2022

AP® CollegeBoard

AP® Physics 2: Algebra-Based

Sample Student Responses and Scoring Commentary

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Free-Response Question 3

- ☑ **Scoring Guidelines**
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Question 3: Quantitative/Qualitative Translation — 12 points

(a) For indicating that the electrostatic force is equal to the net (centripetal) force on the electron, with a correct expression for each — **1 point**

Example Response

$\Sigma\vec{F} = m\vec{a}$

$F_E = F_C$

$\frac{kq^2}{r^2} = \frac{mv^2}{r}$

Scoring Note: An incorrect mass label is acceptable to earn this point.

For using the expressions for the electrostatic and net forces to determine the speed v of the electron (responses must indicate that the mass in the expression represents the mass of the electron and the charge in the expression represents the charge of the electron) — **1 point**

Example Response

$\frac{ke^2}{r^2} = \frac{m_e v^2}{r}$

$v^2 = \frac{ke^2}{m_e r}$

$v = \sqrt{\frac{ke^2}{m_e r}}$

Scoring Note: q_e and q_p are acceptable.

Total for part (a) — **2 points**

(b) For a correct expression for electric potential energy, using charges consistent with charges from part (a) — **1 point**

Example Response

$U = -\frac{ke^2}{r}$

For a correct expression for kinetic energy of the electron, including a substitution consistent with the expression from part (a) to eliminate speed from the equation — **1 point**

Example Response

$K = \frac{1}{2} m_e \left(\frac{ke^2}{m_e r} \right) = \frac{1}{2} \frac{ke^2}{r}$

For indicating that the total energy of the atom is the sum of the electric potential energy and the kinetic energy of the electron **1 point**

Example Response

$$E = U + K$$
$$E = -\frac{ke^2}{r} + \frac{1}{2}\frac{ke^2}{r}$$
$$E = -\frac{ke^2}{2r}$$

Total for part (b) 3 points

(c) For correctly indicating consistency between the equation in part (b) and the description with an explanation that references the equation in part (b) **1 point**

For correctly addressing functional dependence of the energy equation from part (b) to the orbital radius of the electron **1 point**

Example 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.

Total for part (c) 2 points

(d)(i) Fora correct calculation of the energy of the photon **1 point**

Example Response

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

(d)(ii) For a correct calculation of the mass-energy of an electron **1 point**

Example Response

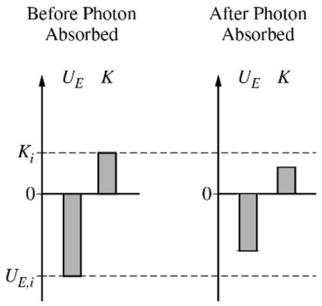
$$E = mc^2$$
$$E = (9.11 \times 10^{-31}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2$$
$$E = 8.20 \times 10^{-14}\ \text{J}$$

For correctly indicating that the photon energy is negligible compared to the mass energy of the electron (or an answer that is consistent with the energies calculated in part (d)(i) and part (d)(ii) **1 point**

Scoring Note: The energy comparison must be from the unit of joules to joules or the unit of electron volts to electron volts in order for this point to be earned.

(d)(iii)	For U smaller in magnitude but still negative	**1 point**
	For K smaller in magnitude but still positive	**1 point**

Example Response



Total for part (d) 5 points

Total for question 3 12 points

Question 3

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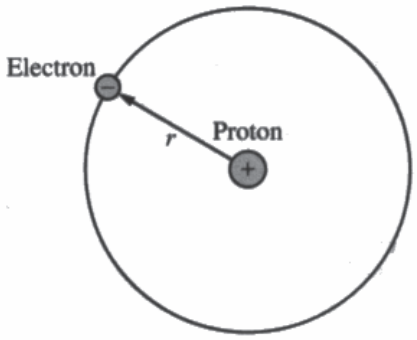

Note: Figure not drawn to scale.

3. (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.

$$F = \frac{k q_E^2}{r^2} = \frac{m_E v^2}{r}$$

$$v = \sqrt{\frac{k q_E^2}{r m_E}}$$

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

$$\sum E = U_E + K_E$$

$$\sum E = \frac{k q_E^2}{r} + \frac{1}{2} m_E v^2$$

$$\sum E = \frac{k q_E^2}{r} + \frac{k q_E^2}{2r} = \frac{3 k q_E^2}{2r}$$

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Question 3

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(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.

No this is inconsistent because a higher radius is this an inverse relationship in the equation, but there an added photon increases both the energy and radius, a direct relationship

(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.

$E_{photon} = hf = (6.63 \times 10^{-34}\ J \cdot s)(3.2 \times 10^{15}\ Hz) = 2.1 \times 10^{-18}\ J$

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.

$E_{(create\ electron)} = m_E c^2 = (9.11 \times 10^{-31})(3.00 \times 10^8)^2 = 8.20 \times 10^{-14}\ J$

only one photon cannot create an electron with its energy. Around 20000 photons would need to be absorbed

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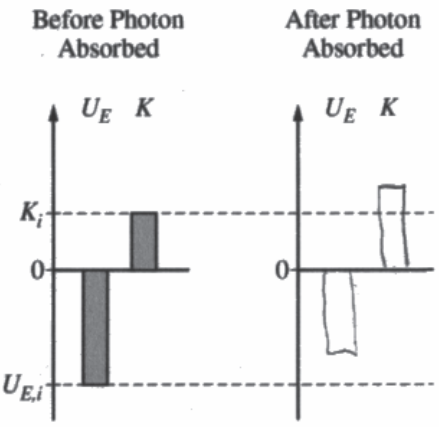

iii. The left bar chart in the figure above is complete and represents the initial electric potential energy $U_{E,i}$ of the atom and the initial kinetic energy K_i of the electron before the photon is absorbed. In the space provided on the right, draw a bar chart to represent a possible final electric potential energy of the atom and final kinetic energy of the electron.

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Question 3

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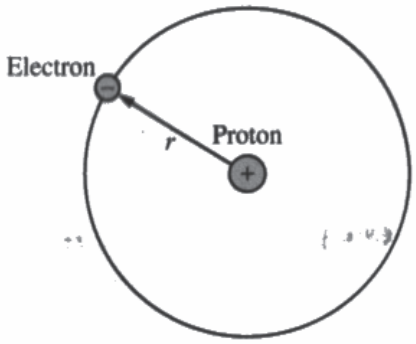

Note: Figure not drawn to scale.

3. (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.

$F_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$

$ma = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$

$\frac{mv^2}{r} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$

$mv^2 = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}$

$a_c = \frac{v^2}{r}$

$v^2 = \frac{1}{4\pi\varepsilon_0}\frac{2(1.60\cdot10^{-19})^2}{r}\frac{1}{9.11\cdot10^{-31}}$

$v = \sqrt{\frac{2(1.60\cdot10^{-19})^2}{4\pi\varepsilon_0 r(9.11\cdot10^{-31})}}$

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

$\Delta U_E = q\Delta V \qquad \Delta V = Ed$

$\Delta U_E = qEd$

$\Delta U_E = q^2 \cdot \frac{1}{4\pi\varepsilon_0}\cdot\frac{1}{r}$

$\Delta U_E = \frac{(1.60\cdot10^{-19})^2}{4\pi\varepsilon_0 r}$

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Question 3

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(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.

This equation is not consistent as the equation illustrates an inverse relationship between radius and energy. Using the equation, energy should decrease as radius increases.

(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.

$E = hf$

$E = 3.2 \cdot 10^{15} \cdot 6.63 \cdot 10^{-34}$

$E = 2.123 \cdot 10^{-18}$ J

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.

$E = mc^2$

$= 9.11 \cdot 10^{-31} \cdot (3 \cdot 10^8)^2$

$= 8.199 \cdot 10^{-14}$ J

There is not sufficient enough energy to add another proton.

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Question 3

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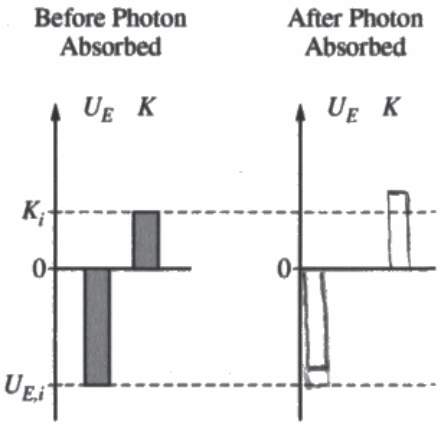

iii. The left bar chart in the figure above is complete and represents the initial electric potential energy $U_{E,i}$ of the atom and the initial kinetic energy K_i of the electron before the photon is absorbed. In the space provided on the right, draw a bar chart to represent a possible final electric potential energy of the atom and final kinetic energy of the electron.

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Question 3

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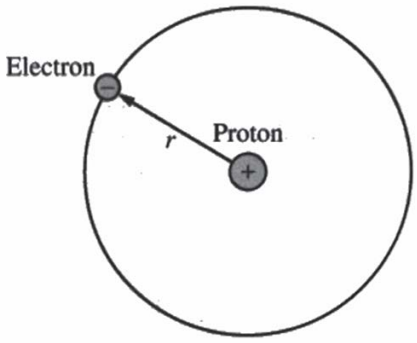

Note: Figure not drawn to scale.

3. (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.

$Q_1 = -1.60 \times 10^{-19}$ C

$Q_2 = -$

$\frac{mv}{r^2}$

$V = \frac{m_{electron}}{r^2}$

F_1

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

$E = m_{nucleus} c^2 + \frac{m_{electron} v_{electron}}{r^2}$

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Question 3

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(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.

Yes, my equation is consistent with this description, as once a photon is absorbed, the kinetic energy and velocity of the electron increase, which also increases the energy of the atom.

(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.

$E = hf$

$E = 6.63 \times 10^{-34}\ J/s\ (3.2 \times 10^{15}\ Hz)$

$= 2.121 \times 10^{-18}\ J$

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.

$E = mc^2$

$E = (9.11 \times 10^{-31})(3 \times 10^8)^2$

$E = 8.199 \times 10^{-14}\ J$

~~Yes, there is suffic~~

No there is not sufficient energy, you need atleast $8.199 \times 10^{-14}\ J$ but only gain $2.121 \times 10^{-18}\ J$.

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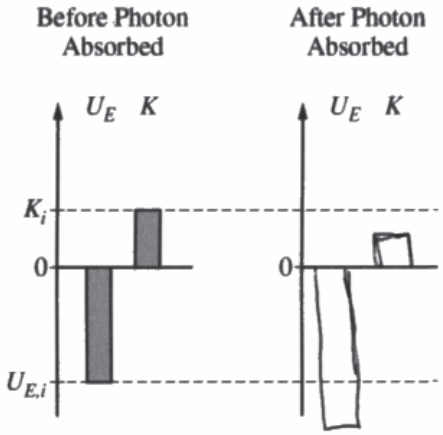

iii. The left bar chart in the figure above is complete and represents the initial electric potential energy $U_{E,i}$ of the atom and the initial kinetic energy K_i of the electron before the photon is absorbed. In the space provided on the right, draw a bar chart to represent a possible final electric potential energy of the atom and final kinetic energy of the electron.

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Question 3

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

Overview

The responses were expected to demonstrate the ability to:

- Derive an expression for the speed of an electron orbiting a proton based on the relationship between the electrostatic force and centripetal acceleration experienced by the electron.
- Derive expressions for kinetic energy of an electron and electric potential energy of an electron-proton system.
- Apply functional dependence in mathematical relationships related to changes in orbital radius and energy.
- Calculate the energy of photons and mass-energy equivalence of electrons, and analyze student claims comparing the values.
- Create representations of potential and kinetic energy (using bar charts) after photon absorption.

Sample: 3A
Score: 10

Part (a) earned 2 points. The first point was earned because the response indicates that the electrostatic force is equal to the net (centripetal) force on the electron, with a correct expression for each. The second point was earned because the response correctly uses the mass of an electron and the charge of an electron and correctly solves the expressions for electrostatic force and net force to determine velocity. Part (b) earned 2 points. The first point was not earned because the response uses the correct variables for electric potential energy but incorrectly labels the expression with a positive value. The second point was earned because the response uses a correct expression for kinetic energy of the electron and includes a correct substitution of velocity from part (a). The third point was earned because the response indicates that the total energy is the sum of both electric potential energy and kinetic energy of the electron. Part (c) earned 2 points. The first point was earned because the response correctly indicates the equation in part (b) is consistent with the explanation in part (c), with an attempted explanation that references the equation in part (b). The second point was earned because the response correctly addresses the functional dependence between radius and energy consistent with the equation from part (b). Part (d)(i) earned 1 point because the response correctly calculates the energy of the photon. Part (d)(ii) earned 2 points. The first point was earned because the response correctly calculates the mass-energy of an electron. The second point was earned because the response uses calculated values to correctly indicate that the energy gained is insufficient to create an additional electron. Part (d)(iii) earned 1 point. The first point was earned because the response correctly indicates a U value that is smaller in magnitude but still negative. The second point was not earned because the response indicates a K value that is still positive but not smaller in magnitude.

Question 3 (continued)

Sample: 3B
Score: 8

Part (a) earned 2 points. The first point was earned because the response indicates that the electrostatic force is equal to the net (centripetal) force on the electron, with a correct expression for each. The second point was earned because the response correctly uses the mass of an electron and the charge of an electron and correctly solves the expressions for electrostatic force and net force to determine velocity. Part (b) earned 0 points. The first point was not earned because the response uses the correct variables for electric potential energy but incorrectly labels the expression with a positive value. The second point was not earned because the response does not include an expression for kinetic energy of the electron. The third point was not earned because the response does not indicate that the total energy is the sum of both electric potential energy and kinetic energy of the electron. Part (c) earned 2 points. The first point was earned because the response indicates that the equation in part (b) is not consistent with the explanation in part (c); however, that indication is correct based on the equation in part (b). The second point was earned because the response correctly addresses the functional dependence between radius and energy consistent with the equation from part (b). Part (d)(i) earned 1 point because the response correctly calculates the energy of the photon. Part (d)(ii) earned 2 points. The first point was earned because the response correctly calculates the mass-energy of an electron. The second point was earned because the response uses calculated values to correctly indicate that the energy gained is insufficient to create an additional electron. Part (d)(iii) earned 1 point. The first point was earned because the response correctly indicates a U value that is smaller in magnitude but still negative. The second point was not earned because the response indicates a K value that is still positive but larger in magnitude.

Sample: 3C
Score: 4

Part (a) earned 0 points. The first point was not earned because the response does not indicate that the electrostatic force is equal to the net (centripetal) force on the electron. The second point was not earned because the response correctly uses the mass of an electron and the charge of an electron to solve for electrostatic force and net force. Part (b) earned 0 points. The first point was not earned because the response does not include an expression for electric potential energy. The second point was not earned because the response does not include an expression for kinetic energy of the electron. The third point was not earned because the response does not indicate that the total energy is the sum of both electric potential energy and kinetic energy of the electron. Part (c) earned 0 points. The first point was not earned because the response does indicate that the equation in part (b) is consistent with the explanation in part (c); however, that indication is incorrect based on the equation in part (b). The second point was not earned because the response incorrectly addresses the functional dependence between radius and energy in the equation from part (b). Part (d)(i) earned 1 point because the response correctly calculates the energy of the photon. Part (d)(ii) earned 2 points. The first point was earned because the response correctly calculates the mass-energy of an electron. The second point was earned because the response uses calculated values to correctly indicate that the energy gained is insufficient to create an additional electron. Part (d)(iii) earned 1 point. The first point was not earned because the response indicates a U value that is not smaller in magnitude. The second point was earned because the response indicates a K value that is still positive and smaller in magnitude.