

# The Photoelectric Effect

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The objective of this experiment is to demonstrate the quantization of energy in electromagnetic waves and to determine Planck's constant  $h$ . You will measure the maximum kinetic energy of electrons ejected by the photoelectric effect from an alkali metal surface as a function of frequency. A constant offset in energy is caused by the work function  $\phi$  of the metal cathode, *i.e.* the minimum energy needed to eject an electron out of the specific metal.

## I. PREPARATORY QUESTIONS

1. If a certain metal with a work function of  $\phi = 2.5$  eV is illuminated by monochromatic light of wavelength 3500 Å, what is the maximum kinetic energy of the electrons ejected in the photoelectric effect? Think about what stopping voltage in your apparatus will correspond to this energy. As you plan your experimental strategy, take this as an estimate of the overall voltage scales involved in the experiment.
2. What are the principal lines (*i.e.* the 5 brightest observable lines or groups of lines) in the spectrum of a mercury discharge lamp (see Reference [1], and [Oriel high power mercury lamp](#) specifications)? Could you observe the photoelectric effect on a silver (as opposed to potassium) cathode?
3. How does a narrow-band optical interference filter work? See [Optical Interference Filters](#) [2].
4. Sketch the expected curves of current against retarding voltage when the cathode of the tube is illuminated with light of wavelengths 3650 Å, 4035 Å, 4360 Å, 5460 Å, and 5775 Å, respectively. Assume  $I_0 = 1$  nA at 3650 Å. (See Reference [1].) Note: you are not being asked for a derivation, or even for the functional form of the curves<sup>1</sup>.

## II. THE PHOTOELECTRIC EFFECT

A very accessible introduction to this material is in the American Institute of Physics's [A Look Inside the Atom](#). In 1895, soon after discovering radio waves, [Heinrich Hertz](#) observed that when ultraviolet light from the sparks of his radio wave generator fell on the negative electrode of his radio wave detector, they induced a flow of electricity in the gap between the electrodes. Pursuing the phenomenon in detail, he discovered the photoelectric effect whereby light of sufficiently short wavelength causes the ejection of electrons from a metal surface. [Philipp Lenard](#) (1905 Nobel laureate) made im-

proved measurements and demonstrated that the ejected particles' charge to mass ratio was identical to that of the electrons which had recently been discovered by 1906 Nobel laureate [J. J. Thomson](#) in experiments with cathode rays.

Crude though the early data were, the qualitative fact of the dependence of the critical cutoff voltage on the wavelength of light emerged with sufficient clarity to induce the young Albert Einstein, working as a patent examiner in the Swiss Patent Office in 1905, to link the effect with the recent idea, introduced by Planck in 1900, that matter radiates its energy in quanta of energy  $h\nu$ . He postulated that light delivers its energy to an absorber in quanta with energy  $h\nu$ . Thus, if it takes an amount of energy  $\phi$  to lift an electron out of the surface and away from its image charge, then the residual kinetic energy  $K$  of the ejected electron is

$$K = h\nu - \phi. \quad (1)$$

The 1921 Nobel Prize was awarded to [Albert Einstein](#) for his discovery of "the law of photoelectric effect". It was not until 1912 that the technical problems of making precision measurements of the photoelectric effect were overcome by 1928 Nobel laureate [Sir Owen Wilans Richardson](#) and K. T. Compton (former MIT president) to the point where the Einstein photoelectric equation could be tested to high accuracy and used in precise determinations of Planck's constant  $h = 6.626 \times 10^{-34}$  J·s =  $4.135 \times 10^{-15}$  eV·s.

In this experiment you will measure the photoelectric current from an alkali metal surface as a function of a retarding potential that opposes the escape of the electrons from the surface. From the data you will be able to derive the value of Planck's constant and the work function  $\phi$  of the cathode material.

## III. EXPERIMENTAL SETUP

The apparatus is depicted in [Figure 1](#). Familiarize yourself with all of the components before turning anything on or making any signal connections. Open the photocell enclosure and observe the photocell itself, noting the height and orientation of the anode ring. Be sure that the photocell is properly aligned with your optical path.

<sup>1</sup> This is "Junior Lab", not "Junior Theory"!

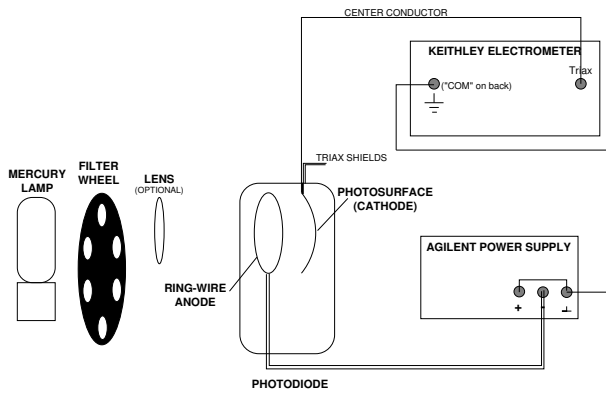


FIG. 1. Experimental arrangement for measuring the photoelectric effect. The lens focuses the light to avoid hitting the anode ring.

The Agilent variable DC Power supply provides the retarding voltage between the anode and the cathode. Pay close attention to the grounding connections between the electrometer and the power supply! If the power supply meter does not have sufficient resolution, try using an external digital voltmeter.

Connect the phototube cathode to the Keithly electrometer (or similar model) operating as an ultra-sensitive ammeter. Note that the input connector to the electrometer requires a *triaxial* connector for double grounding and thus be certain that you insert a BNC-triax connector before connecting the BNC cable from the cathode. Turn on the power supply and reduce the retarding voltage to zero.

### III.1. Light Source

The radiation source for this experiment is a high-power mercury discharge lamp **Oriel 65130**, or similar model. You should turn on the lamp as soon as you begin the lab to allow it to warm up. The spectral output of the lamp will change during the first 10 – 15 minutes. Once the lamp has stabilized, the spectral output is similar to that shown in Figure 2.

The narrow band pass filters used to select individual mercury emission lines have a preferred orientation; point the highly-reflecting side (a silvery color) toward the lamp and the colored side towards the phototube cathode. **Be careful not to place the filters too close to the lamp! The heat can bleach the color of the filters, leading to undefined behavior! Monitor the heat of the filters as you perform the experiment.**

### III.2. Photocell

The cathode of the **Leybold photocell** is a very thin layer of potassium ( $\phi_K = 2.3$  eV) deposited onto an ox-

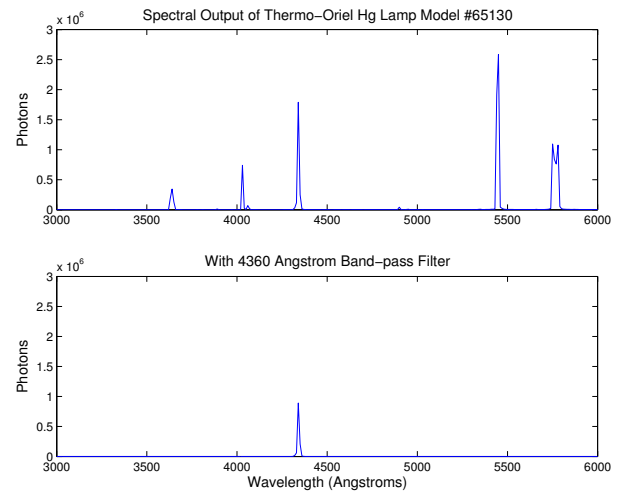


FIG. 2. Top Panel: Spectral output of the Thermo-Oriel 65130 Hg lamp after about 20 minutes warmup. Bottom Panel: Shows the lamp output after passing through the 4360 Å filter.

idized silver coating electrically connected to the cylindrical brass cap on top of the cell. The anode ring is made from platinum-rhodium alloy ( $\phi_{Pt} = 5.7$  eV). The potassium is the source of the photo-ejected electrons in this experiment. It is not possible to precisely determine the work function for removing an electron, because the cathode surface interacts with the remaining gases in the photocell as a getter, so that the surface characteristics change a little from the ideal case. It is important to note that the electronic work function  $\phi$  is a material constant which incorporates the different emission potentials of the cathode and anode. The former is a difficult quantity to estimate due to the manufacturing process which makes the cathode surface inhomogeneous. It is composed of a mixture of potassium, potassium oxide and oxidized silver. For this reason, you need to take care that the same area is always illuminated. The emission work function of the photoelectrons can vary locally!

#### Caution:

1. The photocell consists of an evacuated glass bulb and is fragile!
2. Do not subject the photo cell to mechanical stresses.
3. Protect the photocell from overheating.
4. Protect the photocell against excessive incident light (use filters if necessary!)

## IV. PROCEDURE

Illuminate the photocathode with light of the various spectral lines of mercury selected by the interference filters mounted on the filter wheel. You may want to start

with the more energetic spectral lines. Typical photoelectric currents are 100–1000 pA. Rigorously convince yourself that the current you are measuring is a photoelectric current caused by the mercury lamp. With creative use of black tape and the open hole, one can correct for ambient light effects if necessary.

Measure, tabulate, and plot the phototube current as a function of the the retarding voltage for each filter. Make sure to extend the measurements beyond  $I = 0$  in order to measure the effects of “reverse” current. Repeat the series of measurements **at least five times** to obtain the data necessary for a reliable estimate of the random errors of measurement.

You will need to develop on a strategy to guide your data taking. You must decide:

1. how many wavelength filters to measure,
2. the range and step sizes of applied retarding voltages to use, and
3. the number of repetitions of each voltage scan.

Obviously, for each listed factor, more data is better, but your available resources — in the context of Junior Lab, time is your principle manageable resource — to execute the strategy are *very* limited. You are therefor faced not with the simple question of what strategy is *best*, but rather the more subtle question of which strategies are *good enough*. To evaluate how good a strategy is, you must decide the scientific goal of your experiment: what are you trying to measure, and to what precision?

The following are practical problems with which you must contend:

1. Light striking the anode ring can produce photoelectrons that cause a reverse (negative) current in the electrometer and confuse the identification of the critical cutoff voltage. You may need to focus the light beam so that it passes cleanly through the ring without illuminating it. Experiment with the location of a lens to produce the sharpest image possible at the aperture to the photocell holder.
2. Proper grounding of the apparatus is essential to obtaining reliable data. When the grounding is proper, the electrometer readings should be unaffected by touching or moving your hand near the equipment.
3. Because you are measuring such small currents (the currents you obtain with no retarding voltage should be on the order of hundreds of picoamps), the ammeter will be prone to pick up induced currents from ambient magnetic fields and your induction of charges while moving near the apparatus. You can avoid such interference by keeping the connecting wires as short and direct as possible and free of loops. For instance, you might want to use a short piece of copper wire to ground the positive terminal of the power supply as shown in Figure 1.

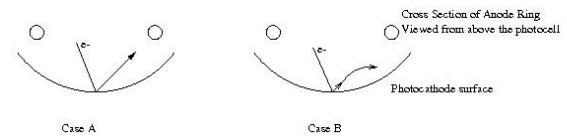


FIG. 3. Case A: electrons will travel in a straight direction when emitted for  $V_{retarding}=0$ . Case B: electron trajectories are nonlinear for finite retarding voltages.

You may also find it useful to twist some of the cables together.

4. Your measurement chain may or may not be sensitive to ambient light. Check to see if the current you are measuring is affected when you cover the experiment with black cloth.

## V. ANALYSIS

To analyze the data, first determine the cutoff value of the retarding voltage for each of the filters, and assess the random and systematic errors of each determination. Then, plot the cutoff voltages against the center frequency of the filter bandpass. According to Eqn. (1), this should go as

$$V = \frac{h}{e}\nu - \frac{1}{e}\phi. \quad (2)$$

Taking into account the uncertainties in the cutoff determinations, use linear fitting methods to compute the best-fit values and uncertainties of  $h$  and  $\phi$  from your plots. Estimate the systematic errors in your best-fit values.

**Discuss in detail how you have determined the cutoff voltage.** If you can use two different methods, the differences in  $h$  and  $\phi$  will give you a lower limit of the systematic errors. Note that the very notion of a well-defined cutoff voltage is implicitly dependent on describing the system by theoretical models which predict a sharp cutoff in the photocurrent. You may find that the data themselves do not support the notion of a sharp cutoff voltage as anything more than an approximation<sup>2</sup>. However, you may find that this approximation is adequate enough for performing the analysis. See References [1] and [3] for discussions of physical effects in the apparatus which confound the identification of the cutoff voltage by virtue of being difficult to capture in a simple model.

<sup>2</sup> Of course, for any model of finite detail, there always exists a sufficiently precise potential future dataset capable of undermining it. The model is still useful for describing less precise datasets, but there is no meaning in quoting measured values of notions defined in the model to a precision greater than that to which the model describes the dataset.

Suggestion: You can probably make more reliable determinations of the change in cutoff voltage from one wavelength to the next if you normalize your current data so that the zero-voltage values are all the same. Plots of normalized current versus retarding voltage will then show clearly the effect of photon energy on the cutoff voltage. One significant problem lies in the observation that the current decrease is not linear close to the cutoff voltage. Consider Figure 3 cases A and B for easy visualization.

### V.1. Topics which may come up during oral exams

1. The wave-particle duality of photons and electrons.
2. The potential energy in eV of an electron as a func-

tion of distance from a smooth conducting plane.

3. Classically consider a metal atom ( $d = 0.3$  nm) bathed in radiation of intensity  $1 \text{ mW m}^{-2}$ . How long does it take to accumulate enough energy to overcome  $\phi = 4$  eV? How can you disprove the classical estimate?

## VI. STATISTICAL EXERCISES

1. From your hopefully independent measurements of current  $I$  at each value of the retarding voltage  $V_r$  and frequency, estimate the variance. What does it mean for measurements to be independent?

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- [1] A. Melissinos, *Experiments in Modern Physics* (Academic Press, 1966).  
 [2] P. Baumeister and G. Pincus, *Sci. Am.* **223**, 58 (1970).  
 [3] L. A. DuBridge, *Physical Review* **43**, 727 (1933).

## Appendix A: Equipment

### 1. Equipment List

| Manufacturer | Description          | URL                 |
|--------------|----------------------|---------------------|
| Thermo Oriel | Low-Pressure Hg Lamp | oriel.com           |
| Thermo Oriel | Hg Line Filters      | oriel.com           |
| Thor Labs    | Optical Components   | thorlabs.com        |
| Leybold      | Photocell            | leybold-didactic.de |

### 2. Baking out the anode ring

Potassium can precipitate on the anode ring in very old photo cells in the course of storage at higher ambient temperatures or under illumination of the photocell at very high intensities, making it necessary to bake out the anode ring. **Bake out the anode ring only if the measurement cannot be improved by any other means, as the potassium atoms baked out of the anode ring can precipitate over the entire photocell. When the process is performed improperly, the potassium layer of the photocathode can be overheated, releasing more potassium and can irreparably damage the device!** Please do not attempt this procedure without first consulting a member of the technical staff!

### 3. Ultraviolet Safety

Ultraviolet radiation (UVR) is emitted from low pressure mercury vapor. The mercury vapor emits UVR when an electrical discharge is passed through it. Most of the energy emitted is at a wavelength of 254 nm. This lies in the UVC portion of the spectrum (180–280 nm). In the case of fluorescent lighting, the 254 nm radiation is used to excite a phosphor which coats the inside of the glass envelope of the lamp. The phosphor will re-emit at visible wavelengths (different phosphors produce different colors), and any UVC which is not absorbed by the phosphor will be absorbed by the glass wall of the lamp. However, the mercury discharge will also emit at other wavelengths — notably at 365 nm, which lies in the UVA (315–400 nm). This UVA radiation may not be absorbed by the phosphor, and much of it will pass out through the lamp walls into the environment. For more information on UV radiation, see the [Health Physics Society](http://www.hps.org/hpspublications/articles/uv.html) site at <http://www.hps.org/hpspublications/articles/uv.html>