

### Experiment 3

#### The Photoelectric Effect

All materials are found to emit electrons (and other particles...) when exposed to electromagnetic (em) radiation. Classically, this would be attributed to the accumulation of energy in the incident em wave...a sort of heating effect that results in the liberation of electrons.

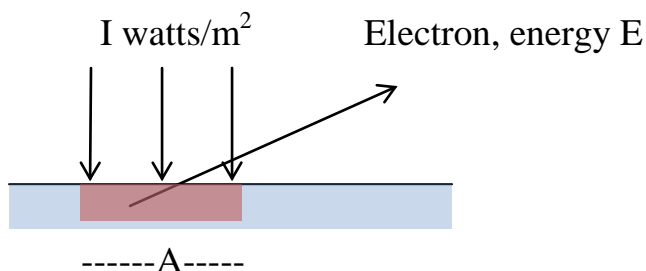
Detection of an electron having energy  $E$  emitted from a solid would then imply that the requisite amount of energy had been accumulated over some time,  $t$ , during exposure to an em wave with intensity (also called irradiance)  $I$  watts/m<sup>2</sup>.

The energy balance in this case is

$$E \text{ (joule)} = A \int_0^t I dt \quad 1$$

Where  $A$  is the area of the surface exposed to em radiation.

**Fig. 1**



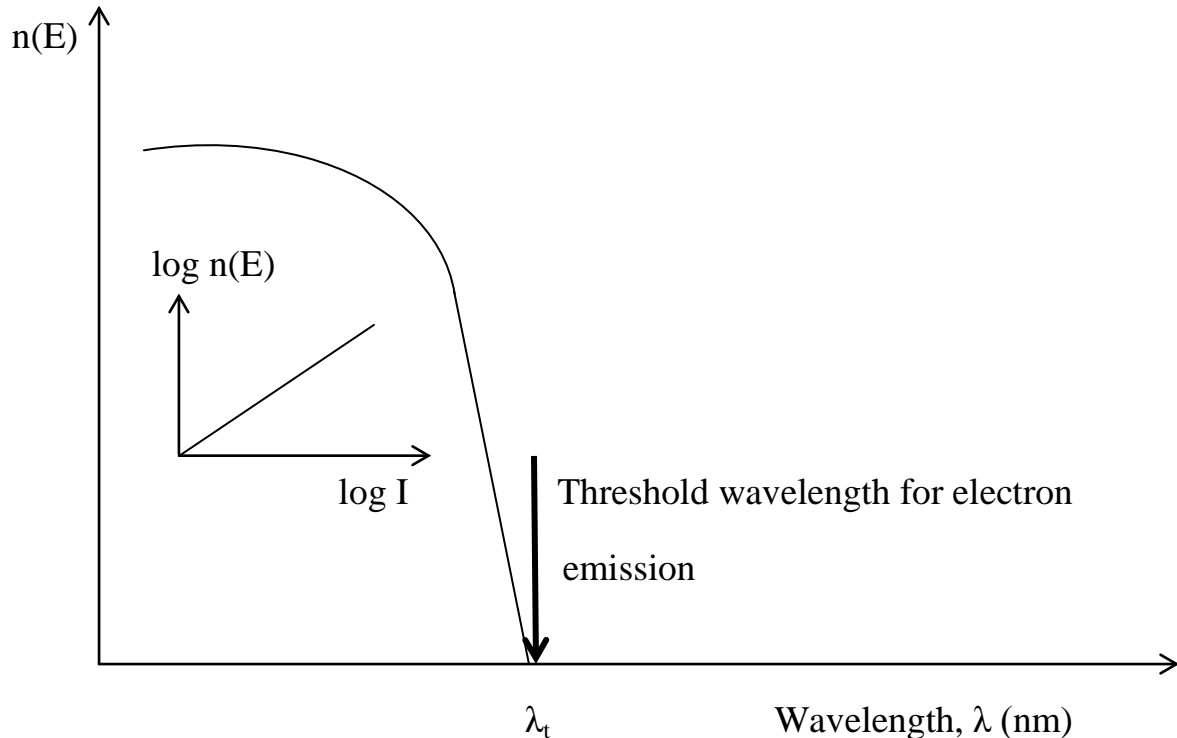
In this classical description of the photoelectric effect (PE), one predicts

1. If  $E$  is constant, then  $t$  must increase as  $I$  becomes smaller
2. All wavelengths of em radiation should be equally effective in producing electrons

Both of these expectations are found to be incorrect and are inconsistent with measurements.

Experimental measurements show that

**Fig. 2**



where  $n(E)$  is the number of electrons emitted with energy  $E$ . The inset shows that  $n(E) \propto I$  once the wavelength of the incident radiation  $\lambda < \lambda_t$ .

These observations are impossible to explain with a classical model, but can be understood if energy levels are quantized in the absorber. This is the basis for the Einstein model (1921 Nobel Prize).

They are consistent with the following energy conservation equation

$$E = (h c / \lambda) - (h c / \lambda_t) \quad 2$$

or

$$E = h\nu - h\nu_t = h\nu - \phi \quad 3$$

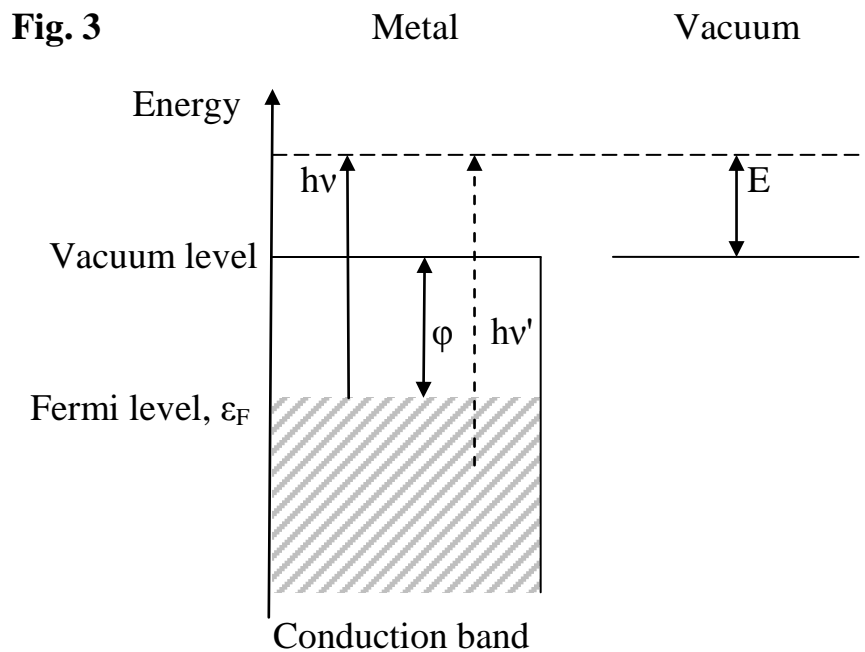
where the threshold energy  $\phi$  is referred to as the “work function” for a solid.

The corresponding threshold energy for an atom is the ionization potential, IP. For the H atom, the above energy balance would be

$$E = h\nu - \text{IP} \quad 4$$

where IP is 13.527 eV. Measuring the energy of the emitted electron for a given photon energy then gives IP. This technique has become known as "photoelectron spectroscopy" (or PES) and has been widely used as an analytical technique in atomic and molecular physics.

In a metallic solid, the energy levels are as follows



The minimum photon energy  $h\nu$  required to release an electron from the metal then gives the work function,  $\phi$ . Note that each absorption of a photon can release an electron, so the emission is "prompt" and no delay in emission is expected even at very low photon flux.

The Fermi level is the highest filled energy level at  $0^\circ\text{K}$ , but as the temperature,  $T$ , increases, some electrons can move from states at  $\varepsilon < \varepsilon_F$  to states at  $\varepsilon > \varepsilon_F$ . the distribution function  $f(\varepsilon)$  for occupied states is

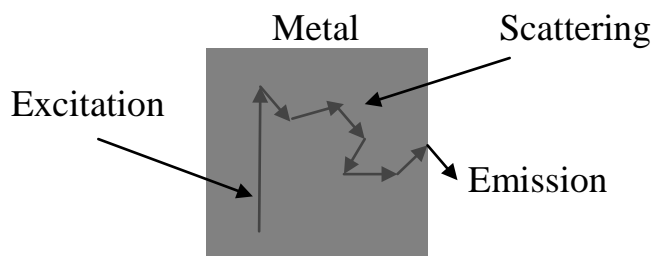
$$f(\epsilon) = 1 / \{ \exp [(\epsilon - \epsilon_F) / kT] + 1 \} \quad 5$$

where  $k$  is the Boltzmann constant ( $1.38 \times 10^{-23}$  J/K). At room temperature ( $T = 300$  K),  $kT = 4.14 \times 10^{-21}$  J = 0.026 eV. The Fermi energy is typically  $\sim 2$ -5 eV for a metal. So thermal excitation of electrons tends to introduce an uncertainty in the measured value of  $\phi$ , but in practice this uncertainty is usually less than other factors that limit the overall accuracy with which the work function can be measured.

Even though an excited electron may have sufficient excess energy to leave the metal, there is often a small surface potential barrier that needs to be overcome in order for emission to occur. In addition, electrons are scattered by other electrons prior to emission and only those having momentum perpendicular to the surface will eventually make it out (Fig. 4). This affects the number of electrons emitted per absorbed photon; the quantum yield  $Y(h\nu)$ . See the following for further discussion of this matter.

[http://ajp.aapt.org/resource/1/ajpias/v46/i10/p1046\\_s1](http://ajp.aapt.org/resource/1/ajpias/v46/i10/p1046_s1)

**Fig. 4**



The dashed vertical line in figure 3 corresponds to another transition that can release an electron with energy  $E$ . This transition at photon energy  $h\nu'$  probes electrons that are deeper in the conduction band leading to some ambiguity in the solution to equation 3. The probability that this occurs depends in part on the number of electron states available, or the "density of states,  $g(\epsilon)$ ". Measuring  $Y(h\nu)$  while keeping  $E$  constant is commonly used to find  $g(\epsilon)$ .