Question 1: Paragraph-Length Response — 10 points

(a)

For indicating that f_B is least and f_C is greatest — **1 point**

For correctly relating the frequency of a photon to the energy of the photon — **1 point**

For indicating that the kinetic energy or speed of an ejected electron is inversely related to the de Broglie wavelength of the electron — **1 point**

For indicating **one** of the following: — **1 point**

- That a greater photon energy or frequency results in a greater kinetic energy for an ejected electron
- That the lowest photon energy or frequency is below the work function or threshold frequency which results in no ejected electron

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

An electron will be ejected if the incident photon has an energy greater than the work function of the metal. Because no electrons were ejected using f_B, the corresponding photon energy, and, therefore, frequency must be the least. A photon with greater frequency will result in an ejected electron with more kinetic energy; the kinetic energy of an electron is inversely related to the de Broglie wavelength of the electron. Because the de Broglie wavelength of electrons ejected by light of frequency f_A is greater than those ejected by light of frequency f_C, f_A must be less than f_C. Therefore, f_C is the greatest.

Total for part (a) — **5 points**

(b) For **one** of the following: **1 point**

- Correctly relating electron de Broglie wavelength to a correct expression that includes h, m, and v
- Relating kinetic energy to a correct expression that includes momentum and mass

Example Responses

$$\lambda_e = \frac{h}{mv}$$

OR

$$K = \frac{p^2}{2m}$$

For correctly substituting an algebraic expression in terms of λ_e for the electron speed or momentum into a relevant equation for kinetic energy **1 point**

Scoring Note: This point can be earned for substituting a numerical value for electron speed or momentum into a relevant equation for kinetic energy.

Example Responses

$$K = \frac{1}{2}m\left(\frac{h}{m\lambda_e}\right)^2 \quad \textbf{OR} \quad K = \frac{\left(\frac{h}{\lambda_e}\right)^2}{2m}$$

For a correct answer with units **1 point**

Example Response

$K = 5 \times 10^{-19}\ \text{J}$

Example Solution

$$\lambda_e = \frac{h}{p} = \frac{h}{mv}$$

$$v = \frac{h}{m\lambda_e}$$

$$K = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{h}{m\lambda_e}\right)^2$$

$$K = \frac{h^2}{2m\lambda_e^2}$$

$$K = \frac{\left(6.63 \times 10^{-34}\ \text{J} \cdot \text{s}\right)^2}{2\left(9.11 \times 10^{-31}\ \text{kg}\right)\left(6.9 \times 10^{-10}\ \text{m}\right)^2} = 5 \times 10^{-19}\ \text{J}$$

Scoring Note: An answer of $3\ \text{eV}$ also earns the final point.

Total for part (b) **3 points**

(c) For indicating that the work function of Metal 1 is less than the work function of Metal 2 with an attempt at a relevant justification **1 point**

For indicating at least **two** of the following: **1 point**

- The correct relationship between the work function and the difference between hf and $K_{\max}$
- The frequency or energy of the incident photons is the same
- The de Broglie wavelength is inversely related to the energy of the ejected electrons

Example Response

The work function of Metal 1 is less than the work function of Metal 2. When light of the same frequency is incident on both metals, the electron ejected by Metal 1 has a smaller de Broglie wavelength than that of Metal 2, so an electron ejected from Metal 1 has more kinetic energy. The work function is the difference between the photon energy and the maximum kinetic energy. Since the photon energy is the same but the maximum kinetic energy is larger for Metal 1, the difference between the energies, and thus the work function, is smaller for Metal 1.

Total for part (c) 2 points

Total for question 1 10 points

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) For a 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

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

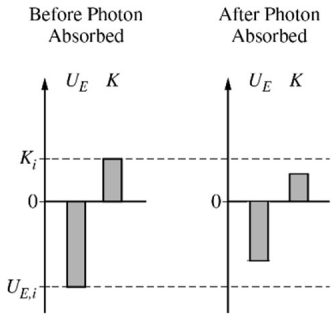
For correctly indicating that the photon energy is negligible compared to the mass energy of the electron (or an answer that is consistent with the energies calculated in part (d)(i) and part (d)(ii)) — **1 point**

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 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)

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

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

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

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)

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

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

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**