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

4. (10 points, suggested time 20 minutes)

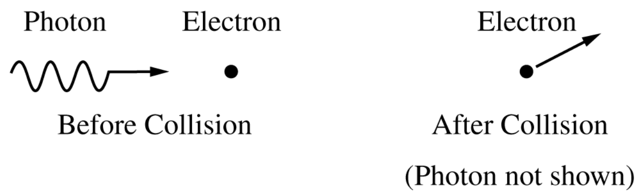
Light and matter can be modeled as waves or as particles. Some phenomena can be explained using the wave model, and others can be explained using the particle model.

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

(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.

GO ON TO THE NEXT PAGE.

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.

GO ON TO THE NEXT PAGE.

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