Corrigendum: ‘Measurement of the ratio $h/e$ with a photomultiplier tube and a set of LEDs’ (Loparco et al 2017 Eur. J. Phys. 38 025208)

D R Lloyd$^1$, F Loparco$^2$, S Rainò$^2$ and P Spinelli$^2$

$^1$ School of Chemistry, Trinity College, Dublin 2, Ireland
$^2$ Dipartimento Interateneo di Fisica ‘M. Merlin’ dell’Università degli Studi e del Politecnico di Bari, I-70126, Bari, Italy

Received 3 February 2018
Accepted for publication 6 March 2018
Published 27 March 2018

This experimental demonstration [1] models Millikan’s original photoemission experiment, where the potential required to reduce the photocurrent at a collector electrode to zero, the ‘stopping potential’, is measured and plotted against the frequency of the light incident on an emitter electrode. In the present case the emitter is the photocathode of a photomultiplier, and the collector is the first dynode. Illumination with various different LEDs provides different light frequencies.

In the original paper it was stated that the slope of the plot allows a measurement of $h/e$, while the intercept measures $W/e$, where $W$ is the work function of the photocathode. The first part of this statement is correct but the second part is not: the relevant work function is actually that of the collector electrode, hereafter $W_{\text{coll}}$. The mistake is widespread in the physics teaching literature, and a number of articles have discussed this point [2–5]. Another discussion [6] appeared at almost the same time as the original paper.

Milikan made clear in his papers that this problem arises because both collector and emitter are in electrical contact via the measuring circuit, so that there is a contact potential difference between the two electrodes, which needs to be taken into account. Perhaps a simpler way of expressing this point is that the collector and emitter each have their own work functions. This is probably most easily demonstrated by drawing out an energy level diagram for the system (see, for example, figure 2 in [5]). In his experiments, Millikan compensated for this effect by using a reference electrode of approximately the same material as his collector, and measuring the difference in contact potential between this reference and the emitter; the plots he shows have been corrected for this difference. However, given that some students have difficulty with the rather abstract concept of contact potential, it may be better to avoid this in initial discussions.

So long as the effect of this difference in work functions (or contact potential) is explained in the laboratory instruction manual, this in no way detracts from the utility of this
experiment as a model of Millikan’s experiment, which gives an approximate determination of $h/e$. Much of the conceptual problem about which work function is measured probably comes from the usual strong emphasis in textbooks on the emitter electrode. A clearer view may come from thinking of the emitter simply as a source of electrons. Referred to the Fermi level of this photocathode, these electrons have a maximum kinetic energy of $h\nu$, as shown in the left-hand column of figure 1. We now concentrate on the process at the collector. Initially, at zero retarding voltage, the Fermi levels of the two metals are equal. The energy of an electron just outside the surface of the collector, with zero kinetic energy, the ‘vacuum level’, is then $W_{\text{coll}}$, the work function of the collector, again referred to the Fermi level, as seen in the second column of figure 1. Under this condition, with the relative energies shown, the vacuum level of the collector is at a lower energy than that of the fastest emitted electrons, so they can travel across the space between the two electrodes and enter the collector. However, as the potential of the collector is raised, both the Fermi level and vacuum level of this electrode move up together; and ultimately there is a cutoff situation, indicated in the third column of figure 1, where electrons can no longer reach this electrode. This occurs when the retarding potential $V_S$ reaches a value such that

$$eV_S + W_{\text{coll}} = h\nu.$$

$V_S$ is therefore a measure of the work function of the collector.

At this point in the explanation it could be appropriate to introduce the idea of contact potential difference as an alternative treatment, since the required diagram is quite similar.

The above argument is due mainly to Prof M G Ramsey at KFU Graz, and we thank him for this, and for the discussions which led to it³. Should students have difficulty in working

---

³ Prof Ramsey notes that there is an additional complication in the German language, where the word for work function, Austrittsarbeit, has a strong suggestion of directionality (‘Exit work’). He suggests, not entirely seriously, that a more appropriate word at the collector would be ‘Eintrittsarbeit’ (‘Entrance work’).
through this argument, it might be of some encouragement for them to know that the wrong answer about work function also appears in Einstein’s 1905 paper (see [5], section 4).

Finally we note that the work function determined in the original paper is surprisingly low, given that the dynodes are made from Cu/Be alloy. It is probably less than 1 eV, though the error limits of the determination of the intercept of the graph do not allow a firm conclusion on this. However it is certainly less than 1.2 eV, the energy of the photons from the red LED, since a noticeable photocurrent from the first dynode is visible in the stopping curve for these photons. This suggests that the surface composition of the first dynode of the photomultiplier may be rather similar to that of the photocathode. This is probably due to small amounts of Cs reaching the dynode during the manufacture of the tube, since a common means of creating such films involves baking an Sb film in Cs vapour [7]. For normal operation of the photomultiplier this would not be a problem.

References

[1] Loparco F, Malagoli Rainò M S and Spinelli P 2017 Measurement of the ratio $h/e$ with a photomultiplier tube and a set of LEDs Eur. J. Phys. 38 025208
[2] James A N 1973 Photoelectric effect, a common fundamental error Phys. Educ. 8 382–4
[3] Rudnick J and Tannhauser D S 1976 Concerning a widespread error in the description of the photoelectric effect Am. J. Phys. 44 796–8
[4] Strnad J 1980 Die Austrittsarbeiten beim Photoeffekt Prax. Naturwissenschaften—Phys. 11 343–4
[5] Lloyd D R 2015 What was measured in Millikan’s study of the photoelectric effect? Am. J. Phys. 83 765–72
[6] Ben-Abu Y 2017 Misleading points in the teaching of Millikan’s experiment on the photoelectric effect Phys. Educ. 52 043006
[7] Garfield B R C and Thumwood R F 1966 Effect of composition on the yield of Cs–Sb photocathodes Br. J. Appl. Phys. 17 1005
Measurement of the ratio $h/e$ with a photomultiplier tube and a set of LEDs

F Loparco$^{1,2}$, M S Malagoli$^1$, S Rainò$^{1,2}$ and P Spinelli$^{1,2}$

$^1$Dipartimento di Interateneo Fisica ‘M. Merlin’ dell’Università degli Studi e del Politecnico di Bari, I-70126, Bari, Italy
$^2$Istituto Nazionale di Fisica Nucleare Sezione di Bari, I-70126, Bari, Italy

E-mail: francesco.loparco@ba.infn.it

Received 15 November 2016, revised 3 January 2017
Accepted for publication 13 January 2017
Published 3 February 2017

Abstract

We propose a laboratory experience aimed at undergraduate physics students to understand the main features of the photoelectric effect and to perform a measurement of the ratio $h/e$, where $h$ is Planck’s constant and $e$ is the electron charge. The experience is based on the method developed by Millikan for his measurements of the photoelectric effect in the years from 1912 to 1915. The experimental setup consists of a photomultiplier tube (PMT) equipped with a voltage divider properly modified to set variable retarding potentials between the photocathode and the first dynode, and a set of LEDs emitting at different wavelengths. The photocathode is illuminated with the various LEDs and, for each wavelength of the incident light, the output anode current is measured as a function of the retarding potential applied between the cathode and the first dynode. From each measurement, a value of the stopping potential for the anode current is derived. Finally, the stopping potentials are plotted as a function of the frequency of the incident light, and a linear fit is performed. The slope and the intercept of the line allow one to respectively evaluate the ratio $h/e$ and the ratio $W/e$, where $W$ is the work function of the photocathode.

Keywords: photoelectric effect, Planck’s constant, photomultiplier tubes

(Some figures may appear in colour only in the online journal)

1. Introduction

Planck’s constant $h$ plays a central role in quantum mechanics. It was first introduced in 1900 by Max Planck in his study on the blackbody radiation [1] as the proportionality constant between the minimal increment of energy of a charged oscillator in a cavity hosting...
blackbody radiation and the frequency of its associated electromagnetic wave. In 1905 Albert Einstein explained the photoelectric effect postulating that luminous energy can be absorbed or emitted only in discrete amounts, called quanta \([2]\). The light quantum behaved as an electrically neutral particle and was called a ‘photon’. The Planck–Einstein relation, \(E = h\nu\), connects the photon energy with its associated wave frequency.

Nowadays, the measurement of Planck’s constant is ordinarily performed by physics students in many educational laboratories, both in universities and in high schools. The most common techniques exploit the blackbody radiation (see [3–7]), the emission of light by LEDs when a forward bias is applied (see [8]) or the photoelectric effect (see [9–13]).

Almost all measurements of \(h\) exploiting the photoelectric effect are based on the principle of the experiment carried out by Millikan in the years from 1912 to 1915 [14]. It is worth pointing out here that, although the title of his 1916 article is ‘A direct photoelectric determination of Planck’s \(h\)’, in his experiment Millikan could not measure \(h\), but he measured the ratio \(h/e\) between Planck’s constant and the electron charge; then, using the value of \(e\) that he had previously measured [15, 16], he was able to evaluate \(h\).

Although the apparatus used by Millikan was rather complex, the method chosen for the measurement of \(h/e\) is quite simple. The detectors basically consisted of a metal surface, which was illuminated with different monochromatic light sources, and a collector electrode, kept at a lower potential with respect to the metal. For each frequency of the incident light, the potential was adjusted until no current flowed through the collector, thus allowing him to evaluate the ‘stopping potential’. It is straightforward to show that the stopping potential increases linearly with the frequency of the incident light, and the slope of the straight line is given by \(h/e\). A linear fit of the stopping potentials at different frequencies therefore allows one to evaluate Planck’s constant if the value of the electric unit charge \(e\) is known.

In the various didactic experiments proposed to measure the ratio \(h/e\) exploiting the photoelectric effect, a variety of devices and light sources are used (see again the examples in [9–13]). In this paper we present a novel didactic experience for measuring \(h/e\) using a photomultiplier tube (PMT) and a set of light emitting diodes (LEDs). We propose this experience to undergraduate physics students attending our introductory laboratory course on quantum physics. PMTs are very common devices in atomic and nuclear physics, and can be easily available in a didactic laboratory. The main advantage of a PMT with respect to a conventional photoelectric cell resides in the fact that photoelectrons extracted at the cathode are considerably amplified (the typical gain is of \(\sim 10^5 \lesssim 10^6\)), thus providing detectable output currents even when a large fraction of them are repelled back to the photocathode. This feature will help in evaluating the stopping potentials, as we will discuss later in section 3. The determination of the stopping potentials is crucial for any measurement of Planck’s constant using the photoelectric effect, and is in general not trivial because the tails of the \(I–V\) curves typically do not vanish rapidly, but can have complex shapes, due to several concurring effects [17].

The paper is organized as follows: in section 2 we describe the instrumentation and the theoretical principles of the measurement; in section 3 we propose a method to analyze the data collected in the experiment; finally in section 4 we discuss the results obtained and some possible strategies to improve the experiment.

\(^{3}\) When discussing his results with sodium, Millikan writes:

‘We may conclude then that the slope of the volt-frequency line for sodium is the mean of 4.124 and 4.131, namely \(4.128 \times 10^{-15}\) which, with my value of \(e\), yields \(h = 6.569 \times 10^{-27}\) erg sec’.
2. Experimental setup

2.1. The photomultiplier tube and the LEDs

PMTs are widely used in many fields of physics to convert an incident flux of light into an electric signal. A PMT is a vacuum tube consisting of a photocathode and an electron multiplier, composed by a set of electrodes called ‘dynodes’ at increasing potentials. Incident light enters into the tube through the photocathode, and the electrons are extracted as a consequence of the photoelectric effect (photoelectrons). Photoelectrons are accelerated by an appropriate electric field towards the first dynode of the multiplier, where a few secondary electrons are extracted. The multiplication process is repeated through all the dynodes, until the electrons ejected from the last dynode are finally collected by the anode, which produces the current signal that can be read out. A PMT can be operated either in pulsed mode or with a continuous light flux.

In our experiment we used a Philips XP 2008 PMT [18]. The photocathode is a thin film (a few nm thick) made of a Sb–Cs alloy deposited over a glass window, and is sensitive to a range of wavelengths that extends from approximately 280 nm to 700 nm. The upper limit of this interval is set by the work function of the metal alloy, while the lower limit is set by the glass of the window, which is opaque to UV photons. The photocathode works in transmission mode, i.e. photoelectrons are collected from the opposite side of incident light. The electron multiplier consists of a set of 10 dynodes, each made of a Be–Cu alloy. Figure 1 shows the electric scheme of the voltage divider used to provide the voltage differences to the dynodes. Unlike a standard PMT voltage divider, here the negative high voltage is supplied to the first dynode (not to the photocathode, which is grounded through the resistor $R_0$), thus ensuring that the photocathode K is kept at a higher voltage with respect to the first dynode Dy1. The voltage difference between the two electrodes can be adjusted by changing the variable resistance $R_1$, and is given by:

$$V_K - V_{Dy1} = \frac{R_1 V_0}{R_0 + R_1} \approx \frac{R_1}{R_0} V_0.$$  (1)

In writing equation (1) we took into account the fact that $R_1 \ll R_0$ (see figure 1). If a high voltage $V_0 = 1000$ V is supplied to the PMT, a maximum voltage difference of 10 V can be applied between K and Dy1. Since $V_K > V_{Dy1}$, photoelectrons extracted from K will be...
slowed down in their motion towards Dy1 and eventually sent back to K. On the other hand, like in standard PMT voltage dividers, the dynodes and the anode are kept at increasing potentials (if $V_0 = 1000$ V, the average voltage differences between each pair of dynodes will be of the order of 100 V). In this way, photoelectrons eventually reaching Dy1 will be multiplied, producing a detectable current signal at the anode $A$, and consequently a voltage difference across the load resistor $R_L$.

To perform our measurements we used five LEDs, emitting visible light of different colors ranging from red to violet. We preliminarily measured their emission spectra using an OCEAN OPTICS HR2000+ spectrometer [19]. Table 1 shows the peak values of the wavelengths and frequencies of each LED. The emission spectra of each LED have been fitted with gaussian functions. The values of the peak wavelengths (frequencies) and the corresponding standard deviations are reported in table 1.

Figure 2 shows the experimental setup. The photocathode window is coupled to a plastic support with a hole drilled at its center where the different LEDs can be inserted. The PMT and the support are wrapped with black tape, to prevent external light entering the device. The hole is also covered with black tape when an LED is inserted to perform a measurement. The LED is connected in series with a low voltage power supply and a current-limiting resistor. The intensity of the light can be controlled by properly setting the voltage supplied to the LED: higher voltages correspond to higher intensities. The voltage differences between $K$ and Dy1 and across the load resistor $R_L$ are measured by two digital multimeters. The knob placed on the left of the PMT is connected to a potentiometer which allows the user to adjust the value of $R_1$ and consequently the voltage $V_{\text{KDy1}}$. The high voltage is supplied to the PMT by means of a CAEN N471A NIM power supply module [20] (not shown in the figure).

### Table 1. Main features of the emission spectra of the LEDs used in the measurement.
The wavelength and frequency spectra $(dN/d\nu \propto (1/\nu^2)dN/d\lambda)$ have been fitted with gaussian functions. Here we report the mean values and, in brackets, the standard deviations of each fit function.

| LED   | Peak wavelength (nm) | Peak frequency ($10^{14}$ Hz) |
|-------|----------------------|-------------------------------|
| Red   | 631(17)              | 4.75(0.13)                    |
| Yellow| 585(15)              | 5.11(0.13)                    |
| Green | 563(12)              | 5.32(0.11)                    |
| Blue  | 472(14)              | 6.34(0.18)                    |
| Violet| 403(6)               | 7.42(0.08)                    |

2.2. Data taking procedure

Students should investigate the dependence of the voltage difference $V_L$ across the load resistor on the retarding potential $V_K = V_K - V_{\text{Dy1}}$ for the various LEDs. The value of $V_L$ is proportional to the anode current and consequently to the rate of photoelectrons collected by Dy1. During a measurement, the voltage across the LED must be kept constant, thus ensuring that the intensity of the light entering the PMT is also constant.

Photoelectrons extracted from the photocathode will have different initial kinetic energies up to a maximum value given by:

$$E_{K,\text{max}} = h\nu - W$$  \hspace{1cm} (2)

where $h\nu$ is the energy of incident photons and $W$ is the work function of the photocathode. If $V_K = 0$, all the photoelectrons extracted from $K$ will be able to reach Dy1, and a current will
flow through $R_L$. If $V_R$ is increased, only the more energetic photoelectrons will be collected by Dy1 and therefore the output current will decrease. When $eV_R \geq E_{K,max}$ the photoelectrons will not be allowed to reach Dy1 and the current flowing through $R_L$ is expected to vanish. The value

$$V_S = \frac{E_{K,max}}{e} = \frac{h\nu - W}{e}$$

represents the stopping potential, that depends on the energy of incident photons and on the work function of the photocathode.
From the plots of $V_L$ as a function of $V_S$ (hereafter we will refer to these plots as ‘photoelectric curves’), the students will be able to evaluate the stopping potential $V_S$ for each LED. The values of $V_S$ will then be plotted against the frequency $\nu$ of the incident light, and

![Figure 3. Examples of photoelectric curves obtained with the various LEDs. The continuous red and green lines represent the fits of the regions $V_{RS} < V_S$ and $V_{RS} > V_S$ with the two functions in equation (4). The values of the fitted parameters and of the $\chi^2$ are shown in the top right panels of each plot, with the same color code. The dashed lines are obtained by extrapolating the two fit functions outside the corresponding fit regions. A black star is drawn at the intersection point between the two fit functions. The abscissa of the intersection point provides the estimate of the stopping potential. A zoom of the region where the stopping potential is found is shown in the inset of each plot.](image)
the data will be fitted with a straight line. According to equation (3), the value of \(h/e\) will be derived from the slope of the line, while the value of \(W/e\) will be derived from the intercept.\(^4\)

3. Data analysis

3.1. Photoelectric curves

Figure 3 shows some examples of photoelectric curves obtained when the PMT is illuminated with the various LEDs. As expected, the value of \(V_L\) decreases with increasing \(V_R\), but never drops to zero. This behavior can be explained by taking into account that a fraction of the incident photons can pass through the photocathode without interacting, and can extract photoelectrons from the first dynode. These electrons are accelerated towards Dy2, thus contributing to the output signal because of the high PMT gain. Hence, even when \(V_R > V_S\), a background current will flow through the load resistor \(R_L\), and consequently a steady positive value of \(V_L\) will be measured. The fraction of photons extracting photoelectrons from the first dynode changes with the photon energy, as the absorption probabilities in the photocathode and in the first dynode are strongly dependent on the photon energy. Another possible contribution to the background anode current could be due to ambient light entering the device, but we ruled out this contribution by performing a preliminary set of measurements where the LEDs are turned off, in which we observed \(V_L = 0\) for any value of \(V_R\). Finally, it is also worth pointing out here that the electron optics of a PMT is designed for electrodes kept at increasing potentials. Therefore electrons emitted from the photocathode are accelerated towards the first dynode and are focused onto its center regardless their emission angle, thus ensuring optimal collection efficiency. Setting in our device a retarding potential between K and Dy1, we introduce a distortion in the electron optics of the PMT, which affects the trajectories of photoelectrons preventing them from reaching the first dynode. However, even when \(V_R > V_S\), some photoelectrons travelling in weaker field regions might be able to reach the first dynode, contributing to the output signal.

We performed several sets of measurements, changing either the high voltage \(V_0\) supplied to the PMT or the intensity of the light emitted by the various LEDs. An increase of \(V_0\) will result in an increase of the gain of the electron multiplier, while an increase of the light intensity will result in an increase of the number of photoelectrons. In particular, we observe that, if the light intensity is kept constant and \(V_0\) is changed, the shape of the photoelectric curves does not change, but the values of \(V_L\) corresponding to a given \(V_R\) increase with increasing \(V_0\). Similarly, if \(V_0\) is kept constant and the light intensity is changed, the shape of the photoelectric curves does not change, but the values of \(V_L\) increase with increasing light intensity. This behavior is observed for a wide range of high voltages (\(V_0 \sim 700 \div 1100\) V) and LED intensities (here the range depends on the color of the LEDs). However, if the voltage across the load resistor becomes too large (\(V_L \gtrsim 1\) V), saturation effects might occur due to the large number of electrons moving across the last dynodes because the capacitors in the last stages of the voltage divider could not be able to keep the voltage differences stable.

Another feature of the photoelectric curves shown in figure 3 is that the transition between the regime in which photoelectrons emitted from K are collected by Dy1 and the regime in which photoelectrons are repelled is not sharp, i.e. the slope of the photoelectric curve changes smoothly with \(V_R\), thus meaning that the determination of \(V_S\) is not straightforward. This behavior is due to the spread in the photoelectron kinetic energies when they

\(^4\) The intercept corresponds to the ratio \(W/e\) with a change of sign. If voltages are measured in units of V, the value of \(W/e\) will also be in units of V, and will correspond to the value of \(W\) in units of eV.
are emitted from the photocathode. It is also worth pointing out here that, since photons emitted by LEDs are not monochromatic (as shown in table 1 the widths of the frequency spectra are $\sim 2 \div 3\%$ of the corresponding peak values), the photoelectric curves cannot be described in terms of a single value of the stopping potential, but it would be more appropriate to take into account the dependence of the stopping potential on the frequency. Hereafter we will neglect this dependence and we will assume that each photoelectric curve can be described in terms of the stopping potential $V_S$ corresponding to the peak frequency of the LED.

3.2. Evaluation of the stopping potentials

The determination of either an analytical or a numerical model of the photoelectric curves would be rather complex and perhaps would go beyond the scope of an introductory laboratory course for undergraduate students. Therefore, to analyze the data collected by the students carrying out the experiment, we developed a phenomenological approach. After the analysis of many photoelectric curves obtained in different conditions (different LED intensities and different PMT high voltages), we noticed that the asymptotic behavior of all photoelectric curves can be adequately described by the following functions:

$$V_k = \begin{cases} a_1 + b_1 e^{-\frac{V_k}{\mu}} & \text{for } V_k < V_S \\ a_2 + b_2 V_k & \text{for } V_k > V_S \end{cases}$$

For each photoelectric curve we select two sets of points, belonging to the regions $V_k < V_S$ and $V_k > V_S$, and we fit these points with the functions in equation (4), thus determining the parameters $a_1$, $b_1$, $c_1$, $a_2$ and $b_2$. The fits are performed using the free data analysis software ROOT [21], provided by CERN. We then define the value of the stopping potential $V_S$ as the abscissa of the intersection point of the two curves, which can be evaluated solving the following non-linear equation:

$$a_1 + b_1 e^{-\frac{V_S}{\mu}} = a_2 + b_2 V_S$$

The previous equation, which gives $V_S$ as a function of the parameters $a_1$, $b_1$, $c_1$, $a_2$ and $b_2$, cannot be solved analytically, but can be easily solved in a numerical way, for instance using the bisection method. This procedure is graphically illustrated in the plots of figure 3, where we superimposed on each photoelectric curve the functions obtained from the two fits, also showing the position of the intersection between the two curves. As we anticipated in section 1, it is worth pointing out here that the detection of a significant steady background current instead of a slowly vanishing current helps to better define the stopping potential.

To evaluate the error on $V_S$ we use the standard error propagation formula, starting from the errors on $a_1$, $b_1$, $c_1$, $a_2$ and $b_2$, which are computed by the ROOT software when performing the fits. However, since $V_S$ is an implicit function of the parameters, a numerical approach is also needed to evaluate its partial derivatives with respect to the various parameters. For instance, to evaluate the partial derivative $\partial V_S / \partial a_1$, we start from the set of fitted parameters and we change $a_1$ into $a_1' = a_1 + \delta a_1$; then we solve equation (5) with the value of $a_1'$, obtaining a new solution $V_S'$ and finally we evaluate the partial derivative as $\partial V_S / \partial a_1 \approx \delta V_S / \delta a_1$, where $\delta V_S = V_S' - V_S$. In the same way we calculate the partial derivatives of $V_S$ with respect to the other parameters.

According to the definition of derivative, the condition $\delta a_1 \to 0$ must be fulfilled, and therefore one must choose $\delta a_1$ such that $|\delta a_1| < |a_1|$.
3.3. Evaluation of the ratio $h/e$ and of the work function

The procedure used to evaluate $h/e$ from the measured stopping potentials is illustrated in figure 4, where the stopping potentials obtained from the analysis of the photoelectric curves shown in figure 3 are plotted against the frequency of the incident light. The error bars associated with the LED frequencies are the widths of their emission spectra, which are taken from table 1, while those associated with the stopping potentials are calculated following the approach described above. A linear fit of the experimental points is then performed. In the example shown in figure 4, the fit procedure yields a $\chi^2/n\,\text{d.f.} = 0.037/3$, which indicates that the error bars associated with the stopping potentials are probably overestimated, a feature which might be a consequence of the phenomenological model that we adopted to describe the photoelectric curves. According to equation (3), the slope of the line corresponds to $h/e$, while its intercept corresponds to $W/e$. Assuming for the electron charge the current value $e = 1.60 \times 10^{-19}$ C, the fit of the data shown in figure 4 yields for Planck’s constant a value $h = (6.75 \pm 1.11) \times 10^{-34}$ Js and for the work function of the photocathode a value $W = (0.78 \pm 0.43)$ eV.

4. Discussion and conclusions

The measurement of $h/e$ proposed in the present paper yields an uncertainty of about 20% on the value of $h/e$ and an uncertainty larger than 50% on $W/e$. The main sources of error are the spreads on the LED frequencies and the uncertainties in the values of the stopping potentials. To mitigate the effects of the frequency spreads, one could use monochromatic light sources coupling the LEDs to appropriate filters, or even using laser sources. The uncertainties in the stopping potentials could also be reduced with a more appropriate modeling of the photoelectric curves, which goes beyond the scope of an introductory laboratory course.

Despite the poor precision attained, we strongly believe that this measurement of $h/e$ is extremely useful from the educational point of view, because not only does it allow students...
to understand the main features of the photoelectric effect, but it also stimulates further considerations about the physics involved in the measurement and the technique adopted.

**References**

[1] Planck M 1901 On the distribution law of energy in the normal spectrum *Annal. Phys. IV* 7 553–63

[2] Einstein A 1905 On a heuristic point of view about the creation and conversion of light *Am. Phys.* 17 132–48

[3] George S *et al* 1972 Planck’s constant from Wien’s displacement law *Am. J. Phys.* 40 621

[4] Manikopoulos C N and Aquirre J F 1977 Determination of the blackbody radiation constant hc/k in the modern physics laboratory *Am. J. Phys.* 45 576

[5] Crandall R E and Delord J F 1983 Minimal apparatus for determination of Planck’s constant *Am. J. Phys.* 51 90

[6] Dryzek J and Ruebenbauer K 1992 Planck’s constant determination from blackbody radiation *Am. J. Phys.* 60 251

[7] Brizuela G and Juan A 1996 Planck’s constant determination using a light bulb *Am. J. Phys.* 64 819

[8] Nieves L *et al* 1997 Measuring the Planck constant with LED’s *Phys. Teach.* 35 108

[9] O’Leary A J 1946 Two elementary experiments to demonstrate the photoelectric law and measure the Planck constant *Am. J. Phys.* 14 245

[10] Hall H and Tuttle R P 1971 Photoelectric effect and Planck’s constant in the introductory laboratory *Am. J. Phys.* 39 50

[11] Bobst R L and Karlow E A 1985 A direct potential measurement in the photoelectric effect experiment *Am. J. Phys.* 53 911

[12] Dean Barnett J and Stokes H T 1988 Improved student laboratory on the measurement of Planck’s constant using the photoelectric effect *Am. J. Phys.* 56 86

[13] Garver W P 2006 The photoelectric effect using LEDs as light sources *Phys. Teach.* 44 272

[14] Millikan R A 1916 A direct photoelectric determination of Planck’s h *Phys. Rev.* 7 355–88

[15] Millikan R A 1911 The isolation of an ion, a precision measurement of its charge, and the correction of Stokes’s law *Phys. Rev. (Ser. I)* 32 349–97

[16] Millikan R A 1913 On the elementary electrical charge and the Avogadro constant *Phys. Rev.* 2 109–43

[17] Keesing R G 1981 The measurement of Planck’s constant using the visible photoelectric effect *Eur. J. Phys.* 2 139–49

[18] Philips Photomultipliers: Data Handbook, PC04 (1990)

[19] http://oceanoptics.com/wp-content/uploads/hr2000-.pdf

[20] http://caen.it/site/CaenProd.jsp?parent=21&idmod=240

[21] https://root.cern.ch/

See also Brun R and Rademakers F 1997 ROOT—an object oriented data analysis framework *Nucl. Inst. Meth. Phys. Res.* A 389 81–6