ملخص الدرس الأول A particle model of wave من الوحدة MODULE 22 : Quantum Theory and the Atom انسباير منهج

Physics

LESSON 1

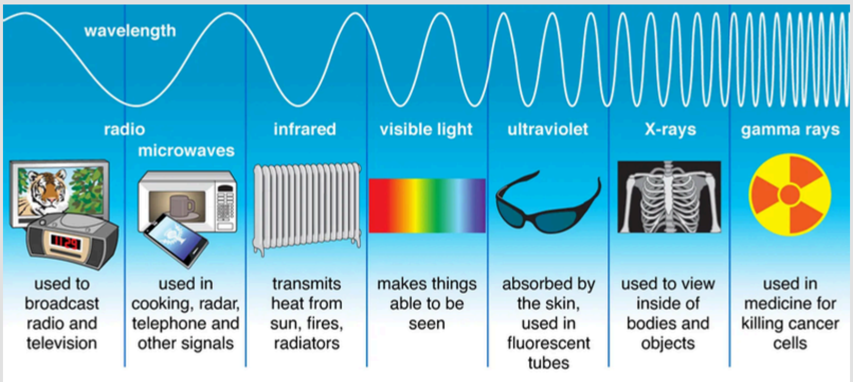
A PARTICLE MODEL OF WAVES

FOCUS QUESTION

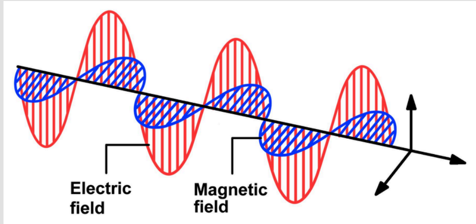
Can light behave like a particle?

@Only_s8

James Maxwell developed the electromagnetic wave theory, which explains that electromagnetic radiation behaves like waves made of changing electric and magnetic fields.

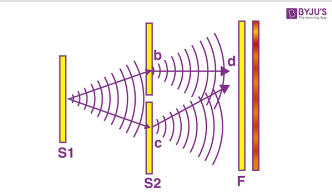


- Electromagnetic Radiation

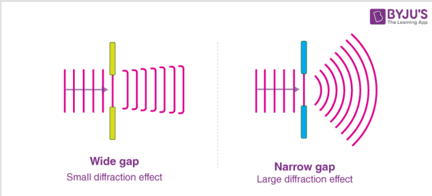


- Electric And Magnetic Fields

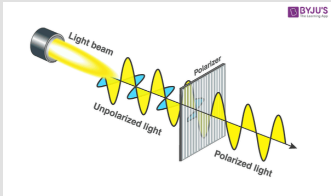
This wave model successfully explains important phenomena such as :



- Interference



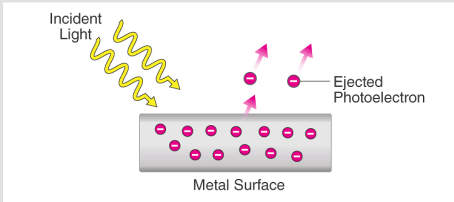
- Diffraction



- Polarization

However, the theory could not explain some key observations, including :

- The spectrum of electromagnetic radiation emitted by objects
- The emission of electrons from metals when exposed to ultraviolet light (photoelectric effect)



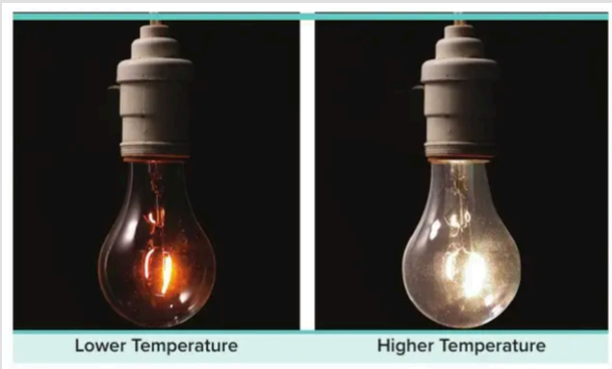
- Photoelectric Effect

- Example : A lightbulb connected to a dimmer shows how electromagnetic radiation changes with temperature.

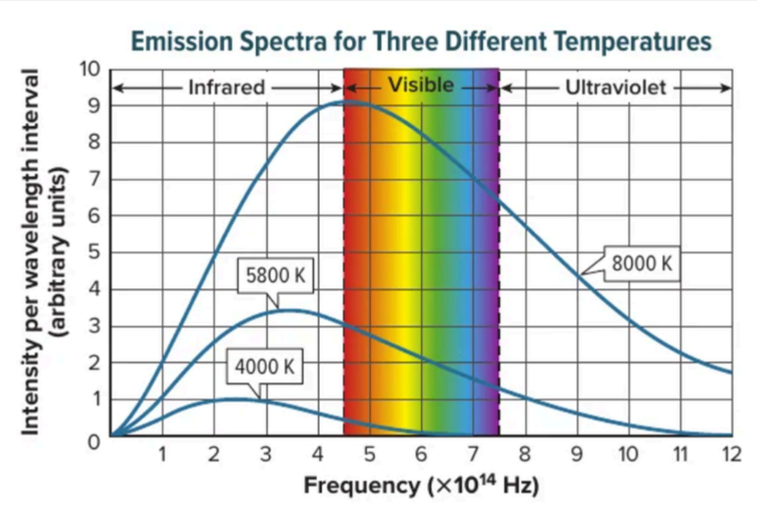
When the potential difference increases :
- The filament's temperature rises
- The emitted light changes color

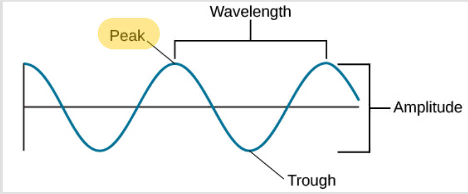
The color progression is :
- Red → Orange → Yellow → White → Blue/Violet

This happens because :
- Higher temperature → higher frequency radiation
- Higher frequency → higher energy



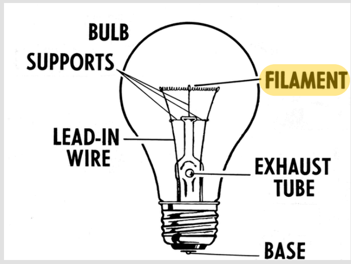
- The color of the glow of the lightbulb depends on the temperature of the filament.





- The frequency at which an object's emission spectrum peaks depends on that object's temperature.
- As the temperature of the object increases, the peak frequency also increases.

Electromagnetic wave theory explains that vibrating charged particles in a lightbulb filament emit electromagnetic radiation, including visible light and infrared radiation.

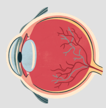


In fact, all objects, whether very cold or very hot, emit a range of electromagnetic waves.

The filament of an incandescent bulb glows brightly because it is very hot, a phenomenon known as incandescence.

The color of the emitted light depends on two main factors:

- The intensity of different frequencies of electromagnetic waves
- The sensitivity of the human eye to those frequencies

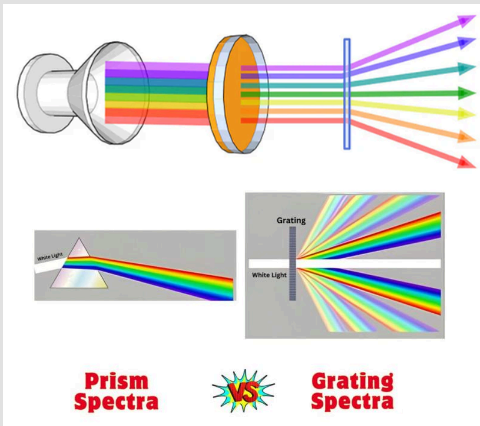


- When the glowing filament is observed through a diffraction grating, it produces a continuous spectrum showing all the colors of the rainbow.
- A continuous spectrum means you see all colors smoothly, like a rainbow.
- The colors you see have frequencies.

For visible light, the frequency is around 6×10^{14} Hz. Each color has a slightly different frequency (red is lower, violet is higher).

- The light bulb also gives off invisible light that we cannot see.

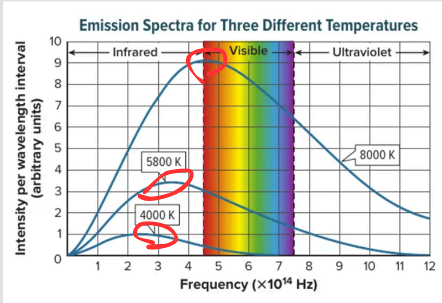
One example is infrared, which is felt as heat.



- Diffraction Grating

- Continuous Spectrum

An emission spectrum is a graph that shows how the intensity of radiation varies with frequency. Different temperatures produce different emission spectra.



For example, objects at 4000 K, 5800 K, and 8000 K each have a peak point where the maximum energy is emitted.

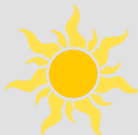
`` As the temperature increases, the peak frequency also increases ``
This means hotter objects emit radiation at higher frequencies (toward the blue end of the spectrum), while cooler objects emit at lower frequencies (toward the red end).

The total power emitted by an object increases as its temperature rises.

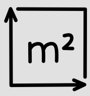
- Power is defined as the energy emitted per second, and for electromagnetic radiation, it is proportional to the object's Kelvin temperature raised to the fourth power (T^4).
- Power $\propto T^4$

This means that even a small increase in temperature results in a large increase in emitted energy. Therefore, hotter objects radiate much more energy per second than cooler ones.

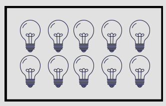
A key example is the Sun, which has a surface temperature of about 5800 K.
⟶ Because of this high temperature, it emits an enormous amount of power ~ approximately 4×10^{26} W.



On Earth, the energy we receive from the Sun is significant.
On average, each square meter of Earth's surface receives about 1000 joules per second (1000 W).



This amount of energy is enough to power about ten 100-watt lightbulbs.



1  = 100 W

Between 1887 and 1900, scientists used classical electromagnetic wave theory to explain emission spectra, but it failed.
The theory predicted that objects would emit energy continuously and even infinitely, which did not match experimental observations.

In 1900, Max Planck proposed a new idea :

- Energy is not continuous
- Energy is emitted or absorbed in discrete amounts (packets) = photons

This idea is called quantization of energy.

Energy of Vibration

The energy emitted or absorbed by a vibrating atom is equal to the product of an integer, Planck's constant, and the frequency of vibration.

$$E = nhf$$

- Planck's Equation

E = energy (J)
n = integer (0, 1, 2, 3, ...)
h = Planck's constant (6.626×10^{-34} J/Hz)
f = frequency (Hz)

- Energy can only take specific values : hf, 2hf, 3hf, ... (n is always an integer)

Fractional values (like ½ hf) are not possible

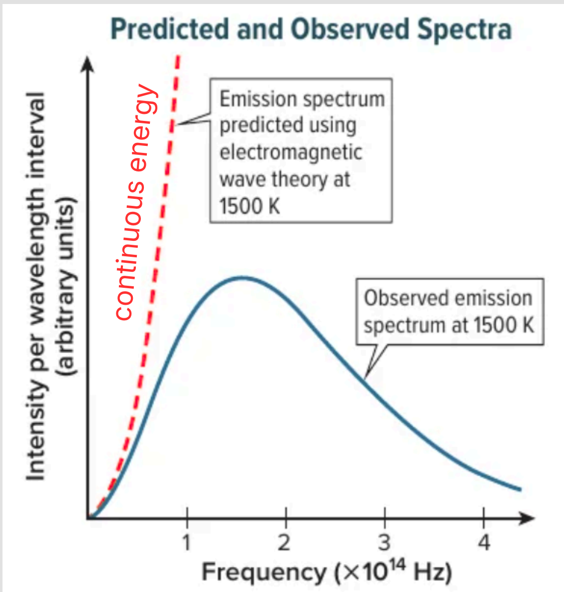
- Energy exists in bundles called quanta

Atoms emit radiation only when their energy changes

The emitted energy equals the difference between energy levels Example :
- From 3hf → 2hf → emits hf
- From 2hf → 3hf → absorbs hf

Planck's constant (h) is extremely small, so :
- Energy steps are very tiny
- In everyday life, energy appears continuous

Classical theory (red dashed line):
Predicts infinite energy
Observed spectrum (blue line):
Shows limited, realistic energy



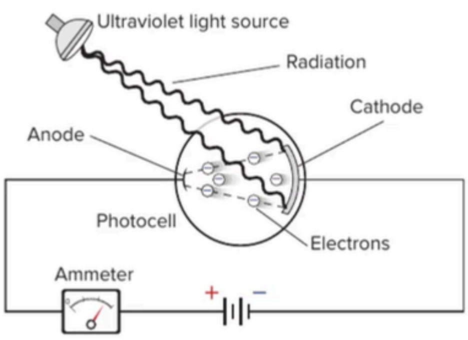
The theory (Electromagnetic Wave Theory) only works well at low frequencies, but fails at high frequencies.

- Energy is quantized, not continuous
- Atoms emit/absorb energy in fixed packets (nhf)
- Planck's idea solved the emission spectrum problem and started modern quantum theory

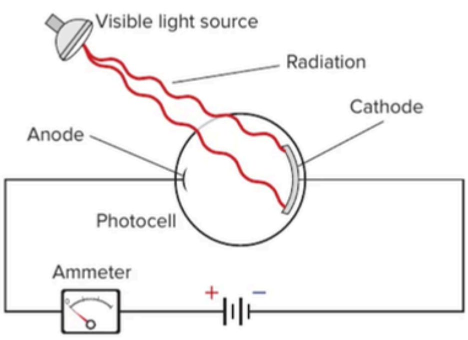
This concept (quantization of energy)

- Challenged classical physics (like Isaac Newton and James Maxwell)
- Became the foundation of quantum physics
- Led to modern technologies such as : Solar cells, Electronics, and Computers

The photoelectric effect is the emission of electrons from a material when light shines on it.



The photoelectric effect is demonstrated by the photocell illuminated by ultraviolet light.



The same photocell, illuminated by visible light, does not display the photoelectric effect.

- When ultraviolet (UV) light shines on a negatively charged zinc plate :

The plate releases electrons (it discharges).
Even low-intensity UV light can cause this electron emission.

- But when visible light shines on the same plate :

No electrons are emitted.
Even if the visible light has very high intensity.

Classical electromagnetic wave theory predicted :
→ Any frequency of light should release electrons if the intensity is high enough.
But experiments showed :
→ Frequency determines whether electrons are released, Not the intensity.

This contradicted classical physics.

Ultraviolet light has a higher frequency → Each photon carries more energy.
Visible light has a lower frequency → Each photon carries less energy.

- Only high-frequency light (like UV) gives enough energy to electrons to free them from the material.

Einstein proposed :

- Light is made of small energy packets called photons.
- The energy of one photon is proportional to its frequency.

Every material has a work function : the minimum energy needed to remove an electron from its surface.

Threshold frequency = minimum frequency needed to overcome work function.

If photon energy ≥ work function :

- The electron is emitted immediately (no delay).
- Higher photon energy → electron leaves with extra kinetic energy (moves faster).

If photon energy < work function :

- No electron will be emitted

Even if you :

- Increase light intensity (more photons)
- Shine light for a longer time

Still no emission occurs

⟶ Electrons need one photon with enough energy, many weak photons can't help

Frequency determines :

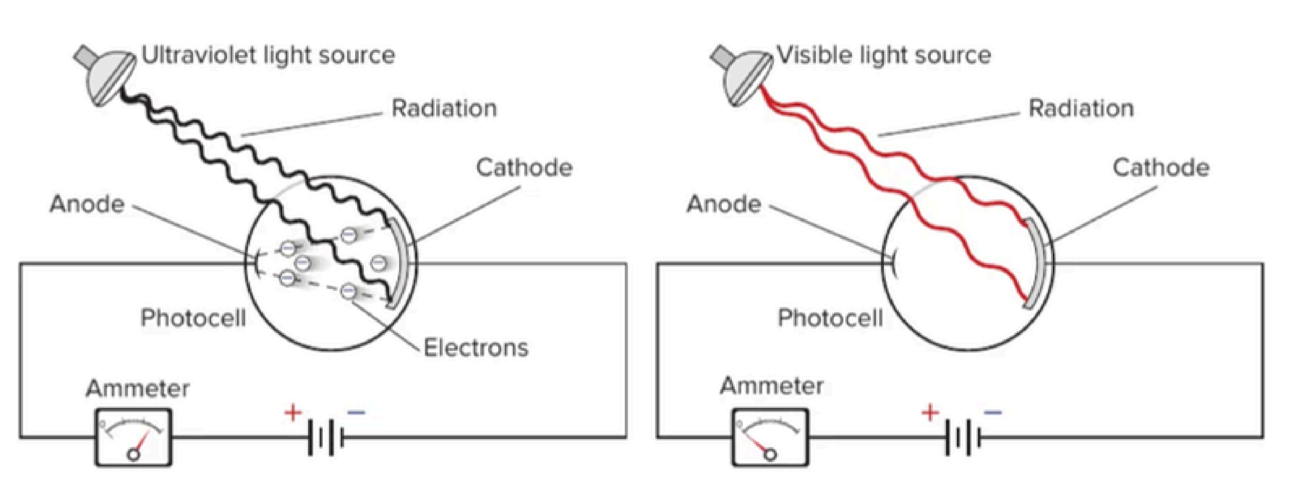
- Whether electrons are emitted (must be above threshold frequency)
- How much kinetic energy electrons have (how fast they move)
- Higher frequency → electrons emitted faster

Intensity :

- number of photons hitting the surface per second
- Does not affect energy of electrons
- Affects only how many electrons are emitted (if frequency is sufficient)

⟶ This explained experimental results classical physics couldn't explain → foundation of quantum physics.

Photon Energy	**Intensity**	**Result**
< Work function	Any	No electrons emitted
= Work function	Any	Electrons emitted (minimum energy)
> Work function	Low	Electrons emitted with extra kinetic energy
> Work function	High	More electrons emitted with extra kinetic energy



The photoelectric effect is demonstrated by the photocell illuminated by ultraviolet light.

The same photocell, illuminated by visible light, does not display the photoelectric effect.

Charges flow in a photocell only if the radiation striking the cathode has enough energy.

- Left Side (UV Light) :

UV photons have enough energy to eject electrons from the metal cathode.
Electrons are released, producing an electric current.

- Right Side (Visible Light):

Visible light photons do not have enough energy to remove electrons.
No electrons are emitted, and no current is detected.

Electron emission depends on photon frequency, not light intensity.
Light behaves as particles (photons), not just waves.
This phenomenon was a key discovery that led to the development of quantum physics.

- The emission of photoelectrons depends on the incident light's frequency.
- The threshold frequency must be exceeded in order to produce photoelectrons.

- Not all light can eject electrons from a metal.

Electrons are released only if the light's frequency is above a minimum value called the threshold frequency.
This threshold varies depending on the type of metal.

- Example : Cesium releases electrons with most visible light (except low-frequency red light).

Zinc does not release electrons with any visible light, only with ultraviolet radiation.

→ Light with frequency below f_o
Even very high intensity light cannot eject electrons if the frequency is too low.
No electrons = no current.
→ Light with frequency at or above f_o
Even low-intensity light will instantly release electrons.
Increasing the intensity (when $f \geq f_o$) increases the current, because more electrons are emitted.

- Classical wave theory says :

Light's energy depends on its intensity, not its frequency.
Electrons should gradually absorb energy and eventually be ejected.

- But experiments show :

Electrons are emitted immediately.
Frequency not intensity determines whether electrons are ejected.
Therefore, wave theory fails to explain the effect.

In 1905, Einstein proposed that light is made of particles called photons.

- Each photon is a packet of energy.
- The energy of a photon depends only on its frequency :
- If a photon's energy (hf) is high enough ($f \geq f_o$), it can eject an electron.

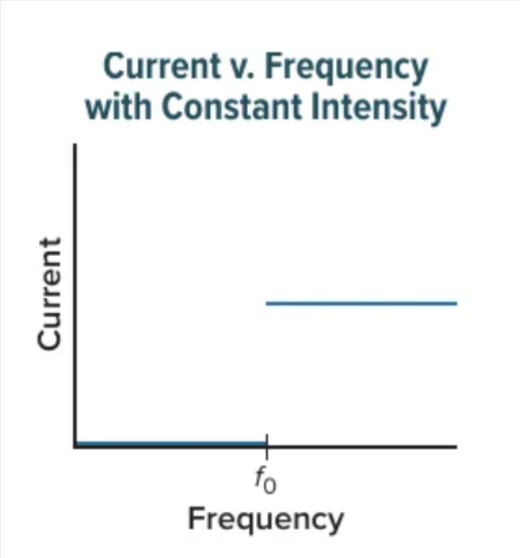
Energy of a Photon

The energy of a photon is equal to the product of Planck's constant and the frequency of the photon.

$$E = hf$$

Real-World Physics

SOLAR PANELS A solar panel consists of a grid of solar cells made of semiconducting material. Solar cells are human-made devices that capture the sun's energy and produce electrical energy. Photons from the Sun that have a certain threshold frequency can cause electrons to break free from atoms of the semiconducting material, resulting in an electric current within the solar panel.

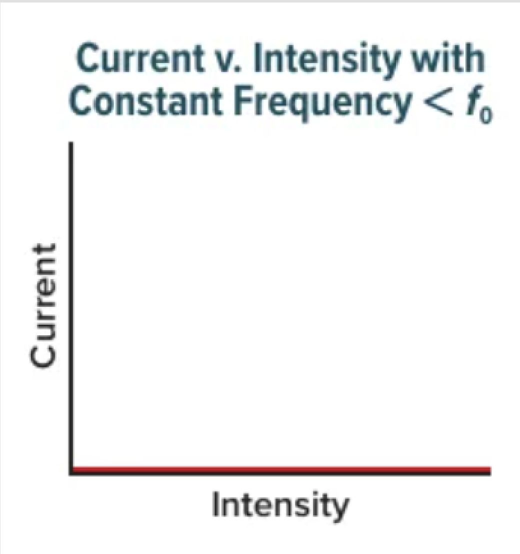


The line is horizontal (constant current).
It starts only after f_o.

What this shows :

- Before f_o : no current
- After f_o : current becomes constant and does not increase with frequency.

Increasing frequency does not change the current (as long as intensity is fixed)

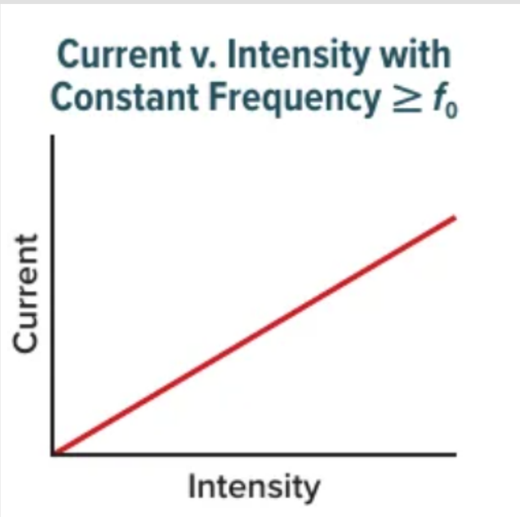


The line is flat at zero.

What this shows :

- As intensity increases → current stays zero

No electrons are emitted at all because $f < f_o$
So current = 0 no matter how strong the light is



The line is straight and increasing.

What this shows :

- As intensity increases → current increases proportionally

Since $f \geq f_o$, electrons are being emitted.
Increasing intensity means more light photons hit the surface.

More photons (More intensity) → more emitted electrons → higher current.

Frequency unit :
Hz = s^{-1}
Therefore :
J/Hz = J·s
- This shows that Planck's constant has units of J·s OR J/Hz

$$1\ \text{eV} = (1.602\times10^{-19}\ \text{C})(1\ \text{V})$$
$$= 1.602\times10^{-19}\ \text{C·V}$$
$$= 1.602\times10^{-19}\ \text{J}$$

→ The joule is too large for atomic-scale energy, so we use electron volt (eV).
- 1 eV = energy gained by an electron moving through 1 volt.

$$f = \frac{c}{\lambda} \qquad E = hf \qquad \rightarrow \qquad E = \frac{hc}{\lambda}$$

6.62×10^{-34} J/Hz, 3×10^{8} m/s

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

★ J → eV ÷ 1.602×10^{-19}
m → nm × 10^{9}

$h = 6.62\times10^{-34}$ J/Hz OR J·s

↳ $\frac{6.62\times10^{-34}}{1.602\times10^{-19}}$ J·s $= 4.13\times10^{-15}$ eV·s

↳ $c = 3\times10^{8}$ m/s $\times 10^{9} = 3\times10^{17}$ nm/s

$$E = \frac{hc}{\lambda} = \frac{4.13\times10^{-15}\ \text{eV·s} \times 3\times10^{17}\ \text{nm/s}}{\lambda}$$

$$E = \frac{1240\ \text{eV·nm}}{\lambda}$$

ف لما نعوض ال λ بـ nm
✓ تطلع ال E بوحدة eV

PRACTICE Problems — ADDITIONAL PRACTICE

Use E = 1240 eV·nm/λ to solve the following problems.

1. What is a photon's energy if the photon's wavelength is 515 nm?
2. A photon's energy is 2.03 eV. What is the photon's wavelength?
3. Rank the following photons from least to greatest energy.
   - **a.** 4.0 eV
   - **b.** 320 nm
   - **c.** 811 nm
   - **d.** 2.1 eV
4. **CHALLENGE** The diagram in **Figure 6** shows the visible light spectrum. What is the range of energies associated with photons in the visible light spectrum?

Figure 6

- Planck's Idea

Energy is quantized (comes in packets).
Atoms emit energy when they vibrate at frequency f.
The energy is given by : $E = nhf$
Planck did NOT say light is made of particles, only that energy is emitted in discrete amounts.

- Einstein's Photon Theory

Einstein extended Planck's idea.
He proposed that light itself is made of particles called photons.
Each photon has energy : $E = hf$

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Einstein applied the formula to a single energy packet, which is like saying $n = 1$.

Every metal has a minimum frequency required to eject electrons, this is called the threshold frequency.

- If $f \geq f_0 \rightarrow$ electrons are emitted
- If $f < f_0 \rightarrow$ no electrons are emitted

Each photon interacts with one electron only.
Electrons cannot store energy from multiple low-energy photons.
Increasing intensity does NOT help if frequency is too low.

Kinetic Energy of an Electron Ejected Due to the Photoelectric Effect

The kinetic emergy of an ejected electron is equal to the difference between the incident photon energy (hf) and the energy of a photon with the threshold frequency (hf_0).

$$KE = hf - hf_0$$

- hf : energy of the incoming photon.
- hf_0 : minimum energy needed (work function).

The equation gives the maximum kinetic energy, it applies to the electron that is easiest to remove, other electrons will have less kinetic energy.

Not all electrons in a metal have the same energy, some electrons are loosely bound, while others are tightly bound.

Some electrons are more tightly bound, these electrons need more energy to escape from the metal.
Electrons that are more tightly bound or lose energy while escaping have lower kinetic energy.
Some electrons will have less energy due to internal losses.

$\longrightarrow$ Therefore, ejected electrons have different kinetic energies.