Chapter 27

Early Quantum Theory and Models of the Atom

Questions

1. Does a lightbulb at a temperature of 2500 K produce as white a light as the Sun at 6000 K? Explain.
2. If energy is radiated by all objects, why can we not see them in the dark? (See also Section 14–8.)
3. What can be said about the relative temperatures of whitish-yellow, reddish, and bluish stars? Explain.
4. Darkrooms for developing black-and-white film were sometimes lit by a red bulb. Why red? Explain if such a bulb would work in a darkroom for developing color film.
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. 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? Explain.
9. 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.

10. (*a*) Does a beam of infrared photons always have less energy than a beam of ultraviolet photons? Explain. (*b*) Does a single photon of infrared light always have less energy than a single photon of ultraviolet light? Why?

11. 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.

*12. If an X-ray photon is scattered by an electron, does the photon's wavelength change? If so, does it increase or decrease? Explain.

*13. In both the photoelectric effect and in the Compton effect, a photon collides with an electron causing the electron to fly off. What is the difference between the two processes?

14. Why do we say that light has wave properties? Why do we say that light has particle properties?

15. Why do we say that electrons have wave properties? Why do we say that electrons have particle properties?

16. What are the differences between a photon and an electron? Be specific: make a list.

17. If an electron and a proton travel at the same speed, which has the shorter wavelength? Explain.

18. An electron and a proton are accelerated through the same voltage. Which has the longer wavelength? Explain why.

19. In Rutherford's planetary model of the atom, what keeps the electrons from flying off into space?

20. 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?

21. How can you tell if there is oxygen near the surface of the Sun?

22. (*a*) List at least three successes of the Bohr model of the atom, according to Section 27–12. (*b*) List at least two observations that the Bohr model could not explain, according to Section 27–13.

23. According to Section 27–11, what were the two main difficulties of the Rutherford model of the atom?

24. 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? Explain.

25. How can the spectrum of hydrogen contain so many lines when hydrogen contains only one electron?

26. Explain how the closely spaced energy levels for hydrogen near the top of Fig. 27–29 correspond to the closely spaced spectral lines at the top of Fig. 27–24.

27. 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?

28. 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?

29. Use conservation of momentum to explain why photons emitted by hydrogen atoms have slightly less energy than that predicted by Eq. 27–10.

30. State if a continuous or a line spectrum is produced by each of the following: (*a*) a hot solid object; (*b*) an excited, rarefied gas; (*c*) a hot liquid; (*d*) light from a hot solid that passes through a cooler rarefied gas; (*e*) a hot dense gas. For each, if a line spectrum is produced, is it an emission or an absorption spectrum?

31. 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?

MisConceptual Questions

1. Which of the following statements is true regarding how blackbody radiation changes as the temperature of the radiating object increases?
   (*a*) Both the maximum intensity and the peak wavelength increase.
   (*b*) The maximum intensity increases, and the peak wavelength decreases.
   (*c*) Both the maximum intensity and the peak wavelength decrease.
   (*d*) The maximum intensity decreases, and the peak wavelength increases.
2. As red light shines on a piece of metal, no electrons are released. When the red light is slowly changed to shorter-wavelength light (basically progressing through the rainbow), nothing happens until yellow light shines on the metal, at which point electrons are released from the metal. If this metal is replaced with a metal having a higher work function, which light would have the best chance of releasing electrons from the metal?
   (*a*) Blue.
   (*b*) Red.
   (*c*) Yellow would still work fine.
   (*d*) We need to know more about the metals involved.
3. A beam of red light and a beam of blue light have equal intensities. Which statement is true?
   (*a*) There are more photons in the blue beam.
   (*b*) There are more photons in the red beam.

(*c*) Both beams contain the same number of photons.

(*d*) The number of photons is not related to intensity.

4. Which of the following is necessarily true?

(*a*) Red light has more energy than violet light.

(*b*) Violet light has more energy than red light.

(*c*) A single photon of red light has more energy than a single photon of violet light.

(*d*) A single photon of violet light has more energy than a single photon of red light.

(*e*) None of the above.

(*f*) A combination of the above (specify).

5. If a photon of energy *E* ejects electrons from a metal with kinetic energy KE, then a photon with energy *E*/2

(*a*) will eject electrons with kinetic energy KE/2.

(*b*) will eject electrons with an energy greater than KE/2.

(*c*) will eject electrons with an energy less than KE/2.

(*d*) might not eject any electrons.

6. If the momentum of an electron were doubled, how would its wavelength change?

(*a*) No change.

(*b*) It would be halved.

(*c*) It would double.

(*d*) It would be quadrupled.

(*e*) It would be reduced to one-fourth.

7. Which of the following can be thought of as either a wave or a particle?

(*a*) Light.

(*b*) An electron.

(*c*) A proton.

(*d*) All of the above.

8. When you throw a baseball, its de Broglie wavelength is

(*a*) the same size as the ball.

(*b*) about the same size as an atom.

(*c*) about the same size as an atom's nucleus.

(*d*) much smaller than the size of an atom's nucleus.

9. Electrons and photons of light are similar in that

(*a*) both have momentum given by h/λ.

(*b*) both exhibit wave-particle duality.

(*c*) both are used in diffraction experiments to explore structure.

(*d*) All of the above.

(*e*) None of the above.

10. In Rutherford's famous set of experiments described in Section 27–10, the fact that some alpha particles were deflected at large angles indicated that (choose all that apply)

(*a*) the nucleus was positive.

(*b*) charge was quantized.

(*c*) the nucleus was concentrated in a small region of space.

(*d*) most of the atom is empty space.

(*e* None of the above.

11. Which of the following electron transitions between two energy states (n) in the hydrogen atom corresponds to the emission of a photon with the longest wavelength?

(*a*) $2 \rightarrow 5$.

(*b*) $5 \rightarrow 2$.

(*c*) $5 \rightarrow 8$.

(*d*) $8 \rightarrow 5$.

12. If we set the potential energy of an electron and a proton to be zero when they are an infinite distance apart, then the lowest energy a bound electron in a hydrogen atom can have is
    (*a*) 0.
    (*b*) –13.6 eV.
    (*c*) any possible value.
    (*d*) any value between –13.6 eV and 0.
13. Which of the following is the currently accepted model of the atom?
    (*a*) The plum-pudding model.
    (*b*) The Rutherford atom.
    (*c*) The Bohr atom.
    (*d*) None of the above.
14. Light has all of the following except:
    (*a*) mass.
    (*b*) momentum.
    (*c*) kinetic energy.
    (*d*) frequency.
    (*e*) wavelength.

For assigned homework and other learning materials, go to the MasteringPhysics website.

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 14 mm in a 0.86-T magnetic field if a perpendicular 640-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 2.60×10^{-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 2.8×10^{-15} kg is held at rest between two large plates separated by 1.0 cm (Fig. 27–3), when the potential difference between the plates is 340 V. How many excess electrons does this drop have?

27–2 Blackbodies; Planck's Quantum Hypothesis

4 (I) How hot is a metal being welded if it radiates most strongly at 520 nm?

5 (I) Estimate the peak wavelength for radiation emitted from (*a*) ice at 0°C, (*b*) a floodlamp at 3100 K, (*c*) helium at 4 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 2200 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 successive values of the oscillation energy?

8. (II) The steps of a flight of stairs are 20.0 cm high (vertically). If a 62.0-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 emitted 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 a 91.7-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 320 keV. What is its wavelength? Would we expect significant diffraction of this type of light when it passes through an everyday opening, such as a door?
13. (I) Calculate the momentum of a photon of yellow light of wavelength 5.80×10^{-7} m.
14. (I) What is the momentum of a $\lambda = 0.014$ nm X-ray photon?
15. (I) For the photoelectric effect, make a table that shows expected observations for a particle theory of light and for a wave theory of light. Circle the actual observed effects. (See Section 27–3.)
16. (II) 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.
17. (II) What minimum frequency of light is needed to eject electrons from a metal whose work function is 4.8×10^{-19} J?
18. (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?
19. (II) What is the longest wavelength of light that will emit electrons from a metal whose work function is 2.90 eV?
20. (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?

21. (II) In a photoelectric-effect experiment it is observed that no current flows unless the wavelength is less than 550 nm. (*a*) What is the work function of this material? (*b*) What stopping voltage is required if light of wavelength 400 nm is used?
22. (II) What is the maximum kinetic energy of electrons ejected from barium (W_0 = 2.48 eV) when illuminated by white light, λ = 400 to 750 nm?
23. (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?
24. (II) When UV light of wavelength 255 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?
25. (II) The threshold wavelength for emission of electrons from a given surface is 340 nm. What will be the maximum kinetic energy of ejected electrons when the wavelength is changed to (*a*) 280 nm, (*b*) 360 nm?
26. (II) A certain type of film is sensitive only to light whose wavelength is less than 630 nm. What is the energy (eV and kcal/mol) needed for the chemical reaction to occur which causes the film to change?
27. (II) When 250-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?
28. (II) In a photoelectric experiment using a clean sodium surface, the maximum energy of the emitted electrons was measured for a number of different incident frequencies, with the following results.

Frequency ($\times 10^{14}$ 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. 29. (II) Show that the energy E (in electron volts) of a photon whose wavelength is λ (nm) is given by

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

Use at least 4 significant figures for values of *h*, *c*, *e* (see inside front cover).

***27–5 Compton Effect**

*30. (I) A high-frequency photon is scattered off of an electron and experiences a change of wavelength of 1.7×10^{-4} nm. At what angle must a detector be placed to detect the scattered photon (relative to the direction of the incoming photon)?

*31. (II) The quantity *h/mc*, 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, mc^2.

*32. (II) X-rays of wavelength λ = 0.140 nm are scattered from carbon. What is the expected Compton wavelength shift for photons detected at angles (relative to the incident beam) of exactly (*a*) 45°, (*b*) 90°, (*c*) 180°?

27–6 Pair Production

33. (I) How much total kinetic energy will an electron-positron pair have if produced by a 3.64-MeV photon?
34. (II) What is the longest wavelength photon that could produce a proton-antiproton pair? (Each has a mass of 1.67×10^{-27} kg.)
35. (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 an electron. What is the wavelength of such a photon?
36. (II) An electron and a positron, each moving at 3.0×10^{5} m/s, collide head on, disappear, and produce two photons, each with the same energy and momentum moving in opposite directions. Determine the energy and momentum of each photon.
37. (II) A gamma-ray photon produces an electron and a positron, each with a kinetic energy of 285 keV. Determine the energy and wavelength of the photon.

27–8 Wave Nature of Matter

38. (I) Calculate the wavelength of a 0.21-kg ball traveling at 0.10 m/s.
39. (I) What is the wavelength of a neutron ($m = 1.67 \times 10^{-27}$ kg) traveling at 8.5×10^{4} m/s?
40. (II) Through how many volts of potential difference must an electron, initially at rest, be accelerated to achieve a wavelength of 0.27 nm?
41. (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.
42. (II) An electron has a de Broglie wavelength $\lambda = 4.5 \times 10^{-10}$ m. (*a*) What is its momentum? (*b*) What is its speed? (*c*) What voltage was needed to accelerate it from rest to this speed?

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

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

45. (II) Calculate the de Broglie wavelength of an electron if it is accelerated from rest by 35,000 V as in Fig. 27–2. 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 the picture on the CRT screen?

46. (III) A Ferrari with a mass of 1400 kg approaches a freeway underpass that is 12 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

47. (II) What voltage is needed to produce electron wavelengths of 0.26 nm? (Assume that the electrons are nonrelativistic.)

48. (II) Electrons are accelerated by 2850 V in an electron microscope. Estimate the maximum possible resolution of the microscope.

27–11 and 27–12 Spectra and the Bohr Model

49. (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*) $n = 4$, $n' = 5$.

50. (I) How much energy is needed to ionize a hydrogen atom in the $n = 3$ state?

51. (I) The second longest wavelength in the Paschen series in hydrogen (Fig. 27–29) corresponds to what transition?

52. (I) Calculate the ionization energy of doubly ionized lithium, Li^{2+}, which has Z = 3 (and is in the ground state).

53. (I) (*a*) Determine the wavelength of the second Balmer line ($n = 4$ to $n = 2$ transition) using Fig. 27–29. Determine likewise (*b*) the wavelength of the second Lyman line and (*c*) the wavelength of the third Balmer line.

54. (I) Evaluate the Rydberg constant R using the Bohr model (compare Eqs. 27–9 and 27–16) and show that its value is $R = 1.0974 \times 10^7\ \text{m}^{-1}$. (Use values inside front cover to 5 or 6 significant figures.)

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

56. (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 11.5 eV?

57. (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 transition occur?

58. (II) Construct the energy-level diagram for the He^+ ion (like Fig. 27–29).

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

60. (II) Determine the electrostatic potential energy and the kinetic energy of an electron in the ground state of the hydrogen atom.

61. (II) A hydrogen atom has an angular momentum of 5.273×10^{-34} kg • m^2/s. According to the Bohr model, what is the energy (eV) associated with this state?

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

63. (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 $\sqrt{1-v^2/c^2}$.

64. (III) Show that the magnitude of the electrostatic potential energy of an electron in any Bohr orbit of a hydrogen atom is twice the magnitude of its kinetic energy in that orbit.

65. (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?

General Problems

66. The Big Bang theory (Chapter 33) 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 today of about 2.7 K. Calculate the peak wavelength of this radiation.

67. 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?

68. A beam of 72-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.)

69. A microwave oven produces electromagnetic radiation at λ = 12.2 cm and produces a power of 720 W. Calculate the number of microwave photons produced by the microwave oven each second.

70. Sunlight reaching the Earth's atmosphere has an intensity of about 1300 W/m^2. Estimate how many photons per square meter per second this represents. Take the average wavelength to be 550 nm.

71. A beam of red laser light (λ = 633 nm) hits a black wall and is fully absorbed. If this light exerts a total force F = 5.8 nN on the wall, how many photons per second are hitting the wall?

72. A flashlight emits 2.5 W of light. As the light leaves the flashlight in one direction, a reaction force is exerted on the flashlight in the opposite direction. Estimate the size of this reaction force.

73. A **pliolomulliplier tube** (a very sensitive light sensor), is based on the photoelectric effect: incident photons strike a metal surface and the resulting ejected electrons are collected. By counting the number of collected electrons, the number of incident photons (i.e., the incident light intensity) can be determined. (*a*) If a photomultiplier tube is to respond properly for incident wavelengths throughout the visible range (410 nm to 750 nm), what is the maximum value for the work function W_0 (eV) of its metal surface? (*b*) If W_0 for its metal surface is above a certain threshold value, the photomultiplier will only function for incident ultraviolet wavelengths and be unresponsive to visible light. Determine this threshold value (eV).

74. 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, (*a*) 1.0 m away, (*b*) 1.0 km away.

75. An electron and a positron collide head on, annihilate, and create two 0.85-MeV photons traveling in opposite directions. What were the initial kinetic energies of electron and positron?

76. By what potential difference must (*a*) a proton ($m = 1.67 \times 10^{-27}$ kg), and (*b*) an electron ($m = 9.11 \times 10^{-31}$ kg), be accelerated from rest to have a wavelength $\lambda = 4.0 \times 10^{-12}$ m?

77. In some of Rutherford's experiments (Fig. 27–19) the α particles (mass = 6.64×10^{-27} kg) had a kinetic energy of 4.8 MeV. How close could they get to the surface of a gold nucleus (radius $\approx 7.0 \times 10^{-15}$ m, charge = $+79e$)? Ignore the recoil motion of the nucleus.

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

79. Calculate the ratio of the gravitational force to the electric force for the electron in the ground state of a hydrogen atom. Can the gravitational force be reasonably ignored?

80. Electrons accelerated from rest 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?

81. In a particular photoelectric experiment, a stopping potential of 2.10 V is measured when ultraviolet light of wavelength 270 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?

82. Neutrons can be used in diffraction experiments to probe the lattice structure of crystalline solids. Since the neutron's wavelength needs to be on the order of the spacing between atoms in the lattice, about 0.3 nm, what should the speed of the neutrons be?

83. In Chapter 22, the intensity of light striking a surface was related to the electric field of the associated electromagnetic wave. For photons, the intensity is the number of photons striking a 1-m^2 area per second. Suppose 1.0×10^{12} photons of 497-nm light are incident on a 1-m^2 surface every second. What is the intensity of the light? Using the wave model of light, what is the maximum electric field of the electromagnetic wave?

84. The intensity of the Sun's light in the vicinity of the Earth is about 1350 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.]

85. Light of wavelength 280 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?

86. 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 3.8 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?

87. What would be the theoretical limit of resolution for an electron microscope whose electrons are accelerated through 110 kV? (Relativistic formulas should be used.)

88. Assume hydrogen atoms in a gas are initially in their ground state. If free electrons with kinetic energy 12.75 eV collide with these atoms, what photon wavelengths will be emitted by the gas?

89. Visible light incident on a diffraction grating with slit spacing of 0.010 mm has the first maximum at an angle of 3.6° 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?

90. (*a*) Suppose an unknown element has an absorption spectrum with lines corresponding to 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?

91. A photon of momentum 3.53×10^{-28} kg • m/s is emitted from a hydrogen atom. To what spectrum series does this photon belong, and from what energy level was it ejected?

92. Light of wavelength 464 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?

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

94. 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 W/m^2.)

95. 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?

96. At what temperature would the average kinetic energy (Chapter 13) of a molecule of hydrogen gas (H_2) be sufficient to excite a hydrogen atom out of the ground state?

Search and Learn

1. Name the person or people who did each of the following: (*a*) made the first direct measurement of the charge-to-mass ratio of the electron (Section 27–1); (*b*) measured the charge on the electron and showed that it is quantized (Section 27–1); (*c*) proposed the radical assumption that the vibrational energy of molecules in a radiating object is quantized (Sections 27–2, 27–3); (*d*) found that light (X-rays) scattered off electrons in a material will decrease the energy of the photons (Section 27–5); (*e*) proposed that the wavelength of a material particle would be related to its momentum in the same way as for a photon (Section 27–8); (*f*) performed the first crucial experiment illustrating electron diffraction (Section 27–8); (*g*) deciphered the nuclear model of the atom by aiming a particles at gold foil (Section 27–10).
2. State the principle of complementarity, and give at least two experimental results that support this principle for electrons and for photons. (See Section 27–7 and also Sections 27–3 and 27–8.)
3. Imagine the following Young's double-slit experiment using matter rather than light: electrons are accelerated through a potential difference of 12 V, pass through two closely spaced slits separated by a distance d, and create an interference pattern. (*a*) Using Example 27–11 and Section 24–3 as guides, find the required value for *d* if the first-order interference fringe is to be produced at an angle of 10°. (*b*) Given the approximate size of atoms, would it be possible to construct the required two-slit set-up for this experiment?
4. Does each of the following support the wave nature or the particle nature of light? (*a*) The existence of the cutoff frequency in the photoelectric

effect; (*b*) Young's double-slit experiment; (*c*) the shift in the photon frequency in Compton scattering; (*d*) the diffraction of light.

5. (*a*) From Sections 22–3, 24–4, and 27–3, estimate the minimum energy (eV) that initiates the chemical process on the retina responsible for vision. (*b*) Estimate the threshold photon energy above which the eye registers no sensation of sight.

6. (*a*) A rubidium atom (m = 85 u) is at rest with one electron in an excited energy level. When the electron jumps to the ground state, the atom emits a photon of wavelength A = 780 nm. Determine the resulting (nonrelativistic) recoil speed v of the atom. (*b*) The recoil speed sets the lower limit on the temperature to which an ideal gas of rubidium atoms can be cooled in a laser-based **atom trap**. Using the kinetic theory of gases (Chapter 13), estimate this "lowest achievable" temperature.

7. 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 0.65 m wide? (*e*) An electron confined to a box has a ground-state energy of 22 eV. What is the width of the box? [*Hint*: See Sections 27–8, 27–13, and 11–12.]