Guided Practice Activities

**Module:** Atomic Theory

**Section:** Electromagnetic Radiation and Matter - Key
Introduction to Electromagnetic Radiation

Activity 1

The purpose of this activity is to check your understanding of the characterization of electromagnetic radiation by answering the following questions.

1. Explain the following: Electromagnetic Radiation is energy on the move.

   Electromagnetic radiation can be thought of in two ways. Most traditionally, we think of light waves. These waves of EM radiation are the result of the oscillation of electric waves and magnetic waves perpendicular to one another. The waves carry information or energy along the transverse axis which we receive as heat, visible light, x-rays, radio waves etc.

   Another way to think about EM radiation is as a beam of photons. Photons are subatomic packets of light energy. They interact with matter as a massless particle that transfers energy into and out of matter.

2. Electromagnetic radiation is modeled mathematically as an oscillating wave moving in a vacuum at the speed of light (light is a generic word for electromagnetic radiation – but normally the layman thinks of this as visible light – which is a narrow section of the entire electromagnetic spectrum). The speed of light (electromagnetic radiation) in a vacuum is $3 \times 10^8 \text{ m/s (c)}$.

3. As the electromagnetic radiation moves through space it oscillates between a positive and negative extremes creating an oscillating electric field in one direction and perpendicular to that an oscillating magnetic field.

4. The rate at which a peak in oscillation passes a fixed point is called the ___ frequency$(_\nu_)$_. The distance between the peaks of oscillation is called the ___wavelength$(_\lambda_)$_.

5. Electromagnetic radiation can be characterized by its wavelength or frequency, and they are related according to the following equation:

   $$c = \frac{\lambda}{\nu}$$
Activity 2

The purpose of this activity is to check your understanding of the characterization of electromagnetic radiation by answering the following questions.

1. List here the various regions of the electromagnetic spectrum including the names of the regions and the associated wavelength range.

   The following ranges are approximations. Some textbooks will have slightly different cutoffs. The most important thing to notice is the magnitudes of the wavelengths and frequencies. The visible spectrum is important to memorize however.
   Radio –
   - Frequencies: (< 3x10^8 Hz)
   - Wavelengths: (> 1 m)
   Microwave –
   - Frequencies: (3x10^8 – 3x10^11 Hz)
   - Wavelengths: (1 m – 1 mm)
   Infrared –
   - Frequencies: (3x10^11 – 4x10^14 Hz)
   - Wavelengths: (1 mm – 700 nm)
   Visible –
   - Frequencies: (4x10^14 – 7x10^14 Hz)
   - Wavelengths: (700 nm – 400 nm)
   Ultra-Violet –
   - Frequencies: (7x10^14 – 3x10^16 Hz)
   - Wavelengths: (400 nm – 10 nm)
   X-Ray –
   - Frequencies: (3x10^16 – 10^18 Hz)
   - Wavelengths: (10 nm – 1 pm)
   Gamma –
   - Frequencies: (> 10^20 Hz)
   - Wavelengths: (< 1 pm)

2. Calculate the wavelength of light in nanometers given the frequency is 5.75 x 10^{14} Hz. State in which region of the electromagnetic spectrum this light is found.
3. Calculate the frequency associated with a wavelength of electromagnetic radiation equal to 1.7 meters. In what region of the spectrum is this light found?

\[ c = \lambda \nu \]
\[ 3.0 \times 10^8 \text{ m/s} = (\lambda)(5.75 \times 10^{14} \text{ Hz}) \]
\[ \lambda = \frac{3.0 \times 10^8 \text{ m/s}}{5.75 \times 10^{14} \text{ s}^{-1}} \]
\[ \lambda = 5.2 \times 10^{-7} \text{ m} = 520 \text{ nm} \]
*Visible Light*

4. What happens to an electron (which carries a negative charge) when placed in a static electric field?

A negatively charged electron in static electric field will move toward the positively charged side of the electric field.

5. What happens to an electron when placed in an oscillating electric field?

A negatively charged electron an oscillating electric field will also oscillate back and forth.

Blackbody Radiation and Ultraviolet Catastrophe

**Activity 1**

The purpose of this activity is to check your understanding of the historical and theoretical background of atomic theory.

1. In the late 19th century scientists were trying to make sense of the interaction of electromagnetic radiation and matter. One experiment that was performed was called the black body radiation. This experiment looked at the relationship between heating a solid object, such as a metal, to different temperatures and measuring the intensity of light emitted and the color
of light being emitted. These scientists found that the higher the temperature, the maximum intensity moved to higher frequency of emitted light.

2. The scientists of the time tried to use classical physics to model the experimental result. Unfortunately, classical physics predicted that any object at nonzero temperature should emit high energy electromagnetic radiation. This result was called the ultraviolet catastrophe.

3. The person who suggested a solution to the physics problem was Max Planck. He suggested that the exchange of energy and between matter and radiation must occur in packets of energy. The packet of energy was called a quantum and photon (eventually).

4. Planck’s hypothesis was that radiation of a certain frequency can only be generated if an oscillator has minimum energy to generate oscillations of that frequency. Hence, low energy oscillations (cooler objects) don’t have oscillations high enough to emit high frequency electromagnetic radiation.

The Photoelectric Effect

Activity 1

The purpose of the following activity is to construct a deeper understanding of the interaction of electromagnetic radiation and matter by investigating the photoelectric effect. Let’s start by engaging with a simulator.

Spend some time exploring the simulator at http://phet.colorado.edu/en/simulation/photoelectric.

1. What happens when you change the metal?

   Changing the metal changes the number and speed of electrons being ejected at different wavelengths of light.

2. What happens when you change the wavelength of light?

   The wavelength of the light sometimes prevents electrons from being ejected, sometimes increases the speed of electrons.

3. What happens when you change the intensity (brightness) of light?

   The intensity of light seems to change the amount of electrons being ejected. Changing the voltage changes the speed and/or direction of electrons moving across the gap.

4. Explore the effects of changing the wavelength and the intensity. Select sodium. Set intensity at 25%. Set color at blue, 455 nm. Set the voltage at 0.00V. Press start “→”. What do you see?

   A few electrons are ejected across the gap at various speeds.
5. What happens when increase “intensity” (Brightness) to 50%?
   
   More electrons are ejected! They still move at various speeds.

6. What happens when increase “intensity” to 90%?
   
   Even more electrons are ejected! They still move at various speeds.

7. Reduce intensity to 25%. Set color at red, 700 nm? Observation?
   
   No electrons are ejected.

8. Increase intensity to 50%. Observation?
   
   No electrons are ejected.

9. Increase intensity to 90%. Observation?
   
   No electrons are ejected.

Activity 2

The purpose of this activity is to continue to explore this concept using the simulator at http://phet.colorado.edu/en/simulation/photoelectric. Explore the effects of metal identity and wavelength.

1. Go back to blue, 455 nm. Switch metal to zinc. Observation?
   
   No electrons are ejected.

2. Increase wavelength to IR region. Observation?
   
   No electrons are ejected.

3. Decrease wavelength to 280 nm. Observation?
   
   Finally, a few electrons are ejected.

4. Decrease wavelength to 185 nm. Observation? Speed of e⁻?
   
   On average, electrons are coming off much faster now.
**Activity 3**

The purpose of this activity is to summarize your explorations in Activities 1 and 2.

1. Were there any differences or similarities between sodium and zinc in this experiment? If so, can you describe them?

   Although electrons easily came off sodium at 455 nm, no electrons would come off of zinc at this wavelength. Still, for both metals, increasing the wavelengths enough meant that the electrons stopped coming off.

2. How did changing the wavelength of light (at a constant intensity) affect the electrons coming off of the surface of the metal? When there were originally no electrons? When there were already some electrons being ejected?

   When there were originally no electrons coming off the surface of the metal, increasing the wavelength still didn’t help. Decreasing the wavelength enough would cause electrons to start coming off. When there were already electrons coming off the surface of the metal, increasing the wavelength would sometimes make them stop coming off or at least move more slowly. Decreasing the wavelength would cause the electrons to eject faster.

3. At a constant wavelength, how did increasing the intensity affect the removal of electrons? When there were originally no electrons? When there were already some electrons being ejected?

   When there were originally no electrons, increasing the intensity did nothing. When there were already electrons present, increasing the intensity increased the number of electrons being ejected from the metal.

**Activity 4**

The purpose of this activity is to build your understanding of the photoelectric effect.

1. Sketch the shape of the graph of the kinetic energy of the ejected electrons versus the frequency of the incident radiation for sodium, and summarize the interpretation of the graph.

   ![Graph of Kinetic Energy vs. Frequency](http://everythingmaths.co.za/science/grade-12/12-optical-phenomena-and-properties-of-matter/12-optical-phenomena-and-properties-of-matter-02.cnxmlplus)
This graph shows that the kinetic energy of a sodium electron increases linearly with increasing frequency of incident light. However, the frequency of incident light must be above a certain threshold frequency (shown here as $f_o$) in order for the electron to move.

2. In 1905, Einstein published his landmark paper in which he interpreted Planck’s photoelectric effect experiment by explaining that exhibited light behaves both like an wave and as a particle called a photon. A photon is defined as:

A “packet” of light energy, a massless particle carrying a particular amount of energy.

3. Summarize here Einstein’s interpretation of the results of Planck’s experiment, including the equation relating the energy of the photon to the frequency of the electromagnetic radiation, for which he was awarded the Nobel Prize in Physics in 1921.

Einstein observed that light was interacting with the electrons of a metal as a particle. For every electron that was ejected a single particle of light energy must have interacted with it. When the intensity of the light source increases the number of photons increases and therefore the number of ejected electrons increases. However, the light source must be of a high enough frequency (low enough wavelength) to overcome the “work function” of the metal in question. If the frequency is not high enough, no electrons will be ejected. Once the energy of the light source is sufficient to overcome the work function, photons can transfer their energy to individual electrons. After the transferred energy overcomes the work function, the remaining energy is translated into kinetic energy. The higher the energy of the light source, the faster the ejected electrons will move. As the frequency of the light increases, so does the transferred energy and therefore the energy of the photon must also be increasing with increasing light frequency. Thus, Einstein observed that the energy of a photon could be calculated as a function of the frequency of the light (or the wavelength):

\[
\begin{align*}
E &= h\nu \\
\frac{c}{\lambda} &= \nu \\
\nu &= \frac{c}{\lambda} \\
E &= \frac{hc}{\lambda}
\end{align*}
\]

Where “$h$” is Planck’s constant ($6.626\times10^{-34}$ Js), “$c$” is the speed of light ($3\times10^8$ m/s), “$\lambda$” is wavelength in meters (m), “$\nu$” is frequency in inverse seconds (s$^{-1}$) and “$E$” is energy in joules (J).
Activity 5

The purpose of this activity is to perform calculations with the photoelectric effect.

1. Determine the energy of a photon with a frequency of $3.17 \times 10^{17}$ Hz.

\[
E = h\nu \\
h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s} \\
\nu = 3.17 \times 10^{17} \text{ Hz} = 3.17 \times 10^{17} \text{ s}^{-1} \\
E = (6.626 \times 10^{-34} \text{ J} \cdot \text{s})(3.17 \times 10^{17} \text{ s}^{-1}) \\
E = 2.10 \times 10^{-16} \text{ J}
\]

2. Define each of the symbols in the following equation.

\[
E_{\nu} = \Phi + KE_{e^-}
\]

$E_{\nu}$ is the energy of the incoming photon

$\Phi$ is the work function of the metal

$KE_{e^-}$ is the kinetic energy of the electron that is ejected due to the incoming photon

3. The work function of chromium metal is 4.37 eV. What wavelength of radiation must be used to eject electrons with a velocity of 2500 km/s?
4. In summary, the major conceptual breakthrough developed from the interpretation of the photoelectric effect experiments was the dual nature of light – that is light has both wavelike and particle-like properties. A packet of quantized energy associated with electromagnetic radiation is called a photon.

The important concept concerning chemistry that you should commit to memory is the idea that if a photon of sufficient energy collides with electrons in the associated matter, an electron can be ejected from the matter!
Wave-Particle Duality and Uncertainty

Activity 1

The purpose of this activity is to build an understanding of the wave-particle nature of light.

1. What observations of electromagnetic radiation support the fact that light has particle like properties?
   
   The photoelectric effect was the biggest indicator of particle-like light behavior. Also, the inferences drawn from the ultraviolet catastrophe helped support Einstein’s theories.

2. What observations of electromagnetic radiation support the fact the light has wavelike properties?
   
   Light passing through small openings makes a diffraction pattern. This behavior indicates that light acts as a wave.

3. This notion the electromagnetic radiation has both wavelike and particle like behavior is called the wave-particle duality of electromagnetic radiation.

Activity 2

The purpose of this activity is to perform calculations using your knowledge of the wave-particle nature of light.

1. de Broglie suggested that like electromagnetic radiation, all matter has dual character as well. He suggested an inverse relationship between the wavelength and the mass and speed of an object. State the de Broglie equation.

   \[ \lambda = \frac{h}{mv} \]

   The constant “h” is Planck’s constant.

2. Estimate the wavelength of proton moving at 1/100 the speed of light.
\[ c = 3.0 \times 10^8 \text{ m/s} \]
\[ v = 0.01c = (0.01)(3.0 \times 10^8 \text{ m/s}) = 3.0 \times 10^6 \text{ m/s} \]
\[ h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s} \]
\[ m_{\text{proton}} = 1.67 \times 10^{-27} \text{ kg} \]
\[ \lambda = \frac{h}{mv} \]
\[ \lambda = \frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{(1.67 \times 10^{-27} \text{ kg})(3.0 \times 10^6 \text{ m/s})} \]
\[ \lambda = 1.3 \times 10^{-13} \text{ m} \]

3. Estimate the wavelength of a kick ball weighing 2 kg moving at a speed of 1 m/sec.

\[ v = 1\text{ m/s} \]
\[ h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s} \]
\[ m = 2\text{ kg} \]
\[ \lambda = \frac{h}{mv} \]
\[ \lambda = \frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{(2\text{ kg})(1\text{ m/s})} \]
\[ \lambda = 3.313 \times 10^{-34} \text{ m} \]

**Activity 3**

The purpose of this activity is to build an understanding of the uncertainty principle.

1. The notion of wave-particle duality completely sweeps away the foundations of classical physics! Most importantly the results of this notion reveal that you cannot know the path or trajectory and the location of an object at any one point in time. This concept is known as the **uncertainty** principle.

2. State here the equation associated with this principle.

\[ \Delta x \Delta p \geq \frac{h}{4\pi} \]

The constant “h” is Planck’s constant.

3. A proton is accelerated in a cyclotron to a high speed with an uncertainty of 200 km/s. What is the minimum uncertainty in the position of the proton?
\[ \Delta x \Delta p \geq \frac{h}{4\pi} \]
\[ \Delta p = m \Delta v \]
\[ m_{\text{proton}} = 1.67 \times 10^{-27} \text{ kg} \]
\[ \Delta v = 200 \text{ km/s} = 200000 \text{ m/s} \]
\[ h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s} \]
\[ \Delta x \cdot m \Delta v \geq \frac{h}{4\pi} \]
\[ \Delta x \geq \frac{h}{4\pi \cdot m \Delta v} \]
\[ \Delta x \geq \frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{4\pi \cdot (1.67 \times 10^{-27} \text{ kg})(200000 \text{ m/s})} \]
\[ \Delta x \geq 1.57 \times 10^{-13} \text{ m} \]