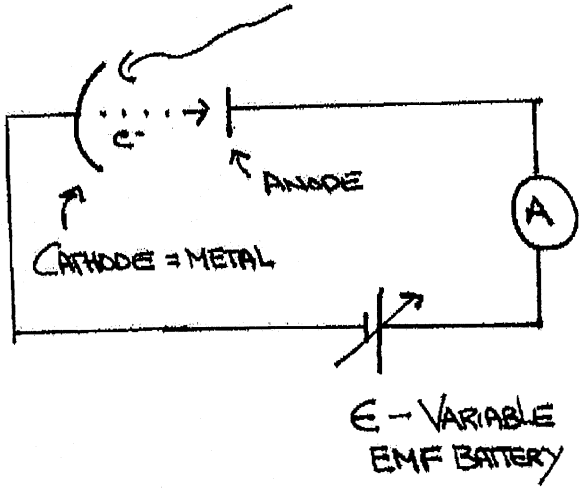
PHYS2002 : PHOTONS, CHAPTER 38

PHOTOELECTRIC EFFECT – LIGHT SHINING ON SOME METALS CAUSE ELECTRONS TO BE EMITTED.



THE BATTERY ALLOWS US TO FIND THE e^-'S KINETIC ENERGY. WHEN $I = 0$, WE SAY $\epsilon = V_0$ = STOPPING POTENTIAL BECAUSE NO ELECTRONS ARE REACHING THE ANODE.

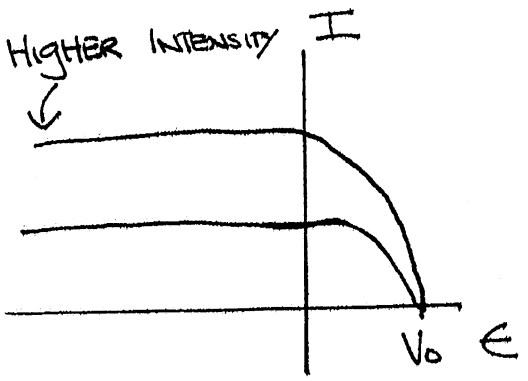
WITH BATTERY ARRANGED AS SHOWN (POSITIVE TERMINAL CONNECTED TO ANODE), THE ELECTRON'S POTENTIAL ENERGY INCREASES BY $+eV_0$ WHEN $\epsilon = V_0$.

$\left(\Delta V = \frac{\Delta U}{q_0} \Rightarrow \Delta U = q_0 \Delta V\right)$, $e = 1.6 \times 10^{-19} C$.

$\Delta U = -\Delta K$ $\quad \Delta K = 0 - K$ (ELECTRONS ARE STOPPED $\Rightarrow K_2 = 0$; K = INITIAL KINETIC ENERGY)

$\Rightarrow \Delta U = K \Rightarrow \boxed{K = eV_0}$

THERE IS A VERY SURPRISING RESULT IN THE PHOTOELECTRIC EFFECT EXPERIMENT. – THE KINETIC ENERGY DOES NOT DEPEND ON THE LIGHT'S INTENSITY.



TWO SOURCES OF MONOCHROMATIC LIGHT. SAME FREQUENCY FOR BOTH SOURCES, BUT DIFFERENT INTENSITIES.
(NOTE I = CIRCUIT'S CURRENT NOT INTENSITY).

SAME VALUE FOR $V_0 \Rightarrow$ SAME KINETIC ENERGY.

THIS DOESN'T MAKE SENSE! THE ELECTRONS GET THEIR KINETIC ENERGY FROM THE LIGHT. INTENSITY = $\frac{\text{POWER}}{\text{AREA}}$. A GREATER INTENSITY MEANS THE ELECTRONS GET MORE POWER $\Rightarrow$ MORE JOULES PER SECOND. SO THEY SHOULD HAVE MORE KINETIC ENERGY.

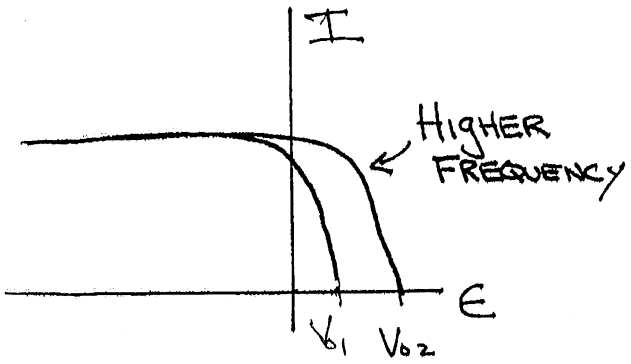
NOTICE THAT INTENSITY DOES DETERMINE THE MAXIMUM CURRENT IN THE CIRCUIT. CURRENT IS A MEASURE OF THE NUMBER OF ELECTRONS BEING EJECTED FROM THE METAL.

$I = \frac{dq}{dt}$. FOR ELECTRONS, $dq = e\,dN$ WHERE N = # OF electrons

$\Rightarrow I = e\frac{dN}{dt}$

SO INTENSITY DETERMINES THE NUMBER OF ELECTRONS.

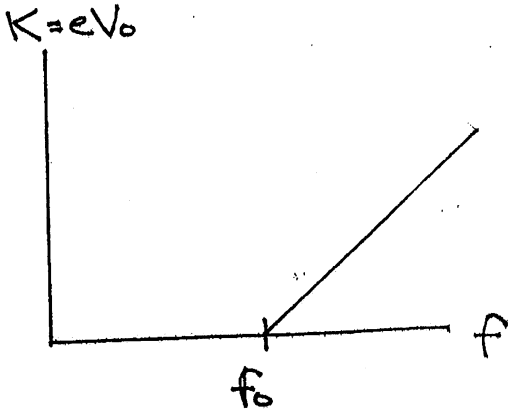
THE OTHER SURPRISING RESULT OF THE PHOTOELECTRIC EFFECT EXPERIMENT IS THAT THE KINETIC ENERGY DEPENDS ON THE LIGHT'S FREQUENCY. MOREOVER THERE IS A MINIMUM FREQUENCY f_0. BELOW f_0 THERE ARE NO ELECTRONS EMITTED BY THE METAL.



Two monochromatic light sources. Same intensity but different frequencies.

Larger V_{02} for higher frequency ⇒ increasing kinetic energy with frequency.

A plot of the electrons' kinetic energy versus frequency looks like:



Experiments show that kinetic energy increases linearly with frequency.

The solution to this problem was worked out by Einstein in 1905. This was done at the same time as his work on special relativity and was the work for which he won his only Nobel Prize.

Einstein was inspired by the work of the German physicist Max Planck on black body radiation. All objects emit "light" due to their temperature. There is a range of frequencies emitted. The maximum frequency is given by $f_{max} = 1 \times 10^{11} \cdot T$ → Wien's law.

To derive this equation (and other related) Planck had been forced to assume that the light emitted from black bodies is composed of small bundles which he called quanta. The energy of the quanta is directly proportional to the light's frequency.

EINSTEIN TOOK THE NEXT STEP AND ASSUMED THAT ALL LIGHT IS COMPOSED OF THESE SMALL BUNDLES CALLED PHOTONS.

THE PHOTON'S ENERGY IS $\boxed{E = hf}$ $\boxed{h = 6.626\times10^{-34}\ J\cdot s}$

PLANK'S CONSTANT

PHOTONS EXPLAIN THE PHOTOELECTRIC EFFECT IN THE FOLLOWING WAY:* THE ENERGY TRANSFER FROM PHOTON TO ELECTRON IS AN ALL OR NOTHING EVENT. IF THE PHOTON HAS ENOUGH ENERGY TO FREE THE ELECTRON FROM THE ATOM, THEN THE ELECTRON ABSORBS ALL THE PHOTON'S ENERGY. IF THE PHOTON DOESN'T HAVE ENOUGH ENERGY TO FREE THE ELECTRON, THE ELECTRON ABSORBS NONE OF THE PHOTON'S ENERGY (THE PHOTON'S ENERGY PROBABLY WILL BE CONVERTED INTO HEAT – THE METAL'S TEMPERATURE WILL INCREASE.). SINCE THE PHOTON'S ENERGY DEPENDS ON ITS FREQUENCY, THERE IS A MINIMUM FREQUENCY TO FREE THE ELECTRONS.

TO ESCAPE FROM ITS ATOM, THE ELECTRON MUST OVERCOME THE POTENTIAL ENERGY BINDING IT TO THE ATOM. THIS BINDING ENERGY IS CALLED THE WORK FUNCTION ϕ. LEFTOVER ENERGY BECOMES KINETIC ENERGY.

$$K = E - \phi = hf - \phi.$$

$$K = eV_0 \Rightarrow \boxed{eV_0 = hf - \phi}$$

ENERGIES HERE ARE USUALLY EXPRESSED IN A UNIT CALLED ELECTRON VOLTS (eV).

1eV = KINETIC ENERGY GAINED BY AN ELECTRON WHEN ACCELERATED THROUGH A $\Delta V = 1V$.

$$\Delta K = -\Delta U = -(-e)\Delta V = e\Delta V \Rightarrow 1eV = (1.6\times10^{-19}C)(1V)$$

$$\Rightarrow \boxed{1eV = 1.6\times10^{-19}J}$$

$$\boxed{h = 6.626\times10^{-34}J\cdot s = 4.136\times10^{-15}eV\cdot s}$$

EXAMPLE: THE WORK FUNCTION FOR SILVER IS 4.3eV. WHAT IS MINIMUM FREQUENCY LIGHT NEEDED FOR A "PHOTO CURRENT"?

$$eV_0 = hf - \phi.$$

MINIMUM FREQUENCY, f_0, OCCURS WHEN ELECTRONS HAVE NO KINETIC ENERGY $\Rightarrow V_0 = 0$.

$$\Rightarrow 0 = hf_0 - \phi \Rightarrow f_0 = \frac{\phi}{h} = \frac{4.3eV}{4.136\times10^{-15}eV\cdot s} = 1.04\times10^{15}Hz \rightarrow \text{UV LIGHT}$$

- WHAT IS THE STOPPING POTENTIAL FOR LIGHT OF FREQUENCY $f = 2.5\times10^{15}Hz$.

$V_0 = ?$

$$eV_0 = hf - \phi = (4.136\times10^{-15}eV\cdot s)(2.5\times10^{15}Hz) - 4.3eV = 6.04eV$$

$$\Rightarrow V_0 = 6.04V$$

- WHAT IS THE MAXIMUM SPEED OF THE ELECTRONS EMITTED BY SILVER WHEN $f = 2.5\times10^{15}$ Hz.

$K = eV_0 = 6.04\,eV$

ONLY THE FASTEST ELECTRONS MAKE IT TO THE ANODE $\Rightarrow$

$$K = \tfrac{1}{2}MV_{MAX}^2 \Rightarrow 6.04\,eV \times \frac{1.6\times10^{-19}\,J}{eV} = 9.666\times10^{-19}\,J = \tfrac{1}{2}(9.11\times10^{-31}\,kg)V^2$$

$$\Rightarrow V = 1.46\times10^{6}\,m/s = .005c \rightarrow \text{NO WORRIES ABOUT RELATIVITY.}$$

* THE LIGHT'S INTENSITY DETERMINES THE NUMBER OF PHOTONS (ALL WITH THE SAME ENERGY $E = hf$). EACH PHOTON FREES ONE ELECTRON SO THE NUMBER OF ELECTRONS BUT NOT THEIR KINETIC ENERGY IS DETERMINED BY THE INTENSITY.