Lecture 34

Photoelectric effect

- occurs when directing a beam of light of short enough wavelength onto a clean metal surface
- light causes electrons to be ejected from surface
- effect is used in video recorders.
- can be shown w/ photoelectric experiments

(show slides)

1st Experiment

- Adjust potential difference V so that collector C is slightly negative w/rt target T.

- potential difference acts to slow down ejected electrons

- vary V until it reaches <u>stopping potential</u> Vstop, @ which point reading on meter A drops to zero & most energetic ejected electrons are turned back before reaching collector.

- Kmax is kinetic energy of these most energetic electrons & from the above, we have that

$$K_{max} = e\, V_{stop}$$

where e is elementary charge (point is that potential difference is such that electrons cannot make it to collector, & so kinetic energy has to equal potential energy)

<u>key observation</u>:

K_{max} does not depend on intensity of light!

- this is a puzzle for classical physics when thinking of light as oscillating wave w/ magnitude.
- one might think that higher amplitude of oscillation would lead to greater kick to electrons to break them free

but this is not what happens.

result can be explained by photons ~~[illegible]~~ each having energy $hf = E$

- Increasing intensity increases number of photons, but doesn't change energy of each photon

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In a second experiment, we can vary the frequency of the incident light & measure associated stopping potential Vstop.

(show slides)

- observe that photoelectric effect does not occur if light frequency is below a cutoff frequency (regardless of light intensity)

- this is another puzzle for classical physics (would not expect a cutoff frequency)

- However, this is explained well by photon theory

- electrons within target are held there by electric forces

- To escape from the targets they need to pick up a certain minimum energy Φ

- Φ is a property of target material called <u>work function</u> ⑥

- If energy hf transferred by a photon $> \Phi$, then electron can escape.

- If not, electron cannot escape.

Following equation summarizes the experiment

$$hf = K_{max} + \Phi$$

(photoelectric equation)

statement of conservation of energy for single photon absorption by target w/ work function Φ.

energy equal to hf is

- transferred to electron

- For electron to escape, it must pick up energy at least Φ

- Additional energy $hf - \Phi$ is transferred as kinetic energy to electron.

Q: What is work function Φ for figure w/ sodium target?

just use cutoff frequency f_0 of photoelectric equation

$$hf_0 = \Phi$$

$$\Rightarrow (6.63 \times 10^{-34}\ \text{J.s})(5.5 \times 10^{14}\ \text{Hz}) = 3.6 \times 10^{-19}\ \text{J}$$

⑧

Momentum of photons

Photon has linear momentum

$$p = \frac{hf}{c} = \frac{h}{\lambda}$$

When a photon interacts w/ matter, energy & momentum are transferred, as if there were a collision in classical sense.

Compton showed this w/ an experiment

- he directed a beam of x rays of wavelength λ onto a carbon target (show slides)

he then measured wavelengths
& intensities of scattered radiation

(show slides for results of
Compton's experiments)

- incident beam has a single wavelength.
- scattered x rays contain a range of wavelengths w/ two prominent intensity peaks
  - one peak @ incident wavelength & another @ wavelength λ'
    - $\Delta\lambda$ is called Compton shift

- classical physics does not explain results but quantum photon theory does

- If a single photon is associated w/ interaction between x-ray & electron, there is a transfer of energy. So energy of scattered photon is less than that of incident photon

- Since $E = hf$ then lower energy means lower frequency & higher wavelength.

To quantify, consider that

$$\underset{\substack{\uparrow \\ \text{energy of incident photon}}}{hf} = \underset{\substack{\uparrow \\ \text{energy of scattered photon}}}{hf'} + \underset{\substack{\uparrow \\ \text{kinetic energy of electron}}}{K} \qquad \text{(conservation of energy)}$$

Since electron recoils @ speed near that of light, we need relativistic expression

$$K = mc^2(\gamma - 1)$$

for kinetic energy

where $\gamma = \dfrac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$

$$\Rightarrow \quad \frac{h}{\lambda} = \frac{h}{\lambda'} + mc(\gamma - 1)$$

by substituting $\lambda f = c$

Now apply law of conservation of momentum to x-ray - electron collision

$$p = h/\lambda \quad \Rightarrow \quad \frac{h}{\lambda} = \frac{h}{\lambda'}\cos\phi + \gamma m v \cos\theta$$

(2D situation)

ϕ is scattering angle for x-ray

θ is scattering angle for electron

$p = \gamma m v$ is momentum for electron

$$0 = \frac{h}{\lambda'} \sin\phi - \gamma m v \sin\theta$$

long steps of algebra to get

$$\Delta\lambda = \frac{h}{mc}\left(1 - \cos\phi\right)$$

which agrees w/ Compton's experimental observations

$\frac{h}{mc}$ is called Compton wavelength