1. Why don't we notice the wave nature of matter in our everyday experience?

Since matter has huge mass, the wavelength will be very large to observe.

2. The average distance to the sun from the earth is 92.58 million miles. How long does it take light from the sun to reach the earth?

\[ C = \text{distance/time} \]
\[ \text{Time} = \frac{92.58 \times 10^6 \text{ mile} \times 1609 \text{ (m/mile)}}{3 \times 10^8 \text{ m/s}} = 496.5 \text{ s} = 8.28 \text{ min} \]

3. What statement is true when comparing red light to blue light?
   1. Red light travels at a greater speed than blue light.
   2. Blue light travels at greater speed than red light.
   3. The wavelength of blue light is longer.
   4. The wavelength of red light is longer.

The last statement is true.

4. If you double the frequency of a wave, what happens to the wavelength of the wave?

Wavelength becomes one-half (1/2) its original value because frequency and wavelength are inversely proportional.

5. What is the wavelength of electromagnetic radiation that has a 60 Hz frequency?

\[ v = \frac{c}{\lambda} \]
\[ 60 = \frac{3 \times 10^8}{\lambda} \]
\[ \lambda = 5.0 \times 10^6 \text{ meters or 5000 km}!! \]

6. The photoelectric effect is the name given to the process where light waves striking the surface of a metal frees some electrons and produces an electric current. How is it possible for a light wave to liberate an electron from a piece of metal?

Light is packets of energy called photons. When a photon of enough energy (greater than the work function of the metal surface) hits a metal surface, some of its energy is transferred to an electron through collision, which releases the electron and may give it some kinetic energy, depending on the initial energy of the photon.

7. For biological organisms, more damage is done to cells by standing in front of a very weak (low power) beam of x-rays than in front of a much brighter red light. How does the photon concept explain this situation that an 18th century physicist would have found paradoxical?

An x-ray beam is far more energetic than an intense bright red light, since the wavelength of the x-ray beam has a much smaller wavelength than the red light.
8. In photoelectric effect experiments, no photoelectrons are produced when the frequency of the incident radiation drops below a cutoff value (which varies depending on the metal used in the experiment), no matter how bright or intense the light is. How can you explain this fact using a “particle” theory of light instead of a wave theory of light?

When the frequency of light hitting a surface is lower than a cut-off value (threshold frequency), photons will not have enough energy to release electrons from the surface. This is because energy of a photon is directly proportional to frequency of the beam, rather than the amplitude of the wave (intensity).

9. What is the energy of one quantum of 5.0 x 10^{14} Hz light?

<table>
<thead>
<tr>
<th>Values of $h$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.62606957(29) x 10^{-34}</td>
<td>J·s</td>
</tr>
<tr>
<td>4.135667516(91) x 10^{-15}</td>
<td>eV·s</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Values of $hc$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.98644568 x 10^{-25}</td>
<td>J·m</td>
</tr>
<tr>
<td>1.23984193</td>
<td>eV·μm</td>
</tr>
</tbody>
</table>

$$E = h

E = 4.136 \times 10^{-15} \text{ eV·s} \times 5.0 \times 10^{14} / \text{s} = 2.07 \text{ eV}$$

10. A photon has $3.3 \times 10^{-19}$ J of energy. What is the wavelength of this photon? What part of electromagnetic spectrum does it come from?

$$3.3 \times 10^{-19} \text{ J} = 6.626 \times 10^{-34} \text{ J·s} \times 3 \times 10^9 / \lambda$$

$$\lambda = 6.02 \times 10^{-7} \text{ m} = 602 \text{ nm}$$

This wavelength comes from the visible region of the electromagnetic spectrum.

11. Which has more energy, a photon of violet light or a photon of red light from the extreme ends of the visible spectrum?

A violet light has more energy, since the wavelength of the violet is shorter than that of the red light.

12. What is the lowest frequency of light that can cause the release of electrons from a metal that has a work function of 2.8 eV?

$$hv = \Phi + K$$

Using the lowest frequency will result in no kinetic energy of the released electron. Therefore $h

4.136 \times 10^{-15} \text{ eV·s} \times \nu_o = 2.8 \text{ eV}$
\( \nu_0 = 6.77 \times 10^{14} \) Hz

13. The threshold wavelength for emission from a metallic surface is 500 nm. What is the work function for that particular metal?

Threshold frequency = \( \frac{c}{\lambda} \)
Threshold frequency = \( \{3 \times 10^8 \text{ (m/s)}\}/\{500 \times 10^{-9} \text{ m}\} = 6 \times 10^{14} \) Hz
\( \Phi = h\nu_0 = 4.136 \times 10^{-15} \text{ eV.s} \times 6 \times 10^{14} \text{ s}^{-1} = 2.48 \text{ eV} \)

14. If the work function of a metal surface is 2.48 eV, calculate the maximum speed of a photoelectron produced by each of the following wavelengths of light:

1. 400 nm

\[ h\nu = \Phi + K \]
\[ KE = h\nu - \Phi \]
\[ KE = \{4.136 \times 10^{-15} \times 3 \times 10^8/400 \times 10^{-9} \text{ m}\} - 2.48 \]
\[ KE = 0.622 \text{ eV} \]

Get the energy in units of Joule, since a Joule = \( \{\text{kg . m}^2/\text{s}^2\} \)

\[ K = 0.622 \text{ eV} \times 1.6 \times 10^{-19} \text{ J/eV} = 9.966 \times 10^{-20} \text{ joule} \]
\[ K = 1/2 mv^2 \]
\[ 9.966 \times 10^{-20} \text{ joule} = 1/2 \times 9.10938291 \times 10^{-31} \text{ kilograms} \times v^2 \]
\[ 0.622 \times 1.78 \times 10^{-36} \text{ kilogram .m/s} = 1/2 \times 9.10938291 \times 10^{-31} \text{ kilograms} \times v^2 \]
\[ V^2 = 2.188 \times 10^{11} \]
\[ V = 4.68 \times 10^5 \text{ m/s} \]

2. 500 nm
For that wavelength, this is the threshold frequency and the electron will have a zero kinetic energy and thus zero velocity. (See problem above)

3. 600 nm
Since the threshold wavelength has higher frequency than 600 nm, this wavelength will not be able to release an electron.

15. The work function for a photoelectric material is 3.5 eV. The material is illuminated with monochromatic light with a wavelength of 300 nm. What is the cutoff frequency for that particular material? Find the stopping potential of emitted photoelectrons

\[ \Phi = h\nu_0 \]
\[ \nu_0 = 3.5 \text{ eV}/4.136 \times 10^{-15} \text{ eV.s} = 8.46 \times 10^{14} \text{ Hz} \]

The stopping potential is the potential (energy / unit charge) measured in volts (joules/coulomb) that must be applied to stop the electrons from being ejected from the surface when the the surface is illuminated by light.

The stopping voltage, in eV, will counteract the maximum kinetic energy. Therefore:
KE = eV_o where V_o is the stopping voltage
KE = hν - Φ
\( eV_o = hν - Φ \)

\( eV_o = \{4.136 \times 10^{-15} \text{ eV.s } \times 3 \times 10^8 \text{ m/s} \} / 300 \times 10^{-9} \text{ m} \) – 3.5 = 0.636 eV

A Volt is Joule/coulomb

\( V_o = \{4.136 \times 10^{-15} \text{ eV.s} \times 3 \times 10^8 \text{ m/s} \} / 300 \times 10^{-9} \text{ m} – 3.5 = 0.636 \text{ V} \)

16. Red light of wavelength 670.0 nm produces photoelectrons from a certain metal which requires a stopping potential of 0.5 V. What is the work function and threshold wavelength of the metal?

\( eV_o = hν - Φ \)

With a stopping potential \( V = 0.5 \text{ V} \), we find

\( Φ = \{4.136 \times 10^{-15} \text{ eV.s } \times 3 \times 10^8 \text{ m/s} \} / 670 \times 10^{-9} \text{ m} \) – e*0.5V = 1.35 eV

\( Φ = 1.35 \text{ eV} \)

**Calculation of the threshold wavelength**

\( Φ = hν_o = hc/λ_o \)

\( λ_o = \{1240 \text{ eV nm/1.35 eV} \} = 919 \text{ nm} \)

Thus, the work function of the metal is 1.35 eV, with a corresponding threshold wavelength of 919 nm.

17. Gold has a work function of 4.82 eV. A block of gold is illuminated with ultraviolet light (\( λ = 160 \text{ nm} \)).

a. Find the maximum kinetic energy of the emitted photoelectrons in electron volts

b. Find the threshold frequency for gold

\( KE = hν - Φ \)

\( KE = \{4.136 \times 10^{-15} \text{ eV.s } \times 3 \times 10^8 \text{ m/s} \} / 160 \times 10^{-9} \text{ m} \) – 4.82 = 2.94 eV

b. The threshold frequency for gold

\( \Phi = hν_o \)

\( ν_o = 2.94 \text{ eV}/4.136 \times 10^{-15} \text{ eV.s} = 7.1 \times 10^{14} \text{ Hz} \)

18. Sodium and silver have work functions of 2.46 eV and 4.73 eV, respectively. What is the cutoff wavelength for each material.

For Na \( λ_o = \{1240 \text{ eV nm/2.46 eV} \} = 504 \text{ nm} \)
19. What is the energy of a photon of blue light that has a frequency of $7.50 \times 10^{14}$ Hz?

E = $h\nu$

$E = \frac{4.136 \times 10^{-15} \text{ eV s} \cdot 7.5 \times 10^{14} \text{ s}}{1} = 3.10 \text{ eV}$

20. What is the energy of a photon that has a wavelength of 466 nm?

E = $\frac{hc}{\lambda}$ = $\frac{1240 \text{ eV nm}}{466 \text{ nm}}$ = $2.66 \text{ eV}$

21. What is the wavelength of a photon that has 2.1 eV of energy?

E = $\frac{hc}{\lambda}$

$2.1 = \frac{1240}{\lambda}$

$\lambda = 590 \text{ nm}$

22. A photoelectric surface has a work function of $3.30 \times 10^{-19}$ J. What is the threshold frequency of this surface?

Change the units of the work function to eV by dividing on the charge of the electron:

Work function = $3.30 \times 10^{-19} \text{ J}/1.602 \times 10^{-19} \text{ eV J} = 2.06 \text{ eV}$

$\Phi = h\nu_o$

$\nu_o = \frac{2.06 \text{ eV}}{4.136 \times 10^{-15} \text{ eV s}} = 4.98 \times 10^{14} \text{ Hz}$

23. A photoelectric surface requires a light of maximum wavelength 675 nm to cause electron emission. What is the work function of this surface?

$\Phi = h\nu_o$

$\Phi = \frac{4.136 \times 10^{-15} \text{ eV s} \cdot 3 \times 10^8 \text{ m/s}}{675 \times 10^{-9} \text{ m}} = 1.84 \text{ eV}$

24. A photoelectric surface has a work function of 2.75 eV. What is the minimum frequency of light that will cause photoelectron emission from this surface?

$\Phi = h\nu_o$

$\nu_o = \frac{2.75 \text{ eV}}{4.136 \times 10^{-15} \text{ eV s}} = 6.65 \times 10^{14} \text{ Hz}$

25. Light with a frequency of $5.00 \times 10^{14}$ Hz illuminates a photoelectric surface that has a work function of $2.10 \times 10^{-19}$ J. What is the maximum kinetic energy of the emitted photoelectrons?
\[ h\nu = \Phi + KE \]
\[ KE = h\nu - \Phi \]

**1 Joule = 6.24 \times 10^{18} \text{ eV}**

\[ KE = \{4.136 \times 10^{-15} \text{ eV} . s * 5.00 \times 10^{14} \text{ s}^{-1}\} - 2.10 \times 10^{-19} \text{ J} * 6.24 \times 10^{18} \text{ eV/J} \]
\[ KE = 0.76 \text{ eV} \]

26. Light with a wavelength of 530 nm falls on a photoelectric surface that has a work function of 1.70 eV. What is the maximum kinetic energy of any emitted photoelectrons?

\[ h\nu = \Phi + KE \]
\[ KE = h\nu - \Phi \]

**1 Joule = 6.24 \times 10^{18} \text{ eV}**

\[ KE = \{4.136 \times 10^{-15} \text{ eV.s} * 3\times10^8 \text{ m/s}/530\times10^{-9} \text{ m}\} - 1.70 \text{ eV} \]
\[ KE = 0.64 \text{ eV} \]

27. Electrons are ejected from a photoelectric surface with a maximum kinetic energy of 2.9 eV. If the photons of incident light have energy of 3.45 eV, what is the minimum frequency needed to cause photoelectron emission?

\[ h\nu = \Phi + KE \]
\[ \Phi = h\nu - KE \]
\[ \Phi = 3.45 - 2.9 = 0.55 \text{ eV} \]
\[ \Phi = h\nu_o \]
\[ \nu_o = 0.55 \text{ eV}/4.136 \times 10^{-15} \text{ eV.s} = 1.33 \times 10^{14} \text{ Hz} \]

28. Electrons are ejected from a photoelectric surface with a maximum speed of 4.20 \times 10^5 \text{ m/s}. If the work function of the metal is 2.55 eV, what is the wavelength of the incident light?

First, calculate the kinetic energy in eV

\[ KE = 1/2mV^2 = 1/2 * 9.10938291 \times 10^{-31} \text{ kilograms} * (4.2\times10^5 \text{ m/s})^2 \]
\[ KE = 8.03 \times 10^{-20} \text{ kg m}^2/\text{s}^2 = 8.03 \times 10^{-20} \text{ J} \]
\[ KE = 8.03 \times 10^{-20} * 6.24 \times 10^{18} \text{ eV/J} = 0.50 \text{ eV} \]
\[ hc/\lambda = \Phi + KE \]
\[ 1240/\lambda = 2.55 + 0.5 \]
\[ \lambda = 406 \text{ nm} \]

29. A photoelectric cell is illuminated with white light (wavelengths from 400 nm to 700 nm). What is the maximum kinetic energy of the electrons emitted by this surface if its work function is 2.30 eV?
Maximum kinetic energy will result from highest energy, which will be due to shortest wavelength.

\[ KE = \frac{hc}{\lambda} - \Phi \]

\[ KE = \{1240 \text{ eV nm}/400 \text{ nm}\} - 2.30 = 0.8 \text{ eV} \]

30. Heisenberg's uncertainty principle can be expressed mathematically as \( \Delta x \Delta p = \frac{\hbar}{4\pi} \), where \( \Delta x \) and \( \Delta p \) denote the uncertainty in position and momentum, respectively, and "\( \hbar \)" is Planck's constant. What would be the uncertainty in the position of a cat (mass = 7.107 \( \times \) \( 10^3 \) g) that was traveling at a velocity of 8.885 \( \times \) \( 10^1 \) m/s if the velocity has an uncertainty of 2.06%?

Planck's constant = 6.626068 \( \times \) \( 10^{-34} \) m\(^2\) kg / s

Given mass = 7.107 \( \times \) \( 10^3 \) g = 7.107 kg

Since uncertainty in velocity is 2.06% i.e. 0.0206

So, by \( \Delta x \Delta p = \frac{\hbar}{4\pi} \) and \( \Delta p = m\Delta v \) assuming that the uncertainty in mass is negligible

\[ \Delta x = \frac{\hbar}{4\pi m\Delta v} \]
\[ \Delta x = 6.63 \times 10^{-34} \text{ m^2 kg s}^{-1}/\{4*3.14*0.8885 \text{ kg} \cdot 0.0206 \text{ m s}^{-1}\} \]
\[ \Delta x = 4.058 \times 10^{-34} \text{ m} \]

\( \Delta x \) is insignificant in this case because the velocity of a cat is considerably low and its mass is too large as compared to subatomic species


The momentum of the moving particle will have higher uncertainty. This means that if the uncertainty in mass is negligible, there should be higher uncertainty in the calculation of its velocity.

32. Why is it impossible to accurately measure the position and velocity of a particle simultaneously?

Since as one attempts to measure the velocity, for example, there will always be an uncertainty in the calculation of the time as the velocity gets higher and higher. This reflects on the position, or the actual distance it really travelled.

33. If you have an electron with a momentum of \((3.28470 \pm 0.00025) \times 10^{-30} \text{ kg m/s}\), what is the minimum uncertainty in the position of the electron?

\[ \Delta x = \frac{\hbar}{4\pi \Delta p} = 6.63 \times 10^{-34} \text{ J s} / 4\pi(0.00025 \times 10^{-30} \text{ kg m/s}) \]

Thus, \( \Delta x = 0.211 \text{ m} \)

34. An electron in a hydrogen atom is known to be somewhere between 0.050 nm and 0.10 nm from a proton. What is the minimum uncertainty in the speed of that electron?
\[ \Delta x = 0.1 - 0.05 = 0.05 \text{ nm} \]

Using the equals sign in the uncertainty principle to express the minimum uncertainty, we have \( \Delta x \Delta p = h/4\pi \)
\[ \Delta p = m \Delta v \]
\[ \Delta v = h/4\pi \ m \Delta x \]

\[ \Delta v = h/4\pi \ m \Delta x = 6.63 \times 10^{-34} \text{ J} \cdot \text{s} / 4\pi (9.11 \times 10^{-31} \text{ kg}) \times 0.05 \times 10^{-9} \text{ m} \]
\[ \Delta v = 1.16 \times 10^6 \text{ m/s} \]

35. Light of wavelength of 100 nm strikes a clean metal surface in vacuum, emitting electrons of maximum kinetic energy of 8.6 eV. To emit electrons with twice this kinetic energy, what wavelength of light should be used? (\( h^*c = 1240 \text{ eV} \cdot \text{nm} \))

\( h \nu = \Phi + K_1 \)
\[ \frac{hc}{\lambda_1} = \Phi + K_1 \quad (1) \]
\[ \frac{hc}{\lambda_2} = \Phi + 2K_1 \quad (2) \]

Subtract 1 from 2
\[ \frac{hc}{\lambda_2} - \frac{hc}{\lambda_1} = K_1 \]
\[ \frac{hc}{\lambda_2} = \frac{hc}{\lambda_1} + K_1 \]
\[ 1240/\lambda_2 = (1240/100) + 8.6 \]
\[ \lambda_2 = 1240/21 = 59 \text{ nm} \]

36. If the position of an electron in an atom is measured to an accuracy of 0.0100 nm, what is the electron’s uncertainty in velocity? (b) If the electron has this velocity, what is its kinetic energy in eV?

**Strategy:**

The uncertainty in position is the accuracy of the measurement, or \( \Delta x = 0.0100 \text{ nm} \). Thus the smallest uncertainty in momentum \( \Delta p \) can be calculated using \( \Delta x \Delta p \geq h/4\pi \). Once the uncertainty in momentum \( \Delta p \) is found, the uncertainty in velocity can be found from \( \Delta p = m \Delta v \).

**Solution for (a):**

Using the equals sign in the uncertainty principle to express the minimum uncertainty, we have \( \Delta x \Delta p = h/4\pi \).

Solving for \( \Delta p \) and substituting known values gives
\[ \Delta p = h/4\pi \Delta x = 6.63 \times 10^{-34} \text{ J} \cdot \text{s} / 4\pi (1.00 \times 10^{-11} \text{ m}) = 5.28 \times 10^{-24} \text{ kg} \cdot \text{m/s} . \]

Thus, \( \Delta p = 5.28 \times 10^{-24} \text{ kg} \cdot \text{m/s} = m \Delta v \)

Solving for \( \Delta v \) and substituting the mass of an electron gives
\[ \Delta v = \Delta p/m = 5.28 \times 10^{-24} \text{ kg} \cdot \text{m/s} / 9.11 \times 10^{-31} \text{ kg} = 5.79 \times 10^6 \text{ m/s} . \]

**Solution for (b):**
KE = 1/2 mv^2 = 1/2*(9.11×10^{-31} kg)(5.79×10^6 m/s)^2 = 1.53×10^{-17} J
KE = (1.53×10^{-17} J) (1 eV/1.60×10^{-19} J) = 95.5 eV.

Discussion:

Since atoms are roughly 0.1 nm in size, knowing the position of an electron to 0.0100 nm localizes it reasonably well inside the atom. This would be like being able to see details one-tenth the size of the atom. But the consequent uncertainty in velocity is large. You certainly could not follow it very well if its velocity is so uncertain. To get a further idea of how large the uncertainty in velocity is, we assumed the velocity of the electron was equal to its uncertainty and found this gave a kinetic energy of 95.5 eV. This is significantly greater than the typical energy difference between levels in atoms, so that it is impossible to get a meaningful energy for the electron if we know its position even moderately well.

37. An atom in an excited state temporarily stores energy. If the lifetime of this excited state is measured to be $1.0×10^{-10}$ s, what is the minimum uncertainty in the energy of the state in eV?

**Strategy**

The minimum uncertainty in energy $\Delta E$ is found by using the equals sign in $\Delta E\Delta t\geq h/4\pi$ and corresponds to a reasonable choice for the uncertainty in time. The largest the uncertainty in time can be is the full lifetime of the excited state, or $\Delta t=1.0×10^{-10}$ s.

**Solution**

Solving the uncertainty principle for $\Delta E$ and substituting known values gives

$\Delta E = h/4\pi\Delta t = 6.63×10^{-34} J\cdot s/4\pi(1.0×10^{-10} s) = 5.3×10^{-25} J$.

Now converting to eV yields

$\Delta E = (5.3×10^{-25} J)(1 eV/1.6×10^{-19} J) = 3.3×10^{-6} eV$.

**Discussion**

The lifetime of $10^{-10}$ s is typical of excited states in atoms which means that they quickly emit their stored energy. An uncertainty in energy of only a few millionths of an eV results. This uncertainty is small compared with typical excitation energies in atoms, which are on the order of 1 eV. So here the uncertainty principle limits the accuracy with which we can measure the lifetime and energy of such states, but not very significantly.

38. Suppose visible light of wavelength 500 nm is used to determine the position of an electron to within the wavelength of the light. What is the minimum uncertainty in the electron's speed?

We shall use the Heisenberg uncertainty relation

$\Delta x\Delta p = h/4\pi$
With \( p = mV \), and assuming negligible uncertainty in the mass of the electron
\[ \Delta p = m\Delta V \]
\[ \Delta V = \frac{h}{4\pi m}\Delta x \]
\[ \Delta V = 6.63 \times 10^{-34} \text{ J} \cdot \text{s} \]
\[ \Delta V = \frac{1}{4\pi \times 3.14 \times 9.11 \times 10^{-31} \text{ kg} \times 500 \times 10^{-9} \text{ m}} \]
\[ \Delta V = 115.9 \text{ m/s} \]
Thus, the minimum uncertainty in the electron's speed is 115.9 m/s.

**Short Questions**

1. In a vacuum, all electromagnetic waves have the same
   a. wavelength.
   b. frequency.
   c. speed.
   d. amplitude.

2. Visible light has a higher frequency than
   a. X-rays.
   b. ultraviolet rays.
   c. infrared rays.
   d. gamma rays.

3. The range of electromagnetic waves placed in a certain order is called the
   a. electromagnetic spectrum.
   b. electromagnetic wavelength.
   c. electromagnetic frequency.
   d. electromagnetic field.

4. The electromagnetic waves with the highest frequencies are called
   a. radio waves.
   b. gamma rays.
   c. X-rays.
   d. visible light.

5. If something vibrates one million times per second, it has a frequency of
   a. 1 hertz.
   b. 10 hertz.
   c. 1 megahertz.
   d. 1 kilohertz.

6. A packet of light energy is called a
   a. wavicle.
   b. photon.
   c. wave.
   d. photoelectron.

7. The speed of an electromagnetic wave is equal to
a. wavelength plus frequency.
b. wavelength times frequency.
c. wavelength divided by frequency.
d. frequency divided by wavelength.