Past-paper walk-through

Electric Potential Energy ▪ 10.4

eXercise

Questions in this set

- 2026 Q4
- 2024 Q4
- 2023 Q4
- 2022 Q3
- 2017 Q4
- 2016 Q3

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

2026 ▪ Q4

Equipotential lines for a region with an electric field are shown.
[Figure: Five curved, roughly vertical equipotential lines are drawn, each concave toward the right, labelled from left to right along the top: $-3V_0$ (leftmost, unlabeled at top but visible at the line itself), $-2V_0$, $-V_0$, 0, V_0, $2V_0$. Point S is marked with a dot on the $-3V_0$ line; Point T is marked with a dot on the $2V_0$ line. An arrow at the bottom right labelled "$+x$" indicates the positive x-direction, pointing right (in the direction of increasing potential).]
A small sphere (not shown) with positive charge $+Q$ has initial speed v_S in the $+x$-direction and kinetic energy K_S when the sphere is at Point S. The sphere moves to Point T. The force from the electric field is the only force that is exerted on the sphere as the sphere moves between Points S and T.
The sphere has final speed v_T and kinetic energy K_T when the sphere is at Point T.

Question 4

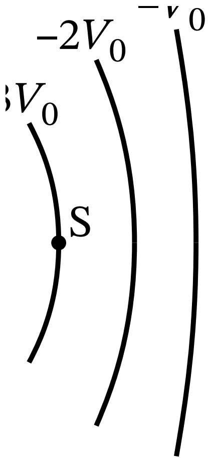
(a) Part A

Indicate whether v_T is greater than, less than, or equal to v_S. Include one of the following relationships in your response.

- $v_T > v_S$ - $v_T < v_S$ - $v_T = v_S$

Justify your answer. Your justification may include expressions/equations but must include conceptual reasoning beyond algebraic solutions.

Question 4



Question 4

2026 ▪ Q4

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A small sphere (not shown) with positive charge $+Q$ has initial speed v_S in the $+x$-direction and kinetic energy K_S when the sphere is at Point S. The sphere moves to Point T. The force from the electric field is the only force that is exerted on the sphere as the sphere moves between Points S and T.

The sphere has final speed v_T and kinetic energy K_T when the sphere is at Point T.

(b) Part B

Question 4

Derive an expression for K_{T} in terms of V_0, Q, K_{S}, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 4

2026 ▪ Q4

Equipotential lines for a region with an electric field are shown.
[Figure: Five curved, roughly vertical equipotential lines are drawn, each concave toward the right, labelled from left to right along the top: $-3V_0$ (leftmost, unlabeled at top but visible at the line itself), $-2V_0$, $-V_0$, 0, V_0, $2V_0$. Point S is marked with a dot on the $-3V_0$ line; Point T is marked with a dot on the $2V_0$ line. An arrow at the bottom right labelled "$+x$" indicates the positive x-direction, pointing right (in the direction of increasing potential).]
A small sphere (not shown) with positive charge $+Q$ has initial speed v_S in the $+x$-direction and kinetic energy K_S when the sphere is at Point S. The sphere moves to Point T. The force from the electric field is the only force that is exerted on the sphere as the sphere moves between Points S and T.

The sphere has final speed v_T and kinetic energy K_T when the sphere is at Point T.

(c) Part C

Question 4

A new, small sphere of the same mass as the original sphere but with negative charge $-Q$ has the same initial speed v_S as the original sphere in the $+x$-direction when the sphere is at Point S. The force from the electric field is the only force that is exerted on the new sphere as the new sphere moves between Points S and T. The new sphere has kinetic energy K_{new} when the new sphere is at Point T.

Indicate whether K_{new} is greater than, less than, or equal to K_T. Include one of the following relationships in your response.

- $K_{new} > K_T$ - $K_{new} < K_T$ - $K_{new} = K_T$

Briefly **justify** your answer by referencing your derivation in part B.

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

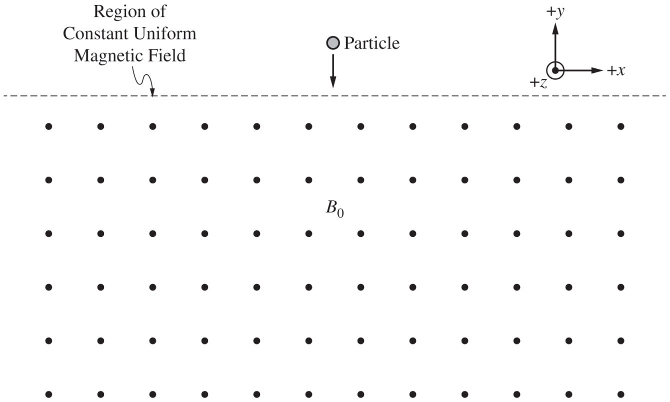

Figure 2

Question 4

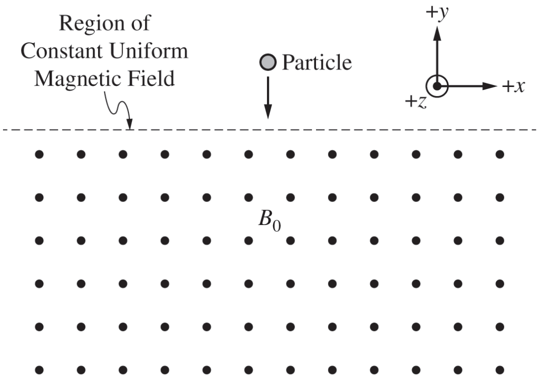

Figure 1

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.

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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.

(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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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.

(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

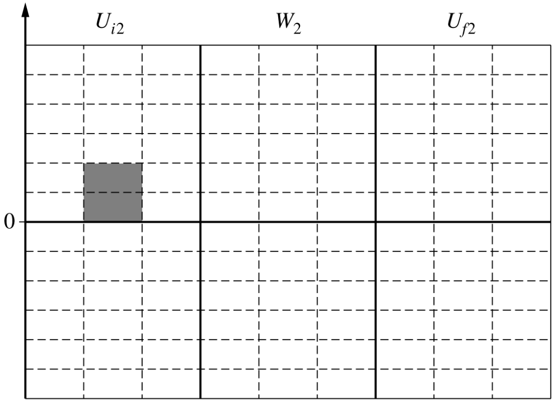
2023 ▪ Q4

(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

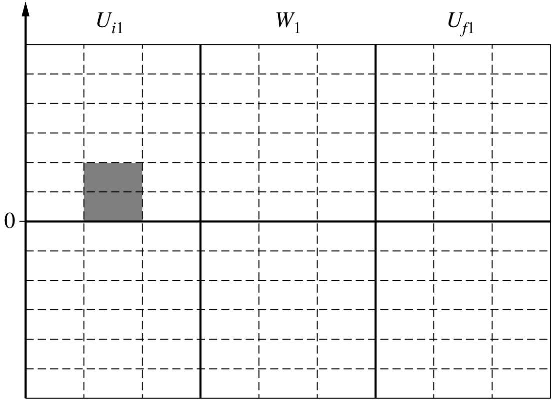
Student Y: "If a particle with positive charge $+2Q$ is placed at the bottom-right vertex, the magnitude of the electric field will be zero at Point P."
Student Z: "To make the value of the electric potential zero at Point P, a particle with negative charge $-Q$ should be placed at the bottom-right vertex."
(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

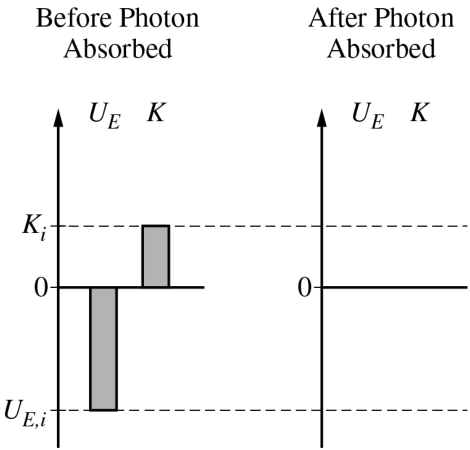
2022 ▪ Q3

[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.]

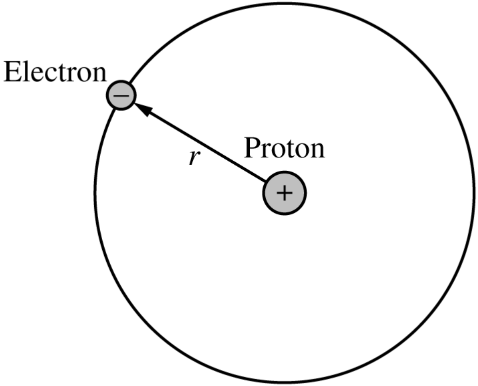
A hydrogen atom can be modeled as an electron in a circular orbit of radius r about a stationary proton, as shown above. The gravitational force between the proton and electron is negligible compared to the electrostatic force between them.

(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: $E = mc^2 = (9.11 \times 10^{-31}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2 = 8.20 \times 10^{-14}$ 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 4

2017 ▪ Q4

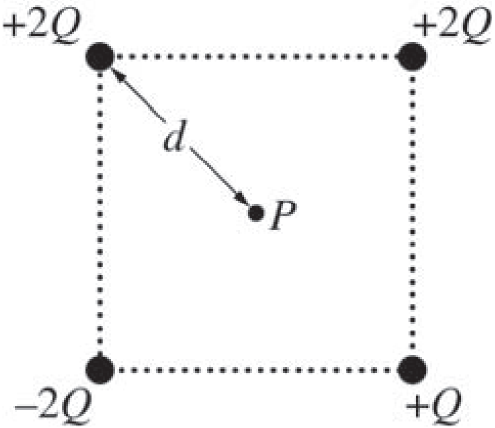
[Figure: A square with a charged object at each corner: top-left corner $+2Q$, top-right corner $+Q$, bottom-left corner $-2Q$, bottom-right corner $+2Q$. Point P is at the center of the square, with a dotted line segment of length d drawn from the top-left corner ($+2Q$) to point P.]

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.

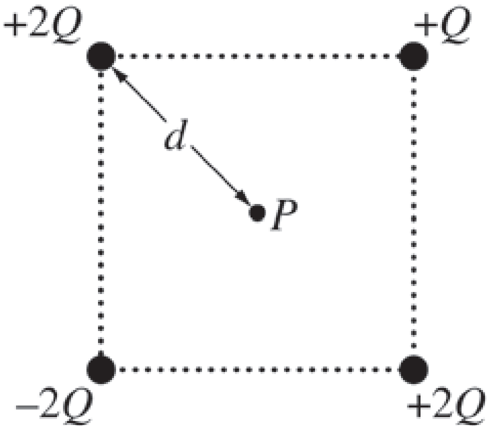
(a) On the dot below, draw an arrow that represents the direction of the net electric force exerted on the object with charge $+Q$ by the other three objects.

[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.]

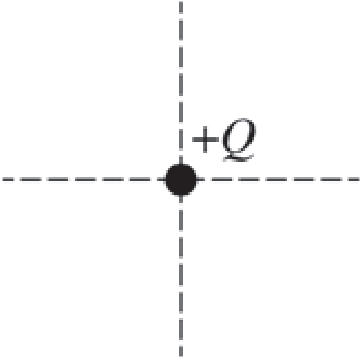
Question 4



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

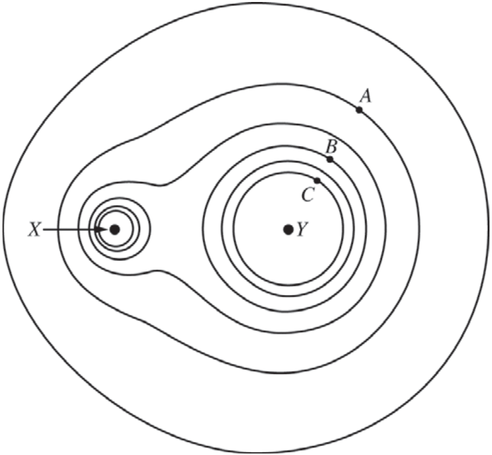
Question 3

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.