(1.6 \times 10^{-19}\ \text{C})(1.49 \times 10^{-9}\ \text{s})} = 10{,}000$ N/C. ENERGY ROUTE: (1) apply conservation of energy, $\Delta K = \Delta U$; (2) use $\Delta U = e\Delta V$, giving $\frac{1}{2}m_e(v_f^2 - v_i^2) = e\Delta V$; (3) relate potential difference to field and plate separation,

Solution 4

$\Delta V = Ed$, giving $\frac{1}{2}m_e(v_f^2 - v_i^2) = eEd$; (4) solve for E and substitute (plate separation d = 0.010 m): $E = \dfrac{m_e(v_f^2 - v_i^2)}{2ed} = \dfrac{(9.11 \times 10^{-31})[(8.02 \times 10^6)^2 - (5.40 \times 10^6)^2]}{2(1.6 \times 10^{-19}\ \mathrm{C})(0.010\ \mathrm{m})} = 10{,}000$ N/C. Each of the four labeled steps in whichever route the student uses earns one point.

Solution 4

(c)

Mark scheme

- Use the parallel-plate relation $E = Q/(\varepsilon_0 A)$, rearranged to $Q = \varepsilon_0 AE$, and correctly substitute the known values (plate area $A = 0.25$ m^2, $E = 10{,}000$ N/C from part (b)):
  $Q = (8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2)(0.25\ \text{m}^2)(10{,}000\ \text{N/C}) = 2.2 \times 10^{-8}$ C. This is the magnitude of the charge on each plate.

Solution 4

(d)(i)

Mark scheme

- Draw a reasonably circular arc from the point where the electron leaves the bottom plate to point X (no penalty for exactly where the path starts relative to the arrow tip) (1 point). Explain that the magnetic force on a moving charge is always perpendicular to its velocity ($\vec{F} = q\vec{v} \times \vec{B}$), so as the electron moves, this force continuously acts perpendicular to the instantaneous velocity — a centripetal-type force that continuously turns the velocity direction without changing speed, producing a curved, circular path from the bottom plate to X (1 point).

Solution 4

(d)(ii) Mark scheme

- The magnetic field points out of the page. For the electron to reach point X, the magnetic field must exert a centripetal force on the electron directed toward the top-right corner of the dashed box (curving its path toward X). Using the right-hand rule for a positive charge moving with the electron's velocity would give a force in one rotational sense; since the electron is negatively charged, the actual force (and hence the field needed to produce it) is reversed from that positive-charge result (equivalently, apply the left-hand rule directly for the negative charge). Working through the rule with the electron's actual velocity and the required centripetal direction shows the field must point out of the page. No credit for stating the field direction without this explanation; credit can be earned

Solution 4

for a correct analysis at any individual point along the path, not just the entry point.