

Detectors: Photoelectric Effect and Photo Emitters

Emmett Ientilucci, Ph.D.
Digital Imaging and Remote Sensing Laboratory
Chester F. Carlson Center for Imaging Science
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Detector Types

- Thermal Detectors
 - Thermistor
- Photon Detectors
 - Photoconductive (no p-n junction, conductivity varies with $h\nu$)
 - Photovoltaic (based on p-n junction)
 - Photoemissive
 - Based on photoelectric effect
 - Photomultiplier tube (PMT)

Physics in the 19th Century

- Prior to 1900, physicists believed only in the **wave** description of light
 - As seen through interference and diffraction
 - Though Newton thought of light as a particle
 - This was discredited with Young's (1773-1829) double slit experiment in 1802
 - By 1830, most physicists believe the **wave** theory
- Back to particles (the photoelectric effect)
 - However, in 1887, German physicists Heinrich Hertz (1857-1894) discovered:
 - When light shines on a metal surface, the surface emits electrons

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Heinrich Hertz

- German physicist (1857-1894)
 - Was a student of Kirchhoff and Helmholtz
 - 1886-7, discovered **photoelectric effect**
 - Though he would do nothing with it
 - 1886-7, First to demonstrate existence of EM radiation by building an apparatus to produce **radio waves**
 - Einstein (1905) would later explain the photoelectric effect mathematically based on work done by Planck
 - Nobel Prize in Physics (1921)



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Some Nobel Laureates in Physics

1938 Fermi
1933 Schrödinger, Dirac
1932 Heisenberg
1930 Raman
1929 Broglie
1925 Franck, Gustav Hertz
1923 Millikan
1922 Niels Bohr
1921 Albert Einstein
1918 Max Planck
1915 William Bragg, Lawrence Bragg
1911 Wilhelm Wien
1910 Johannes Diderik van der Waals
1907 Albert A. Michelson
1906 J.J. Thomson
1905 Philipp Lenard
1904 Lord Rayleigh
1903 Henri Becquerel, Pierre Curie, Marie Curie

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Methods of Electron Emission

- Today we know of many ways to remove electrons
 - Thermionic emission
 - Application of heat allows electrons to gain enough energy to escape
 - Secondary emission
 - The electron gains enough energy by transfer from another high-speed particle that had struck the material from outside
 - Field emission
 - A strong external electric field pulls the electron out of the material
 - Photoelectric effect

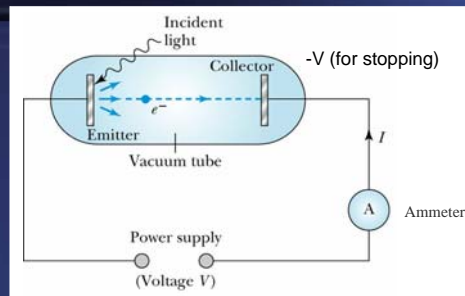
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The Photoelectric Effect

- Photoelectric effect
 - Electrons are emitted from any surface when light of a sufficiently high-frequency shines on that surface

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Typical Experimental Setup



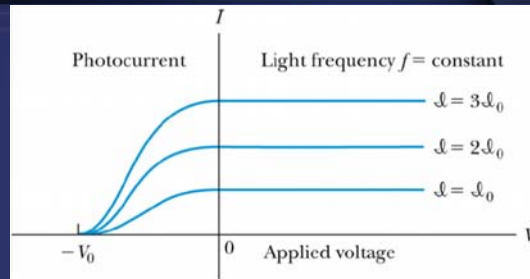
- Incident (monochromatic) light triggers emission of (photo) electrons from the cathode
- Some of them travel toward the collector (anode) with initial KE
- The applied voltage V either accelerates (if positive) or decelerates (if negative) the incoming electrons
- The current, I measured in the ammeter (photocurrent) arises from the flow of photoelectrons from emitter to collector

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Measurement 1

Additional experiments were carried out around 1900:

- Philipp Lenard (1902) NP-1905
- Robert Millikan (1910) NP-1923

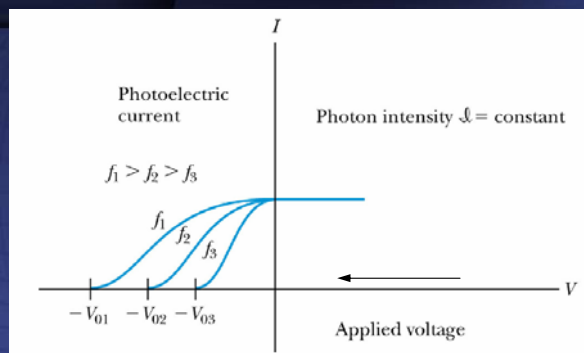


FIXED FREQUENCY (vary intensity)

- The **amount** of photoelectrons is proportional to the **incident light intensity**
- The retarding potential V_0 is independent of the incoming light **intensity**

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Measurement 2



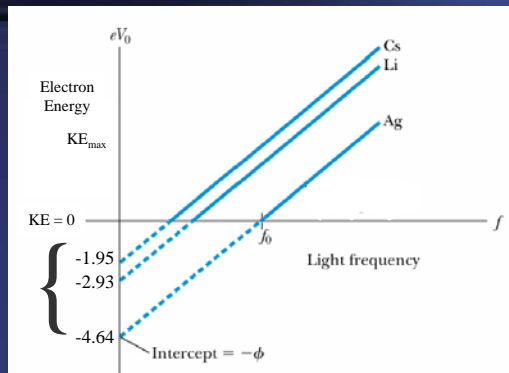
-So what's the relationship between V and f ?

FIXED INTENSITY (vary frequency)

- The **retarding potential depends on the frequency**
- Higher frequencies generate higher energy electrons
- Photoelectrons are being ejected **having larger KE, as a function of frequency**
- That is, KE_{max} of a photoelectron, only depends on the frequency!

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Measurement 3



- There is a minimal amount of required KE that allows electrons to escape the material. This is called the **work function, ϕ**
 - That is, the **work function** is the minimum binding energy of the electron to the material
- The **smaller the work function** of the emitter material, the **smaller is the threshold frequency** of the light that can eject photoelectrons

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Typical Experimental Setup

Work function for various materials

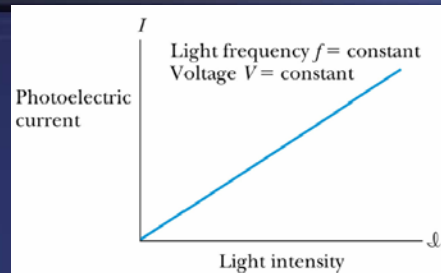
Element	ϕ (eV)	Element	ϕ (eV)	Element	ϕ (eV)
Ag	4.64	K	2.29	Pd	5.22
Al	4.20	Li	2.93	Pt	5.64
C	5.0	Na	2.36	W	4.63
Cs	1.95	Nd	3.2	Zr	4.05
Cu	4.48	Ni	5.22		
Fe	4.67	Pb	4.25		

eV (energy gained by an electron in an accelerating potential of 1 Volt)

$$1\text{eV} = \text{Volts} * e = (\text{J/coulombs}) * (1.6 \times 10^{-19} \text{ coulombs}) = 1.6 \times 10^{-19} \text{ coulombs}$$

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Measurement 4



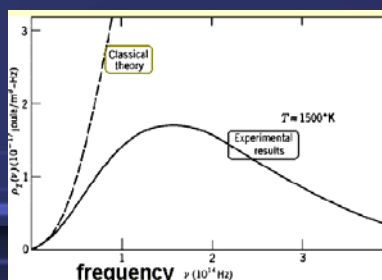
FIXED FREQUENCY and STOPPING VOLTAGE (vary intensity)

- When **photoelectrons** are produced, however, their number is **proportional** to the **intensity** of the light

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...After Hertz

- Quantum Theory
 - Beginnings lie with the frequency spectrum emitted by a solid when heated (blackbody radiation)
 - Experimental measurements show a **continuous spectrum** with a shape that is temperature dependent
 - “Classical” theoretical prediction says energy radiated to **increase as the square of the frequency**



Called the
“Ultraviolet
Catastrophe”

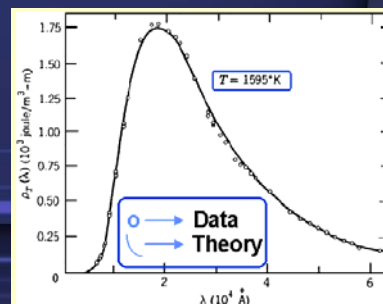
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Planck's Solution



- Planck's Radical Idea in 1900
 - Came up with a formula that agreed very closely with experimental data
 - But it only worked if he **assumed** that the **energy**, E of a vibrating molecule was **quantized**
 - E was proportion to frequency multiplied by a certain constant (Planck's constant, $h = 6.626 \times 10^{-34} \text{ J s}$)
 - $E = h\nu$

IT Works!



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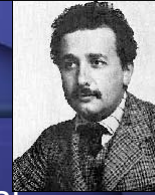
Planck's Solution



- Planck's Radical Idea in 1900
 - Initially called his theory "an act of desperation"
 - He did not know what he had stumbled upon
 - He thought he was **fudging** the math to get the right answer, for now, and someone else would come up with a better explanation.
 - This would be a complete **break from classical physics**, where all physical quantities are always continuous

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Einstein's Theory



- He took Planck's hypothesis seriously and used it to explain Hertz's experimental findings
 - Einstein proposed that if light is **generated** in quantized units, then it should also **arrive** at the metal with quantized amount of energy
 - Each with energy, $E = h\nu$ (like Planck before)
 - He called them quanta or **photons**
 - When a **photon collides** with an electron, it gives away ALL its energy (which is **transferred to the electron as KE**)
 - Collision: **Photon = Particle**

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Einstein published his works on **relativity**, on the **photoelectric effect** and on the **Brownian motion** in 1905 (the miracle year).

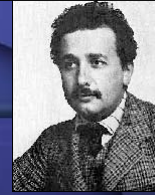
Einstein's Theory



- Conservation of Energy
 - **Energy before (photon) = Energy after (electron)**
 - $h\nu = \phi + KE$
 - $h\nu = \phi + \frac{1}{2}mv^2$
 - Where the retarding potential is
 - $eV_0 = \frac{1}{2}mv_{\max}^2 = KE_{\max}$
 - Proposed that the **stopping potential** should be linearly related to the **light frequency**, with **slope "h"**
 - $KE_{\max} = h\nu - \phi$

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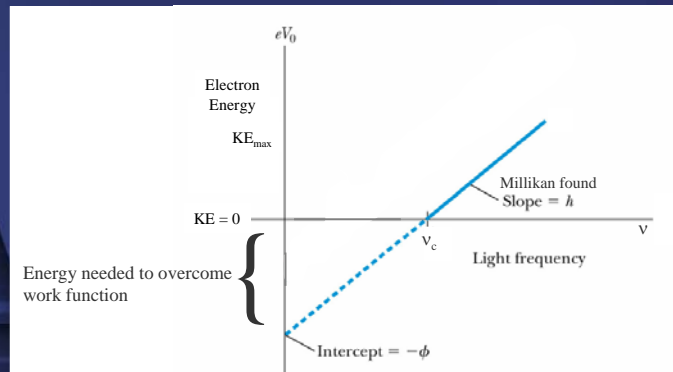
Einstein's Theory



- Experiment

- Done accurately by Millikan in 1916

- $KE_{\max} = h\nu - \phi$
 - $KE_{\max} = h\nu - h\nu_c$



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Hertz – Planck – Einstein – Bohr

- This idea of quantized energy values would lead to a new model of the Atom (1912)

- Niels Bohr (1885-1962)

- Realized the significance that the quantization could explain the stability of the atom
 - Which won him the 1922 Noble Prize for physics

- So at the end of the day, we give up classical physics

- Things are not necessarily continuous
 - Wave-particle duality



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...Onto Photo-emissive Detectors

- Detectors based on the photoelectric effect
 - Vacuum Phototube
 - Photo-multiplier Tube (PMT)
 - Micro-channel Plate

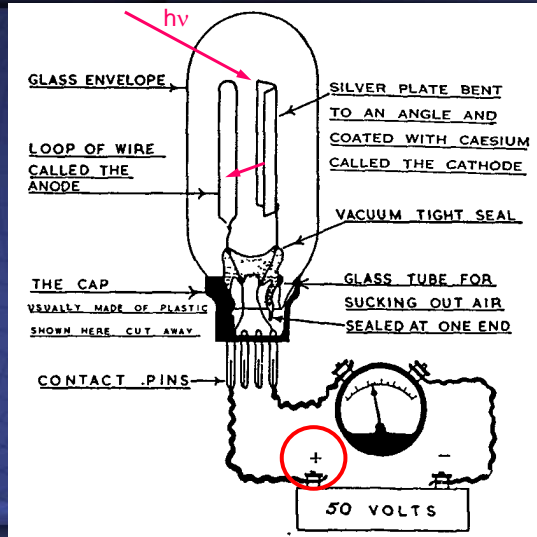
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Vacuum Phototube

- Not to be confused with the “Vacuum Tube”
- Basically the photoelectric experiment with a positive stopping potential (acceleration)
 - No amplification of photoelectrons
 - Current: **micro-Amps**
- Were superseded by the photo-resistor and photodiode.

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Vacuum Phototube

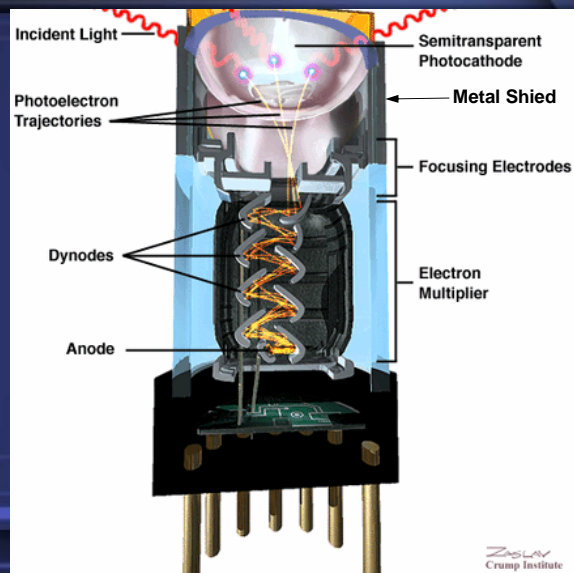
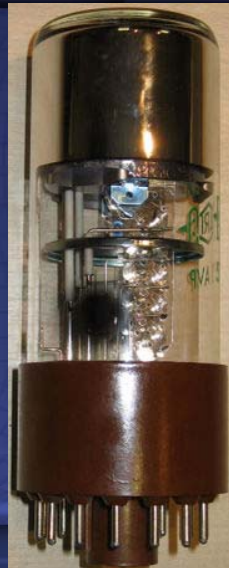


-1 photon \rightarrow 1 photoelectron

-Current output is **linearly** proportional to the flux received by the cathode

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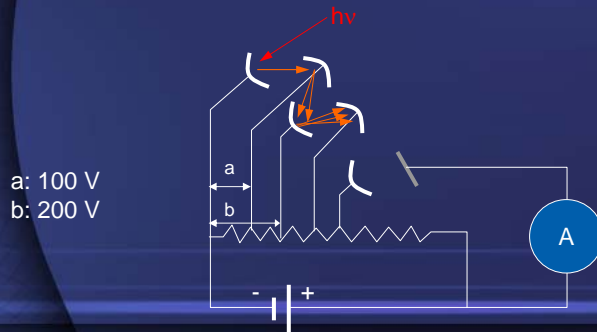
Photomultiplier Tube (PMT)



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Photomultiplier Tube (PMT)

- Used to provide several orders of gain (10^6)
 - Includes “several” intermediate anodes (dynodes)
 - Each is given a voltage higher than the previous one
 - e^- arrives with enough energy to eject **multiple** electrons



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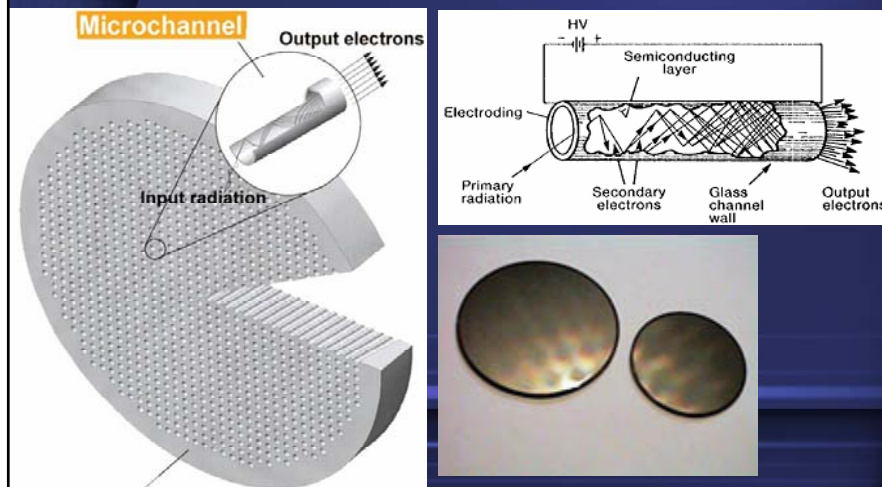
Photomultiplier Tube (PMT)

- Advantages
 - Standard device
 - Large signals
 - Large active area possible
 - Fast rise time possible
- Disadvantages
 - Large physical dimension
 - High voltage required
 - Gain instability as a function of temperature
 - Sensitive to magnetic fields

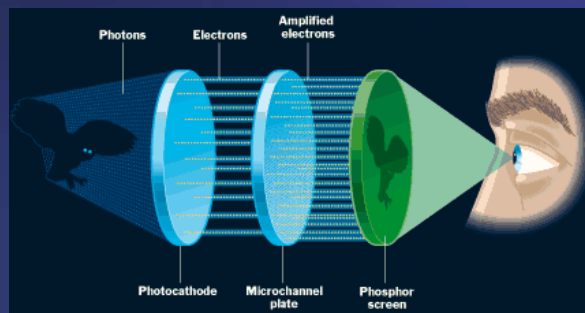
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Microchannel Plate

- A 2d array of photo-multiplier tubes
 - Uses a “continuous” dynode chain



Microchannel Plate



<http://www.nightvision.com/howitworks.html>



Photomultiplier Tube Examples

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