Section 29.1 The Wave-Particle Duality
Section 29.2 Blackbody Radiation and Planck’s Constant
Section 29.3 Photons and the Photoelectric Effect

1. Light is usually thought of as wave-like in nature and electrons as particle-like. In which one of the following activities does light behave as a particle or does an electron behave as a wave?
   (a) A Young’s double slit experiment is conducted using blue light.
   (b) X-rays are used to examine the crystal structure of sodium chloride.
   (c) Water is heated to its boiling point in a microwave oven.
   (d) An electron enters a parallel plate capacitor and is deflected downward.
   (e) A beam of electrons is diffracted as it passes through a narrow slit.

2. Upon which one of the following parameters does the energy of a photon depend?
   (a) mass  
   (b) amplitude  
   (c) polarization  
   (d) frequency  
   (e) phase relationships

3. For which one of the following problems did Max Planck make contributions that eventually led to the development of the “quantum” hypothesis?
   (a) photoelectric effect  
   (b) uncertainty principle  
   (c) blackbody radiation curves  
   (d) the motion of the earth in the ether  
   (e) the invariance of the speed of light through vacuum

4. Determine the energy of a single photon in a beam of light of wavelength 450 nm.
   (a) 2.0 eV  
   (b) 2.5 eV  
   (c) 2.8 eV  
   (d) 4.2 eV  
   (e) 4.5 eV

5. A laser emits a single, 2.0-ms pulse of light that has a frequency of $2.83 \times 10^{11}$ Hz and a total power of 75 000 W. How many photons are in the pulse?
   (a) $8.0 \times 10^{23}$  
   (b) $1.6 \times 10^{24}$  
   (c) $2.4 \times 10^{25}$  
   (d) $3.2 \times 10^{25}$  
   (e) $4.0 \times 10^{26}$

6. A laser emits a pulse of light with energy $5.0 \times 10^{3}$ J. Determine the number of photons in the pulse if the wavelength of light is 480 nm.
   (a) $5.2 \times 10^{16}$  
   (b) $2.5 \times 10^{19}$  
   (c) $1.2 \times 10^{22}$  
   (d) $3.1 \times 10^{22}$  
   (e) $8.1 \times 10^{22}$

7. A laser emits photons of energy 2.5 eV with a power of $10^{3}$ W. How many photons are emitted in one second?
   (a) $4.0 \times 10^{14}$  
   (b) $2.5 \times 10^{15}$  
   (c) $4.0 \times 10^{18}$  
   (d) $1.0 \times 10^{21}$  
   (e) $2.5 \times 10^{21}$

8. An X-ray generator produces photons with energy 49 600 eV or less. Which one of the following phrases most accurately describes the wavelength of these photons?
   (a) 0.025 nm or longer  
   (b) 0.050 nm or longer  
   (c) 0.75 nm or longer  
   (d) 0.25 nm or shorter  
   (e) 0.75 nm or shorter
9. A laser produces 3.0 W of light at wavelength 600 nm. How many photons per second are produced?
   (a) $7.3 \times 10^{15}$
   (b) $4.2 \times 10^{17}$
   (c) $1.0 \times 10^{17}$
   (d) $3.0 \times 10^{18}$
   (e) $9.1 \times 10^{18}$

10. The graph shows the variation in radiation intensity per unit wavelength versus wavelength for a perfect blackbody at temperature $T$. Complete the following statement: As the blackbody temperature is increased, the peak in intensity of this curve
   (a) will remain constant.
   (b) will be shifted to longer wavelengths and its magnitude will increase.
   (c) will be shifted to shorter wavelengths and its magnitude will increase.
   (d) will be shifted to longer wavelengths and its magnitude will decrease.
   (c) will be shifted to shorter wavelengths and its magnitude will decrease.

11. Complete the following statement: The photon description of light is necessary to explain
   (a) polarization
   (b) photoelectric effect
   (c) diffraction of light
   (d) electron diffraction
   (e) interference of light

12. Which one of the following phrases best describes the term work function?
   (a) the minimum energy required to vaporize a metal
   (b) the work required to place a charged particle on a metal surface
   (c) the minimum energy required to remove electrons from the metal
   (d) the minimum energy required to remove an atom from a metal surface
   (e) the work done by electromagnetic radiation when it hits a metal surface

13. Which one of the following quantities is the same for all photons in vacuum?
   (a) speed
   (b) frequency
   (c) kinetic energy
   (d) wavelength
   (e) total energy

14. Complete the following statement: The term photon applies
   (a) only to X-rays.
   (b) only to visible light.
   (c) to any form of wave motion.
   (d) to any form of particle motion.
   (e) to any form of electromagnetic radiation.

15. Which type of wave motion does not involve photons?
   (a) gamma rays
   (b) microwaves
   (c) radio waves
   (d) infrared radiation
   (e) sound waves

16. Which one of the following statements concerning photons is false?
   (a) Photons have zero mass.
   (b) The rest energy of all photons is zero.
   (c) Photons travel at the speed of light in a vacuum.
   (d) Photons have been brought to rest by applying a strong magnetic field to them.
   (e) The energy of a photon is proportional to its frequency.

17. Photons of what minimum frequency are required to remove electrons from gold?
   Note: The work function for gold is 4.8 eV.
   (a) $7.3 \times 10^{14}$ Hz
   (b) $1.2 \times 10^{15}$ Hz
   (c) $3.8 \times 10^{17}$ Hz
   (d) $6.5 \times 10^{15}$ Hz
   (e) $4.6 \times 10^{14}$ Hz
18. Photons of energy 6 eV cause electrons to be emitted from a certain metal with a maximum kinetic energy of 2 eV. If photons of twice the wavelength are incident on this metal which one of the following statements is true?
   (a) No electrons will be emitted.
   (b) Electrons will be emitted with a maximum kinetic energy of 4 eV.
   (c) Electrons will be emitted with a maximum kinetic energy of 8 eV.
   (d) Electrons will be emitted with a maximum kinetic energy of 10 eV.
   (e) Electrons will be emitted with a maximum kinetic energy of 20 eV.

19. White light consisting of wavelengths $380 \text{ nm} \leq \lambda \leq 750 \text{ nm}$ is incident on a lead surface. For which one of the following ranges of wavelengths will photoelectrons be emitted from the lead surface (work function $W_0 = 6.63 \times 10^{-19}$ J)?
   (a) $380 \text{ nm} \leq \lambda \leq 750 \text{ nm}$
   (b) $380 \text{ nm} \leq \lambda \leq 630 \text{ nm}$
   (c) $380 \text{ nm} \leq \lambda \leq 540 \text{ nm}$
   (d) $380 \text{ nm} \leq \lambda \leq 410 \text{ nm}$
   (e) No photoelectrons will be emitted.

20. When ultraviolet photons with a wavelength of $3.45 \times 10^{-7}$ m are incident on an unknown metal surface in a vacuum, electrons with a maximum kinetic energy of 1.52 eV are emitted from the surface. What is the work function of the metal?
   (a) 3.60 eV
   (b) 3.11 eV
   (c) 2.59 eV
   (d) 2.08 eV
   (e) 1.98 eV

21. Photons of energy 5.0 eV strike a metal whose work function is 3.5 eV. Determine which one of the following best describes the kinetic energy of the emitted electrons.
   (a) 1.5 eV or less
   (b) 1.5 eV or more
   (c) 2.5 eV or more
   (d) 3.5 eV or more
   (e) 3.5 eV or less

22. The work function for a particular metal is 4.0 eV. Which one of the following best describes the wavelength of electromagnetic radiation needed to eject electrons from this metal?
   (a) 310 nm or greater
   (b) 310 nm or smaller
   (c) 620 nm or greater
   (d) 620 nm or smaller
   (e) 800 nm or greater

Questions 23 and 24 pertain to the situation described below:

A physicist wishes to produce electrons by shining light on a metal surface. The light source emits light with a wavelength of 450 nm. The table lists the only available metals and their work functions.

<table>
<thead>
<tr>
<th>Metal</th>
<th>$W_0$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>barium</td>
<td>2.5</td>
</tr>
<tr>
<td>lithium</td>
<td>2.3</td>
</tr>
<tr>
<td>tantalum</td>
<td>4.2</td>
</tr>
<tr>
<td>tungsten</td>
<td>4.5</td>
</tr>
</tbody>
</table>

23. Which metal(s) can be used to produce electrons by the photoelectric effect?
   (a) barium only
   (b) tungsten only
   (c) tungsten or tantalum
   (d) barium or lithium
   (e) lithium, tantalum, or tungsten

24. Which entry in the table below correctly identifies the metal that will produce the most energetic electrons and their energies?

<table>
<thead>
<tr>
<th>Metal</th>
<th>Maximum electron energy observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>lithium</td>
<td>2.3 eV</td>
</tr>
<tr>
<td>lithium</td>
<td>0.5 eV</td>
</tr>
<tr>
<td>tungsten</td>
<td>1.8 eV</td>
</tr>
<tr>
<td>tungsten</td>
<td>2.8 eV</td>
</tr>
<tr>
<td>tungsten</td>
<td>4.5 eV</td>
</tr>
</tbody>
</table>
Section 29.4 The Momentum of a Photon and the Compton Effect

25. A digital wireless telephone communicates via microwaves that have a frequency of 1930 MHz. What are the momentum and energy for the microwave photons emitted by the telephone?

<table>
<thead>
<tr>
<th>photon momentum (kg • m/s)</th>
<th>photon energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 8.73 \times 10^{-32}</td>
<td>2.72 \times 10^{-25}</td>
</tr>
<tr>
<td>(b) 4.27 \times 10^{-33}</td>
<td>1.28 \times 10^{-24}</td>
</tr>
<tr>
<td>(c) 4.27 \times 10^{-33}</td>
<td>5.79 \times 10^{-25}</td>
</tr>
<tr>
<td>(d) 9.04 \times 10^{-34}</td>
<td>2.72 \times 10^{-25}</td>
</tr>
<tr>
<td>(e) 9.04 \times 10^{-34}</td>
<td>1.28 \times 10^{-24}</td>
</tr>
</tbody>
</table>

26. In the Compton effect, a photon of wavelength \( \lambda \) and frequency \( f \) hits an electron that is initially at rest. Which one of the following occurs as a result of the collision?

(a) The photon is absorbed completely.
(b) The photon gains energy, so the final photon has a frequency greater than \( f \).
(c) The photon gains energy, so the final photon has a wavelength greater than \( \lambda \).
(d) The photon loses energy, so the final photon has a frequency less than \( f \).
(e) The photon loses energy, so the final photon has a wavelength less than \( \lambda \).

27. Which one of the following is demonstrated by the Compton effect?

(a) time dilation
(b) length contraction
(c) the uncertainty principle
(d) electrons have wave properties
(e) electromagnetic radiation has particle properties

28. Complete the following statement: The photon or "particle" theory of electromagnetic radiation is necessary to explain the

(a) refraction of light by a prism.
(b) diffraction of light by a grating.
(c) reflection of light from a mirrored surface.
(d) results of Compton scattering experiments.
(e) interference of light in Young's double-slit experiment.

29. In the Compton scattering experiment shown in the figure, a monochromatic beam of X-rays strikes a target containing free electrons. Scattered X-rays are detected with a wavelength of 2.50 \times 10^{-12} m at an angle of 45° away from the original beam direction. What is the wavelength of the incident monochromatic X-rays?

**Note:** The mass of an electron is 9.11 \times 10^{-31} kg.

<table>
<thead>
<tr>
<th>scattered X-rays (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 3.21 \times 10^{-12}</td>
</tr>
<tr>
<td>(b) 2.86 \times 10^{-12}</td>
</tr>
<tr>
<td>(c) 2.50 \times 10^{-12}</td>
</tr>
<tr>
<td>(d) 2.03 \times 10^{-12}</td>
</tr>
<tr>
<td>(e) 1.79 \times 10^{-12}</td>
</tr>
</tbody>
</table>

30. What is the speed of an electron that has the same momentum as a photon with a wavelength in a vacuum of 380 nm? The mass of an electron is 9.11 \times 10^{-31} kg.

<table>
<thead>
<tr>
<th>electron speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 1.9 \times 10^3</td>
</tr>
<tr>
<td>(b) 2.1 \times 10^4</td>
</tr>
<tr>
<td>(c) 2.5 \times 10^5</td>
</tr>
<tr>
<td>(d) 2.7 \times 10^6</td>
</tr>
<tr>
<td>(e) 2.9 \times 10^8</td>
</tr>
</tbody>
</table>

31. A photon of wavelength 200 nm is scattered by an electron that is initially at rest. Which one of the following statements concerning the wavelength of the scattered photon is true?

(a) The wavelength is zero nm.
(b) The wavelength is 200 nm.
(c) The wavelength is 100 nm.
(d) The wavelength is greater than 200 nm.
(e) The wavelength is less than 200 nm, but greater than zero.
32. Incident X-rays in a Compton scattering experiment have a wavelength of 0.400 nm. Determine the wavelength of the scattered X-rays that are detected at an angle of 80.0°. The Compton wavelength of the electron is $2.43 \times 10^{-12}$ m.

(a) 0.041 nm  
(b) 0.398 nm

(c) 0.399 nm  
(d) 0.402 nm

(e) 0.403 nm

33. A photon has a collision with a stationary electron ($h/mc = 2.43 \times 10^{-12}$ m) and loses 5.0% of its energy. The photon scattering angle is 180°. What is the wavelength of the incident photon in this scattering process?

(a) $2.4 \times 10^{-12}$ m  
(b) $4.6 \times 10^{-11}$ m

(c) $9.2 \times 10^{-11}$ m  
(d) $1.9 \times 10^{-10}$ m

(e) $3.1 \times 10^{-12}$ m

Section 29.5 The De Broglie Wavelength and the Wave Nature of Matter

34. What kinetic energy must each neutron in a beam of neutrons have if their wavelength is 0.10 nm? The mass of a neutron is $1.67 \times 10^{-27}$ kg.

(a) $6.6 \times 10^{-19}$ J  
(b) $1.3 \times 10^{-20}$ J

(c) $2.6 \times 10^{-20}$ J  
(d) $6.3 \times 10^{-20}$ J

(e) $7.1 \times 10^{-20}$ J

35. Approximately, what is the de Broglie wavelength of an electron that has been accelerated through a potential difference of 150 V? The mass of an electron is $9.11 \times 10^{-31}$ kg.

(a) 0.1 nm  
(b) 1 nm

(c) 10 nm  
(d) 100 nm

(e) 1000 nm

36. Which experimental evidence confirms the hypothesis that matter exhibits wave properties?

(a) photoelectric experiments  
(b) electron diffraction experiments

(d) Compton scattering experiments  
(e) Michelson-Morley experiment

(c) Young's double-slit experiments

37. Complete the following statement: According to the de Broglie relation, the wavelength of a "matter" wave is inversely proportional to

(a) Planck's constant.  
(b) the mass of the particle.

(d) the frequency of the wave.  
(e) the speed of the particle.

(c) the momentum of the particle.

38. What is the de Broglie wavelength of an electron ($m = 9.11 \times 10^{-31}$ kg) in a $5.0 \times 10^3$-volt X-ray tube?

(a) 0.007 nm  
(b) 0.014 nm

(c) 0.017 nm  
(d) 0.028 nm

(e) 0.034 nm

39. Determine the de Broglie wavelength of a neutron ($m = 1.67 \times 10^{-27}$ kg) that has a speed of 5.0 m/s.

(a) 79 nm  
(b) 162 nm

(c) 395 nm  
(d) 529 nm

(e) 1975 nm

40. The de Broglie wavelength of an electron ($m = 9.11 \times 10^{-31}$ kg) is $1.2 \times 10^{-10}$ m. Determine the kinetic energy of the electron.

(a) $1.5 \times 10^{-15}$ J  
(b) $1.6 \times 10^{-16}$ J

(c) $1.7 \times 10^{-17}$ J  
(d) $1.8 \times 10^{-18}$ J

(e) $1.9 \times 10^{-19}$ J
41. What is the kinetic energy of each electron in a beam of electrons if the beam produces a diffraction pattern of a crystal which is similar to that of a beam of 1.00 eV neutrons?  
**Note:** The electron mass is $9.11 \times 10^{-31}$ kg; and the neutron mass is $1.67 \times 10^{-27}$ kg.  
(a) 1830 eV  (c) $3.35 \times 10^6$ eV  (e) $2.34 \times 10^{-2}$ eV  
(b) 42.8 eV  (d) $5.46 \times 10^{-4}$ eV

42. What happens to the de Broglie wavelength of an electron if its momentum is doubled?  
(a) The wavelength decreases by a factor of 4.  (d) The wavelength increases by a factor of 2.  
(b) The wavelength increases by a factor of 4.  (e) The wavelength decreases by a factor of 2.  
(c) The wavelength increases by a factor of 3.

43. The Hubble Space Telescope has an orbital speed of $7.56 \times 10^3$ m/s and a mass of 11 600 kg.  What is the de Broglie wavelength of the telescope?  
(a) $8.77 \times 10^7$ m  (c) $6.63 \times 10^{-34}$ m  (e) $7.56 \times 10^{-42}$ m  
(b) $5.81 \times 10^{-26}$ m  (d) $3.78 \times 10^{-40}$ m

44. A beam of electrons is incident on a single slit that has a width of $1.00 \times 10^{-6}$ m and a diffraction pattern is observed on a screen located 15.0 m from the slit.  The momentum of an individual electron in the beam is $5.91 \times 10^{-24}$ kg•m/s.  What is the width of the central maximum fringe?  
(a) $5.87 \times 10^{-5}$ m  (c) $6.67 \times 10^{-4}$ m  (e) $7.50 \times 10^{-3}$ m  
(b) $1.33 \times 10^{-4}$ m  (d) $3.37 \times 10^{-3}$ m

45. In a computer monitor, electrons approach the screen at $1.20 \times 10^8$ m/s.  What is the de Broglie wavelength of these electrons?  **Note:** the mass of electrons is $9.109 \times 10^{-31}$ kg; and use the relativistic momentum in your calculation.  
(a) $4.31 \times 10^{-12}$ m  (c) $6.07 \times 10^{-12}$ m  (e) $7.85 \times 10^{-12}$ m  
(b) $5.56 \times 10^{-12}$ m  (d) $6.62 \times 10^{-12}$ m

Questions 46 and 47 pertain to the situation described below:  
It is desired to obtain a diffraction pattern for electrons using a diffraction grating with lines separated by 10 nm.  The mass of an electron is $9.11 \times 10^{-31}$ kg.  

46. What is the approximate kinetic energy of electrons that would be diffracted by such a grating?  
(a) $1.5 \times 10^{-6}$ eV  (c) $1.5 \times 10^{-2}$ eV  (e) $1.5 \times 10^8$ eV  
(b) $1.5 \times 10^{-4}$ eV  (d) $1.5 \times 10^2$ eV

47. Suppose it is desired to observe diffraction effects for a beam of electromagnetic radiation using the same grating.  Roughly, what is the required energy of the individual photons in the beam?  
(a) $10^{-6}$ eV  (c) $10^{-2}$ eV  (e) $10^4$ eV  
(b) $10^{-4}$ eV  (d) $10^2$ eV

**Section 29.6 The Heisenberg Uncertainty Principle**

48. If Planck’s constant were changed to 660 J•s, what would be the minimum uncertainty in the position of a 120-kg football player running at a speed of 3.5 m/s?  
(a) 0.032 m  (c) 0.13 m  (e) 0.50 m  
(b) 0.065 m  (d) 0.25 m
49. In an experiment to determine the speed and position of an electron \( m = 9.11 \times 10^{-31} \text{ kg} \), three researchers claim to have measured the position of the electron to within \( \pm 10^{-9} \text{ m} \). They reported the following values for the speed of the electron:

- **Researcher A** \[ 3 \times 10^6 \pm 2 \times 10^4 \text{ m/s} \]
- **Researcher B** \[ 4 \times 10^8 \pm 2 \times 10^7 \text{ m/s} \]
- **Researcher C** \[ 2 \times 10^7 \pm 5 \times 10^5 \text{ m/s} \]

Which of these measurements violates one or more basic laws of modern physics?

(a) A only  
(b) B only  
(c) A and B  
(d) B and C  
(e) A, B, and C

50. The \( x \) component of the velocity of an electron \( m = 9.11 \times 10^{-31} \text{ kg} \) is known to be between 100 m/s and 300 m/s. Which one of the following is a true statement concerning the uncertainty in the \( x \) coordinate of the electron?

(a) The maximum uncertainty is about \( 10^6 \text{ m} \).
(b) The minimum uncertainty is about \( 6 \times 10^{-7} \text{ m} \).
(c) The maximum uncertainty is about \( 6 \times 10^{-7} \text{ m} \).
(d) The minimum uncertainty is about \( 3 \times 10^{-36} \text{ m} \).
(e) The maximum uncertainty is about \( 3 \times 10^{-36} \text{ m} \).

51. The position of a 1-g object moving in the \( x \) direction at 1 cm/s is known to within ±10 nm. In which range is the fractional uncertainty, \( \frac{\Delta p_x}{p_x} \), in the \( x \) component of its momentum?

(a) \( 10^{-2} \) to \( 10^{-4} \)  
(b) \( 10^{-12} \) to \( 10^{-14} \)  
(c) \( 10^{-16} \) to \( 10^{-18} \)  
(d) \( 10^{-20} \) to \( 10^{-22} \)  
(e) less than \( 10^{-30} \)

52. The speed of a bullet with a mass of 0.050 kg is 420 m/s with an uncertainty of 0.010\%. What is the minimum uncertainty in the bullet’s position if it is measured at the same time as the speed is measured?

(a) \( 2.5 \times 10^{-31} \text{ m} \)  
(b) \( 5.0 \times 10^{-32} \text{ m} \)  
(c) \( 7.5 \times 10^{-33} \text{ m} \)  
(d) \( 2.5 \times 10^{-34} \text{ m} \)  
(e) \( 6.0 \times 10^{-36} \text{ m} \)

53. The position of a hydrogen atom \( m = 1.7 \times 10^{-27} \text{ kg} \) is known to within \( 2.0 \times 10^{-6} \text{ m} \). What is the minimum uncertainty in the atom’s velocity?

(a) zero m/s  
(b) 0.0085 m/s  
(c) 0.011 m/s  
(d) 0.016 m/s  
(e) 0.031 m/s

54. A proton \( m_p = 1.673 \times 10^{-27} \text{ kg} \) and an electron \( m_e = 9.109 \times 10^{-31} \text{ kg} \) are confined such that the \( x \) position of each is known to within \( 1.50 \times 10^{-10} \text{ m} \). What is the ratio of the minimum uncertainty in the \( x \) component of the velocity of the electron to that of the proton, \( \Delta v_e/\Delta v_p \)?

(a) \( 5.444 \times 10^{-4} \)  
(b) \( 0.2272 \)  
(c) \( 808.2 \)  
(d) \( 1837 \)  
(e) \( 36 \, 290 \)