2021

AP® CollegeBoard

AP® Physics 2: Algebra-Based

Sample Student Responses and Scoring Commentary

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Free Response Question 4

☑ Scoring Guideline

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Question 4: Short Answer Paragraph Argument — 10 points

(a)	For obtaining the correct relationship between electron wavelength and speed	**1 point**
	For correctly substituting values	**1 point**

Example response for part (a)

$\lambda = h/p = h/mv$

$$v = \frac{(6.63 \times 10^{-34}\ \text{J•s})}{(9.11 \times 10^{-31}\ \text{kg})(5.0 \times 10^{-9}\ \text{m})}$$

$v = 1.5 \times 10^{5}\ \text{m/s}$

Total for part (a) — 2 points

(b)	For using $E = mc^2$ to convert mass to energy	**1 point**
	For including the kinetic energy of the electron	**1 point**
	For including the equivalent energy of both particles and correct substitutions, with a speed consistent with the answer to part (a)	**1 point**

Example response for part (b)

$E_{tot} = 2(9.11 \times 10^{-31}\ \text{kg})(3 \times 10^{8}\ \text{m/s})^2 + (1/2)(9.11 \times 10^{-31}\ \text{kg})(1.5 \times 10^{5}\ \text{m/s})^2$

$E_{tot} = 1.6 \times 10^{-13}\ \text{J}$

Total for part (b) — 3 points

(c)	For indicating that the photon has a component of momentum (or velocity) toward the bottom of the page	**1 point**
	For indicating that momentum must be conserved in both the horizontal and vertical directions	**1 point**
	For indicating that energy is conserved	**1 point**
	For indicating that the new photon has less energy, so it has a lower frequency	**1 point**
	For a logical, relevant, and internally consistent argument that addresses the required argument or question asked and follows the guidelines described in the published requirements for the paragraph-length response	**1 point**

Example response for part (c)

In order to conserve momentum in the vertical direction, the photon must have a component of its momentum toward the bottom of the page. If the horizontal component of the momentum of the electron after the collision is less than the initial momentum of the photon, then the photon must move toward the right after the interaction. In order to conserve energy, the frequency of the photon after the collision is less than what it was before the collision because it gave some of its energy to the electron.

Total for part (c) — 5 points

Total for question 4 — 10 points

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

4. (10 points, suggested time 20 minutes)

Light and matter can be modeled as waves or as particles. Some phenomena can be explained using the wave model, and others can be explained using the particle model.

(a) Calculate the speed, in m/s, of an electron that has a wavelength of 5.0 nm.

$\lambda = \frac{h}{p}$ $\quad 5\times10^{-9}\,m = \frac{6.63\times10^{-34}\,J\cdot s}{(9.11\times10^{-31}\,kg)v}$ $\quad p = mv$

$4.555\times10^{-39}v = 6.63\times10^{-34}$

$v = 14554.3\ m/s$

(b) The electron is moving with the speed calculated in part (a) when it collides with a positron that is at rest. A positron is a particle identical to an electron except that its charge is positive. The two particles annihilate each other, producing photons. Calculate the total energy of the photons.

$E = \Delta mc^2$ $\quad \Delta m = 2(9.11\times10^{-31}) = 1.822\times10^{-30}$

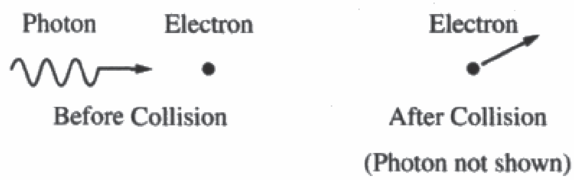
$p_o = p_f$

$14554(m_e) = mv$

$E = 1.822\times10^{-30}(3\times10^8)^2$

$E = 1.64\times10^{-13}\ J$

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



(c) A photon approaches an electron at rest, as shown above on the left, and collides elastically with the electron. After the collision, the electron moves toward the top of the page and to the right, as shown above on the right, at a known speed and angle. In a coherent, paragraph-length response, indicate a possible direction for the photon that exists after the collision and its frequency compared to that of the original photon. Describe the application of physics principles that can be used to determine the direction of motion and frequency of the photon that exists after the collision.

The initial momentum has to equal to final momentum in all directions. The frequency of the original will be greater than the final frequency as energy must be conserved and it depends on frequency. The photon will travel back towards the bottom of the page as to conserve momentum of the vertical axis but the angle will be less than the electron to conserve horizontal momentum.

GO ON TO THE NEXT PAGE.

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

4. (10 points, suggested time 20 minutes)

Light and matter can be modeled as waves or as particles. Some phenomena can be explained using the wave model, and others can be explained using the particle model.

(a) Calculate the speed, in m/s, of an electron that has a wavelength of 5.0 nm.

$p = mv$

$\lambda = \frac{h}{p}$

$\lambda = \frac{h}{mv}$ $\quad$ $v = \frac{h}{\lambda m}$

$V = \frac{6.63 \times 10^{-34}}{(5 \times 10^{-9})(9.11 \times 10^{-31})}$

$V = 150000 \text{ m/s}$

(b) The electron is moving with the speed calculated in part (a) when it collides with a positron that is at rest. A positron is a particle identical to an electron except that its charge is positive. The two particles annihilate each other, producing photons. Calculate the total energy of the photons.

$mv + m(0) = \frac{h}{\lambda}$ $\quad$ $c = f\lambda$

$150{,}000(9.11 \times 10^{-31})$

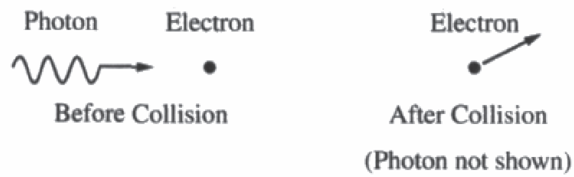
$\lambda = \frac{h}{(1.3665 \times 10^{-25})}$

$\lambda = 4.85 \times 10^{-9}$

$E = hf$ $\quad$ $E = h\left(\frac{c}{\lambda}\right)$

$E = 4.10 \times 10^{-17} \text{ J}$

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



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A possible direction for the photon is down and still to the right. The collision is elastic, meaning that energy is conserved. Thus, the photon must have some downward component of energy as it was horizontal initially and the vertical components of energy must cancel.

The frequency of the photon is modeled by the equation $E = hf$. Plank's constant remains the same. But, some of the energy of the photon initially is transfered to the electron. Thus, E must be lower, and as frequency and Energy are directly proportional, the frequency must decrease.

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

4. (10 points, suggested time 20 minutes)

Light and matter can be modeled as waves or as particles. Some phenomena can be explained using the wave model, and others can be explained using the particle model.

(a) Calculate the speed, in m/s, of an electron that has a wavelength of 5.0 nm.

$\lambda = \frac{v}{f}$

$E = hf$

$1 eV = 4.14 \times 10^{-15}$ eV·s

$f\lambda = v$

$f = 2.415 \times 10^{14}$ Hz

$(2.415 \times 10^{14})(5 \times 10^{-9}) = v$

$\boxed{v = 1.2077 \times 10^{6} \text{ m/s}}$

(b) The electron is moving with the speed calculated in part (a) when it collides with a positron that is at rest. A positron is a particle identical to an electron except that its charge is positive. The two particles annihilate each other, producing photons. Calculate the total energy of the photons.

$mv^2 + mv^2 = p$

$(9.11 \times 10^{-31})(1.2077 \times 10^{6})^2 + 0 = p$

$p = 1.3287 \times 10^{-18}$

$\lambda = \frac{h}{p}$

$\lambda = \frac{6.63 \times 10^{-34}}{1.3287 \times 10^{-18}}$

$\lambda = 4.9897 \times 10^{-16}$

$v = f\lambda$

$3 \times 10^{8} = f(4.9897 \times 10^{-16})$

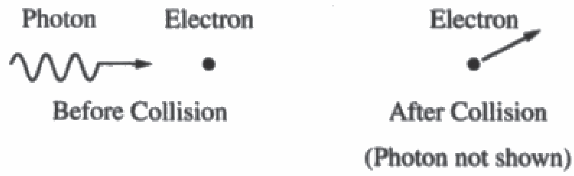
$f = 6.01235 \times 10^{23}$

$E = hf$

$E = (6.63 \times 10^{-34})(6.01235)$

$\boxed{E = 3.986 \times 10^{-10} \text{ J}}$

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



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~~Since the photon and electron collide elastically, we could use conservation of momentum to find the velocity of the electron.~~

Upon colliding with the electron, the photon will lose some energy, this causes its frequency to decrease as a result. As for a direction of the photon's movement after the collision, we would need to use the conservation of momentum and energy. As stated earlier, the photon will give some of its energy to the electron, but it will continue to travel near the speed of light after the collision. The kinetic energy gained by electron will give it some velocity. We can use this velocity and the given direction of its motion to find the direction of the photon after the collision, since the total energy and momentum must be conserved.

Question 4

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

Overview

Responses to this question were expected to demonstrate that changes that occur as a result of interactions are constrained by conservation laws. They were also expected to demonstrate that photons can exhibit particle properties and that material particles can exhibit wave properties. Responses to this question were also expected to demonstrate that mass is part of the energy of a system. They were also expected to make predictions about the internal energy of a system and how that might change. They were also expected to use conservation laws to make predictions about how a system might change and how those changes would manifest in the system.

Sample: P2 Q4 A
Score: 9

Part (a) earned 2 points. One point was earned for obtaining the correct relationship between electron wavelength and speed, and 1 point was earned for correctly substituting values. Part (b) earned two points. One point was earned for using $E=mc^2$ to convert mass to energy, and 1 point was earned for including the equivalent energy of both particles and correct substitutions. No points were earned for not including the kinetic energy of the electron. Part (c) earned 5 points. One point was earned for indicating that the photon has a component of momentum (or velocity) toward the bottom of the page. One point was earned for indicating that momentum must be conserved in both the horizontal and vertical directions. One point was earned for indicating that energy is conserved. One point was earned for indicating that the new photon has less energy, so it has a lower frequency. One point was earned for writing a response that follows the guidelines described in the published requirements for the paragraph-length response.

Sample: P2 Q4 B
Score: 6

Part (a) earned 2 points. One point was earned for obtaining the correct relationship between electron wavelength and speed. One point was earned for correctly substituting values. Part (b) earned no points. There is no attempt at conversion of mass to energy, no mention of the kinetic energy of the electron, and the equivalent energy of both particles is not included. Part (c) earned 4 points. One point was earned for indicating that the photon has a component of momentum (or velocity) toward the bottom of the page. One point was earned for indicating that energy is conserved. One point was earned for indicating that the new photon has less energy, so it has a lower frequency. One point was earned for writing a response that follows the guidelines described in the published requirements for the paragraph-length response. There is no indication that momentum must be conserved in both the horizontal and vertical directions. Only the vertical direction is mentioned.

Question 4 (continued)

Sample: P2 Q4 C
Score: 3

Part (a) earned no points. There is no correct relationship between electron wavelength and speed, and there are no correctly substituted values. Part (b) earned no points. There is no conversion of mass to energy, there is no mention of the kinetic energy of the electron, and the equivalent energy of both particles is not included. Part (c) earned 3 points. There is no indication that the photon has a component of momentum (or velocity) toward the bottom of the page, and there is no indication that momentum must be conserved in both the horizontal and vertical directions. One point was earned for indicating that energy is conserved. One point was earned for indicating that the new photon has less energy, so it has a lower frequency. One point was earned for writing a response that follows the guidelines described in the published requirements for the paragraph-length response.