3.E: Photons and Matter Waves (Exercise)

Conceptual Questions

6.1 Blackbody Radiation

1. Which surface has a higher temperature – the surface of a yellow star or that of a red star?

2. Describe what you would see when looking at a body whose temperature is increased from 1000 K to 1,000,000 K.

3. Explain the color changes in a hot body as its temperature is increased.

4. Speculate as to why UV light causes sunburn, whereas visible light does not.

5. Two cavity radiators are constructed with walls made of different metals. At the same temperature, how would their radiation spectra differ?

6. Discuss why some bodies appear black, other bodies appear red, and still other bodies appear white.

7. If everything radiates electromagnetic energy, why can we not see objects at room temperature in a dark room?

8. How much does the power radiated by a blackbody increase when its temperature (in K) is tripled?

6.2 Photoelectric Effect

9. For the same monochromatic light source, would the photoelectric effect occur for all metals?

10. In the interpretation of the photoelectric effect, how is it known that an electron does not absorb more than one photon?

11. Explain how you can determine the work function from a plot of the stopping potential versus the frequency of the incident radiation in a

photoelectric effect experiment. Can you determine the value of Planck's constant from this plot?

12. Suppose that in the photoelectric-effect experiment we make a plot of the detected current versus the applied potential difference. What information do we obtain from such a plot? Can we determine from it the value of Planck's constant? Can we determine the work function of the metal?

13. Speculate how increasing the temperature of a photoelectrode affects the outcomes of the photoelectric effect experiment.

14. Which aspects of the photoelectric effect cannot be explained by classical physics?

15. Is the photoelectric effect a consequence of the wave character of radiation or is it a consequence of the particle character of radiation? Explain briefly.

16. The metals sodium, iron, and molybdenum have work functions 2.5 eV, 3.9 eV, and 4.2 eV, respectively. Which of these metals will emit photoelectrons when illuminated with 400 nm light?

6.3 The Compton Effect

17. Discuss any similarities and differences between the photoelectric and the Compton effects.

18. Which has a greater momentum: an UV photon or an IR photon?

19. Does changing the intensity of a monochromatic light beam affect the momentum of the individual photons in the beam? Does such a change affect the net momentum of the beam?

20. Can the Compton effect occur with visible light? If so, will it be detectable?

21. Is it possible in the Compton experiment to observe scattered X-rays that have a shorter wavelength than the incident X-ray radiation?

22. Show that the Compton wavelength has the dimension of length.

23. At what scattering angle is the wavelength shift in the Compton effect equal to the Compton wavelength?

6.4 Bohr's Model of the Hydrogen Atom

24. Explain why the patterns of bright emission spectral lines have an identical spectral position to the pattern of dark absorption spectral lines for a given gaseous element.

25. Do the various spectral lines of the hydrogen atom overlap?

26. The Balmer series for hydrogen was discovered before either the Lyman or the Paschen series. Why?

27. When the absorption spectrum of hydrogen at room temperature is analyzed, absorption lines for the Lyman series are found, but none are found for the Balmer series. What does this tell us about the energy state of most hydrogen atoms at room temperature?

28. Hydrogen accounts for about 75% by mass of the matter at the surfaces of most stars. However, the absorption lines of hydrogen are strongest (of highest intensity) in the spectra of stars with a surface temperature of about 9000 K. They are weaker in the sun spectrum and are essentially nonexistent in very hot (temperatures above 25,000 K) or rather cool (temperatures below 3500 K) stars. Speculate as to why surface temperature affects the hydrogen absorption lines that we observe.

29. Discuss the similarities and differences between Thomson's model of the hydrogen atom and Bohr's model of the hydrogen atom.

30. Discuss the way in which Thomson's model is nonphysical. Support your argument with experimental evidence.

31. If, in a hydrogen atom, an electron moves to an orbit with a larger radius, does the energy of the hydrogen atom increase or decrease?

32. How is the energy conserved when an atom makes a transition from a higher to a lower energy state?

33. Suppose an electron in a hydrogen atom makes a transition from the **(n+1)**th orbit to the nth orbit. Is the wavelength of the emitted photon longer for larger values of **n**, or for smaller values of **n**?

34. Discuss why the allowed energies of the hydrogen atom are negative.

35. Can a hydrogen atom absorb a photon whose energy is greater than 13.6 eV?

36. Why can you see through glass but not through wood?

37. Do gravitational forces have a significant effect on atomic energy levels?

38. Show that Planck's constant has the dimensions of angular momentum.

6.5 De Broglie's Matter Waves

39. Which type of radiation is most suitable for the observation of diffraction patterns on crystalline solids; radio waves, visible light, or X-rays? Explain.

40. Speculate as to how the diffraction patterns of a typical crystal would be affected if $\gamma - rays$ were used instead of X-rays.

41. If an electron and a proton are traveling at the same speed, which one has the shorter de Broglie wavelength?

42. If a particle is accelerating, how does this affect its de Broglie wavelength?

43. Why is the wave-like nature of matter not observed every day for macroscopic objects?

44. What is the wavelength of a neutron at rest? Explain.

45. Why does the setup of Davisson–Germer experiment need to be enclosed in a vacuum chamber? Discuss what result you expect when the chamber is not evacuated.

6.6 Wave-Particle Duality

46. Give an example of an experiment in which light behaves as waves. Give an example of an experiment in which light behaves as a stream of photons.

47. Discuss: How does the interference of water waves differ from the interference of electrons? How are they analogous?

48. Give at least one argument in support of the matter-wave hypothesis.

49. Give at least one argument in support of the particle-nature of radiation.

50. Explain the importance of the Young double-slit experiment.

51. Does the Heisenberg uncertainty principle allow a particle to be at rest in a designated region in space?

52. Can the de Broglie wavelength of a particle be known exactly?

53. Do the photons of red light produce better resolution in a microscope than blue light photons? Explain.

54. Discuss the main difference between an SEM and a TEM.

Problems

6.1 Blackbody Radiation

55. A 200-W heater emits a 1.5-µm radiation.

(a) What value of the energy quantum does it emit?

(b) Assuming that the specific heat of a 4.0-kg body is $0.83 kcal/kg \cdot K$, how many of these photons must be absorbed by the body to increase its temperature by 2 K?

(c) How long does the heating process in (b) take, assuming that all radiation emitted by the heater gets absorbed by the body?

56. A 900-W microwave generator in an oven generates energy quanta of frequency 2560 MHz.

(a) How many energy quanta does it emit per second?

(b) How many energy quanta must be absorbed by a pasta dish placed in the radiation cavity to increase its temperature by 45.0 K? Assume that the dish has a mass of 0.5 kg and that its specific heat is $0.9 kcal/kg \cdot K$.

(c) Assume that all energy quanta emitted by the generator are absorbed by the pasta dish. How long must we wait until the dish in (b) is ready?

57. (a) For what temperature is the peak of blackbody radiation spectrum at 400 nm?

(b) If the temperature of a blackbody is 800 K, at what wavelength does it radiate the most energy?

58. The tungsten elements of incandescent light bulbs operate at 3200 K. At what wavelength does the filament radiate maximum energy?

59. Interstellar space is filled with radiation of wavelength $970 \mu m$. This radiation is considered to be a remnant of the "big bang." What is the corresponding blackbody temperature of this radiation?

60. The radiant energy from the sun reaches its maximum at a wavelength of about 500.0 nm. What is the approximate temperature of the sun's surface?

6.2 Photoelectric Effect

61. A photon has energy 20 keV. What are its frequency and wavelength?

62. The wavelengths of visible light range from approximately 400 to 750 nm. What is the corresponding range of photon energies for visible light?

63. What is the longest wavelength of radiation that can eject a photoelectron from silver? Is it in the visible range?

64. What is the longest wavelength of radiation that can eject a photoelectron from potassium, given the work function of potassium 2.24 eV? Is it in the visible range?

65. Estimate the binding energy of electrons in magnesium, given that the wavelength of 337 nm is the longest wavelength that a photon may have to eject a photoelectron from magnesium photoelectrode.

66. The work function for potassium is 2.26 eV. What is the cutoff frequency when this metal is used as photoelectrode? What is the stopping potential when for the emitted electrons when this photoelectrode is exposed to radiation of frequency 1200 THz?

67. Estimate the work function of aluminum, given that the wavelength of 304 nm is the longest wavelength that a photon may have to eject a photoelectron from aluminum photoelectrode.

68. What is the maximum kinetic energy of photoelectrons ejected from sodium by the incident radiation of wavelength 450 nm?

69. A 120-nm UV radiation illuminates a silver-plated electrode. What is the maximum kinetic energy of the ejected photoelectrons?

70. A 400-nm violet light ejects photoelectrons with a maximum kinetic energy of 0.860 eV from sodium photoelectrode. What is the work function of sodium?

71. A 600-nm light falls on a photoelectric surface and electrons with the maximum kinetic energy of 0.17 eV are emitted. Determine

(a) the work function and

(b) the cutoff frequency of the surface.

(c) What is the stopping potential when the surface is illuminated with light of wavelength 400 nm?

72. The cutoff wavelength for the emission of photoelectrons from a particular surface is 500 nm. Find the maximum kinetic energy of the ejected photoelectrons when the surface is illuminated with light of wavelength 600 nm.

73. Find the wavelength of radiation that can eject 2.00-eV electrons from calcium electrode. The work function for calcium is 2.71 eV. In what range is this radiation?

74. Find the wavelength of radiation that can eject 0.10-eV electrons from potassium electrode. The work function for potassium is 2.24 eV. In what range is this radiation?

75. Find the maximum velocity of photoelectrons ejected by an 80-nm radiation, if the work function of photoelectrode is 4.73 eV.

6.3 The Compton Effect

76. What is the momentum of a 589-nm yellow photon?

77. What is the momentum of a 4-cm microwave photon?

78. In a beam of white light (wavelengths from 400 to 750 nm), what range of momentum can the photons have?

79. What is the energy of a photon whose momentum is $3.0 \times 10^{-24} kg \cdot m/s$?

80. What is the wavelength of

(a) a 12-keV X-ray photon;

(b) a 2.0-MeV γ-ray photon?

81. Find the momentum and energy of a 1.0-Å photon.

82. Find the wavelength and energy of a photon with momentum $5.00 \times 10^{-29} kg \cdot m/s$.

83. A γ-ray photon has a momentum of $8.00 \times 10^{-21} kg \cdot m/s$. Find its wavelength and energy.

84. (a) Calculate the momentum of a $2.5 - \mu m$ photon.

(b) Find the velocity of an electron with the same momentum.

(c) What is the kinetic energy of the electron, and how does it compare to that of the photon?

85. Show that $p = h/\lambda$ and $E_f = hf$ are consistent with the relativistic formula $E^2 = p^2c^2 + m_0^2c^2$.

86. Show that the energy E in eV of a photon is given by $E = 1.241 \times 10^{-6} eV \cdot m/\lambda$, where λ is its wavelength in meters.

87. For collisions with free electrons, compare the Compton shift of a photon scattered as an angle of 30° to that of a photon scattered at 45°.

88. X-rays of wavelength 12.5 pm are scattered from a block of carbon. What are the wavelengths of photons scattered at

(a) 30°;

(b) 90°; and,

(c) 180°?

6.4 Bohr's Model of the Hydrogen Atom

89. Calculate the wavelength of the first line in the Lyman series and show that this line lies in the ultraviolet part of the spectrum.

90. Calculate the wavelength of the fifth line in the Lyman series and show that this line lies in the ultraviolet part of the spectrum.

91. Calculate the energy changes corresponding to the transitions of the hydrogen atom:

(a) from $n=3$ to $n=4$;

(b) from $n=2$ to $n=1$; and

(c) from $n=3$ to $n=\infty$.

92. Determine the wavelength of the third Balmer line (transition from $n=5$ to $n=2$).

93. What is the frequency of the photon absorbed when the hydrogen atom makes the transition from the ground state to the $n=4$ state?

94. When a hydrogen atom is in its ground state, what are the shortest and longest wavelengths of the photons it can absorb without being ionized?

95. When a hydrogen atom is in its third excided state, what are the shortest and longest wavelengths of the photons it can emit?

96. What is the longest wavelength that light can have if it is to be capable of ionizing the hydrogen atom in its ground state?

97. For an electron in a hydrogen atom in the $n=2$ state, compute:

(a) the angular momentum;

(b) the kinetic energy;

(c) the potential energy; and

(d) the total energy.

98. Find the ionization energy of a hydrogen atom in the fourth energy state.

99. It has been measured that it required 0.850 eV to remove an electron from the hydrogen atom. In what state was the atom before the ionization happened?

100. What is the radius of a hydrogen atom when the electron is in the first excited state?

101. Find the shortest wavelength in the Balmer series. In what part of the spectrum does this line lie?

102. Show that the entire Paschen series lies in the infrared part of the spectrum.

103. Do the Balmer series and the Lyman series overlap? Why? Why not? (Hint: calculate the shortest Balmer line and the longest Lyman line.)

104. (a) Which line in the Balmer series is the first one in the UV part of the spectrum?

(b) How many Balmer lines lie in the visible part of the spectrum?

(c) How many Balmer lines lie in the UV?

105. A $4.653-\mu m$ emission line of atomic hydrogen corresponds to transition between the states $n_f=5$ and n_i. Find n_i.

6.5 De Broglie's Matter Waves

106. At what velocity will an electron have a wavelength of 1.00 m?

107. What is the de Broglie wavelength of an electron travelling at a speed of $5.0\times10^{6} m/s$?

108. What is the de Broglie wavelength of an electron that is accelerated from rest through a potential difference of 20 kV?

109. What is the de Broglie wavelength of a proton whose kinetic energy is 2.0 MeV? 10.0 MeV?

110. What is the de Broglie wavelength of a 10-kg football player running at a speed of 8.0 m/s?

111. (a) What is the energy of an electron whose de Broglie wavelength is that of a photon of yellow light with wavelength 590 nm?

(b) What is the de Broglie wavelength of an electron whose energy is that of the photon of yellow light?

112. The de Broglie wavelength of a neutron is 0.01 nm. What is the speed and energy of this neutron?

113. What is the wavelength of an electron that is moving at a 3% of the speed of light?

114. At what velocity does a proton have a 6.0-fm wavelength (about the size of a nucleus)? Give your answer in units of **c**.

115. What is the velocity of a 0.400-kg billiard ball if its wavelength is 7.50 fm?

116. Find the wavelength of a proton that is moving at 1.00% of the speed of light (when $\beta = 0.01$).

6.6 Wave-Particle Duality

117. An AM radio transmitter radiates 500 kW at a frequency of 760 kHz. How many photons per second does the emitter emit?

118. Find the Lorentz factor γ and de Broglie's wavelength for a 50-GeV electron in a particle accelerator.

119. Find the Lorentz factor γ and de Broglie's wavelength for a 1.0-TeV proton in a particle accelerator.

120. What is the kinetic energy of a 0.01-nm electron in a TEM?

121. If electron is to be diffracted significantly by a crystal, its wavelength must be about equal to the spacing, **d**, of crystalline planes. Assuming $d = 0.250nm$, estimate the potential difference through which an electron must be accelerated from rest if it is to be diffracted by these planes.

122. X-rays form ionizing radiation that is dangerous to living tissue and undetectable to the human eye. Suppose that a student researcher working in an X-ray diffraction laboratory is accidentally exposed to a fatal dose of radiation. Calculate the temperature increase of the researcher under the following conditions: the energy of X-ray photons is 200 keV and the researcher absorbs 4×10^{13} photons per each kilogram of body weight during the exposure. Assume that the specific heat of the student's body is $0.83 kcal/kg \cdot K$.

123. Solar wind (radiation) that is incident on the top of Earth's atmosphere has an average intensity of $1.3 kW/m^2$. Suppose that you are building a solar sail that is to propel a small toy spaceship with a mass of 0.1 kg in the space between the International Space Station and the moon. The sail is made from a very light material, which perfectly reflects the incident radiation. To assess whether such a project is feasible, answer the following questions, assuming that radiation photons are incident only in normal direction to the sail reflecting surface.

(a) What is the radiation pressure (force per m^2) of the radiation falling on the mirror-like sail?

(b) Given the radiation pressure computed in (a), what will be the acceleration of the spaceship when the sail has of an area of $10.0 m^2$?

(c) Given the acceleration estimate in (b), how fast will the spaceship be moving after 24 hours when it starts from rest?

124. Treat the human body as a blackbody and determine the percentage increase in the total power of its radiation when its temperature increases from 98.6° F to 103° F.

125. Show that Wien's displacement law results from Planck's radiation law. (Hint: substitute $x = hc/\lambda kT$ and write Planck's law in the form $I(x,T) = Ax^5/(e^x - 1)$, where $A = 2\pi (kT)^5/(h^4 c^3)$. Now, for fixed **T**, find the position of the maximum in **I(x,T)** by solving for **x** in the equation $dI(x,T)/dx = 0$.)

126. Show that Stefan's law results from Planck's radiation law. **Hint:** To compute the total power of blackbody radiation emitted across the entire spectrum of wavelengths at a given temperature, integrate Planck's law over the entire spectrum

$P(T)=\int_0^{\infty} I(\lambda,T)d\lambda$. Use the substitution $x=hc/\lambda kT$ and the tabulated value of the integral $\int_0^{\infty} dx x^3/(e^x-1)=\pi^4/15$.

Additional Problems

127. Determine the power intensity of radiation per unit wavelength emitted at a wavelength of 500.0 nm by a blackbody at a temperature of 10,000 K.

128. The HCl molecule oscillates at a frequency of 87.0 THz. What is the difference (in eV) between its adjacent energy levels?

129. A quantum mechanical oscillator vibrates at a frequency of 250.0 THz. What is the minimum energy of radiation it can emit?

130. In about 5 billion years, the sun will evolve to a red giant. Assume that its surface temperature will decrease to about half its present value of 6000 K, while its present radius of $7.0\times10^8 m$ will increase to $1.5\times10^{11} m$ (which is the current Earth-sun distance). Calculate the ratio of the total power emitted by the sun in its red giant stage to its present power.

131. A sodium lamp emits 2.0 W of radiant energy, most of which has a wavelength of about 589 nm. Estimate the number of photons emitted per second by the lamp.

132. Photoelectrons are ejected from a photoelectrode and are detected at a distance of 2.50 cm away from the photoelectrode. The work function of the photoelectrode is 2.71 eV and the incident radiation has a wavelength of 420 nm. How long does it take a photoelectron to travel to the detector?

133. If the work function of a metal is 3.2 eV, what is the maximum wavelength that a photon can have to eject a photoelectron from this metal surface?

134. The work function of a photoelectric surface is 2.00 eV. What is the maximum speed of the photoelectrons emitted from this surface when a 450-nm light falls on it?

135. A 400-nm laser beam is projected onto a calcium electrode. The power of the laser beam is 2.00 mW and the work function of calcium is 2.31 eV.

(a) How many photoelectrons per second are ejected?

(b) What net power is carried away by photoelectrons?

136. (a) Calculate the number of photoelectrons per second that are ejected from a $1.00-mm^2$ area of sodium metal by a 500-nm radiation with intensity $1.30 kW/m^2$ (the intensity of sunlight above Earth's atmosphere).

(b) Given the work function of the metal as 2.28 eV, what power is carried away by these photoelectrons?

137. A laser with a power output of 2.00 mW at a 400-nm wavelength is used to project a beam of light onto a calcium photoelectrode. (a) How many photoelectrons leave the calcium surface per second? (b) What power is carried away by ejected photoelectrons, given that the work function of calcium is 2.31 eV? (c) Calculate the photocurrent. (d) If the photoelectrode suddenly becomes electrically insulated and the setup of two electrodes in the circuit suddenly starts to act like a 2.00-pF capacitor, how long will current flow before the capacitor voltage stops it?

138. The work function for barium is 2.48 eV. Find the maximum kinetic energy of the ejected photoelectrons when the barium surface is illuminated with:

(a) radiation emitted by a 100-kW radio station broadcasting at 800 kHz;

(b) a 633-nm laser light emitted from a powerful He-Ne laser; and

(c) a 434-nm blue light emitted by a small hydrogen gas discharge tube.

139. (a) Calculate the wavelength of a photon that has the same momentum as a proton moving with 1% of the speed of light in a vacuum.

(b) What is the energy of this photon in MeV?

(c) What is the kinetic energy of the proton in MeV?

140. (a) Find the momentum of a 100-keV X-ray photon.

(b) Find the velocity of a neutron with the same momentum.

(c) What is the neutron's kinetic energy in eV?

141. The momentum of light, as it is for particles, is exactly reversed when a photon is reflected straight back from a mirror, assuming negligible recoil of the mirror. The change in momentum is twice the photon's incident momentum, as it is for the particles. Suppose that a beam of light has an intensity $1.0 kW/m^2$ and falls on a $-2.0-m^2$ area of a mirror and reflects from it.

(a) Calculate the energy reflected in 1.00 s.

(b) What is the momentum imparted to the mirror?

(c) Use Newton's second law to find the force on the mirror.

(d) Does the assumption of no-recoil for the mirror seem reasonable?

142. A photon of energy 5.0 keV collides with a stationary electron and is scattered at an angle of 60°. What is the energy acquired by the electron in the collision?

143. A 0.75-nm photon is scattered by a stationary electron. The speed of the electron's recoil is $1.5 \times 10^6 m/s$.

(a) Find the wavelength shift of the photon.

(b) Find the scattering angle of the photon.

144. Find the maximum change in X-ray wavelength that can occur due to Compton scattering. Does this change depend on the wavelength of the incident beam?

145. A photon of wavelength 700 nm is incident on a hydrogen atom. When this photon is absorbed, the atom becomes ionized. What is the lowest possible orbit that the electron could have occupied before being ionized?

146. What is the maximum kinetic energy of an electron such that a collision between the electron and a stationary hydrogen atom in its ground state is definitely elastic?

147. Singly ionized atomic helium He^{+1} is a hydrogen-like ion.

(a) What is its ground-state radius?

(b) Calculate the energies of its four lowest energy states.

(c) Repeat the calculations for the Li^{2+} ion.

148. A triply ionized atom of beryllium Be^{3+} is a hydrogen-like ion. When Be^{3+} is in one of its excited states, its radius in this nth state is exactly the same as the radius of the first Bohr orbit of hydrogen. Find **n** and compute the ionization energy for this state of Be^{3+}.

149. In extreme-temperature environments, such as those existing in a solar corona, atoms may be ionized by undergoing collisions with other atoms. One example of such ionization in the solar corona is the presence of C^{5+} ions, detected in the Fraunhofer spectrum.

(a) By what factor do the energies of the C^{5+} ion scale compare to the energy spectrum of a hydrogen atom?

(b) What is the wavelength of the first line in the Paschen series of C^{5+}?

(c) In what part of the spectrum are these lines located?

150. (a) Calculate the ionization energy for He^+.

(b) What is the minimum frequency of a photon capable of ionizing He^+?

151. Experiments are performed with ultra cold neutrons having velocities as small as 1.00 m/s. Find the wavelength of such an ultracold neutron and its kinetic energy.

152. Find the velocity and kinetic energy of a 6.0-fm neutron. (Rest mass energy of neutron is $E_0 = 940 MeV$.)

153. The spacing between crystalline planes in the NaCl crystal is 0.281 nm, as determined by X-ray diffraction with X-rays of wavelength 0.170 nm. What is the energy of neutrons in the neutron beam that produces diffraction peaks at the same locations as the peaks obtained with the X-rays?

154. What is the wavelength of an electron accelerated from rest in a 30.0-kV potential difference?

155. Calculate the velocity of a $1.0-\mu m$ electron and a potential difference used to accelerate it from rest to this velocity.

156. In a supercollider at CERN, protons are accelerated to velocities of 0.25**c**. What are their wavelengths at this speed? What are their kinetic energies? If a beam of protons were to gain its kinetic energy in only one pass through a potential difference, how high would this potential difference have to be? (Rest mass energy of a proton is $E_0 = 938 MeV$).

157. Find the de Broglie wavelength of an electron accelerated from rest in an X-ray tube in the potential difference of 100 keV. (Rest mass energy of an electron is $E_0 = 511 keV$.)

158. The cutoff wavelength for the emission of photoelectrons from a particular surface is 500 nm. Find the maximum kinetic energy of the ejected photoelectrons when the surface is illuminated with light of wavelength 450 nm.

159. Compare the wavelength shift of a photon scattered by a free electron to that of a photon scattered at the same angle by a free proton.

160. The spectrometer used to measure the wavelengths of the scattered X-rays in the Compton experiment is accurate to $5.0 \times 10^{-4} nm$. What is the minimum scattering angle for which the X-rays interacting with the free electrons can be distinguished from those interacting with the atoms?

161. Consider a hydrogen-like ion where an electron is orbiting a nucleus that has charge $q = +Ze$. Derive the formulas for the energy E_n of the electron in nth orbit and the orbital radius r_n.

162. Assume that a hydrogen atom exists in the $n = 2$ excited state for $10^{-8} s$ before decaying to the ground state. How many times does the electron orbit the proton nucleus during this time? How long does it take Earth to orbit the sun this many times?

163. An atom can be formed when a negative muon is captured by a proton. The muon has the same charge as the electron and a mass 207 times that of the electron. Calculate the frequency of the photon emitted when this atom makes the transition from $n = 2$ to the $n = 1$ state. Assume that the muon is orbiting a stationary proton.
