The Photoelectric Effect

There have been three key discoveries needed to explain light:

1. The discovery by Maxwell that the speed of light could be obtained from the electric and magnetic constants ϵ_0 and μ_0 if the equations of electromagnetism were modified to allow for changing electric fields to contribute to magnetic fields. This theory and its supporting experiments **showed that light was an electromagnetic wave traveling in a vacuum at a speed** $c=1/\sqrt{\mu_0\epsilon_0}$.

2. The photoelectric effect which Einstein explained by proposing that light came in discrete chunks (quanta) with an energy proportional to frequency: $E=hf$ where the proportionality constant *h* has the value $h=6.62606896\times10^{-34}\,\mathrm{J\cdot s}$. This experiment and Einstein's explanation **showed that light behaved like a particle**.

3. The complete merging of electrodynamics and quantum mechanics into quantum electrodynamics. This provided a complete and highly accurate theory of the interaction of light and matter.

We have just finished studying the experiments and equations behind the first discovery. This note will explain the second discovery. The final discovery is too difficult to deal with in this course.

The equations of electrodynamics known to Maxwell could explain many aspects of electricity, magnetism and light, but experiments that dealt with the emission of electrons from a metal in response to having light shined on the metal gave results that could not be explained by that theory.

The energy of a beam of light striking a surface can be calculated from its intensity. Double the brightness of a light beam and the power (energy per unit time) striking a surface is doubled. In the photoelectric experiment, light was shined on a metal in a vacuum (to eliminate any effect of air) and electrodes were arranged to detect any emitted electrons and to measure their kinetic energy.

Maxwell's electrodynamic theory predicted the following result:

1. A cloud of electrons would be emitted with a spread of energies.

2. As the power of the beam was increased, it was expected that the total energy of the electron cloud would increase accordingly.

3. It was not expected that the frequency of the light would matter, just its total power.

The experiment was performed with the following result:

1. Below a particular light frequency, no electrons at all were emitted.

2. Above that threshold frequency the kinetic energy per electron was proportional to the frequency difference between the higher frequency and the threshold frequency:

$$KE=h(f-f_{\text{threshold}})=(6.63\times10^{-34}\,\mathrm{J\cdot s})(f-f_{\text{threshold}})$$

3. More light power produced more electrons, but did not change the energy per electron.

Einstein proposed the following resolution to this contradiction:

1. Light comes in chunks called photons, each photon having an energy proportional to the light frequency: $E=h\,f$ where $h=6.63\times10^{-34}\,\mathrm{J\cdot s}$ is called Planck's Constant, first suggested in connection with the physics of glowing objects, but not really as meaning that light really came in chunks.

2. Each electron is ejected by a single photon. Some of the photon energy, $h\,f_{\text{threshold}}$, is used to escape the metal, the remainder, $h\,(f - f_{\text{threshold}})$, provides the electron's kinetic energy.

3. The intensity of a light beam of a particular frequency is proportional to the number of energy quanta per second provided by that beam.