Questions

1. What can be said about the relative temperatures of whitish-yellow, reddish, and bluish stars? Explain.
2. If energy is radiated by all objects, why can we not see them in the dark? (See also Section 14–8.)
3. Does a lightbulb at a temperature of 2500 K produce as white a light as the Sun at 6000 K? Explain.
4. Darkrooms for developing black-and-white film were sometimes lit by a red bulb. Why red? Would such a bulb work in a darkroom for developing color photographs?
5. If the threshold wavelength in the photoelectric effect increases when the emitting metal is changed to a different metal, what can you say about the work functions of the two metals?
6. Explain why the existence of a cutoff frequency in the photoelectric effect more strongly favors a particle theory rather than a wave theory of light.
7. UV light causes sunburn, whereas visible light does not. Suggest a reason.
8. If an X-ray photon is scattered by an electron, does its wavelength change? If so, does it increase or decrease?
9. In both the photoelectric effect and in the Compton effect, a photon collides with an electron causing the electron to fly off. What then, is the difference between the two processes?
10. Consider a point source of light. How would the intensity of light vary with distance from the source according to (*a*) wave theory, (*b*) particle (photon) theory? Would this help to distinguish the two theories?
11. Explain how the photoelectric circuit of Fig. 27–6 could be used in (*a*) a burglar alarm, (*b*) a smoke detector, (*c*) a photographic light meter.
12. Why do we say that light has wave properties? Why do we say that light has particle properties?
13. Why do we say that electrons have wave properties? Why do we say that electrons have particle properties?
14. What is the difference between a photon and an electron? Be specific: make a list.
15. If an electron and a proton travel at the same speed, which has the shorter wavelength? Explain.
16. In Rutherford's planetary model of the atom, what keeps the electrons from flying off into space?
17. How can you tell if there is oxygen near the surface of the Sun?
18. When a wide spectrum of light passes through hydrogen gas at room temperature, absorption lines are observed that correspond only to the Lyman series. Why don't we observe the other series?
19. Explain how the closely spaced energy levels for hydrogen near the top of Fig. 27–27 correspond to the closely spaced spectral lines at the top of Fig. 27–22.
20. Is it possible for the de Broglie wavelength of a "particle" to be greater than the dimensions of the particle? To be smaller? Is there any direct connection?
21. In a helium atom, which contains two electrons, do you think that on average the electrons are closer to the nucleus or farther away than in a hydrogen atom? Why?
22. How can the spectrum of hydrogen contain so many lines when hydrogen contains only one electron?
23. The Lyman series is brighter than the Balmer series, because this series of transitions ends up in the most common state for hydrogen, the ground state. Why then was the Balmer series discovered first?
24. Use conservation of momentum to explain why photons emitted by hydrogen atoms have slightly less energy than that predicted by Eq. 27–10.
25. The work functions for sodium and cesium are 2.28 eV and 2.14 eV, respectively. For incident photons of a given frequency, which metal will give a higher maximum kinetic energy for the electrons?
26. (*a*) Does a beam of infrared photons always have less energy than a beam of ultraviolet photons? Explain. (*b*) Does a single infrared photon always have less energy than a single ultraviolet photon?
27. Light of 450-nm wavelength strikes a metal surface, and a stream of electrons emerges from the metal. If light of the same intensity but of wavelength 400 nm strikes the surface, are more electrons emitted? Does the energy of the emitted electrons change? Explain.
28. Suppose we obtain an emission spectrum for hydrogen at very high temperature (when some of the atoms are in excited states), and an absorption spectrum at room temperature, when all atoms are in the ground state. Will the two spectra contain identical lines?

Problems

27–1 Discovery of the Electron

1. (I) What is the value of e/m for a particle that moves in a circle of radius 7.0 mm in a 0.86-T magnetic field if a perpendicular 320-V/m electric field will make the path straight?
2. (II) (*a*) What is the velocity of a beam of electrons that go undeflected when passing through crossed (perpendicular) electric and magnetic fields of magnitude 1.88×10^4 V/m and 2.90×10^{-3} T, respectively? (*b*) What is the radius of the electron orbit if the electric field is turned off?
3. (II) An oil drop whose mass is determined to be 2.8×10^{-15} kg is held at rest between two large plates separated by 1.0 cm when the potential difference between them is 340 V. How many excess electrons does this drop have?

27–2 Planck's Quantum Hypothesis

4. (I) How hot is a metal being welded if it radiates most strongly at 440 nm?
5. (I) Estimate the peak wavelength for radiation from (*a*) ice at 0°C, (*b*) a floodlamp at 3500 K, (*c*) helium at 4 K, (*d*) for the universe at $T = 2.725$ K, assuming blackbody emission. In what region of the EM spectrum is each?
6. (I) (*a*) What is the temperature if the peak of a blackbody spectrum is at 18.0 nm? (*b*) What is the wavelength at the peak of a blackbody spectrum if the body is at a temperature of 2000 K?

7. (I) An HCl molecule vibrates with a natural frequency of 8.1×10^{13} Hz. What is the difference in energy (in joules and electron volts) between possible values of the oscillation energy?

8. (II) The steps of a flight of stairs are 20.0 cm high (vertically). If a 68.0-kg person stands with both feet on the same step, what is the gravitational potential energy of this person, relative to the ground, on (*a*) the first step, (*b*) the second step, (*c*) the third step, (*d*) the n^{th} step? (*e*) What is the change in energy as the person descends from step 6 to step 2?

9. (II) Estimate the peak wavelength of light issuing from the pupil of the human eye (which approximates a blackbody) assuming normal body temperature.

27–3 and 27–4 Photons and the Photoelectric Effect

10. (I) What is the energy of photons (joules) emitted by an 88.5-MHz FM radio station?

11. (I) What is the energy range (in joules and eV) of photons in the visible spectrum, of wavelength 400 nm to 750 nm?

12. (I) A typical gamma ray emitted from a nucleus during radioactive decay may have an energy of 300 keV. What is its wavelength? Would we expect significant diffraction of this type of light when it passes through an everyday opening, like a door?

13. (I) About 0.1 eV is required to break a "hydrogen bond" in a protein molecule. Calculate the minimum frequency and maximum wavelength of a photon that can accomplish this.

14. (I) Calculate the momentum of a photon of yellow light of wavelength 6.00×10^{-7} m.

15. (I) What is the momentum of a $\lambda = 0.010$ nm X-ray photon?

16. (II) The human eye can respond to as little as 10^{-18} J of light energy. For a wavelength at the peak of visual sensitivity, 550 nm, how many photons lead to an observable flash?

17. (II) What minimum frequency of light is needed to eject electrons from a metal whose work function is 4.3×10^{-19} J?

18. (II) What is the longest wavelength of light that will emit electrons from a metal whose work function is 3.10 eV?

19. (II) The work functions for sodium, cesium, copper, and iron are 2.3, 2.1, 4.7, and 4.5 eV, respectively. Which of these metals will not emit electrons when visible light shines on it?

20. (II) In a photoelectric-effect experiment it is observed that no current flows unless the wavelength is less than 570 nm. (*a*) What is the work function of this material? (*b*) What is the stopping voltage required if light of wavelength 400 nm is used?

21. (II) What is the maximum kinetic energy of electrons ejected from barium $(W_0 = 2.48\text{ eV})$ when illuminated by white light, $\lambda = 400$ to 750 nm?

22. (II) Barium has a work function of 2.48 eV. What is the maximum kinetic energy of electrons if the metal is illuminated by UV light of wavelength 365 nm? What is their speed?

23. (II) When UV light of wavelength 285 nm falls on a metal surface, the maximum kinetic energy of emitted electrons is 1.40 eV. What is the work function of the metal?

24. (II) The threshold wavelength for emission of electrons from a given surface is 350 nm. What will be the maximum kinetic energy of ejected electrons when the wavelength is changed to (*a*) 280 nm, (*b*) 360 nm?

25. (II) A certain type of film is sensitive only to light whose wavelength is less than 660 nm. What is the energy (eV and kcal/mol) needed for the chemical reaction to occur which causes the film to change?

26. (II) When 230-nm light falls on a metal, the current through a photoelectric circuit (Fig. 27–6) is brought to zero at a stopping voltage of 1.64 V. What is the work function of the metal?

27. (II) In a photoelectric experiment using a clean sodium surface, the maximum energy of the emitted photons was measured for a number of different incident frequencies, with the following results.

Frequency (10^{14} Hz)	Energy (eV)
11.8	2.60
10.6	2.11
9.9	1.81
9.1	1.47
8.2	1.10
6.9	0.57

Plot the graph of these results and find: (*a*) Planck's constant; (*b*) the cutoff frequency of sodium; (*c*) the work function.

28. (II). Show that the energy E (in electron volts) of a photon whose wavelength is λ (nm) is given by

$$E = \frac{1.240 \times 10^3\ \text{eV}\cdot\text{nm}}{\lambda\ (\text{nm})}.$$

* 27–4 Compton Effect

* 29. (II) The quantity h/m_0c, which has the dimensions of length, is called the *Compton wavelength*. Determine the Compton wavelength for (*a*) an electron, (*b*) a proton. (*c*) Show that if a photon has wavelength equal to the Compton wavelength of a particle, the photon's energy is equal to the rest energy of the particle.

* 30. (II) X-rays of wavelength $\lambda = 0.120$ nm are scattered from carbon. What is the Compton wavelength shift for photons detected at angles (relative to the incident beam) of (*a*) 45°, (*b*) 90°, (*c*) 180°?

* 31. (III) In the Compton effect, a 0.100-nm photon strikes a free electron in a head-on collision and knocks it into the forward direction. The rebounding photon recoils directly backward. Use conservation of (relativistic) energy and momentum to determine (*a*) the kinetic energy of the electron, and (*b*) the wavelength of the recoiling photon. (*Note*: use Eq. 27–6, but not Eq. 27–7.)

27–6 Pair Production

32. (I) How much total kinetic energy will an electron–positron pair have if produced by a 3.84-MeV photon?

33. (II) What is the longest wavelength photon that could produce a proton–antiproton pair? (Each has a mass of 1.67×10^{-27} kg.)

34. (II) What is the minimum photon energy needed to produce a $\mu^+ - \mu^-$ pair? The mass of each μ (muon) is 207 times the mass of the electron. What is the wavelength of such a photon?

35. (II) An electron and a positron, each moving at 1.0×10^5 m/s, collide head on, disappear, and produce two photons, each with the same energy and momentum moving in opposite directions. What is the energy and momentum of each photon?

36. (II) A gamma-ray photon produces an electron–positron pair, each with a kinetic energy of 245 keV. What was the energy and wavelength of the photon?

27–8 Wave Nature of Matter

37. (I) Calculate the wavelength of a 0.23-kg ball traveling at 0.10 m/s.

38. (I) What is the wavelength of a neutron ($m = 1.67 \times 10^{-27}$ kg) traveling at 6.5×10^4 m/s?

39. (I) Through how many volts of potential difference must an electron be accelerated to achieve a wavelength of 0.24 nm?

40. (II) Calculate the ratio of the kinetic energy of an electron to that of a proton if their wavelengths are equal. Assume that the speeds are nonrelativistic.

41. (II) An electron has a de Broglie wavelength $\lambda = 5.0 \times 10^{-10}$ m. (*a*) What is its momentum? (*b*) What is its speed? (*c*) What voltage was needed to accelerate it to this speed?

42. (II) What is the wavelength of an electron of energy (*a*) 10 eV, (*b*) 100 eV, (*c*) 1.0 keV?

43. (II) Show that if an electron and a proton have the same nonrelativistic kinetic energy, the proton has the shorter wavelength.

44. (II) Calculate the de Broglie wavelength of an electron in your TV picture tube if it is accelerated by 30,000 V. Is it relativistic? How does its wavelength compare to the size of the "neck" of the tube, typically 5 cm? Do we have to worry about diffraction problems blurring our picture on the screen?

45. (III) A Ferrari with a mass of 1400 kg approaches a freeway underpass that is 10 m across. At what speed must the car be moving, in order for it to have a wavelength such that it might somehow "diffract" after passing through this "single slit"? How do these conditions compare to normal freeway speeds of 30 m/s?

* 27–9 Electron Microscope

* 46. (II) What voltage is needed to produce electron wavelengths of 0.20 nm? (Assume that the electrons are nonrelativistic.)

* 47. (II) Electrons are accelerated by 2450 V in an electron microscope. What is the maximum possible resolution?

27–12 Bohr Model

48. (I) For the three hydrogen transitions indicated below, with n being the initial state and n' being the final state, is the transition an absorption or an emission? Which is higher, the initial state energy or the final state energy of the atom? Finally, which of these transitions involves the largest energy photon? (*a*) $n = 1,\ n' = 3$ (*b*) $n = 6,\ n' = 2$ (*c*) $n = 4,\ n' = 5$.

49. (I) How much energy is needed to ionize a hydrogen atom in the $n = 2$ state?

50. (I) The third longest wavelength in the Paschen series in hydrogen (Fig. 27–27) corresponds to what transition?

51. (I) Calculate the ionization energy of doubly ionized lithium, Li^{2+}, which has $Z = 3$.

52. (I) (*a*) Determine the wavelength of the second Balmer line ($n = 4$ to $n = 2$ transition) using Fig. 27–27. Determine likewise (*b*) the wavelength of the second Lyman line and (*c*) the wavelength of the third Balmer line.

53. (I) Evaluate the Rydberg constant R using Bohr theory (compare Eqs. 27–9 and 27–16) and show that its value is $R = 1.0974 \times 10^7\ \text{m}^{-1}$.

54. (II) What is the longest wavelength light capable of ionizing a hydrogen atom in the ground state?

55. (II) What wavelength photon would be required to ionize a hydrogen atom in the ground state and give the ejected electron a kinetic energy of 10.0 eV?

56. (II) In the Sun, an ionized helium (He^+) atom makes a transition from the $n = 6$ state to the $n = 2$ state, emitting a photon. Can that photon be absorbed by hydrogen atoms present in the Sun? If so, between what energy states will the hydrogen atom jump?

57. (II) Construct the energy-level diagram for the He^+ ion (see Fig. 27–27).

58. (II) Construct the energy-level diagram for doubly ionized lithium, Li^{2+}.

59. (II) What is the potential energy and the kinetic energy of an electron in the ground state of the hydrogen atom?

60. (II) An excited hydrogen atom could, in principle, have a radius of 1.00 mm. What would be the value of n for a Bohr orbit of this size? What would its energy be?

61. (II) Is the use of nonrelativistic formulas justified in the Bohr atom? To check, calculate the electron's velocity, v, in terms of c, for the ground state of hydrogen, and then calculate $\sqrt{1 - v^2/c^2}$.

62. (III) Suppose an electron was bound to a proton, as in the hydrogen atom, but by the gravitational force rather than by the electric force. What would be the radius, and energy, of the first Bohr orbit?

27–13 de Broglie's Hypothesis Applied to Atoms

63. (III) Suppose a particle of mass m is confined to a one-dimensional box of width L. According to quantum theory, the particle's wave (with $\lambda = h/mv$) is a standing wave with nodes at the edges of the box. (*a*) Show the possible modes of vibration on a diagram. (*b*) Show that the kinetic energy of the particle has quantized energies given by $\text{KE} = n^2h^2/8mL^2$, where n is an integer. (*c*) Calculate the ground-state energy ($n = 1$) for an electron confined to a box of width 0.50×10^{-10} m. (*d*) What is the ground-state energy, and speed, of a baseball ($m = 140$ g) in a box 0.50 m wide? (*e*) An electron confined to a box has a ground-state energy of 22 eV. What is the width of the box?

General Problems

64. The Big Bang theory states that the beginning of the universe was accompanied by a huge burst of photons. Those photons are still present today and make up the so-called cosmic microwave background radiation. The universe radiates like a blackbody with a temperature of about 2.7 K. Calculate the peak wavelength of this radiation.

65. At low temperatures, nearly all the atoms in hydrogen gas will be in the ground state. What minimum frequency photon is needed if the photoelectric effect is to be observed?

66. A beam of 85-eV electrons is scattered from a crystal, as in X-ray diffraction, and a first-order peak is observed at $\theta = 38°$. What is the spacing between planes in the diffracting crystal? (See Section 25–11.)

67. A microwave oven produces electromagnetic radiation at $\lambda = 12.2$ cm and produces a power of 760 W. Calculate the number of microwave photons produced by the microwave oven each second.

68. Sunlight reaching the Earth's surface has an intensity of about $1000\,\text{W/m}^2$. Estimate how many photons per square meter per second this represents. Take the average wavelength to be 550 nm.

69. A beam of red laser light $(\lambda = 633\,\text{nm})$ hits a black wall and is fully absorbed. If this light exerts a total force $F = 5.5\,\text{nN}$ on the wall, how many photons per second are hitting the wall?

70. If a 100-W lightbulb emits 3.0% of the input energy as visible light (average wavelength 550 nm) uniformly in all directions, estimate how many photons per second of visible light will strike the pupil (4.0 mm diameter) of the eye of an observer 1.0 km away.

71. An electron and a positron collide head on, annihilate, and create two 0.90-MeV photons traveling in opposite directions. What were the initial kinetic energies of electron and positron?

72. By what potential difference must (*a*) a proton $(m = 1.67 \times 10^{-27}\,\text{kg})$, and (*b*) an electron $(m = 9.11 \times 10^{-31}\,\text{kg})$, be accelerated to have a wavelength $\lambda = 5.0 \times 10^{-12}\,\text{m}$?

73. In some of Rutherford's experiments (Fig. 27–18) the α particles $(\text{mass} = 6.64 \times 10^{-27}\,\text{kg})$ had a kinetic energy of 4.8 MeV. How close could they get to a gold nucleus (charge $= +79e$)? Ignore the recoil motion of the nucleus.

74. By what fraction does the mass of an H atom decrease when it makes an $n = 3$ to $n = 1$ transition?

75. Calculate the ratio of the gravitational to electric force for the electron in a hydrogen atom. Can the gravitational force be safely ignored?

76. Electrons accelerated by a potential difference of 12.3 V pass through a gas of hydrogen atoms at room temperature. What wavelengths of light will be emitted?

77. In a particular photoelectric experiment, a stopping potential of 2.10 V is measured when ultraviolet light of wavelength 290 nm is incident on the metal. Using the same setup, what will the new stopping potential be if blue light of wavelength 440 nm is used, instead?

78. In an X-ray tube (see Fig. 25–35 and discussion in Section 25–11), the high voltage between filament and target is V. After being accelerated through this voltage, an electron strikes the target where it is decelerated (by positively charged nuclei) and in the process one or more X-ray photons are emitted. (*a*) Show that the photon of shortest wavelength will have

$$\lambda_0 = \frac{hc}{eV}.$$

(*b*) What is the shortest wavelength of X-ray emitted when accelerated electrons strike the face of a 30-kV television picture tube?

79. The intensity of the Sun's light in the vicinity of the Earth is about $1000\,\text{W/m}^2$. Imagine a spacecraft with a mirrored square sail of dimension 1.0 km. Estimate how much thrust (in newtons) this craft will experience due to collisions with the Sun's photons. [*Hint*: assume the photons bounce off the sail with no change in the magnitude of their momentum.]

80. Light of wavelength 300 nm strikes a metal whose work function is 2.2 eV. What is the shortest de Broglie wavelength for the electrons that are produced as photoelectrons?

81. Photons of energy 6.0 eV are incident on a metal. It is found that current flows from the metal until a stopping potential of 4.0 V is applied. If the wavelength of the incident photons is doubled, what is the maximum kinetic energy of the ejected electrons? What would happen if the wavelength of the incident photons was tripled?

82. Visible light incident on a diffraction grating with slit spacing of 0.010 mm has the first maximum at an angle of 3.5° from the central peak. If electrons could be diffracted by the same grating, what electron velocity would produce the same diffraction pattern as the visible light?

83. (*a*) Suppose an unknown element has an absorption spectrum with lines at 2.5, 4.7, and 5.1 eV above its ground state and an ionization energy of 11.5 eV. Draw an energy level diagram for this element. (*b*) If a 5.1-eV photon is absorbed by an atom of this substance, in which state was the atom before absorbing the photon? What will be the energies of the photons that can subsequently be emitted by this atom?

84. Light of wavelength 424 nm falls on a metal which has a work function of 2.28 eV. (*a*) How much voltage should be applied to bring the current to zero? (*b*) What is the maximum speed of the emitted electrons? (*c*) What is the de Broglie wavelength of these electrons?

85. An electron accelerated from rest by a 96-V potential difference is injected into a $3.67 \times 10^{-4}\,\text{T}$ magnetic field where it travels in an 18-cm-diameter circle. Calculate e/m from this information.

86. Estimate the number of photons emitted by the Sun in a year. (Take the average wavelength to be 550 nm and the intensity of sunlight reaching the Earth (outer atmosphere) as $1350\,\text{W/m}^2$.)

87. Apply Bohr's assumptions to the Earth–Moon system to calculate the allowed energies and radii of motion. Given the known distance between the Earth and Moon, is the quantization of the energy and radius apparent?

Answers to Exercises

A: $\lambda_p = 725\,\text{nm}$, so red.
B: More 1000-nm photons (lower frequency).
C: $5.50 \times 10^{14}\,\text{Hz}$, 545 nm.
D: Only λ.
E: Decrease.