Experiment 45

The Planck and Boltzmann Constants

1 Preparation

1.1 Work function, Photoelectric effect and photocells
Berkeley 4: 1.41-1.46
Eisberg, Fundamentals of Modern Physics: p.76-81
American Institute of Physics Handbook, 3rd ed. 9-173

1.2 Interference filters
Alonso and Finn II, example 22.3

1.3 Vacuum diodes
Berkeley II, 4.2

1.4 Review on semiconductor basics
Alonzo and Finn III, 6.6

1.5 p-n junctions
Kittel 3rd ed.: p324-329

1.6 Boltzmann distribution
Eisberg: p. 57-68

1.7 Measuring Boltzmann's constant
American Journal of Physics 67, p. 1129 (1999)
(file available on webpage)

1.8 Instrument manuals
K5 Thermostat
Keithley 179 TRMS digital multimeter
Metrix VX 203A multimeter
Picoampmeter (Knick or Keithley)

2 Experiments

2.1 Measurement of Planck's constant

The fundamental energy quantum, called planck's constant h, can be determined starting from the Einstein equation (Berkeley IV, eq. 42a):

$$E = h\nu - W = eU \tag{1}$$

which described the photoelectric effect, and relates the energy E of electrons emitted from a material with a work function W to the frequency v of the illuminating photons. Experimentally, that energy can be determined by measuring the breaking voltage U needed to decelerate the emitted electrons down to zero velocity. By plotting U as a function of ν, and knowing the value of the fundamental charge e, one can extract h from the slope of the curve even without knowing the work function of the target material.
A mercury lamp serves as a light source for the experiment. It's beam is collimated with a lens and passes through an interference filter which transmit only a specific wavelength before hitting the photocell target. In order to minimize errors from stray light sources, the filter should be placed as close as possible to the photocell. To prevent damage to the photocell from exposure to high light intensities, it is essential to **block the entrance of the photocell with an aluminium plate when changing the filter.** Note also that since **the mercury lamp has very long heating/cooling times (∼20 minutes), once it is turned on it should be left on until the experiment is over.** Turning the lamp on and off during the experiment could damage it.

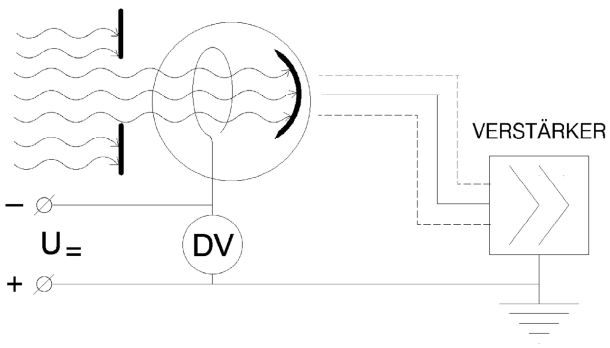

Figure 1: Schematic of the photocell. Verstärker = Amplifier.

Figure 1 shows a schematic of the measurement setup. The cathode of the vacuum photocell is made of sodium (Na) and the anode consist of a thin platinum (Pt) ring. In front of the photocell is a shield (black tube) to prevent the anode from being directly bombarded by incoming photons.
A variable voltage is applied between the anode and the cathode, and decelerates electrons emitted from the cathode. This voltage can be measured with a digital voltmeter. The cathode is connected to the input of a very sensitive picoamperemeter (the voltage drop over this instrument is negligible). Care should be taken not to touch the shielded cable carrying the current from the photocell to the amperemeter as it is very susceptible to errors coming from charging currents

associated with any change of capacitance in the cable.
The cable with the two black banana plugs is used to bake-out the anode, an operation which must be handled with great care, and that may only be performed under direct supervision of an instructor. **Take care never to connect the decelerating voltage to these black banana plugs.** The cathode lead is connected to the hole in the support post under the photocell.

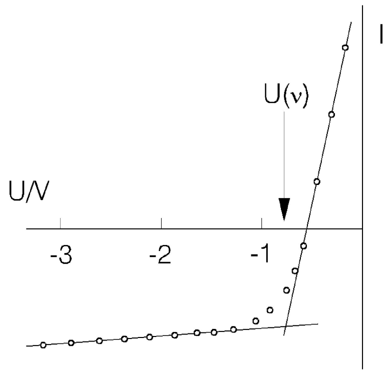

Figure 2: Typical graph of cathode current versus deceleration voltage.

A graph of the cathode current versus deceleration voltage should look qualitatively similar to figure 2. The current at high negative voltage comes from the anode being hit by stray light and thus emitting electrons which are accelerated towards the cathode by the applied voltage. While the high work function of the platinum should prevent emission of photoelectrons at the photon energies used in the experiment, impurities on the anode's surface still exhibit some photoemission which unfortunately complicates the exact determination of the breaking voltage.
A detailed description of the possible analysis techniques for determining the breaking voltage is available at the experimental station. Pick one of the suggested techniques (Threshold or Asymptotical) and plot the breaking voltage as a function of the photon frequency ν for the five wavelengths (577, 546, 436, 406 and 365 nm) available. For measurement at each wavelength, determine first roughly the voltage at which the current crosses zero, and then decide on sensible measurement voltages, collecting data points starting at -3V and choosing intervals such that you have enough data points in the interesting region to be able to determine the breaking voltage accurately.
Produce a linear fit of the measured data points, and use it to determine Planck's constant as well as the work function of the anode. How does this value compared to the expected value for Na?

2.2 Measurement of Boltzmann's constant

A technique for determining Boltzmann's constant was described in detail by M.D. Sturge and Song Bac Toh in the American Journal of Physics (Volume 67 (12), page 1129, December 1999). We will follow the method they described, adjusting only for minor difference in equipment.

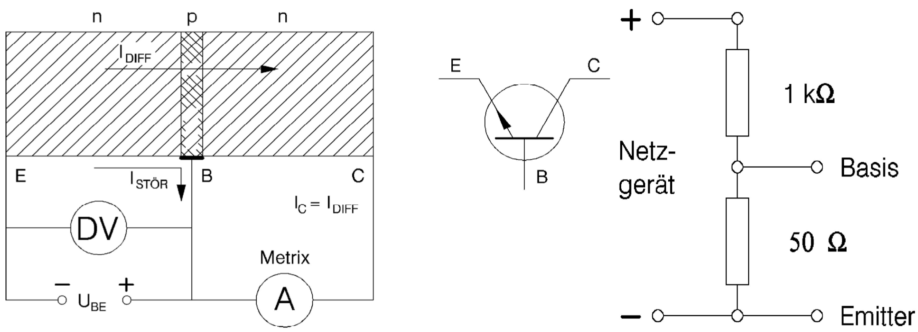

Figure 3: Left: Measuring Boltzmann's constant using a transistor. Right: Schematic of a voltage divider.

The npn-transistor (2N 3055) that we will use is mounted in a thermal bath with temperature control. Use the circuit of figure 3 to measure the $I_{Collector}$ versus $U_{Base-Emitter}$ curve at 3 temperatures corresponding to about 20, 60 and 100K above room temperature, starting from $U_{Base-Emitter}$=0 and continuing up to a current of $\sim$ 10 mA. Remember to choose an appropriate range on the current amplifier knowing that near $U_{Base-Emitter}$=0, only infinitesimal current will flow. In order to better control the base-emitter voltage, use a voltage divider as shown in figure 3.

Note that the thermal bath takes a long time to cool, so make sure that you are finished taking the measurement you need at a given temperature before moving to the next higher temperature.

Plot the results at each temperature on a semi-log graph, and determine Boltzmann's constant by fitting the results to equation 5 from Sturge and Toh for each temperature.

A note on terminology: Sturge and Toh refer to their equation 5 as the "Ebers-Moll" equation. However, this equation is more often called the "Shockley" equation, which is actually a special case of the more general Ebers-Moll equations that describe the complete functioning of bipolar junctions, relating current at either the emitter or the collector to any combination of applied voltages.

2.3 Error analysis

For both the Planck and Boltzmann constants, estimate the experimental error on your determination of the constants. Then, compare the values you obtained with known values from the literature. Comment on the level of agreement, and discuss potential explanations in the case of discrepancy.