Physics 223
Experiment 10: The Photoelectric Effect

April 28, 2009

In the late 1800's, many thought that all the main principles and law of nature had been discovered. However, there were still a few puzzling discrepancies. One of these is the experimental data on the emission and absorption of electromagnetic radiation from a blackbody. The classical theory of that time (Rayleigh-Jeans Law) predicted that the amount of light emitted from a blackbody would increase dramatically as the wavelength (frequency) decreased (increased). The experimental measurement showed instead the opposite, that as the wavelength decreases, the radiation emitted approached zero. This discrepancy became known as the ultraviolet catastrophe. Furthermore, experimental results for the radiation emitted by a hot, glowing body showed that the maximum intensity of the emitted light also departed significantly from the known classical laws (Wien's Law). To reconcile the experimental data with the classical theories, Planck introduced a new model in which electromagnetic radiation was emitted in discrete bundles of energy called quanta.

Planck published his law of radiation in 1901. In it he introduced the idea of discrete energy values for electromagnetic (EM) radiation. Emission and absorption of radiation were associated with the transition between two discrete energy states or levels. The magnitude of the radiant energy E was given by

$$E = h\nu \tag{1}$$

where ν is the frequency of the radiation, and h is a fundamental constant of nature known as Planck's constant. Einstein later applied Planck's idea of discrete quanta of electromagnetic radiation to the photoelectric phenomena. In the photoelectric effect, electromagnetic radiation strikes the surface of a material, usually a metal, causing electrons to be ejected. Depending on the initial energy of the electromagnetic radiation, the ejected electrons will have a certain final kinetic energy (K). In the classical picture, the electromagnetic radiation is considered to be a wave. Recall that for a typical classical simple harmonic oscillator such as the oscillation of a mass at the end of a spring, the energy of the mass-spring system depends on the amplitude of the oscillation of the mass. Thus, the energy of the electromagnetic radiation was thought to also depend on the amplitude of the wave, i.e. the higher the intensity (brightness) of the electromagnetic radiation, the higher the energy. If this idea is applied to the photoelectric effect, we would expect that the maximum kinetic energy of the ejected photoelectrons would depend on the intensity of the incoming light. This is not the case. In the early 1900's, experimenters found that the kinetic energy of the photoelectrons did not depend on the intensity of the light, but rather on the wavelength or frequency of the light. In fact, below a certain frequency, no photoelectrons could be ejected from a particular material no matter how intense the light was! Einstein argued that this phenomenon could be explained if one adopted Planck's quantized picture of electromagnetic radiation, where the energy of light depends on its frequency and not on its intensity. Each quantum of light contains energy of the amount $h\nu$ as described in Equation 1. When directed to the surface of a metal, for instance, a quantum of light can be absorbed by an electron in the material. If this energy is greater than the net "attractive energy" the electron experiences within the material, then the electron is ejected from the surface of the material with a net kinetic energy. This can be described as

$$E = h\nu = K_{max} + \phi_o$$

$$K_{max} = \frac{hc}{\lambda} - \phi_o$$

where λ is the wavelength of the incoming light, K_{max} is the maximum kinetic energy of the emitted photoelectrons, and ϕ_o is the work function, which is the energy needed to remove an electron from the surface of a particular material (see Figure 1).

This shows that if the incoming electromagnetic radiation is less than the work function of the material, no electrons can be ejected from the material no matter how high the intensity is. [In this picture, the intensity of the electromagnetic radiation is defined as the number of quanta of energy passing through a unit area per unit time. Hence, a light source with a higher intensity simply means that there will be more photoelectrons ejected out of the material per unit time. However, their average kinetic energy will not be any different than light with the same frequency but with a lower intensity.]

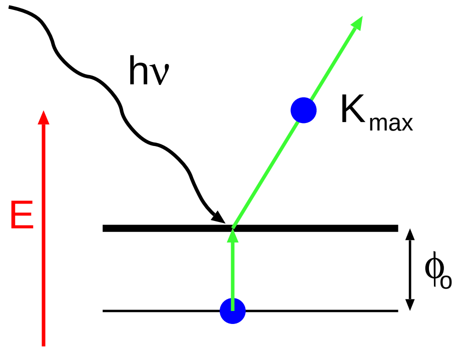

Figure 1: Schematic of the photoelectric effect. A photon strikes the surface of a metal and ejects an electron with work function ϕ_o, which leaves the surface with kinetic energy.

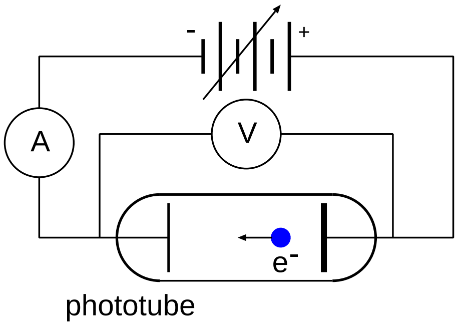

Figure 2: Schematic of the photoelectric measurement apparatus. The power supply is used to prevent electrons from reacing the anode and producing a current.

Photoelectric Effect Measurement

The apparatus used for the photoelectric effect measurement consists of a metal target from which the electrons are ejected and a voltage supply which can be used to apply an accelerating potential to the electrons in order to prevent them reaching the anode. The potential applied to the anode is called the "stopping potential" (V_{stop}) and is directly related to the maximum kinetic energy of the photoelectrons when the current to the anode just reaches zero.

$$eV_{stop} = K_{max}$$

In order to perform the photoelectric effect experiment, you will need to have several monochromatic (or nearly so) sources of light of different frequencies. You will have the atomic sources you measured in the previous laboratory exercise as well as red, green and blue filters. Using what you know about the atomic spectra, which wavelength will be relevant when you use them for a photoelectric effect measurement? Is it important for a light source to be completely monochromatic in order to measure the maximum kinetic energy of the photoelectrons?

Using the atomic sources, measure the stopping potential as a function of frequency and extract a value for Planck's constant from your measurements. (Note: make sure to come up with a consistent procedure for determining the point at which the current *just* falls to zero.) In addition to the measurements as a function of frequency, use the neutral filters provided in the laboratory to measure the stopping potential as a function of light intensity. Are your results consistent with the quantum picture of the photoelectric effect described in the introduction?