Q3. According to the photon model, light carries its energy in packets called quanta or photons. Why then don’t we see a series of flashes when we look at things?

Normally, things you see are emitting thousands to millions of photons (but see P2), so their lumpiness isn’t noticed. Some electronic detectors do in fact count individual photons, as in fig. 38.16.

Q4. Would you expect effects due to the photon nature of light to be generally more important at the low-frequency end of the electromagnetic spectrum (radio waves) or at the high-frequency end (x rays and gamma rays)? Why?

The photon nature of light is more important at the high-frequency end of the spectrum. Each individual photon has more energy and momentum.

Q5. During the photoelectric effect, light knocks electrons out of metals. So why don’t the metals in your home lose their electrons when you turn on the lights?

First, most metals require UV photons to lose electrons. Second, if a piece of metal loses electrons, it becomes positively charged, making further loss impossible. And a small charge goes a long way.

Q10. In an experiment involving the photoelectric effect, if the intensity of the incident light (having frequency higher than the threshold frequency) is reduced by a factor of 10 without changing anything else, which (if any) of the following statements about this process will be true? (a) The number of photoelectrons will most likely be reduced by a factor of 10. (b) The maximum kinetic energy of the ejected photoelectrons will most likely be reduced by a factor of 10. (c) The maximum speed of the ejected photoelectrons will most likely be reduced by a factor of 10. (d) The maximum speed of the ejected photoelectrons will most likely be reduced by a factor of . (e) The time for the first photoelectron to be ejected will be increased by a factor of 10.

(a) True. Lowering the intensity of the light means lowering the photon impact rate. 
(b) False. The maximum KE of an individual electron is the photon energy minus the work function, which does not depend on intensity. Most electrons come off with less than the maximum because they lose energy inside the metal. 
(c) False. The electrons are slow enough that \( K = \frac{1}{2}mv^2 \) is accurate; so \( v \) and \( K \), discussed in (b), go hand in hand. 
(d) False. Same as (b). 
(e) False. The ejection is essentially instantaneous when the photon impacts. There is no need to build up energy.

Q11. The materials called phosphors that coat the inside of a fluorescent lamp convert ultraviolet radiation (from the mercury-vapor discharge inside the tube) into visible light. Could one also make a phosphor that converts visible light to ultraviolet? Explain.

No, at least not readily. The conversion process calls for absorbing a photon, converting some of its energy into some other form, then emitting the remainder as a photon of lower energy.
To emit a photon of higher energy (e.g., convert a visible photon to ultraviolet) would require adding energy to the photon. Removing energy is much easier.

P1. (a) A proton is moving at a speed much slower than the speed of light. It has kinetic energy \( K_1 \) and momentum \( p_1 \). If the momentum of the proton is doubled, so \( p_2 = 2p_1 \), how is its new kinetic energy \( K_2 \) related to \( K_1 \)? (b) A photon with energy \( E_1 \) has momentum \( p_2 \). If another photon has momentum \( p_2 \) that is twice \( p_2 \), how is the energy \( E_2 \) of the second photon related to \( E_1 \)?

(a) In Newtonian mechanics, we can write \( K = p^2/2m \). Doubling \( p \) quadruples \( K \), so \( K_2 = 4K_1 \).
(b) \( E_{\text{photon}} = p_{\text{photon}}c \). So doubling \( p \) doubles \( E_{\text{photon}} \). \( E_2 = 2E_1 \). This is approximated for protons (or any other particle) as their speed approaches \( c \).

P2. Response of the Eye. The human eye is most sensitive to green light of wavelength 505 nm. Experiments have found that when people are kept in a dark room until their eyes adapt to the darkness, a single photon of green light will trigger receptor cells in the rods of the retina. (a) What is the frequency of this photon? (b) How much energy (in joules and electron volts) does it deliver to the receptor cells? (c) To appreciate what a small amount of energy this is, calculate how fast a typical bacterium of mass \( 9.5 \times 10^{-12} \) g would move if it had that much energy.

(a) \( f = c/\lambda = (3 \times 10^8 \text{ m/s})/(5.05 \times 10^{-7} \text{ m}) = 5.94 \times 10^{14} \text{ Hz} \).
(b) \( E = hf = (6.63 \times 10^{-34} \text{ Js})(5.94 \times 10^{14} \text{ Hz}) = 3.94 \times 10^{-19} \text{ J} \).
(c) \( K = (1/2)mv^2 \Rightarrow v = \sqrt{2K/m} = \sqrt{2 \cdot (3.94 \times 10^{-19} \text{ J})/(9.5 \times 10^{-15} \text{ kg})} = 9.11 \times 10^{-3} \text{ m/s} \).

P6. A photon has momentum of magnitude \( 8.24 \times 10^{-28} \text{ kg m/s} \). (a) What is the energy of this photon? Give your answer in joules and in electron volts. (b) What is the wavelength of this photon? In what region of the electromagnetic spectrum does it lie?

(a) \( E = pc = (8.24 \times 10^{-28} \text{ kg m/s})(3 \times 10^8 \text{ m/s}) = 2.47 \times 10^{-19} \text{ J} = 1.54 \text{ eV} \).
(b) \( E = hc/\lambda \Rightarrow \lambda = hc/E \). In class, I gave \( hc = 1240 \text{ eV \cdot nm} \), so
\[ \lambda = (1240 \text{ eV \cdot nm})/(1.54 \text{ eV}) = 803 \text{ nm} \text{. Infrared.} \]

P7. The graph in Fig. E38.7 shows the stopping potential as a function of the frequency of the incident light falling on a metal surface. (a) Find the photoelectric work function for this metal. (b) What value of Planck’s constant does the graph yield? (c) Why does the graph not extend below the \( x \)-axis? (d) If a different metal were used, which characteristics of the graph would you expect to be the same and which ones would be different?

(a) A linear fit on the curve yields \( V = 3.85f - 4.81 \), where \( f \) is in units of \( 10^{15} \text{ Hz} \). The \( y \)-intercept, when multiplied by the charge on the electron, is the negative of the work function \( \phi \).
\[ \phi = 4.81 \text{ eV} \).
So the energy of an electron in eV is numerically equal to the voltage.
(b) The slope is \( 3.85 \times 10^{-15} \text{ V/Hz} \). The electron energy in eV is again numerically equal to the voltage, so from this data
\[ h = 3.85 \times 10^{-15} \text{ eV/Hz} = 3.85 \times 10^{-15} \text{ eV \cdot s} \.}
(c) Light of frequency below $1.25 \times 10^{15}$ Hz does not eject any electrons at all. The current is zero, even if the collector is biased to attract them.

(d) The slope would be the same (maybe more, since the value from the graph is slightly less than the correct $h$). The $y$-intercept would be different, since a different metal would have a different work function.

**P14.** The cathode-ray tubes that generated the picture in early color televisions were sources of x-rays. If the acceleration voltage in a television tube is 15.0 kV, what are the shortest-wavelength x-rays produced by the television? (Modern televisions contain shielding to stop these x rays.)

For 15 kV, the highest photon energy by bremsstrahlung is 15 keV.

$$\lambda = \frac{hc}{E} = \frac{1240 \text{ eV} \cdot \text{nm}}{15000 \text{ eV}} = 0.0827 \text{ nm} = 82.7 \text{ pm}.$$  

LCD and plasma TVs don’t use cathode-ray tubes, so emit no x-rays from this origin.

**P29. Exposing Photographic Film.** The light-sensitive compound on most photographic films is silver bromide, AgBr. A film is “exposed” when the light energy absorbed dissociates this molecule into its atoms. (The actual process is more complex, but the quantitative result does not differ greatly.) The energy of dissociation of AgBr is $1.00 \times 10^5$ J/mol. For a photon that is just able to dissociate a molecule of silver bromide, find (a) the photon energy in electron volts; (b) the wavelength of the photon; (c) the frequency of the photon. (d) What is the energy in electron volts of a photon having a frequency of 100 MHz? (e) Light from a firefly can expose photographic film, but the radiation from an FM station broadcasting 50,000 W at 100 MHz cannot. Explain why this is so.

(a) We need to convert J/mol to eV/particle. Multiply by suitable representations of 1.

$$1 \text{ J/mol} = (1 \text{ J/mol}) \left(\frac{(1 \text{ eV})}{(1.602 \times 10^{-19} \text{ J})} \right) \left(\frac{(1 \text{ mol})}{(6.022 \times 10^{23} \text{ particles})}\right) = 1.036 \times 10^{-5} \text{ eV/particle}.$$  

Hence $1.00 \times 10^5$ J/mol = 1.04 eV/particle, and **1.04 eV**.

(b) $\lambda = \frac{hc}{E} = \frac{(1240 \text{ eV} \cdot \text{nm})}{(1.04 \text{ eV})} = 1192 \text{ nm}.$

(c) $f = \frac{c}{\lambda} = 2.52 \times 10^{14} \text{ Hz}$.

(d) $E = hf = (4.135 \times 10^{-15} \text{ eV} \cdot \text{s})(1.0 \times 10^8 \text{ Hz}) = 4.14 \times 10^{-7} \text{ eV}$.

(e) The lowest photon energy that will dissociate the AgBr is about 1 eV, corresponding to 1192 nm, in the near infrared. The photons from the radio station have less than one-millionth this energy.