Chapter 29: Introduction to Quantum Physics

# 29.1 Quantization of Energy

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| 1. | *A LiBr molecule oscillates with a frequency of . (a) What is the difference in energy in eV between allowed oscillator states? (b) What is the approximate value of  for a state having an energy of 1.0 eV?* |
| Solution | (a)  so that  (b) Using the equation , we can solve for : |
| 2. | *The difference in energy between allowed oscillator states in HBr molecules is 0.330 eV. What is the oscillation frequency of this molecule?* |
| Solution |  |
| 3. | *A physicist is watching a 15-kg orangutan at a zoo swing lazily in a tire at the end of a rope. He (the physicist) notices that each oscillation takes 3.00 s and hypothesizes that the energy is quantized. (a) What is the difference in energy in joules between allowed oscillator states? (b) What is the value of  for a state where the energy is 5.00 J? (c) Can the quantization be observed?* |
| Solution | (a)  so that  (b)  (c) No, is much too small and  is much too large. |

# 29.2 The Photoelectric Effect

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| 4. | *What is the longest-wavelength EM radiation that can eject a photoelectron from silver, given that the binding energy is 4.73 eV? Is this in the visible range?* |
| Solution | No, this is UV. |
| 5. | *Find the longest-wavelength photon that can eject an electron from potassium, given that the binding energy is 2.24 eV. Is this visible EM radiation?* |
| Solution | Yes, it is visible as green light. |
| 6. | *What is the binding energy in eV of electrons in magnesium, if the longest-wavelength photon that can eject electrons is 337 nm?* |
| Solution |  |
| 7. | *Calculate the binding energy in eV of electrons in aluminum, if the longest-wavelength photon that can eject them is 304 nm.* |
| Solution | The longest wavelength corresponds to the shortest frequency, or the smallest energy. Therefore, the smallest energy is when the kinetic energy is zero. From the equation , we can calculate the binding energy (writing the frequency in terms of the wavelength): |
| 8. | *What is the maximum kinetic energy in eV of electrons ejected from sodium metal by 450-nm EM radiation, given that the binding energy is 2.28 eV?* |
| Solution |  |
| 9. | *UV radiation having a wavelength of 120 nm falls on gold metal, to which electrons are bound by 4.82 eV. What is the maximum kinetic energy of the ejected photoelectrons?* |
| Solution |  |
| 10. | *Violet light of wavelength 400 nm ejects electrons with a maximum kinetic energy of 0.860 eV from sodium metal. What is the binding energy of electrons to sodium metal?* |
| Solution |  |
| 11. | *UV radiation having a 300-nm wavelength falls on uranium metal, ejecting 0.500-eV electrons. What is the binding energy of electrons to uranium metal?* |
| Solution |  |
| 12. | *What is the wavelength of EM radiation that ejects 2.00-eV electrons from calcium metal, given that the binding energy is 2.71 eV? What type of EM radiation is this?* |
| Solution | This is ultraviolet radiation. |
| 13. | *Find the wavelength of photons that eject 0.100-eV electrons from potassium, given that the binding energy is 2.24 eV. Are these photons visible?* |
| Solution | so  Yes, these photons are visible. |
| 14. | *What is the maximum velocity of electrons ejected from a material by 80-nm photons, if they are bound to the material by 4.73 eV?* |
| Solution |  |
| 15. | *Photoelectrons from a material with a binding energy of 2.71 eV are ejected by 420-nm photons. Once ejected, how long does it take these electrons to travel 2.50 cm to a detection device?* |
| Solution |  |
| 16. | *A laser with a power output of 2.00 mW at a wavelength of 400 nm is projected onto calcium metal. (a) How many electrons per second are ejected? (b) What power is carried away by the electrons, given that the binding energy is 2.31 eV?* |
| Solution | (a)    (b) |
| 17. | *(a) Calculate the number of photoelectrons per second ejected from a 1.00-mm2 area of sodium metal by 500-nm EM radiation having an intensity of  (the intensity of sunlight above the Earth’s atmosphere). (b) Given that the binding energy is 2.28 eV, what power is carried away by the electrons? (c) The electrons carry away less power than brought in by the photons. Where does the other power go? How can it be recovered?* |
| Solution | (a) First calculate *n*, the number of photons per second hitting a square-meter area. Each photon has energy    The number of ejected electrons per second equals the number of photons per second hitting the sodium metal, or :    (b)  (c) The other energy goes to the sodium metal to free the electrons (binding energy). This lost power can be recovered by the spontaneous absorption of electrons by sodium metal. For each electron absorbed an energy of 2.28eV will be released. |
| 18. | ***Unreasonable Results*** *Red light having a wavelength of 700 nm is projected onto magnesium metal to which electrons are bound by 3.68 eV. (a) Use  to calculate the kinetic energy of the ejected electrons. (b) What is unreasonable about this result? (c) Which assumptions are unreasonable or inconsistent?* |
| Solution | (a)  and since  (b) Negative kinetic energy is impossible.  (c) The assumption that the photon can knock the electron free is unreasonable. |
| 19. | ***Unreasonable Results*** *(a) What is the binding energy of electrons to a material from which 4.00-eV electrons are ejected by 400-nm EM radiation? (b) What is unreasonable about this result? (c) Which assumptions are unreasonable or inconsistent?* |
| Solution | (a) We want to use the equation  to determine the binding energy, so we first need to determine an expression of . Using , we know:    and since :  (b) The binding energy is too large for the given photon energy.  (c) The electron’s kinetic energy is too large for the given photon energy; it cannot be greater than the photon energy. |

# 29.3 Photon Energies and the Electromagnetic Spectrum

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| 20. | *What is the energy in joules and eV of a photon in a radio wave from an AM station that has a 1530-kHz broadcast frequency?* |
| Solution |  |
| 21. | *(a) Find the energy in joules and eV of photons in radio waves from an FM station that has a 90.0-MHz broadcast frequency. (b) What does this imply about the number of photons per second that the radio station must broadcast?* |
| Solution | (a)  (b) This implies that a tremendous number of photons must be broadcast per second. In order to have a broadcast power of, say 50.0 kW, it would take  . |
| 22. | *Calculate the frequency in hertz of a 1.00-MeV -ray photon.* |
| Solution |  |
| 23. | *(a) What is the wavelength of a 1.00-eV photon? (b) Find its frequency in hertz. (c) Identify the type of EM radiation.* |
| Solution | (a)  (b)  (c) The radiation is in the infrared part of the spectrum. |
| 24. | *Do the unit conversions necessary to show that , as stated in the text.* |
| Solution |  |
| 25. | *Confirm the statement in the text that the range of photon energies for visible light is 1.63 to 3.26 eV, given that the range of visible wavelengths is 380 to 760 nm.* |
| Solution |  |
| 26. | *(a) Calculate the energy in eV of an IR photon of frequency . (b) How many of these photons would need to be absorbed simultaneously by a tightly bound molecule to break it apart? (c) What is the energy in eV of a  ray of frequency ? (d) How many tightly bound molecules could a single such  ray break apart?* |
| Solution | (a)  (b)  (c)  (d) |
| 27. | *Prove that, to three-digit accuracy, , as stated in the text.* |
| Solution |  |
| 28. | *(a) What is the maximum energy in eV of photons produced in a CRT using a 25.0-kV accelerating potential, such as a color TV? (b) What is their frequency?* |
| Solution | (a)  (b) |
| 29. | *What is the accelerating voltage of an x-ray tube that produces x rays with a shortest wavelength of 0.0103 nm?* |
| Solution |  |
| 30. | *(a) What is the ratio of power outputs by two microwave ovens having frequencies of 950 and 2560 MHz, if they emit the same number of photons per second? (b) What is the ratio of photons per second if they have the same power output?* |
| Solution | (a) Let  be the number of photons per second  since  (b)  since |
| 31. | *How many photons per second are emitted by the antenna of a microwave oven, if its power output is 1.00 kW at a frequency of 2560 MHz?* |
| Solution |  |
| 32. | *Some satellites use nuclear power. (a) If such a satellite emits a 1.00-W flux of  rays having an average energy of 0.500 MeV, how many are emitted per second? (b) These  rays affect other satellites. How far away must another satellite be to only receive one  ray per second per square meter?* |
| Solution | (a)  (b) |
| 33. | *(a) If the power output of a 650-kHz radio station is 50.0 kW, how many photons per second are produced? (b) If the radio waves are broadcast uniformly in all directions, find the number of photons per second per square meter at a distance of 100 km. Assume no reflection from the ground or absorption by the air.* |
| Solution | (a)  Then,  (b) To calculate the flux of photons, we assume that the broadcast is uniform in all directions, so the area is the surface area of a sphere giving: |
| 34. | *How many x-ray photons per second are created by an x-ray tube that produces a flux of x rays having a power of 1.00 W? Assume the average energy per photon is 75.0 keV.* |
| Solution |  |
| 35. | *(a) How far away must you be from a 650-kHz radio station with power 50.0 kW for there to be only one photon per second per square meter? Assume no reflections or absorption, as if you were in deep outer space. (b) Discuss the implications for detecting intelligent life in other solar systems by detecting their radio broadcasts.* |
| Solution | (a)  (b) The distance calculated in part (a) is approximately 1/3 ly. Therefore, if radio stations from intelligent life in other solar systems are to be detected, their broadcasts would have to have substantial power outputs. Also, since there are stray radio waves in outer space, their signals would have to be large compared to the background radio waves. This means it is rather unlikely for us to detect intelligent life by detecting their radio broadcasts. |
| 36. | *Assuming that 10.0% of a 100-W light bulb’s energy output is in the visible range (typical for incandescent bulbs) with an average wavelength of 580 nm, and that the photons spread out uniformly and are not absorbed by the atmosphere, how far away would you be if 500 photons per second enter the 3.00-mm diameter pupil of your eye? (This number easily stimulates the retina.)* |
| Solution |  |

# 29.4 Photon Momentum

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| 38. | *(a) Find the momentum of a 4.00-cm-wavelength microwave photon. (b) Discuss why you expect the answer to (a) to be very small.* |
| Solution | (a)  (b) The wavelength of microwave photons is large, so the momentum they carry is very small. |
| 39. | *(a) What is the momentum of a 0.0100-nm-wavelength photon that could detect details of an atom? (b) What is its energy in MeV?* |
| Solution | (a)  (b) |
| 40. | *(a) What is the wavelength of a photon that has a momentum of ? (b) Find its energy in eV.* |
| Solution | (a) Using  (b) Using |
| 41. | *(a) A -ray photon has a momentum of . What is its wavelength? (b) Calculate its energy in MeV.* |
| Solution | (a)  (b) |
| 42. | *(a) Calculate the momentum of a photon having a wavelength of . (b) Find the velocity of an electron having the same momentum. (c) What is the kinetic energy of the electron, and how does it compare with that of the photon?* |
| Solution | (a)  (b)  (c) |
| 43. | *Repeat the previous problem for a 10.0-nm-wavelength photon.* |
| Solution | (a)  (b)  (c) |
| 44. | *(a) Calculate the wavelength of a photon that has the same momentum as a proton moving at 1.00% of the speed of light. (b) What is the energy of the photon in MeV? (c) What is the kinetic energy of the proton in MeV?* |
| Solution | (a)  (b)  (c) |
| 45. | *(a) Find the momentum of a 100-keV x-ray photon. (b) Find the equivalent velocity of a neutron with the same momentum. (c) What is the neutron’s kinetic energy in keV?* |
| Solution | (a)  (b)  (c) |
| 46. | *Take the ratio of relativistic rest energy, , to relativistic momentum, , and show that in the limit that mass approaches zero, you find .* |
| Solution | so  As the mass of particle approaches zero, its velocity will approach  so that the ratio of energy to momentum approaches  , which is consistent with the equation  for photons. |
| 48. | ***Unreasonable Results*** *A car feels a small force due to the light it sends out from its headlights, equal to the momentum of the light divided by the time in which it is emitted. (a) Calculate the power of each headlight, if they exert a total force of  backward on the car. (b) What is unreasonable about this result? (c) Which assumptions are unreasonable or inconsistent?* |
| Solution | (a)  (b) This is far too much energy for a car headlight.  (c) The force assumed is much too large, although it would have only a small effect on the car. |

# 29.6 The Wave Nature of Matter

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| 49. | *At what velocity will an electron have a wavelength of 1.00 m?* |
| Solution |  |
| 50. | *What is the wavelength of an electron moving at 3.00% of the speed of light?* |
| Solution |  |
| 51. | *At what velocity does a proton have a 6.00-fm wavelength (about the size of a nucleus)? Assume the proton is nonrelativistic. (1 femtometer = .)* |
| Solution |  |
| 52. | *What is the velocity of a 0.400-kg billiard ball if its wavelength is 7.50 cm (large enough for it to interfere with other billiard balls)?* |
| Solution |  |
| 53. | *Find the wavelength of a proton moving at 1.00% of the speed of light.* |
| Solution |  |
| 54. | *Experiments are performed with ultracold neutrons having velocities as small as 1.00 m/s. (a) What is the wavelength of such a neutron? (b) What is its kinetic energy in eV?* |
| Solution | (a)  (b) |
| 55. | *(a) Find the velocity of a neutron that has a 6.00-fm wavelength (about the size of a nucleus). Assume the neutron is nonrelativistic. (b) What is the neutron’s kinetic energy in MeV?* |
| Solution | (a) .  (b) |
| 56. | *What is the wavelength of an electron accelerated through a 30.0-kV potential, as in a TV tube?* |
| Solution |  |
| 57. | *What is the kinetic energy of an electron in a TEM having a 0.0100-nm wavelength?* |
| Solution | Note that in the previous problem the electron with  of 30 KeV was found to have a wavelength of 0.007 nm. To obtain this  of 0.01 nm, the electron would have to accelerate through a potential difference of , which is consistent with the above result. |
| 58. | *(a) Calculate the velocity of an electron that has a wavelength of . (b) Through what voltage must the electron be accelerated to have this velocity?* |
| Solution | (a)  (b) |
| 59. | *The velocity of a proton emerging from a Van de Graaff accelerator is 25.0% of the speed of light. (a) What is the proton’s wavelength? (b) What is its kinetic energy, assuming it is nonrelativistic? (c) What was the equivalent voltage through which it was accelerated?* |
| Solution | (a)  (b)  (c) |
| 60. | *The kinetic energy of an electron accelerated in an x-ray tube is 100 keV. Assuming it is nonrelativistic, what is its wavelength?* |
| Solution |  |
| 61. | ***Unreasonable Results*** *(a) Assuming it is nonrelativistic, calculate the velocity of an electron with a 0.100-fm wavelength (small enough to detect details of a nucleus). (b) What is unreasonable about this result? (c) Which assumptions are unreasonable or inconsistent?* |
| Solution | (a)  (b) It is many times faster than the speed of light (an impossibility).  (c) The non-relativistic assumption is unreasonable at the given wavelength. |

# 29.7 Probability: The Heisenberg Uncertainty Principle

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| 62. | *(a) If the position of an electron in a membrane is measured to an accuracy of , what is the electron’s minimum uncertainty in velocity? (b) If the electron has this velocity, what is its kinetic energy in eV? (c) What are the implications of this energy, comparing it to typical molecular binding energies?* |
| Solution | (a)  (b)  (c) From Table 29.1 we see that typical molecular binding energies range from about 1eV to 10 eV; therefore the result in part (b) is approximately 9 orders of magnitude smaller than typical molecular binding energies. |
| 63. | *(a) If the position of a chlorine ion in a membrane is measured to an accuracy of , what is its minimum uncertainty in velocity, given its mass is ? (b) If the ion has this velocity, what is its kinetic energy in eV, and how does this compare with typical molecular binding energies?* |
| Solution | (a)  (b) |
| 64. | *Suppose the velocity of an electron in an atom is known to an accuracy of  (reasonably accurate compared with orbital velocities). What is the electron’s minimum uncertainty in position, and how does this compare with the approximate 0.1-nm size of the atom?* |
| Solution |  |
| 65. | *The velocity of a proton in an accelerator is known to an accuracy of 0.250% of the speed of light. (This could be small compared with its velocity.) What is the smallest possible uncertainty in its position?* |
| Solution |  |
| 66. | *A relatively long-lived excited state of an atom has a lifetime of 3.00 ms. What is the minimum uncertainty in its energy?* |
| Solution | , so |
| 67. | *(a) The lifetime of a highly unstable nucleus is . What is the smallest uncertainty in its decay energy? (b) Compare this with the rest energy of an electron.* |
| Solution | (a)  (b) |
| 68. | *The decay energy of a short-lived particle has an uncertainty of 1.0 MeV due to its short lifetime. What is the smallest lifetime it can have?* |
| Solution |  |
| 69. | *The decay energy of a short-lived nuclear excited state has an uncertainty of 2.0 eV due to its short lifetime. What is the smallest lifetime it can have?* |
| Solution |  |
| 70. | *What is the approximate uncertainty in the mass of a muon, as determined from its decay lifetime?* |
| Solution |  |
| 71. | *Derive the approximate form of Heisenberg’s uncertainty principle for energy and time, , using the following arguments: Since the position of a particle is uncertain by , where  is the wavelength of the photon used to examine it, there is an uncertainty in the time the photon takes to traverse . Furthermore, the photon has an energy related to its wavelength, and it can transfer some or all of this energy to the object being examined. Thus the uncertainty in the energy of the object is also related to . Find  and ; then multiply them to give the approximate uncertainty principle.* |
| Solution |  |

# 29.8 The Particle-Wave Duality Reviewed

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| 72. | ***Integrated Concepts*** *The 54.0-eV electron in Example 29.7 has a 0.167-nm wavelength. If such electrons are passed through a double slit and have their first maximum at an angle of , what is the slit separation ?* |
| Solution | Using the equation , we can solve for the slit separation when  for the first order maximum: |
| 73. | ***Integrated Concepts*** *An electron microscope produces electrons with a 2.00-pm wavelength. If these are passed through a 1.00-nm single slit, at what angle will the first diffraction minimum be found?* |
| Solution |  |
| 74. | ***Integrated Concepts*** *A certain heat lamp emits 200 W of mostly IR radiation averaging 1500 nm in wavelength. (a) What is the average photon energy in joules? (b) How many of these photons are required to increase the temperature of a person’s shoulder by , assuming the affected mass is 4.0 kg with a specific heat of . Also assume no other significant heat transfer. (c) How long does this take?* |
| Solution | (a)  (b)  (c) |
| 75. | ***Integrated Concepts*** *On its high power setting, a microwave oven produces 900 W of 2560 MHz microwaves. (a) How many photons per second is this? (b) How many photons are required to increase the temperature of a 0.500-kg mass of pasta by , assuming a specific heat of ? Neglect all other heat transfer. (c) How long must the microwave operator wait for their pasta to be ready?* |
| Solution | (a)  (b)  (c) |
| 76. | ***Integrated Concepts*** *(a) Calculate the amount of microwave energy in joules needed to raise the temperature of 1.00 kg of soup from  to . (b) What is the total momentum of all the microwave photons it takes to do this? (c) Calculate the velocity of a 1.00-kg mass with the same momentum. (d) What is the kinetic energy of this mass?* |
| Solution | Assume soup has the same specific heat as water.  (a)  (b)  (c)  (d) |
| 77. | ***Integrated Concepts*** *(a) What is  for an electron emerging from the Stanford Linear Accelerator with a total energy of 50.0 GeV? (b) Find its momentum. (c) What is the electron’s wavelength?* |
| Solution | (a)  (b) For such a large  (within part in )    (c) |
| 78. | ***Integrated Concepts*** *(a) What is  for a proton having an energy of 1.00 TeV, produced by the Fermilab accelerator? (b) Find its momentum. (c) What is the proton’s wavelength?* |
| Solution | (a) Using    (b)  (c) |
| 79. | ***Integrated Concepts*** *An electron microscope passes 1.00-pm-wavelength electrons through a circular aperture  in diameter. What is the angle between two just-resolvable point sources for this microscope?* |
| Solution |  |
| 80. | ***Integrated Concepts*** *(a) Calculate the velocity of electrons that form the same pattern as 450-nm light when passed through a double slit. (b) Calculate the kinetic energy of each and compare them. (c) Would either be easier to generate than the other? Explain.* |
| Solution | (a)  (b) For the photon:  For the electron:    The photon energy is  times greater.  (c) The light is probably easier to make, because 450 nm light is blue light and therefore easy to make. Creating electrons with  of energy would not be difficult, but would require a vacuum. |
| 81. | ***Integrated Concepts*** *(a) What is the separation between double slits that produces a second-order minimum at  for 650-nm light? (b) What slit separation is needed to produce the same pattern for 1.00-keV protons.* |
| Solution | (a)  (b) , so that |
| 82. | ***Integrated Concepts*** *A laser with a power output of 2.00 mW at a wavelength of 400 nm is projected onto calcium metal. (a) How many electrons per second are ejected? (b) What power is carried away by the electrons, given that the binding energy is 2.31 eV? (c) Calculate the current of ejected electrons. (d) If the photoelectric material is electrically insulated and acts like a 2.00-pF capacitor, how long will current flow before the capacitor voltage stops it?* |
| Solution | (a)  (b)  (c)  (d)  is the voltage across the capacitor. This  will stop the flow when the energy required to cross the capacitor, , equals or exceeds the kinetic energy of the electrons. |
| 83. | ***Integrated Concepts*** *One problem with x rays is that they are not sensed. Calculate the temperature increase of a researcher exposed in a few seconds to a nearly fatal accidental dose of x rays under the following conditions. The energy of the x-ray photons is 200 keV, and  of them are absorbed per kilogram of tissue, the specific heat of which is . (Note that medical diagnostic x-ray machines* cannot *produce an intensity this great.)* |
| Solution | First, we know the amount of heat absorbed by 1.00 kg of tissue is equal to the number of photons times the energy each one carry, so:    Next, using the equation , we can determine how much 1.00 kg tissue is heated: |
| 84. | ***Integrated Concepts*** *A 1.00-fm photon has a wavelength short enough to detect some information about nuclei. (a) What is the photon momentum? (b) What is its energy in joules and MeV? (c) What is the (relativistic) velocity of an electron with the same momentum? (d) Calculate the electron’s kinetic energy.* |
| Solution | (a)  (b)  (c) , so that    Since  is very small, use the binomial expansion:    (d)  Relativistic kinetic energy |
| 85. | ***Integrated Concepts*** *The momentum of light is exactly reversed when reflected straight back from a mirror, assuming negligible recoil of the mirror. Thus the change in momentum is twice the photon momentum. Suppose light of intensity  reflects from a mirror of area . (a) Calculate the energy reflected in 1.00 s. (b) What is the momentum imparted to the mirror? (c) Using the most general form of Newton’s second law, what is the force on the mirror? (d) Does the assumption of no mirror recoil seem reasonable?* |
| Solution | (a)  (b)  (c)  (d) Yes, with such a small force on the mirror, it will move very little during the time it takes for the photons to bounce off the mirror. |
| 86. | ***Integrated Concepts*** *Sunlight above the Earth’s atmosphere has an intensity of . If this is reflected straight back from a mirror that has only a small recoil, the light’s momentum is exactly reversed, giving the mirror twice the incident momentum. (a) Calculate the force per square meter of mirror. (b) Very low mass mirrors can be constructed in the near weightlessness of space, and attached to a spaceship to sail it. Once done, the average mass per square meter of the spaceship is 0.100 kg. Find the acceleration of the spaceship if all other forces are balanced. (c) How fast is it moving 24 hours later?* |
| Solution | In one second the incident energy per square meter will be 1.30 kJ.  (a)  (b)  (c) |

# Test Prep For AP® Courses

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| 1. | *The visible spectrum sunlight shows a range of colors from red to violet. This spectrum has numerous dark lines spread throughout it. Noting that the surface of the Sun is much cooler than the interior, so that the surface is comparable to a cool gas through which light passes, which of the following statements correctly explains the dark lines?*  (a) The cooler, denser surface material scatters certain wavelengths of light, forming dark lines.  (b) The atoms at the surface absorb certain wavelengths of light, causing the dark lines at those wavelengths.  (c) The atoms in the Sun’s interior emit light of specific wavelength, so that parts of the spectrum are dark.  (d) The atoms at the surface are excited by the high interior temperatures, so that the dark lines are merely wavelengths at which those atoms don’t emit energy. |
| Solution | (b) |
| 2. | *A log in a fireplace burns for nearly an hour, at which point it consists mostly of small, hot embers. These embers glow a bright orange and whitish-yellow color. Describe the characteristics of the energy of this system, both in terms of energy transfer and the quantum behavior of blackbodies.* |
| Solution | The chemical potential energy in the log is released through combustion. Because of energy conservation, some of this energy is transferred to the surrounding air by heat. The rest of the energy is emitted as electromagnetic radiation. The greater the temperature of the embers, the greater the energy of the emitted light. The emitted radiation follows the curve typical of blackbody radiators, in that it increases quickly with temperature, peaks at a certain wavelength, and then decreases gradually at higher frequencies. If more energy were emitted as electromagnetic radiation, the embers would glow more brightly and at colors with shorter wavelengths (for example, the white glow of metal that has been heated to “white hot”). Because electromagnetic energy is emitted at certain frequencies by blackbodies, the amount of energy is finite. This is in keeping with both the quantum interpretation of blackbody behavior and the principle of conservation of energy. |
| 3. | *A metal exposed to a beam of light with a wavelength equal to or shorter than a specific wavelength emits electrons. What property of light, as described in the quantum explanation of blackbody radiation, accounts for this photoelectric process?*  (a) The energy of light increases as its speed increases.  (b) The energy of light increases as its intensity increases.  (c) The energy of light increases as its frequency increases.  (d) The energy of light increases as its wavelength increases. |
| Solution | (c) |
| 4. | *During his experiments that confirmed the existence of electromagnetic waves, Heinrich Hertz used a spark across a gap between two electrodes to provide the rapidly changing electric current that produced electromagnetic waves. He noticed, however, that production of the spark required a lower voltage in a well-lighted laboratory than when the room was dark. Describe how this curious event can be explained in terms of the quantum interpretation of the photoelectric effect.* |
| Solution | High-energy (high-frequency) photons in the light caused electrons to be dislodged from the metal in the electrodes. This made it easier for a spark to cross the gap at a lower voltage. This is consistent with the quantum theory of light, but not the classical model. Electromagnetic waves were regarded as mechanical waves, and the energy of mechanical waves is associated with their intensity, which depends on amplitude. However, experimental evidence revealed that the energy of electromagnetic waves depends on their frequency. This could be explained only by the quantum theory of light. |
| 5. | *A microwave oven produces electromagnetic radiation in the radio portion of the spectrum. These microwave photons are absorbed by water molecules, resulting in an increase in the molecules’ rotational energies. This added energy is transferred by heat to the surrounding food, which as a result becomes hot very quickly. If the energy absorbed by a water molecule is 1.0 × 10–5 eV, what is the corresponding wavelength of the microwave photons?*  (a) 1.22 GHz  (b) 2.45 GHz  (c) 4.90 GHz  (d) 9.80 Hz |
| Solution | (b) |
| 6. | *In the intensity versus frequency curve for x rays (Figure 29.14), the intensity is mostly a smooth curve associated with bremsstrahlung (“breaking radiation”). However, there are two spikes (characteristic x rays) that exhibit high-intensity output. Explain how the smooth curve can be described by classical electrodynamics, whereas the peaks require a quantum mechanical interpretation. (Recall that the acceleration or deceleration of electric charges causes the emission of electromagnetic radiation.)* |
| Solution | The smooth intensity curve is produced by electrons that are decelerated as they interact with the repulsive electric fields of the atoms in the anode metal. The change in electron speeds can occur over a continuous range of values, and so is described by classical electromagnetic theory. In contrast to this, the characteristic x rays occur when energy from the electrons is conveyed to the atoms of the anode, causing excitation of the electrons in those atoms. This energy is then re-emitted as photons with specific x-ray energies. According to the quantum mechanical model of the atom, only certain energies can be absorbed and re-emitted by atoms. The x-ray photons at the frequencies associated with these energies account for the characteristic spikes in the curve. |
| 7. | *The mass of a proton is 1.67 × 10–27 kg. If a proton has the same momentum as a photon with a wavelength of 325 nm, what is its speed?*  (a) 2.73 × 10–3 m/s  (b) 0.819 m/s  (c) 1.22 m/s  (d) 2.71 × 104 m/s |
| Solution | (c) |
| 8. | *A strip of metal foil with a mass of 5.00 × 10–7 kg is suspended in a vacuum and exposed to a pulse of light. The velocity of the foil changes from zero to 1.00 × 10–3 m/s in the same direction as the initial light pulse, and the light pulse is entirely reflected from the surface of the foil. Given that the wavelength of the light is 450 nm, and assuming that this wavelength is the same before and after the collision, how many photons in the pulse collide with the foil?* |
| Solution | From conservation of linear momentum, the total momentum of the system before the collision equals the total momentum after the collision. Before the collision, the momentum of the system is the momentum of the light pulse, which consists of *N* photons: . The momentum of the system after the collision, because the foil and momentum are moving in opposite directions, is the difference of the momentum of the foil and the photons: . Because momentum is conserved,    The light pulse therefore consists of 1.70 × 1017 photons. |
| 9. | *In an experiment in which the Compton effect is observed, a “gamma ray” photon with a wavelength of 5.00 × 10–13 m scatters from an electron. If the change in the electron energy is 1.60 × 10–15 J, what is the wavelength of the photon after the collision with the electron?*  (a) 4.95 × 10–13 m  (b) 4.98 × 10–13 m  (c) 5.02 × 10–13 m  (d) 5.05 × 10–13 m |
| Solution | (c) |
| 10. | *Consider two experiments involving a metal sphere with a radius of 2.00 μm that is suspended in a vacuum. In one experiment, a pulse of N photons reflects from the surface of the sphere, causing the sphere to acquire momentum. In a second experiment, an identical pulse of photons is completely absorbed by the sphere, so that the sphere acquires momentum. Identify each type of collision as either elastic or inelastic, and, assuming that the change in the photon wavelength can be ignored, use linear momentum conservation to derive the expression for the momentum of the sphere in each experiment.* |
| Solution | In the first situation, where the photons are reflected, the collision is perfectly elastic. Therefore, the equation for the system momentum before the collision (left of = sign) and the momentum after the collision (right of = sign) is , so that the momentum of the sphere is . In the second experiment, the photons are absorbed, which is analogous to an inelastic collision. Therefore, all of the photon momentum is transferred to the combined sphere and photon system, which, because photons lack mass, has the same mass as the sphere alone. The momentum is . |
| 11. | *The ground state of a certain type of atom has energy of –E0. What is the wavelength of a photon with enough energy to ionize the atom when it is in the ground state, so that the ejected electron has kinetic energy equal to 2E0?*  (a)  (b)  (c)  (d) |
| Solution | (a) |
| 12. | *While the quantum model explains many physical processes that the classical model cannot, it must be consistent with those processes that the classical model does explain. Energy and momentum conservation are fundamental principles of classical physics. Use the Compton and photoelectric effects to explain how these conservation principles carry over to the quantum model of light.* |
| Solution | In classical mechanics, waves transfer energy, and in their interactions with matter, energy and momentum are transferred to that matter. In the photoelectric effect, the energy of the photon is transferred to an atom of a given metal. Provided that this energy is equal to or greater than the binding energy of the metal, an electron is emitted. The binding energy and energy of the electron equal the energy of the photon, confirming energy conservation. Similarly, in the Compton effect, the interaction between light and matter is a type of collision in which momentum is conserved. The momentum from the photon is transferred to an electron, causing the electron to gain momentum and the photon to lose some of its momentum. |
| 13. | *The least massive particle known to exist is the electron neutrino. Though scientists once believed that it had no mass, like the photon, they have now determined that this particle has an extremely low mass, equivalent to a few electron volts. Assuming a mass of 2.2 eV/c2 (or 3.9 × 10–36 kg) and a speed of 4.4 × 106 m/s, which of the following values equals the neutrino’s de Broglie wavelength?*  (a) 3.8 × 10–5 m  (b) 4.7 × 10–7 m  (c) 1.7 × 10–10 m  (d) 8.9 × 10–14 m |
| Solution | (a) |
| 14. | *Using the definition of the de Broglie wavelength, explain how wavelike properties of matter increase with a decrease in mass or decrease in speed. Use as examples an electron (mass = 9.11 × 10–31 kg) with a speed of 5.0 × 106 m/s and a proton (mass = 1.67 × 10–27 kg) with a speed of 8.0 × 106 m/s.* |
| Solution | The de Broglie wavelength is given by the equation . Therefore, as either *m* or *v* become smaller, *λ* increases, so that the wavelike properties of matter become more pronounced. In the case of the examples, the electron would have a wavelength of  . This is comparable to the wavelength of energetic x rays. For the proton, , which corresponds to the wavelength for gamma particles. |
| 15. | *In a Davisson-Germer type of experiment, a crystal with a parallel-plane separation (d) of 9.1 × 10–2 nm produces constructive interference with an electron beam at an angle of θ = 50°. Which of the following is the maximum de Broglie wavelength for these electrons?*  (a) 0.07nm  (b) 0.09 nm  (c) 0.14 nm  (d) 0.21 nm |
| Solution | (c) |
| 16. | *In a Davisson-Germer experiment, electrons with a speed of 6.5 × 106 m/s exhibit third-order (n = 3) constructive interference for a crystal with unknown plane separation, d. Given an angle of incidence of θ = 45°, compute the value for d. Compare the de Broglie wavelength to electromagnetic radiation with the same wavelength. (Recall that the mass of the electron is 9.11 × 10–31 kg.)* |
| Solution | The equation for electron or x-ray diffraction is . Substituting the equation for the de Broglie wavelength (), the diffraction equation takes the form . For the given conditions, , or 0.24 nm. The de Broglie wavelength of the electrons is about 0.11 nm, which is the same as the wavelength of x rays. |
| 17. | [Figure 29\_M7\_wave\_img]    *The figure above shows graphical representations of the wave functions of two particles, X and Y, both of which are moving in the positive x-direction. The amplitude, when squared, represents probability. The maximum amplitude of particle X’s wave function is A0. Which particle has a greater probability of being located at position x0 at this instant, and why?*  (a) Particle *X*, because the wave function of particle *X* spends more time passing through *x*0 than the wave function of particle *Y*. (b) Particle *X*, because the wave function of particle *X* has a longer wavelength than the wave function of particle *Y*.  (c) Particle *Y*, because the wave function of particle *Y* is narrower than the wave function of particle *X*.  (d) Particle *Y*, because the wave function of particle *Y* has a greater amplitude near *x*0 than the wave function of particle *X*. |
| Solution | (d) |
| 18. | *From the figure shown above, explain which particle has a more precisely measured value of momentum, and why this is the case.* |
| Solution | According to Heisenberg’s uncertainty principle, the momentum and position of a particle cannot be measured with exact precision. The more precise (less uncertain) the measurement of position is, the less precise (more uncertain) the measurement of the particle’s momentum. From the figure of the two wave functions for the two particles, particle *Y* has a more precisely determined position, so its Δ*x* is smaller than that of particle *X*. Therefore, from the uncertainty principle (Δ*x*Δ*p* ≈ *h*), Δ*p* is greater for particle *Y* than for particle *X*. Particle *X*, therefore, has the more precisely measured value for momentum. |
| 19. | *Which of the following describes one of the main features of wave-particle duality?*  (a) As speed increases, the wave nature of matter becomes more evident.  (b) As momentum decreases, the particle nature of matter becomes more evident.  (c) As energy increases, the wave nature of matter becomes easier to observe. (d) As mass increases, the wave nature of matter is less easy to observe. |
| Solution | (d) |
| 20. | *Explain why Heisenberg’s uncertainty principle limits the precision with which either momentum or position of a subatomic particle can be known, but becomes less applicable for matter at the macroscopic level.* |
| Solution | For macroscopic objects, such as a large rock, any measurement of its position will not change its momentum in a significant way. This is because the product of change in momentum (Δ*p*) and change in position (Δ*x*), although not zero, is close to zero because it is on the order of Planck’s constant (~10–34). The change in either quantity is extremely small compared to the macroscopic values for *p* and *x*. As matter becomes smaller in size and mass, measurement becomes more difficult, because making the measurement affects the property being measured. For example, using a beam of neutrons to measure the position of an atom will change the atom’s momentum. The change in *p* or *x* is on the same order of magnitude as those values themselves. |

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