Q28.5 - High intensity light \((f > f_{\text{threshold}})\) ejects more electrons from the metal’s surface. Higher frequency light ejects individual electrons of higher energy but not more of them.

Q28.6 - The wave theory predicts that the photoelectric effect should occur at any frequency, provided the light intensity is high enough; however, as seen in the photoelectric effect experiments, the light must have a sufficiently high frequency for the effect to occur.

Q28.14 - The discovery of \(e^-\) diffraction by Davisson and Germer was a fundamental advance in our understanding of the motion of material particles. Newton’s laws do not properly describe the motion of an object with small mass. It moves as a wave, not as a particle. From this idea the development of QM made possible describing the motion of \(e^-\) in atoms; understanding molecular structure and the behavior of matter on the atomic scale, including electronics, photonics and engineered materials; accounting for the motion of nucleons in nuclei; and studying elementary particles.

Q11.14 - The little \(k\) in the following equation represents some constants used in electrostatics. The negative sign indicates an attractive (and not repulsive) potential.

\[
-|E| = -\frac{ke^2}{2r} = \frac{ke^2}{2r} - \frac{ke^2}{r} = K_e + U_e
\]  
then \(K_e = |E|\) and \(U_e = -2|E|\)  

Q11.17 - If the \(e^-\) moved like a hockey puck, it could have any arbitrary frequency of revolution around a nucleus. If it behaved like a charge in a radio antenna, it would radiate light with a frequency equal to its own frequency of oscillation. The the \(e^-\) in a hydrogen atom would emit a continuous spectrum of electromagnetic waves with all frequencies smeared together.
\( d = 0.281 \text{ nm}, \lambda_{\text{xray}} = 0.140 \text{ nm} \) \hspace{1cm} (3)

\[ 2d \sin \theta = m\lambda \] \hspace{1cm} (4)

\[ \sin \theta = \frac{1}{2} \frac{\lambda}{d} = \frac{0.140 \text{ nm}}{2(0.281) \text{ nm}} = 0.2491 \]

\[ \theta = 14.4^\circ \] \hspace{1cm} (5)

P27.38

For constructive interference Bragg diffraction gives:

\[ 2d \sin \theta = m\lambda \] \hspace{1cm} (7)

\[ m = 1 \rightarrow \lambda_1 = 2d \sin \theta = 2(2.80 \text{ m}) (\sin 80.0^\circ) = 5.51 \text{ m} \] \hspace{1cm} (8)

\[ m = 2 \rightarrow \lambda_2 = \frac{2d \sin \theta}{2} = (2.80 \text{ m}) (\sin 80.0^\circ) = 2.76 \text{ m} \] \hspace{1cm} (9)

\[ m = 3 \rightarrow \lambda_3 = \frac{2d \sin \theta}{3} = (0.667)(2.80 \text{ m}) (\sin 80.0^\circ) = 1.84 \text{ m} \] \hspace{1cm} (10)

P27.39

The parallel narrow slits make a diffraction grating. Constructive interference:

\[ d \sin \theta = m\lambda \] \hspace{1cm} (11)

\[ m = 1, \lambda = 632.8 \text{ nm}, L = 1.40 \text{ m} \text{ and } d = 1.20 \text{ mm} \] \hspace{1cm} (12)

small angle approximation: \( \theta = \frac{y_m}{L} \) \hspace{1cm} (13)

\[ \frac{dy_m}{L} = \lambda \] \hspace{1cm} (14)

\[ y_m = \frac{L\lambda}{d} = \frac{(1.40 \text{ m})(632.8 \times 10^{-9} \text{ m})}{1.20 \times 10^{-3} \text{ m}} = 7.38 \times 10^{-4} \text{ m} = 0.738 \text{ mm} \] \hspace{1cm} (15)

Many equally spaced transparent lines on the film act like a diffraction grating. When the same light is sent through the film it produces interference maxima separated according to:

\[ d \sin \theta = m\lambda = \lambda \text{ for } m = 1 \] \hspace{1cm} (16)

\[ \sin \theta = \frac{\lambda}{d} = \frac{632.8 \times 10^{-9} \text{ m}}{0.738 \times 10^{-3} \text{ m}} = 0.000857 \] \hspace{1cm} (17)

\[ y = L \tan \theta = (1.40 \text{ m}) \tan \theta = (1.40 \text{ m})(0.000857) = 1.20 \text{ mm} \] \hspace{1cm} (18)
P24.37

\[ S = S_0 \cos^2 \theta \longrightarrow \cos \theta = \sqrt{\frac{S}{S_0}} \longrightarrow \theta = \cos^{-1} \left[ \sqrt{\frac{S}{S_0}} \right] \quad (19) \]

\[ \frac{S}{S_0} = \frac{1}{3} \longrightarrow \theta = \cos^{-1} \left[ \sqrt{\frac{1}{3}} \right] = 54.7^\circ \quad (20) \]

\[ \frac{S}{S_0} = \frac{1}{5} \longrightarrow \theta = \cos^{-1} \left[ \sqrt{\frac{1}{5}} \right] = 63.4^\circ \quad (21) \]

\[ \frac{S}{S_0} = \frac{1}{10} \longrightarrow \theta = \cos^{-1} \left[ \sqrt{\frac{1}{10}} \right] = 71.6^\circ \quad (22) \]

P24.39

Through the first polarizer the transmitted intensity is \( \frac{1}{2} I_0 \) of the unpolarized light (refer to p. 920, about 3/4 of the way down).

\[ I_{\text{max}} = \frac{1}{2} I_0 \cos^2 (45^\circ) \quad (23) \]

\[ I = \left[ \frac{1}{2} I_0 \cos^2 (45^\circ) \right] \cos^2 (45^\circ) \quad (24) \]

\[ \frac{I}{I_0} = \frac{1}{2} \cos^2 (45^\circ) \cos^2 (45^\circ) = \frac{1}{2} \left( \frac{1}{2} \right) \left( \frac{1}{2} \right) = \frac{1}{8} \quad (25) \]

\[ \frac{I}{I_0} = \frac{1}{8} \quad (26) \]

P24.40

Orient the first polarizer at an angle \( \theta \) with respect to the incoming polarized light.

\[ I_1 = I_0 \cos^2 \theta \quad (27) \]

Let the second polarizer be at an angle of \( \theta \) with respect to the first polarizer.

\[ I_2 = I_1 \cos^2 \theta = (I_0 \cos^2 \theta) \cos^2 \theta = I_0 \cos^4 \theta \quad (28) \]

One more time: let the third polarizer be at the same angle of \( \theta \) with respect to the second polarizer.

\[ I_3 = (I_0 \cos^4 \theta) \cos^2 \theta = I_0 \cos^6 \theta \quad (29) \]

Generalize: let the \( n^{th} \) polarizer be at an angle \( \theta \) with respect to polarizer (n-1).

\[ I_n = I_0 \cos^{2n} \theta, \quad (30) \]
which has to be greater than 90% since we want $I_{\text{max}}$ to be reduced by no more than 10%.

\[
I_0 \cos^{2n} \theta \geq 0.90 I_0 \quad (31)
\]

\[
\cos^{2n} \theta \geq 0.90 \quad (32)
\]

But $\theta$ is a fraction of 45°, i.e.,

\[
\cos^{2n} \left( \frac{45^\circ}{n} \right) \geq 0.90 \quad (33)
\]

\[
n = 1 \rightarrow \cos^2(45) = \frac{1}{2} \nless 0.90 \quad (34)
\]

\[
n = 2 \rightarrow \cos^4(45/2) = 0.73 \nless 0.90 \quad (35)
\]

\[
n = 3 \rightarrow \cos^6(45/3) = 0.82 \nless 0.90 \quad (36)
\]

\[
n = 4 \rightarrow \cos^8(45/4) = 0.86 \nless 0.90 \quad (37)
\]

\[
n = 5 \rightarrow \cos^{10}(45/5) = 0.88 \nless 0.90 \quad (38)
\]

\[
n = 6 \rightarrow \cos^{12}(45/6) = 0.90 \quad (39)
\]

Thus a minimum of 6 polarizers will do.

\[
\theta = \frac{45}{6} = 7.5^\circ \quad (40)
\]

**P28.9**

\[
\lambda_g = 546.1 \text{ nm} \quad \rightarrow \quad V_{\text{stop}} = 0.376 \text{ V} \quad (41)
\]

(a) $K_{\text{max}} = hf - \phi \quad (42)$

\[
\phi = hf - K_{\text{max}} \quad (43)
\]

\[
= \frac{hc}{\lambda} - (eV_{\text{stop}}) \quad (44)
\]

\[
= \left( \frac{6.63 \times 10^{-34} \text{ J s}}{546.1 \text{ nm}} \right) \left( 3 \times 10^8 \text{ m/s} \right) - (1.60 \times 10^{-19} \text{ C}) \left( 0.376 \text{ V} \right) \quad (45)
\]

\[
= 3.64 \times 10^{-19} \text{ J} - 6.02 \times 10^{-20} \text{ J} \quad (46)
\]

\[
= 3.04 \times 10^{-19} \text{ J or} \quad (47)
\]

\[
\phi = 1.89 \text{ eV} \quad (48)
\]

The work function $\phi$ doesn’t change: it is a property of the metal. Use it in part b.

\[
K_{\text{max}} = hf - \phi \quad (49)
\]

\[
eV_{\text{stop}} = \left( \frac{6.63 \times 10^{-34} \text{ J s}}{587.5 \text{ nm}} \right) \left( 3 \times 10^8 \text{ m/s} \right) - 3.04 \times 10^{-19} \text{ J} \quad (50)
\]

\[
eV_{\text{stop}} = 3.46 \times 10^{-20} \text{ J} \quad (51)
\]

\[
V_{\text{stop}} = \frac{3.46 \times 10^{-20} \text{ J}}{1.60 \times 10^{-19} \text{ C}} = 0.22 \text{ J/C} = 0.22 \text{ V} \quad (52)
\]
P28.10

Energy needed is $1.00 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$. Energy absorbed is

\[ E = P \cdot \Delta t \text{ where } P = IA \]  
\[ E = IA \Delta t \]  
\[ \Delta t = \frac{E}{IA} = \frac{1.6 \times 10^{-19} \text{ J}}{(500 \text{ W/m}^2)(\pi [2.81 \times 10^{-15} \text{ m}]^2)} \] 
\[ \Delta t = 1.29 \times 10^7 \text{ s} \] 

which is absurd since

\[ \Delta t_{\text{photocurrent}} \sim 1 \times 10^{-9} \text{ s}. \]  

Also

\[ \Delta t = 1.28 \times 10^7 \text{ s} = 149 \text{ days} \] 

Looks like a classical wave analysis won’t work here!

handout

When lead is illuminated with ultraviolet light with a wavelength of 250 nm, the stopping potential is 0.82 V. Using this information, find:
(a) the stopping potential if the wavelength is changed to 215 nm, and
(b) the work function of lead.

The maximum kinetic energy an electron could have is the stopping potential (in eV); this is equal to the difference between the photon energy and the work function.

\[ K_{\text{max}} = eV_s = hf - \phi \rightarrow eV_s - hf = -\phi \]  

I’ll label with a superscript prime those quantities associated with the 215 nm wavelength. The work function is a property of the metal, so it’s independent of the light shining on the metal.

\[ eV'_s - hf' = -\phi \]  
\[ eV_s - hf = eV'_s - hf' \]  
\[ eV_s - hf + hf' = eV'_s \]  
\[ eV_s + hc \left( \frac{1}{\lambda'} - \frac{1}{\lambda} \right) = eV'_s \] 

We’ll probably want to work in eV, so we have to convert $hf$.

\[ eV_s + hc \left( \frac{1}{\lambda'} - \frac{1}{\lambda} \right) \frac{1 \text{ eV}}{1.602 \times 10^{-19} \text{ J}} = eV'_s \]  
\[ 0.82 \text{ eV} + (6.626 \times 10^{-34} \text{ J s}) (2.998 \times 10^8 \text{ m/s}) \left( \frac{1}{2.15 \times 10^{-7} \text{ m}} - \frac{1}{2.50 \times 10^{-7} \text{ m}} \right) \frac{1 \text{ eV}}{1.602 \times 10^{-19} \text{ J}} = eV'_s \]  
\[ eV'_s = 1.627 \text{ eV} = 1.6 \text{ eV} \]
To get the work function we again want to work in eV.

\[
f = \frac{c}{\lambda} \rightarrow hf = \frac{hc}{\lambda} = (6.626 \times 10^{-24} \text{ J s}) \left(\frac{2.998 \times 10^8 \text{ m/s}}{2.50 \times 10^{-7} \text{ m}}\right)
\]

\[
hf = 7.946 \times 10^{-19} \text{ J}
\]  

(67)

\[
hf = 7.946 \times 10^{-19} \text{ J} \left(\frac{1 \text{ eV}}{1.602 \times 10^{-19} \text{ J}}\right) = 4.96 \text{ eV}
\]  

(68)

\[
\phi = hf - K_{\text{max}} = 4.96 \text{ eV} - 0.82 \text{ eV} = 4.14 \text{ eV}
\]  

(69)

P11.26

(a) Since

\[
\Delta E = E_n - E_{n-1}, \text{ where } E_n = -\frac{13.6 \text{ eV}}{n^2}\text{ for hydrogen,}
\]

\[
\Delta E = -\frac{13.6 \text{ eV}}{3^2} - \left(\frac{-13.6 \text{ eV}}{2^2}\right)
\]

\[
= -1.51 \text{ eV} + 3.4 \text{ eV}
\]

\[
\Delta E = 1.89 \text{ eV}
\]  

(71)

\[
\Delta E = hf \rightarrow f = \frac{\Delta E}{\hbar} = \frac{1.89 \text{ eV} \times 1.602 \times 10^{-19} \text{ J}}{1 \text{ eV} \cdot \frac{6.63 \times 10^{-34} \text{ J s}}{2 \pi}} = 4.57 \times 10^{14} \text{ Hz}
\]

(72)

\[
c = f \lambda \rightarrow \lambda = \frac{3.00 \times 10^8 \text{ m/s}}{4.57 \times 10^{14} \text{ Hz}} = 6.56 \times 10^{-7} \text{ m}
\]  

(73)

P11.29

For a hydrogen atom in the n=2 state

(a) \(r_{n=2} = n^2 a_0 = 4 \left(0.53 \times 10^{-10} \text{ m}\right) = 2.12 \times 10^{-10} \text{ m} = r_2\)

\[
(b) L = mvr_n = nh \rightarrow mv = p = \frac{nh}{r_n} = \frac{2 \left(6.63 \times 10^{-34} \text{ J s}\right)}{2.12 \times 10^{-10} \text{ m}} = 9.96 \times 10^{-25} \text{ kg m/s}
\]

\[
(c) L = mvr_n = p_2r_2 = 2.11 \times 10^{-34} \frac{\text{kg m}^2}{\text{s}}
\]  

(74)

\[
(d) KE = \frac{1}{2}m_eV_e^2 = \frac{m_e^2V_e^2}{2m_e} = \frac{p_e^2}{2m_e} = \frac{(9.96 \times 10^{-25} \text{ kg m/s})^2}{2 (9.11 \times 10^{-31} \text{ kg})}
\]

\[
KE = 5.43 \times 10^{-19} \text{ J} = 3.4 \text{ eV}
\]  

(75)

\[
(d) U_e = -\frac{ke^2}{r_e} = -\left(9 \times 10^9 \frac{\text{N m}^2}{\text{C}^2}\right) \left(1.602 \times 10^{-19} \text{ C}\right)^2 \left(\frac{2.12 \times 10^{-10} \text{ m}}{2.12 \times 10^{-10} \text{ m}}\right) = -1.09 \times 10^{-18} \text{ J} = -6.8 \text{ eV}
\]

\[
(f) E_2 = KE_2 + U_2 = 3.40 \text{ eV} - 6.8 \text{ eV} = -3.40 \text{ eV}
\]  

(76)

(77)

(78)

(79)

(80)

(81)

(82)

(83)
P28.18

One could either turn everything into eV or into J; let’s do the latter.

\[
(3.00 \text{ eV}) \left( \frac{1.602 \times 10^{-19} \text{ J}}{1 \text{ eV}} \right) = 4.806 \times 10^{-19} \text{ J}
\]

(84)

For the electron and the deBroglie equation we need the momentum. I’m going to write the electron’s kinetic energy in a funny (but convenient) way:

\[
K = \frac{p^2}{2m} \rightarrow p = \sqrt{2mK}
\]

(85)

\[
p = \sqrt{2 \left( 9.101 \times 10^{-31} \text{ kg} \right) \left( 4.806 \times 10^{-19} \text{ J} \right)} = 9.358 \times 10^{-25} \text{ kg m/s}
\]

(86)

\[
\lambda = \frac{h}{p} = \frac{6.626 \times 10^{-34} \text{ J s}}{9.358 \times 10^{-25} \text{ kg m/s}} = 7.08 \times 10^{-10} \text{ m}
\]

(87)

For the photon we use the Einstein relation:

\[
E = hf = \frac{hc}{\lambda} \rightarrow \lambda = \frac{hc}{E}
\]

(88)

\[
\lambda = \left( 6.626 \times 10^{-24} \text{ J s} \right) \left( \frac{2.998 \times 10^8 \text{ m/s}}{4.806 \times 10^{-19} \text{ J}} \right) = 413 \text{ nm}
\]

(89)

P28.20

(a) We’re looking for a speed, but first we should find the deBroglie wavelength. Let \( w \) be the width of the aperture (doorway). The problem gives a rule of thumb that significant diffraction occurs when the aperture is less than ten times the wavelength.

\[
\lambda_{\text{student}} = \frac{h}{p} = \frac{h}{mv}
\]

(90)

\[
w \leq 10 \left( \frac{h}{mv} \right) \rightarrow v \leq 10 \left( \frac{h}{mw} \right)
\]

(91)

\[
v \leq 10 \left( \frac{6.63 \times 10^{-34} \text{ J s}}{(80.0 \text{ kg})(0.750 \text{ m})} \right)
\]

\[
v \leq 1.11 \times 10^{-34} \text{ m/s}
\]

(92)

(b) At this speed it should take:

\[
t = \frac{d}{v} = \frac{0.150 \text{ m}}{1.11 \times 10^{-34} \text{ m/s}} = 1.36 \times 10^{33} \text{ s}
\]

(94)

\[
\frac{1.36 \times 10^{33} \text{ s}}{4 \times 10^{17} \text{ s}} \approx 3 \times 10^{15}
\]

(95)

(c) No.
P28.22

I'm not happy about this problem, as it’s sneaky: part of what you would like to know is in a footnote on p. 1059 and part is opposite the inner back cover! It also requires you to actually remember material from Physics 17! Furthermore, I found it easier to do the problem “out of order” starting with the momentum.

\[(20 \text{ GeV })(1.602 \times 10^{-10} \text{ J/eV }) = 3.20 \times 10^{-9} \text{ J} \quad (96)\]

\[P = \frac{E}{c} = \frac{3.20 \times 10^{-9} \text{ J}}{3.00 \times 10^8 \text{ m/s}} = 1.07 \times 10^{-17} \text{ kg m/s} \quad (97)\]

And the wavelength:

\[\lambda = \frac{\hbar}{p} = \frac{6.626 \times 10^{-34} \text{ J s}}{1.068 \times 10^{-17} \text{ kg m/s}} = 6.20 \times 10^{-17} \text{ m} \quad (98)\]

compared to the size of a nucleus of about \(10^{-14} \text{ m}\). To find gamma you should use the hidden knowledge in the aforementioned footnote and the secret knowledge of Einstein: \(E = mc^2 = \gamma m_0 c^2\). The \(m_0\) is known as the rest mass; for the electron this is \(m_e\). And a third bit of arcana, expressing mass in \(MeV/c^2\): \(m_e c^2 = 0.511 \text{ MeV}\). Thus:

\[E = \gamma mc^2 \quad (99)\]

\[m_e = 0.511 \text{ MeV} \quad (100)\]

\[\gamma = \frac{20 \times 10^3 \text{ MeV}}{0.511 \text{ MeV}} = 3.9 \times 10^4 \quad (101)\]