Quantum Theory

Discovery of the Electron

- Towards the end of the 19th century experiments were being done on the discharge of electricity through rarefied gases using gas discharge tubes
- When a high voltage was applied there was a dark space near the cathode and the anode end would glow

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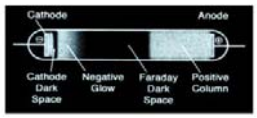

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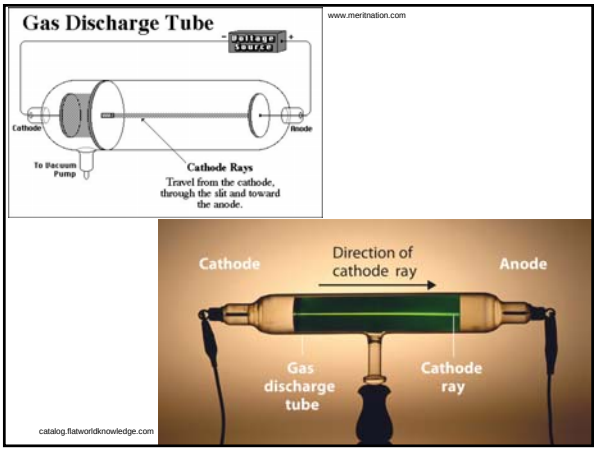
- When a slit or small hole was place between the anode and cathode, the glow as restricted to a tiny spot at the end of the tube
- Something was being emitted by the cathode and traveling to the other end of the tube
- These were named cathode rays



Planck's Quantum Hypothesis

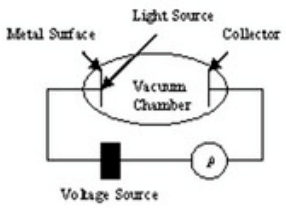
- In 1900, Planck proposed a theory that was able to reproduce the spectrum for blackbody radiation
- The energy of the oscillations of atoms within molecules cannot have just any value; instead each has energy which is a multiple a value related to the frequency, hf

- It wasn't until Einstein entered the field in 1905 where the full significance of this theory became apparent

The Photoelectric Effect

- 1887, Heinrich Hertz
  - Conducting experiments to test the electromagnetic theory of light
  - Certain metals produce an electric current when exposed to light of very short wavelength
  - Called the photoelectric effect

- A typical experimental setup involves the use of a vacuum tube which contains a photosensitive cathode (metal)

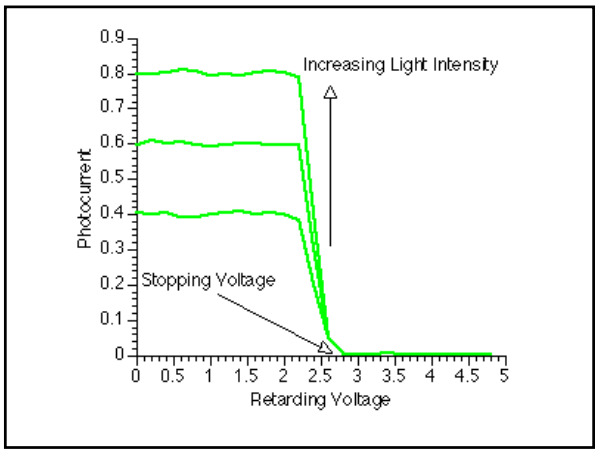


- We can use this setup to measure the amount of current produced
- We could also reverse the voltage of the power supply and instead measure the voltage required to stop the flow of electrons
  - **Stopping voltage** or **stopping potential**

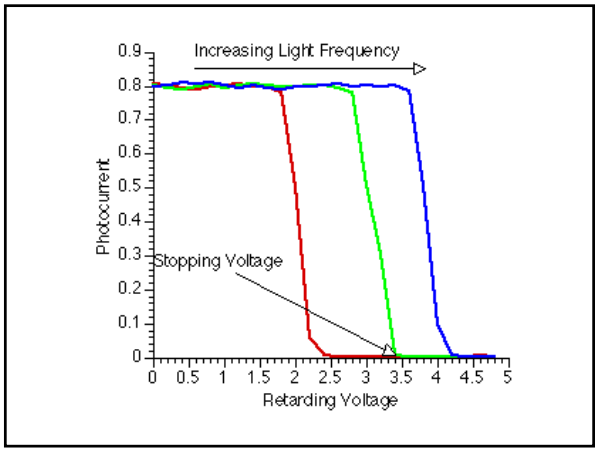
Observations

- When the intensity of light is increased it is observed that the current increases
- This current increase could be because more electrons are emitted or the velocity (kinetic energy) of the electrons increases (or both)
- We can determine which case it is by determining the stopping voltage, V_s

- The stopping voltage gives us the maximum kinetic energy of the electrons, eV_s
- We find that the stopping voltage stays the same no matter what the intensity of the light source is
- Thus, the current increase is due to more electrons being emitted
- The intensity of the light has no effect on the maximum energy of the electrons

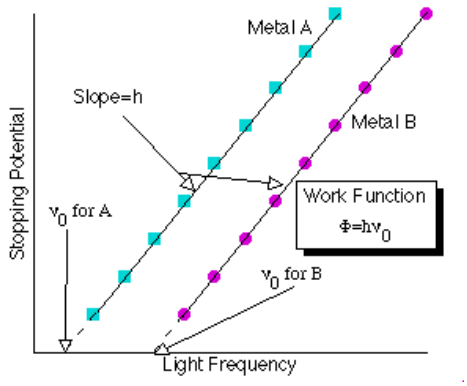


- We also find that the stopping voltage depends on the frequency of the light source
- The larger the frequency, the larger the stopping voltage
  - The emitted electrons have more energy
- It was also seen that the current was constant (at a maximum) until the voltage was near the stopping voltage



- This tells us that there exists a frequency, called the threshold (or critical) frequency f_c, such that no electrons are emitted at all if the frequency of the light is less than f_c
  - Even if very intense light is allowed to fall on the metal

- If the experiment is repeated with different metals, it is found that the threshold frequency is different for every metal
- A plot of kinetic energy vs frequency is found to be a straight line
- For every type of metal, the slope of the line is the same
  - The lines are parallel
- This indicates that a minimum amount of energy is needed for an electron to be emitted (called the **work function**)



- The last observation is that the electrons are released immediately after the light is incident on the metal
- There is no apparent time delay

Summary of Observations

- The intensity of the incident light does not effect the energy of the emitted electrons
- The electron energy depends on the frequency of the incident light
- There is a certain minimum frequency of light below which no electrons are emitted
- Electrons are emitted with no time delay

Problems

- The observations are in violation of the standard laws of physics
- According to the laws of classical electromagnetic theory, a more intense beam of light has more energy and therefore should cause the emission of more energetic electrons

- Classical electromagnetism cannot explain why the frequency of light should affect the electron energy
- It also can't explain why there should exist a threshold frequency
- As well, a very low intensity beam of light carries little energy. So an electron should have to wait a considerable amount of time before it has accumulated enough energy to escape from the metal.
- This would cause a noticeable delay in emission

Albert Einstein (1905)

- Einstein suggested that light consists of quanta (packets of energy and momentum) called photons
- The energy of a photon is given by

$$E = hf$$

f is frequency

h is Planck's constant (6.63×10^{-34} J)

- This implies that light can act as a particle and that the energy of that particle depends only on the frequency of the wave

Work Function

- If a photon of frequency *f* is absorbed by an electron, the electron's energy will increase by hf
- It takes a certain amount of energy, ϕ, to free the electron from the pull of the nuclei
- The electron will be emitted if $hf > \phi$
- The difference will be the kinetic energy of the now free electron

$$E_k = hf - \phi$$

- We have seen this work function on the graphs
- The work function and the threshold frequency are related as follows:

$$hf_c = \phi$$

Since E_k=0 in that case

- Therefore, we can say…

$$\boxed{E_{\max} = hf - \phi}$$

Momentum of a Photon

- We know that a photon has energy, but it also has momentum
- The existence of a photon momentum is supported by the Compton effect
  - The scattering of photons off electrons or photons
- The photon has no mass
- For such particles, a more general definition of momentum allows zero-mass particles to have momentum

$$p = \frac{E}{c} = \frac{hf}{c}$$

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

Photon Interactions

- When a photon passes through matter, it interacts with the atoms and electrons
- There are four important types of interactions that a photon can undergo:
  - Photoelectric effect
  - Knock an atomic electron to a higher energy level
  - Scattered and lose energy
  - Pair production

Pair Production

- The photon disappears and an electron positron pair is created
- This is an example of mass being created from energy according to E=mc2
- The inverse occurs when an electron collides with a positron
  - The two annihilate each other and a photon with the energy equal to the mass of the electron and positron appears

Wave-Particle Duality

- Young's double slit experiment clearly proves that light is a wave
- The photoelectric effect clearly proves that light is a particle
- Conclusion
  - Light is both a wave and a particle (wave-particle duality)

Principle of Complementarity

- Niels Bohr (Danish)
  - To understand an experiment , sometimes we find and explanation using wave theory and sometimes using particle theory. Yet we must be aware of both the wave and particle aspects of light if we are to have a full understanding of light. Therefore these two aspects of light complement one another.

De Broglie's Wavelength

- Louis de Broglie, 1923, suggested that a particle with momentum *p* would have a corresponding wavelength given by

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

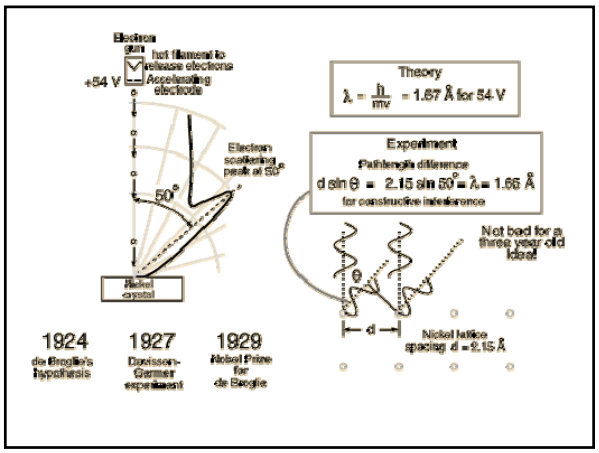
- De Broglie's hypothesis assigns wave-like properties to a particle
- Extends wave-particle duality to matter

The Electron

- Is an electron a particle or a wave?
- Waves must demonstrate diffraction
- To test this with electrons we need an obstacle (or opening) smaller than the wavelength of the electron
- Clinton J. Davisson, Lester H. Germer, and George Thomson (1927), performed an experiment that demonstrated diffraction

Davisson-Germer Experiment

- Electrons of kinetic energy 54 eV were directed at a surface of nickel where a single crystal had been grown and were scattered by it
- Using the Bragg formula (derived by Bragg to describe the spacing of atoms in a crystal and the wavelength of X-rays) and the known separation of the crystal atoms allowed the determination of the wavelength


Electron gun
hot filament to release electrons
+54 V
Accelerating electrode
Electron scattering peak at 50°
50°
Nickel crystal
Theory
$\lambda = \frac{h}{mv}$ = 1.67 Å for 54 V
Experiment
Pathlength difference
d sin θ = 2.15 sin 50° = λ = 1.66 Å
for constructive interference
Not bad for a three year old ideal
θ
d
Nickel lattice spacing d = 2.15 Å
1924
de Broglie's hypothesis
1927
Davisson-Germer experiment
1929
Nobel Prize for de Broglie