Photo-electric Effect and Measurement of h/e

Sources:
http://www.pha.jhu.edu/~c173_608/photoelectric/photoelectric.html
http://hyperion.cc.uregina.ca/~szymanss/uglabs/p242/Experiments/EXPT2.pdf

Background: Planck's theory of radiation

In late 19th century, Max Planck was working on a theory of black body radiation, and ran into two problems:

"Ultraviolet catastrophe": the classical theory of radiation (Rayleigh-Jeans Law) predicted that the intensity of light emitted by a black body would increase to infinity as the wavelength decreased.
Wien's Law disproved by experiments: maximal intensity of the light of a hot, glowing body disagreed from the prediction of the classical model (Wien's Law).
Planck resolved both problems by postulating that the exchange of light is done in finite amounts, called quanta. In his 1901 paper, he stated that oscillators responsible for absorption and emission of light have discrete spectra of energy, and that the values in between are forbidden. In this model, the smallest unit of light that can be emitted or absorbed is

$$E = h\,v$$

where E is the energy of the `quantum', v is the frequency of radiation, and h is a fundamental constant. The constant, later known as Planck's constant, has significance beyond the model of black body radiation, and is a major building block of Quantum Mechanics and Quantum Field Theory.

The Photoelectric Effect and Einstein's explanation

Photoelectric emission is a process in which light strikes a surface of material (e.g. a metal), and electrons come out. The kinetic energy of these electrons can be measured by subjecting them to a retarding electric field. The maximal kinetic energy is obtained when the electric field is strong enough to overcome all electrons.

In early 1900s, several experiments showed that:
-The kinetic energy of electrons depended on the color of light (i.e., its frequency) and not on its intensity, and that dependence is linear.

-There exists some minimal frequency below which the light is unable to free any electrons, whereas above that critical frequency the light always succeeds in liberating electrons.
-The photoelectric current (the number of electrons emitted) depended on intensity of the light.

These experimental facts ran counter to the classical intuition of the time, since in the classical model the intensity of the light would imply larger amplitude of the light waves, which would result in larger energy transfer to electrons when the light hit the atoms of the surface.

Einstein took Planck's theory one step further and in 1905 stated that in the photoelectric process a photon of energy $E = h\,v$ is absorbed by electrons that are assumed to be bound within the surface of material with some energy W_0. The energy of the photon is used by the electron to escape the atom and the rest is electron's kinetic energy E_{kin}. This is summed up in Einstein's famous equation:

$$h\,v = E_{kin} + W_0$$

If a retarding potential V is used to stop electrons, that will happen when eV =E_{kin}. (Note that in truth a third term exists - the kinetic energy of the recoiling material necessary to ballance the electron's momentum, but it's neglected as infinitely small.) When solved for stopping potential V, this turns into

$$V = \frac{h}{e}v - \frac{W_0}{e}$$

so, if we plot V as a function of frequency v, we should get a linear dependence with a slope equal to h/e. Here W_0/e is called work function and is a property of the material.

This model thus makes a very definite prediction as to what the dependence of V on v ought to be. The goal of this experiment is to verify it, and, if true, to use it to measure h/e.

Notes

Max Planck was awarded the Nobel Prize in 1918 for his quantum theory. Albert Einstein got his in 1921 - for the explanation of the photoelectric effect. Robert Millikan felt very strongly that Einstein's explanation was wrong, and worked very hard for many years to perform ever more precise measurements of photoelectric effect. In the end he failed, confirming the quantum explanation. But he got a Nobel Prize as a consolation.

The Experiment

Experimentally, we need a clean surface of a metal which will be exposed to light and yield electrons, and therefore called the "cathode" below. We also need another surface to collect electrons - an "anode" - facing the cathode, and both are sealed in vacuum. The optical system is completely enclosed and optically isolated from the ambient lighting to ensure that only monochromatic light at the wavelengths listed reaches the cathode. We shine light of different intensities and frequencies (colors) onto the cathode, and it emits electrons that are collected on the anode. (The stream of electrons forms so-called photoelectric current.)

As a source of monochromatic light it is customary to use a mercury bulb. The most readily available lines are:

Color	Frequency [10^14 Hz]	Wavelength [nm]
Yellow	5.18672	578
Green	5.48996	546.074
Blue-green (weak)	6.09830	491.6
Blue	6.87858	435.835
Violet	7.40858	404.656
Ultraviolet	8.20264	365.483

The values for green, blue, violet and ultraviolet are copied from PASCO manual which quotes "Handbook of Chemistry and Physics", 46th ed. The wavelength for Yellow was determined experimentally by PASCO using a grating with 600 lines/mm. The line is a doublet at 578 and 589 nm. The value for blue-green was copied from Melissinos.

Although invisible, the ultraviolet light can be seen on the white reflective mask of the h/e apparatus, which is made of a special fluorescent material. Ultraviolet line will appear as blue. The violet will also appear bluish.