

Begin your response to **QUESTION 4** on this page.

4. (10 points, suggested time 20 minutes)

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 $\frac{K_2}{K_1}$.

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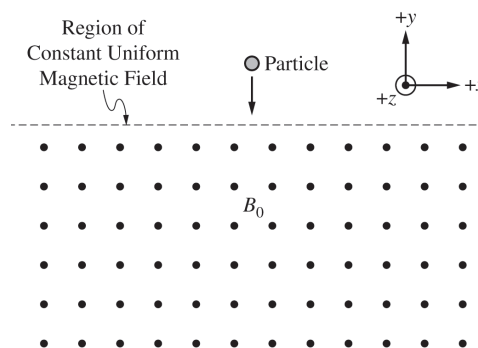
Continue your response to **QUESTION 4** on this page.

Figure 1

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.

(b)

- i. **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.

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

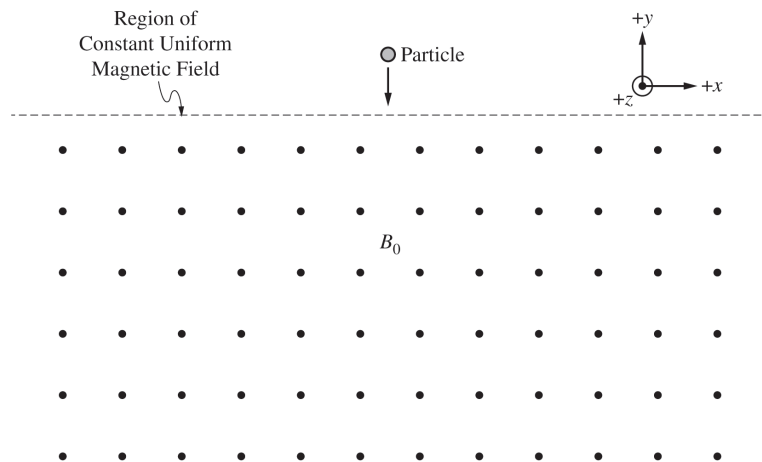


Figure 2

- (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.

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STOP

END OF EXAM

(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 length d , as shown. Point P is located equidistant from each vertex of the triangle.

Students Y and Z discuss the electric field and the electric potential at Point P after a third charged particle is placed at 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.”

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.

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Continue your response to QUESTION 4 on this page.

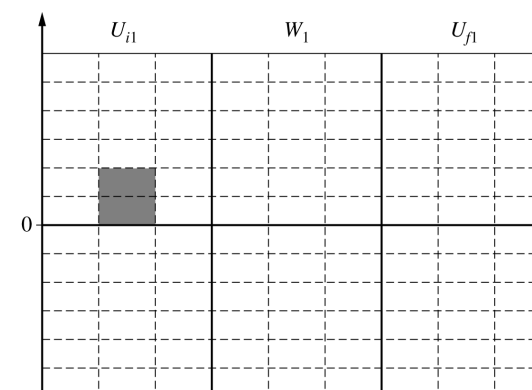
(b) Particles A and B are once again held in place at two vertices of the equilateral triangle. The students want to represent the electric potential energy of a system of particles when a third charged particle is brought from very far away to the bottom-right vertex. Scenarios 1 and 2 are considered.

i. 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.

- 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.



Scenario 1

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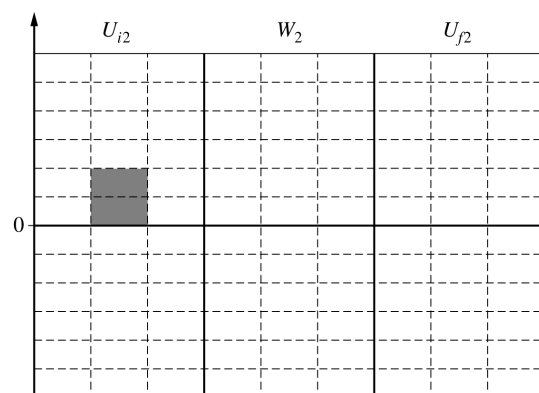
Continue your response to **QUESTION 4** on this page.

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 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.

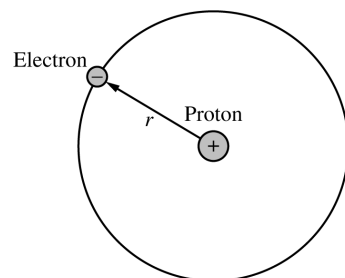
- Draw a bar to represent the work W_2 required to move the particle with negative charge from very far away to the bottom-right vertex.
- Draw another bar to represent the electric potential energy U_{f2} of the system consisting of all three particles when the particle with negative charge is held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

The height of each bar should be proportional to the energy represented. If the quantity is zero, write a “0” in that column.



Scenario 2

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Begin your response to **QUESTION 3** on this page.

Note: Figure not drawn to scale.

(12 points, suggested time 25 minutes)

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.

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

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Continue your response to **QUESTION 3** on this page.

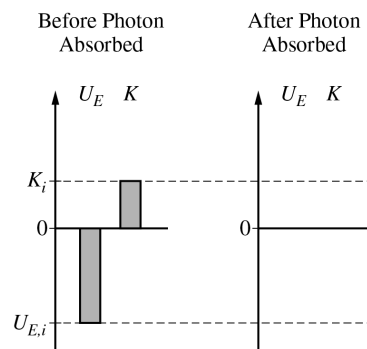
(c) When the hydrogen atom absorbs a photon, the electron moves to an orbit with a larger radius and the total energy of the atom increases. Is your equation for the energy derived in part (b) consistent with this description of the model of a hydrogen atom absorbing a photon? Explain why the equation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

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

i. Calculate the energy of a photon with this frequency.

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. 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.

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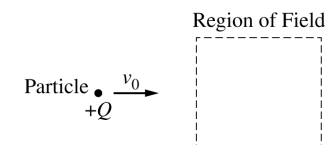
Continue your response to **QUESTION 3** on this page.

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

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PHYSICS 2**Section II****Time—1 hour and 30 minutes****4 Questions**

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.

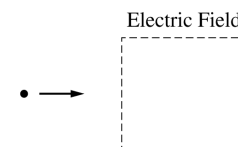


1. (10 points, suggested time 20 minutes)

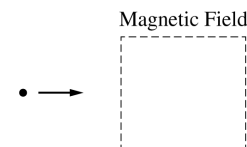
The figure above shows a particle with positive charge $+Q$ traveling with a constant speed v_0 to the right and in the plane of the page. The particle is approaching a region, shown by the dashed box, that contains a constant uniform field. The effects of gravity are negligible.

(a)

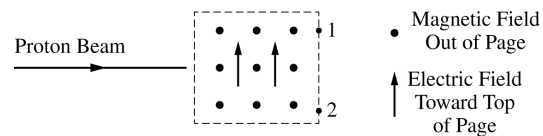
- i. On the figure below, draw a possible path of the particle in the region if the region contains only an electric field directed toward the bottom of the page.



- 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.



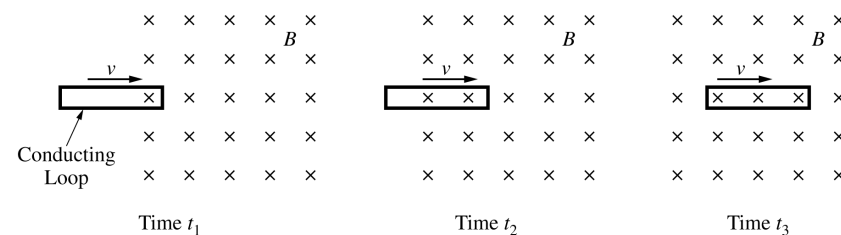
- iii. For which of the previous situations is the motion more similar to that of a projectile in only a gravitational field near Earth's surface, and why?



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

PHYSICS 2**Section II****Time—1 hour and 30 minutes****4 Questions**

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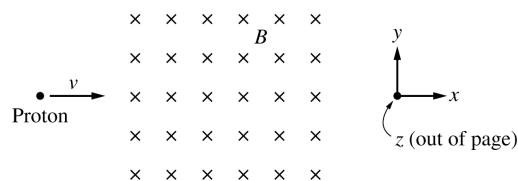


1. (10 points, suggested time 20 minutes)

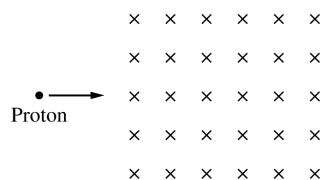
The figures above show a rectangular conducting loop at three instants in time. The loop moves at a constant speed v into and through a region of constant, uniform magnetic field B directed into the page. The magnetic field is zero outside the region.

- (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.

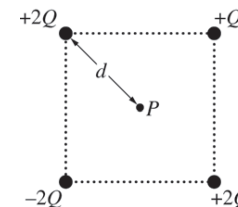
- (b) The loop is removed. A proton traveling to the right in the plane of the page, as shown below, then enters the region of magnetic field with a speed $v = 3.0 \times 10^5$ m/s. The magnitude of the field is 0.030 T. The effects of gravity are negligible.



- Calculate the magnitude of the force on the proton as it enters the field.
- On the figure below, sketch a possible path of the proton as it travels through the magnetic field. Clearly label the path P1.



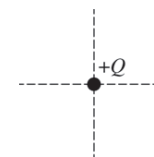
- A second proton now enters the magnetic field at the same point and from the same direction but at a greater speed than the first proton. On the figure above, draw the path of the second proton as it travels through the field. Clearly label the path P2.
- Next an electric field is applied in the same 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).



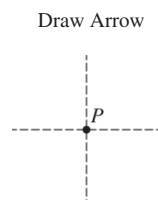
4. (10 points, suggested time 20 minutes)

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.

- 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.



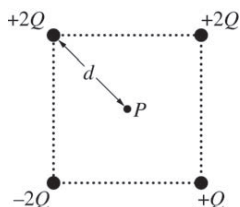
- Calculate the magnitude of the electric field at point P due to all four objects. On the dot below, draw an arrow to indicate the direction of the net field at point P .



Calculate Electric Field

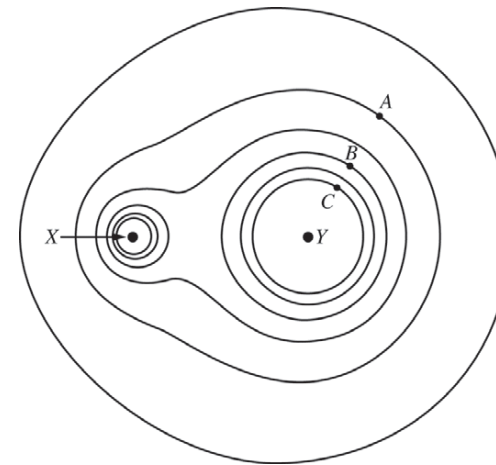
- Calculate the electric potential at point P due to all four objects.

- (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.



STOP

END OF EXAM



3. (12 points, suggested time 25 minutes)

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.

- (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 _____

- (b)

- 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.
- 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.

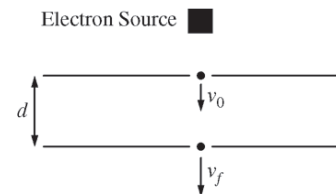
Let the potentials at the three labeled points be V_A , V_B , and V_C . A proton with charge $+q$ and mass m is released from rest at point B .

- (c) 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.

(d) 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.
- 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.
- Two students are discussing how and why the kinetic energy of the proton would change after it is released.
 - 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.



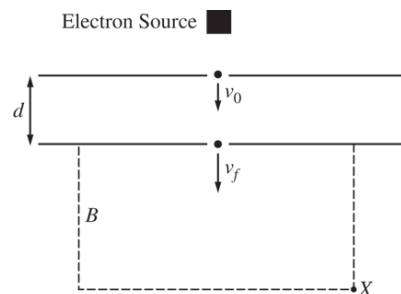
Note: Figure not drawn to scale.

4. (10 points - suggested time 20 minutes)

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 $d = 0.010\text{ m}$. 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 $v_0 = 5.40 \times 10^6\text{ m/s}$, take 1.49 ns to travel between the plates, and leave the bottom plate with speed $v_f = 8.02 \times 10^6\text{ m/s}$.

- 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.
- Calculate the magnitude of the electric field between the plates.
- Calculate the magnitude of the charge on each plate.

- (d) 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 .



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.
- Indicate whether the magnetic field is directed into the page or out of the page. Briefly explain your choice.

STOP

END OF EXAM