# *Physics 111 Homework Solutions Week #9 - Wednesday*

## *Friday, February 28, 2104*

***Chapters 19 & 24***

***Questions***

24.6 The Compton shift in wavelength for the proton and the electron are given by $\Delta\lambda_p = \frac{h}{m_p c}(1-\cos\phi)$ and $\Delta\lambda_e = \frac{h}{m_e c}(1-\cos\phi)$ respectively. Evaluating the ratio of the shift in wavelength for the proton to the electron, evaluated at the same detection angle φ, we find $\frac{\Delta\lambda_p}{\Delta\lambda_e} = \frac{m_e}{m_p} = \frac{1.67\times10^{-27}kg}{9.11\times10^{-31}kg} = \frac{1}{1833} = 5\times10^{-4}$. Therefore the shift in wavelength for the proton is smaller than the wavelength shift for the electron.

***Multiple-Choice***

19.16 D
19.17 A

***Problems***

19.15 The frequency is given as $f = \frac{c}{\lambda} = \frac{3\times10^8 \frac{m}{s}}{5.5\times10^{-7}m} = 5.5\times10^{14}s^{-1}$.

19.17 A Neodymium-YAG laser

a. The number of photons is given as the total beam energy divided by the energy per photon, or $\# = \frac{5J}{hc/\lambda} = \frac{5J}{6.63\times10^{-34}Js\times3\times10^8\frac{m}{s}}\times1.06\times10^{-6}m = 1.33\times10^{20}$.

b. The power in the beam is the energy delivered per unit time, or $P = \frac{\Delta E}{\Delta t} = \frac{5J}{1\times10^{-9}s} = 5\times10^9W = 5GW$.

c. The average power output of the laser is $P = \frac{5J}{pulse}\times\frac{10pulses}{1s} = 50W$.

19.18 The range of frequencies is given as $f_{400nm} = \frac{c}{\lambda_{400nm}} = \frac{3\times10^8\frac{m}{s}}{400\times10^{-9}m} = 7.5\times10^{14}Hz$ through $f_{750nm} = \frac{c}{\lambda_{750nm}} = \frac{3\times10^8\frac{m}{s}}{750\times10^{-9}m} = 4\times10^{14}Hz.$ The energies are given by $E = \frac{hc}{\lambda} = hf$ which for *750 nm* the energy is

$$E = \frac{(6.63\times10^{-34}Js)(3\times10^8\frac{m}{s})}{750\times10^{-9}m} = 2.65\times10^{-19}J\times\frac{1eV}{1.6\times10^{-19}J} = 1.66eV$$ while the

energy for the *400 nm* photon is

$$E = \frac{(6.63\times10^{-34}\,Js)(3\times10^{8}\,\tfrac{m}{s})}{400\times10^{-9}m} = 4.97\times10^{-19}J\times\frac{1eV}{1.6\times10^{-19}J} = 3.11eV.$$

19.20 The energy of the emitted photon is equal to the difference in energies of the two levels: $\Delta E = -1.51eV-(-3.4eV) = 1.89eV\times\frac{1.6\times10^{-19}J}{1eV} = 3.02\times10^{-19}J$. Then setting this energy equal to $\frac{hc}{\lambda}$ we find

$$\lambda = \frac{hc}{E} = \frac{6.63\times10^{-34}Js\times3\times10^{8}\tfrac{m}{s}}{3.02\times10^{-19}J} = 6.58\times10^{-7}m = 658nm.$$

19.21 Another Neodymium-YAG laser

a. Each photon has an energy given by

$$E = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}Js\times3\times10^{8}\tfrac{m}{s}}{532\times10^{-9}m} = 3.74\times10^{-19}J$$ per photon. Similarly the momentum is $p = \frac{h}{\lambda} = \frac{6.63\times10^{-34}Js}{532\times10^{-9}m} = 1.25\times10^{-27}\tfrac{kgm}{s}$ per photon.

b. Since the total energy is 5J, we calculate the number of photos by dividing the total energy by the energy per photon. Thus we have

$$\# = \frac{E_{total}}{E/photon} = \frac{5J}{3.74\times10^{-19}\,J/photon} = 1.34\times10^{19}$$ photons.

c. In *1 ns*, if all the photons in part *b* are absorbed, each carrying a momentum *p*, then the force is the total change in momentum and is given by

$$F = N\frac{\Delta p}{\Delta t} = 1.34\times10^{19}\times\frac{1.25\times10^{-27}\tfrac{kgm}{s}}{1\times10^{-9}s} = 16.7N.$$

24.7 For a $1.2\times10^{6}eV\times\frac{1.6\times10^{-19}J}{1eV} = 1.92\times10^{-13}J$ photon,

a. its momentum is given by $p = \frac{E}{c} = \frac{1.92\times10^{-13}J}{3\times10^{8}\tfrac{m}{s}} = 6.4\times10^{-22}\tfrac{kgm}{s}$.

b. its wavelength is given by the de Broglie relation

$$\lambda = \frac{h}{p} = \frac{6.63\times10^{-34}Js}{6.4\times10^{-22}\tfrac{kgm}{s}} = 1.04\times10^{-12}m.$$

c. its frequency is given by $f = \frac{c}{\lambda} = \frac{3\times10^{8}\tfrac{m}{s}}{1.04\times10^{-12}m} = 2.9\times10^{20}s^{-1}$.

24.11 A Compton effect experiment

a. The wavelength and momentum of the incident gamma ray are given as

$$E = \frac{hc}{\lambda} \rightarrow \lambda = \frac{hc}{E} = \frac{\left(6.63\times10^{-34}Js\right)\left(3\times10^{8}\,\tfrac{m}{s}\right)}{1.6\times10^{6}eV\times\frac{1.6\times10^{-19}J}{1eV}} = 7.77\times10^{-13}m \text{ and}$$

$$p = \frac{h}{\lambda} = \frac{E}{c} = \frac{6.63\times10^{-34}Js}{7.77\times10^{-13}m} = 8.53\times10^{-22}\,\tfrac{kgm}{s} \text{ respectively.}$$

b. Using the Compton formula for the wavelength of the scattered photon and the fact that the energy is inversely proportional to the wavelength we can write

$$\lambda' = \lambda + \frac{h}{m_e c}\left(1-\cos\phi\right) \rightarrow \frac{\lambda'}{hc} = \frac{\lambda}{hc} + \frac{1}{m_e c^2}\left(1-\cos\phi\right) \rightarrow \frac{1}{E'} = \frac{1}{E} + \frac{\left(1-\cos\phi\right)}{m_e c^2}.$$

c. The energy of the scattered gamma ray photon is

$$\frac{1}{E'} = \frac{1}{1.6MeV} + \frac{\left(1-\cos 50\right)}{0.511MeV} = 1.324MeV^{-1} \rightarrow E' = 0.755MeV$$ where the rest mass of the electron is given as

$$m_e c^2 = \left(9.11\times10^{-31}kg\right)\left(3\times10^{8}\,\tfrac{m}{s}\right)^2 \times \frac{1eV}{1.6\times10^{-19}J} = 0.511MeV.$$

d. The kinetic energy of the recoiling electron is found using conservation of energy where when the incident gamma ray photon interacts with electrons in the sample, the gamma ray photon loses some energy to the electron as it scatters. Thus the kinetic energy of the recoiling electron is

$$E_{incident} = E_{scattered} + KE_{e^-}$$

$$\therefore KE_{e^-} = E_{incident} - E_{scattered} = 1.6MeV - 0.755MeV = 0.845MeV$$

e. The speed of the recoiling electron is given by using the expression for the relativistic kinetic energy. We have

$$KE = 0.845MeV = \left(\gamma-1\right)m_e c^2 = \left(\gamma-1\right)0.511MeV$$

$$\gamma = 1 + \frac{0.845MeV}{0.511MeV} = 1 + 1.654 = 2.654 = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \rightarrow v^2 = 0.858c^2 \rightarrow v = 0.926c$$

24.12 X-rays on a foil target

a. The energy is given by $E = \frac{hc}{\lambda} = \frac{\left(6.63\times10^{-34}Js\right)\left(3\times10^{8}\,\tfrac{m}{s}\right)}{0.012\times10^{-9}m} = 1.66\times10^{-14}J = 0.104MeV.$

b. The scattered wavelength is given by

$$\lambda_f - \lambda_i = \frac{h}{mc}\left(1-\cos\phi\right) = \frac{2h}{mc} = \frac{2\left(6.63\times10^{-34}Js\right)}{\left(9.11\times10^{-31}kg\right)\left(3\times10^{8}\,\tfrac{m}{s}\right)} = 4.86\times10^{-12}m.$$ Thus,

$\lambda_f = 4.86\times10^{-12}m + 1.2\times10^{-11}m = 1.686\times10^{-11}m$. The energy is given by the formula in part a, and is $1.18\text{x}10^{-14}$ J = 0.0741 MeV.

c. The energy given to the foil is

$$\Delta E_{foil} = E_{incident} - E_{backscattered} = 0.104MeV - 0.0741MeV = 0.03MeV = 30keV.$$

24.15 To determine the number of photos that strike a screen every second, we divide the total energy per second (*1 mW*) by the energy per photon. The energy of a photon is given as $E = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}Js\times3\times10^{8}\,\frac{m}{s}}{633\times10^{-9}m} = 3.14\times10^{-19}J$. Therefore the number of photons that strike per second is

$$\frac{\#}{s} = \frac{P}{E_{ph}} = \frac{1\times10^{-3}\,\frac{J}{s}}{3.14\times10^{-19}\,\frac{J}{photon}} = 3.2\times10^{15}\,\frac{photons}{s}.$$

# *Monday, March 3, 2014*

***Chapter 24***

***Questions***

24.2 In a photoelectric experiment the intensity refers to the number of photons incident on the metal surface per second. Let a beam of green light with intensity I be incident on the surface and note that it produces a photocurrent. If we switch to blue light of the *same intensity I*, the energy of the individual photons is greater and thus the maximum kinetic energy of the ejected photoelectrons is greater. The intensity is a constant, which is the total energy of the photons in the beam of light. The total energy is a product of the energy of each photon multiplied by the total number of photons. If the energy of each individual photon increases then the number of photons in the beam decreases since we want the total energy of the beam (which is proportional to the intensity) to remain constant. Since the number of photons decreases the number of photoelectrons decreases and the photocurrent decreases.

24.4 If for a particular wavelength of green light we find a stopping potential of –1.5V, this allows us to determine the work function φ, or the minimum energy needed to eject a photoelectron. Now, if we switch to a blue light the wavelength is shorter than that of green light and the maximum kinetic energy of the ejected photoelectrons will thus be greater using blue light as opposed to green light.

***Multiple-Choice***

24.2 B
24.3 C
24.4 D
24.6 C

***Problems***

24.8 Photoelectric effect in cesium

We are given the work function for cesium is $\phi = 2.9\ eV = 4.64x10^{-19}\ J$.

a. The maximum wavelength corresponds to the minimum frequency. Therefore, $KE_{\min} = hf_{\min} - \phi = 0$ which gives $f_{\min} = \frac{\phi}{h} = \frac{4.64\times10^{-19}J}{6.63\times10^{-34}Js} = 7.0\times10^{14}s^{-1}$. From

$$c = f_{\min}\lambda_{\max} \rightarrow \lambda_{\max} = \frac{c}{f_{\min}} = \frac{3\times10^{8}\,\frac{m}{s}}{7.0\times10^{14}s^{-1}} = 4.28\times10^{-7}m = 428nm.$$

b. If *400nm* photons are used, their energy is given by

$$E = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}Js\times3\times10^{8}\,\frac{m}{s}}{400\times10^{-9}m} = 4.97\times10^{-19}J\times\frac{1eV}{1.6\times10^{-19}J} = 3.11eV\,.$$

Therefore the maximum kinetic energy is given as

$$KE_{\max} = hf - \phi = 3.11eV - 2.9eV = 0.21eV\times\frac{1.6\times10^{-19}J}{1eV} = 3.33\times10^{-20}J\,.$$

c. A *1 W* beam of photons corresponds to *1 J of photons incident per second*. In *1 J* of photons there are $\frac{1J}{4.97\times10^{-19}\,\frac{J}{photon}} = 2.01\times10^{18}$ photons. If the photo ejection of an electron is 100% efficient, then for each photon lost, one electron is produced. Thus the photocurrent is the amount of charge produced each second, where *1* electron has $1.6x10^{-19}$ *C* of charge. This corresponds to a total charge of $Q = 2.01\times10^{18}\times1.6\times10^{-19}C = 0.322C$ of charge in *1 second*. Therefore the photocurrent is *0.322 A = 322 mA*.

d. If green photons are used with a wavelength of *500 nm*, this corresponds to an energy of

$$E = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}Js\times3\times10^{8}\,\frac{m}{s}}{500\times10^{-9}m} = 3.98\times10^{-19}J\times\frac{1eV}{1.6\times10^{-19}J} = 2.49eV\,.$$

The maximum *f* that will allow for photo ejection of electrons is the one where the electrons are ejected with a maximum kinetic energy equal to zero. Therefore $KE_{\min} = hf_{\min} - \phi = 0$, and solving for $\phi$ we obtain $hf_{\min} = \phi = 2.49eV$.

24.9 The maximum KE is given by the product of the stopping potential (0.82V) and the electron's charge ($e^-$). Thus the maximum $KE = eV_{stop} = 0.82eV$. This is equal to the energy of the photons incident minus the work function (the minimum energy needed to eject a photoelectron). In symbols,

$$KE_{\max} = hf - \phi = \frac{hc}{\lambda} - \phi$$

$$\rightarrow 0.82eV = \left(\frac{6.63\times10^{-34}Js\times3\times10^{8}\,\frac{m}{s}}{400\times10^{-9}m}\right)\times\frac{1eV}{1.6\times10^{-19}J} - \phi \rightarrow \phi = 2.29eV$$

24.10 A photoelectric effect experiment

a. The maximum kinetic energy is given by

$$KE_{\max} = hf - \phi = \frac{hc}{\lambda} - \phi$$

$$KE_{\max} = \left(\frac{6.63\times10^{-34}Js\times3\times10^{8}\,\frac{m}{s}}{410\times10^{-9}m}\right)\times\frac{1eV}{1.6\times10^{-19}J} - 2.28eV$$

$$KE_{\max} = 3.03eV - 2.28eV = 0.75eV$$

In order to calculate the speed, we use the expression for the relativistic kinetic energy. We have

$$KE = 0.75eV = (\gamma - 1)m_e c^2 = (\gamma - 1)0.511MeV$$

$$\gamma = 1 + \frac{0.75eV}{0.511 \times 10^6 eV} = 1 + 0000015 = 1.0000015$$

and the speed is therefore $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \rightarrow v^2 = 2.94 \times 10^{-6} c^2 \rightarrow v = 0.0017c$

b. Based on the speed calculated in *part a*, the electron is not relativistic.

c. The minimum frequency corresponds to an electron ejected with a kinetic energy equal to zero. Therefore, $KE_{\min} = hf_{\min} - \phi = 0$ which gives

$$f_{\min} = \frac{\phi}{h} = \frac{2.28eV \times \frac{1.6 \times 10^{-19} J}{1eV}}{6.63 \times 10^{-34} Js} = 5.5 \times 10^{14} s^{-1}.$$

d. The minimum frequency corresponds to the maximum wavelength. Therefore we have $c = f_{\min}\lambda_{\max} \rightarrow \lambda_{\max} = \frac{c}{f_{\min}} = \frac{3 \times 10^8 \frac{m}{s}}{5.5 \times 10^{14} s^{-1}} = 5.45 \times 10^{-7} m = 545nm$.

e. For *700nm* photons we have the maximum kinetic energy given as

$$KE_{\max} = hf - \phi = \frac{hc}{\lambda} - \phi$$

$$KE_{\max} = \left( \frac{6.63 \times 10^{-34} Js \times 3 \times 10^8 \frac{m}{s}}{700 \times 10^{-9} m} \right) \times \frac{1eV}{1.6 \times 10^{-19} J} - 2.28eV$$

$$KE_{\max} = 1.78eV - 2.28eV = -0.50eV$$

Or, we have that no photoelectrons are produced. In addition we know that the maximum wavelength for photo production is 545nm, and we are well beyond this, so no photocurrent would be produced.