Modern Physics: Quantization

This Lecture
- Polarization
- Quantization in general
- Light quantization
- Photons

From previous Lecture
- EM waves and their properties
- Poynting vector, radiation intensity and pressure
- Polarization
Polarization of Light Waves (34.8)

- **Linearly polarized waves**: E-field oscillates at all times in the plane of polarization.

  **Unpolarized** light: E-field in random directions. **Superposition** of waves with E vibrating in many different directions.

- **Linearly polarized light**: E-field has one spatial orientation.
Circular and elliptical polarization

- **Circularly polarized light:** superposition of 2 waves of equal amplitude with orthogonal linear polarizations, and 90° out of phase. The tip of \( \mathbf{E} \) describes a circle (counterclockwise = RH and clockwise=LH depending on y component ahead or behind)

- The electric field rotates in time with constant magnitude.

- If amplitudes differ \( \Rightarrow \) **elliptical polarization**
Producing polarized light

- Polarization by **selective absorption**: material that transmits waves whose E-field vibrates in a plain parallel to a certain direction and absorbs all others.

This polarization **absorbed**

This polarization **transmitted**

**transmission axis**

Long-chain hydrocarbon molecules

Polaroid sheet (E. Land 1928)
If linearly polarized light (plane of polarization indicated by red arrow) of intensity $I_0$ passes through a polarizing filter with transmission axis at an angle $\theta$ along $y$

$$E_{\text{inc}} = E_0 \sin \theta \, \hat{i} + E_0 \cos \theta \, \hat{j}$$

After the polarizer

$$E_{\text{transm}} = E_0 \cos \theta \, \hat{j}$$

So the intensity transmitted is

$$I_{\text{transm}} \propto E_0^2 \cos^2 \theta = I_0 \cos^2 \theta$$

Transmitted intensity: $I = I_0 \cos^2 \theta$  $I_0 = \text{intensity of polarized beam on analyzer} \ (\text{Malus' law})$
Unpolarized light on polarizers

Only $I_0/2$ is transmitted of unpolarized light by a polarizer and it is polarized along the transmission axis. An **analyzer** rotated at an angle $\theta$ respect to the polarizer transmits 100% of the incident intensity when $\theta = 0$ and zero when $\theta = 90^\circ$. 

**Diagram:**
- Unpolarized light
- Polarizer
- Analyzer
- Transmission axis
- Polarized light
- Polaroid sheets
- Allowed component parallel to analyzer axis
Relative orientation of polarizers

- Transmitted amplitude is $E_o \cos \theta$  
  \textit{(component of polarization along polarizer axis)}
- Transmitted intensity is $I_o \cos^2 \theta$  
  \textit{(square of amplitude)}
- Perpendicular polarizers give zero intensity.
1) Light transmitted by first polarizer is vertically polarized. $I_1 = I_0/2$

2) Angle between it and second polarizer is $\theta=45^\circ$. $I_2 = I_1 \cos^2(45^\circ) = 0.5I_1 = 0.25I_0$

3) Light transmitted through second polarizer is polarized 45º from vertical. Angle between it and third polarizer is $\theta=45^\circ$. $I_3 = I_2 \cos^2(45^\circ) = 0.125I_0$
Polarization by reflection

- Unpolarized light reflected from a surface becomes partially polarized.
- Degree of polarization depends on angle of incidence.
- If reflected and refracted beams are orthogonal, complete polarization occurs.
- Brewster’s law: angle of incidence is given by \( \tan \theta_p = n \) (\( n \) = index of refraction).
Reducing glare

A polarizer can substantially reduce intensity of reflections, since the reflections are partially polarized.

Sunlight reflected from water, glass, snow is partially polarized. If surface is horizontal the E-field vector of reflected light has strong horizontal component. Polarized glasses: vertical transmission axis absorbs strong horizontal component. Reflected light can be eliminated!
Polarization by scattering

Scattering: a photon excites an electron in an atom that absorbs its energy and re-radiate like an antenna a new photon in a random direction. If incident light is polarized, the plane of polarization of re-radiated light is the same of incident light. If the incident light is unpolarized, the E-field vibrates in a plane perpendicular to the direction of the beam. The electron in the molecule vibrates in that plane and the light scattered at 90 deg will look polarized and at intermediate angles it is partially polarized.

The sky looks blue because shorter wavelengths are more likely to be scattered than longer (red) ones by air molecules. The sun looks yellow-white because the light has still all colors. But if you look at the horizon (a lot of air) most of the blue is scattered out and the sun appears red.
Optically active materials (your lab)!

- They rotate the plane of polarization of incident light.
- Solution with sugar: when polarized light passes through the Karo syrup, the direction of its polarization is changed.
- The rotation angle is proportional to depth and concentration of syrup.
- The rotation angle depends on the wavelength or color of the light. Blue light, with its shorter wavelength, rotates more than the longer-wavelength red light.
Modern Physics

- 1600-1800s classical description of the laws of the world we can see (Galileo, Newton, …)
- Late 1800s: Maxwell’s equations describe propagation of EM waves in exquisite detail.

- Physics changed drastically in the early 1900’s

- Relativity
  - Changed the way we think about space, time, and gravity

- Quantum mechanics
  - Changed our conceptions of matter.

  *Photoelectric effect, Matter waves, atoms*
Quantum mechanics

- The quantum mechanical world is VERY different!
  - Energy not continuous, but can take on only particular discrete values.
  - Light has particle-like properties, so that light can bounce off objects just like balls.
    
    **Energy is quantized in discrete units!!**
    
    **Light is made of ‘quanta’ called photons**
  - Particles also have wave-like properties, so that two particles can interfere just like light does.
  - Physics is not deterministic, but events occur with a probability determined by quantum mechanics.
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).
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 is the light: until the light wavelength passes a certain threshold, no electrons are ejected.
Wavelength dependence

Short wavelength: electrons ejected

Long wavelength: NO electrons ejected

Threshold depends on material

High-energy photons

Low-energy photons
Einstein’s explanation

- light is made up of photons, each with energy \( E = hf \)
  \( h = \text{Planck constant} \ f = \text{frequency}. \)

\[ h = 6.626 \ 068 \ 96(33) \times 10^{-34} \ J \cdot s = 4.135 \ 667 \ 33(10) \times 10^{-15} \ eV \cdot s \]

- One photon collides with one electron
  - knocks it out of metal if photon has enough energy to transferred to the electron

- Power ( = \# photons / sec= Nh\(f/s)\) doesn’t change this.

Minimum frequency (maximum wavelength) required to eject electron.

Need UV!

Nobel prize 1921
A red and green laser produce light at a power level of 2.5 mW. Which one produces more photons/second?

A. Red
B. Green
C. Same

\[
\text{# photons/second} = \frac{\text{Power}}{\text{Energy/photons}} = \frac{\text{Power}}{hf}
\]

Frequency of green light is larger than red one.

Red light has less energy per photon so needs more photons!
Summary of Photoelectric effect

- Explained by quantized light.
- **Red** light is low frequency, **low energy**.
- (Ultra)**violet** is high frequency, **high energy**.

- Red light will not eject electron from metal, no matter how intense.
  - Single photon energy $hf$ is too low.
- Need ultraviolet light
Work Function

- Max kinetic energy of electrons ejected from the surface of the metal and not making collisions with other metal atoms before escaping
  \[ K_{\text{max}} = hf - \phi \]
  - \( \phi \) is called the work function and depends on metal
  - minimum energy needed to free electron from the substance.
  - Silver: 4.26 eV
  - Alluminium: 4.28 eV
  - Copper: 4.65 eV
  - Gold 5.1 eV

- cutoff frequency is
  \[ f_c = \frac{\phi}{h} \]
The experiment

- No light $\Rightarrow$ the ammeter reads zero
- E illuminated by light with appropriate $\lambda$ $\Rightarrow$ current in ammeter (photoelectrons emitted from negative plate and collected at positive one)
  - At large values of $\Delta V$, current is max (all electrons emitted at $E$ collected at $C$)
  - Electrons accelerate if $\Delta V > 0$ since $\Delta K = -\Delta U = e \Delta V$
  - When $\Delta V$ is reversed they slow down
- **Stopping potential**: even the photoelectron with $K_{\text{max}}$ cannot reach $C$ when $K_{\text{max}} = e \Delta V_s$
  - Stopping potential is a measure of $K_{\text{max}}$
  - When $\Delta V$ is equal to or more negative than $\Delta V_s$, the current is zero

$$K_{\text{max}} = hf - \Phi$$
Classical physics predicts that light of sufficient intensity causes emission of photoelectrons, independent of frequency and without a cutoff frequency. Also, the greater the intensity, the larger the maximum kinetic energy of the electrons.
Photomultipliers and IceCube

- The experiment that will use the largest amount of photo-multipliers in the largest volume
- More than 4800 in 1 km$^3$

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