From Last Time...

Energy and power in an EM wave

Polarization of an EM wave:
oscillation plane of E-field

Exam 3 is Tuesday Nov. 25
5:30-7 pm, 2103 Ch (here)

Covers: all material since exam 2.

Bring: Calculator
One (double-sided) 8 1/2 x 11 note sheet

Exam review: Thursday, Nov. 20, in class

Origin of Malus’ law
- Polarizer
  - transmits component of E-field parallel to transmission axis
  - absorbs component of E-field perpendicular to transmission axis
- Transmitted intensity: \( I = I_0 \cos^2 \theta \)
  \( I_0 \) = intensity of polarized beam on analyzer (Malus’ law)

Circular and elliptical polarization
- Circularly polarized light is a superposition of two waves with orthogonal linear polarizations, and 90° out of phase.
- The electric field rotates in time with constant magnitude.

Energy of light
- Quantization also applies to other physical systems
  - In the classical picture of light (EM wave), we change the brightness by changing the power (energy/sec).
  - This is the amplitude of the electric and magnetic fields.
  - Classically, these can be changed by arbitrarily small amounts

The photoelectric effect
- A metal is a bucket holding electrons
- Electrons need some energy in order to jump out of the bucket.
  - Light can supply this energy.
  - Energy transferred from the light to the electrons.
- Electron uses some of the energy to break out of bucket.
  - Remainder appears as energy of motion (kinetic energy).
The experiment

- Light ejects electrons from cathode with range of velocities
- Reverse potential: applies electric force opposing electron motion
- Stopping potential: voltage at which highest kinetic energy ($K_{\text{max}}$) electrons turned back

$$V_{\text{stop}} = K_{\text{max}}/e$$

Unusual experimental results

- Not all kinds of light work
- Red light does not eject electrons
- More red light doesn’t either

No matter how intense the red light, no electrons ever leave the metal

Until the light wavelength passes a certain threshold, no electrons are ejected.

Einstein’s explanation

- Einstein said that light is made up of photons, individual ‘particles’, each with energy $hf$.
- One photon collides with one electron - knocks it out of metal.
- If photon doesn’t have enough energy, cannot knock electron out.
- Intensity ($= # \text{ photons / sec}$) doesn’t change this.

Einstein said that light is made up of photons, individual ‘particles’, each with energy $hf$.

- One photon collides with one electron - knocks it out of metal.
- Minimum frequency (maximum wavelength) required to eject electron

Wavelength dependence

- Short wavelength: electrons ejected
- Long wavelength: NO electrons ejected

Threshold depends on material

Hi-energy photons

Lo-energy photons
Question

Potassium has a work function of 2.3 eV for photoelectric emission. Which of the following wavelengths is the longest wavelength for which photoemission occurs?

a. 400 nm  

b. 450 nm

c. 500 nm  

d. 550 nm

e. 600 nm

\[ K_{\text{max}} = hf - \Phi = \frac{hc}{\lambda} - \Phi \]

The maximum wavelength is when \( K_{\text{max}} = 0 \): \[ \lambda = \frac{hc}{\Phi} = 539.1 \text{ nm} \]

Quantization and photons

- Quantum mechanically, brightness can only be changed in steps, with energy differences of hf.
- Possible energies for green light (\( \lambda = 500 \text{ nm} \))
  - One quantum of energy: one photon
  - Two quanta of energy: two photons
  - etc
  - Think about light as a particle rather than wave.

The particle perspective

- Light comes in particles called photons.
- Energy of one photon is \( E = hf \)
  - \( f \) = frequency of light
- Photon is a particle, but moves at speed of light!
  - This is possible because it has zero mass.
- Zero mass, but it does have momentum:
  - Photon momentum \( p = E/c \)

One quantum of green light

- One quantum of energy for 500 nm light
  \[ E = hf = \frac{6.634 \times 10^{-34} \text{ J s}}{500 \times 10^{-9} \text{ m}} = 4 \times 10^{-19} \text{ J} \]

Quite a small energy!
Quantum mechanics uses new ‘convenience unit’ for energy:

- 1 electron-volt (eV) = 1 eV = (charge on electron) x (1 volt) = 1.602 \times 10^{-19} \text{ C} x (1 \text{ volt}) = 1.602 \times 10^{-19} \text{ J}

In these units,
\[ E(1 \text{ photon green}) = (4 \times 10^{-19} \text{ J} x (1 \text{ eV} / 1.602 \times 10^{-19} \text{ J})) = 2.5 \text{ eV} \]

Simple relations

- Translation between wavelength and energy has simple form in electron-volts and nano-meters

Green light example:
\[ E = \frac{hc}{\lambda} \]

\[ \begin{align*}
\text{constant [in eV - nm]} & = 1240 \frac{\text{eV}}{\text{nm}} \\
\text{wavelength [in nm]} & = 500 \text{ nm} \\
\text{E} & = 2.5 \text{ eV}
\end{align*} \]
**Photon energy**

What is the energy of a photon of red light ($\lambda=635$ nm)?

A. 0.5 eV  
B. 1.0 eV  
C. 2.0 eV  
D. 3.0 eV

\[ E = \frac{hc}{\lambda} = \frac{1240 \text{ eV nm}}{635 \text{ nm}} = 1.95 \text{ eV} \]

**How many photons can you see?**

In a test of eye sensitivity, experimenters used 1 millisecond (0.001 s) flashes of green light. The lowest power light that could be seen was 4 x 10^{-14} Watt. How many green (500 nm, 2.5 eV) photons is this?

A. 10 photons  
B. 100 photons  
C. 1,000 photons  
D. 10,000 photons

\[ \text{Power} = \frac{4 \times 10^{-14} \text{J}}{0.001 \text{s}} = 4 \times 10^{-11} \text{J} \]
\[ \text{Energy per photon} = 250 \text{ eV} \]
\[ \text{Photons} = \frac{250 \text{ eV}}{2.5 \text{ eV}} = 100 \text{ photons} \]

**Photon properties of light**

- Photon of frequency $f$ has energy $hf$
- Red light made of ONLY red photons
- The intensity of the beam can be increased by increasing the number of photons/second.
- Photons/second = energy/second = power

**Question**

A red and green laser both produce light at a power level of 2.5 mW. Which one produces more photons/second?

A. Red  
B. Green  
C. Same

Red light has less energy per photon so needs more photons!

**Nobel Trivia**

For which work did Einstein receive the Nobel Prize?

A. Special Relativity: $E=mc^2$  
B. General Relativity: gravity bends Light  
C. Photoelectric Effect & Photons
Neither wave nor particle

- Light in some cases shows properties typical of waves
- In other cases shows properties we associate with particles.
- Conclusion:
  - Light is not a wave, or a particle, but something we haven’t thought about before.
  - Reminds us in some ways of waves.
  - In some ways of particles.

Particle-wave duality

- Light has a dual nature
  - Can show particle-like properties (collisions, etc)
  - Can show wavelike properties (interference).
- It is neither particle nor wave, but some new object.
- Can describe it using “particle language” or “wave language” whichever is most useful