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Improved student laboratory on the measurement of Planck's constant using the photoelectric effect

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$= 29.8$ km/s), and $v_s =$ escape speed from Earth's orbit ($\sqrt{2GM_s/r_e} = \sqrt{2}v_0 = 42.1$ km/s). ($R_e =$ Earth's radius; $r_e =$ Earth's orbit radius.) Putting in the numerical values, this gives

$$v(\varphi) = (2785 - 2509 \sin \varphi)^{1/2} \text{ km/s}.$$

For $\varphi = +90°$ (launching along the direction of the Earth's motion), this gives $v = 16.6$ km/s (Hendel *et al.*); for $\varphi = 0$ (radially away from the sun) we have 52.8 km/s (the Menon–Agrawal result); and for $\varphi = -90°$ we get 72.8 km/s.[6] This spectrum of values has an interesting connection with the inverse problem of the arrival at the Earth of meteoroids from outer space. A large body of observational data[7] shows that the arrival speeds range from about 10 to 70 km/s, with a mean of about 40 km/s, very much as one would expect from the above calculations if the meteoroids are assumed to start with small velocities at very large distances from the Earth.

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[1] V. J. Menon and D. C. Agrawal, Am. J. Phys. **54**, 752 (1986).

[2] A. Z. Hendel and Michael J. Longo, Am. J. Phys. **56**, 82 (1988).

[3] A. Z. Hendel, Am. J. Phys. **51**, 746 (1983).

[4] A. Díaz-Jiménez, Am. J. Phys. **51**, 749 (1983).

[5] *Handbook of Astronautics*, edited by N. Ya. Kondrat'ev and V. A. Odintsov (Israel Program for Scientific Translations, Jerusalem, 1968). [Originally published as *Spravochnik po kosmonavtike* (Voennoe Izdatel'stvo Ministerstva Oborony SSSR, Moscow, 1966).]

[6] Note that, to get the direction of launch relative to the Earth, one must take account of the Earth's orbital motion, so that $\varphi = 0$ corresponds (as Hendel and Longo point out) to a launch angle of 124°, not 90°, with respect to the Earth's forward velocity.

[7] D. W. R. McKinley, *Meteor Science and Engineering* (McGraw-Hill, New York, 1961), pp. 135–137.

Improved student laboratory on the measurement of Planck's constant using the photoelectric effect

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Recently, Bobst and Karlow[1] described a remarkably simple method for measuring the photoelectric effect. We built the apparatus they described and implemented it in a student laboratory. However, we implemented some improvements, which we report in this note.

Basically, the approach described by Bobst and Karlow is to measure the potential between the emitter and collector of a phototube directly, using a high-input-impedance device shorted with a small integrating capacitor. As in the conventional approach, various bandpass filters are placed in front of a mercury-arc lamp to pick up dominant spectral lines present. This method provides four different wavelengths of light: 577.0, 564.1, 435.8, and 404.7 nm. Bobst and Karlow also report a photopotential for the unfiltered light and assign an ultraviolet frequency associated with the limiting frequency transmitted by the glass envelope of the phototube. We discarded this point as being unreliable.

In Fig. 1, we plot the potential versus frequency data for the four well-known wavelengths as reported by Bobst and Karlow[1] (the circles) along with a straight line obtained by a least-squares fit to these four points from their data. The slope of the line yields $h = 7.9 \times 10^{-34}$ J s for Planck's constant. (The accepted value for Planck's constant is $h = 6.626 \times 10^{-34}$ J s.) In initial testing, we obtained values that were consistently below the accepted value.

When using this high-impedance voltmeter technique, errors result mainly from three phenomena: (a) the inherent residual leakage across the tube itself, through the preamp, or across the integrating capacitor; (b) small reverse photocurrent caused by light impinging on the collector; or (c) small amounts of light of higher frequency than the desired monochromatic light striking the emitter. The effects of (a) are reduced as the monochromatic-light intensity on the emitter is increased and as the leakage resistances are increased. The effects of (b) are diminished by making the collector out of a metal with a high work function (as commercial phototubes are made) and minimizing the amount of light allowed to strike the collector. The effects of (c) are reduced by the use of narrow-band filters and the effective elimination of stray light both from the mercury light source and from the room.

To address these problems, the following precautions were taken and/or improvements were made (many of which were discussed by Bobst and Karlow, but we restate them for emphasis):

(1) We used a high-leakage-resistance capacitor ($C = 10^{-10}$ F, $R > 10^{13}$ Ω).

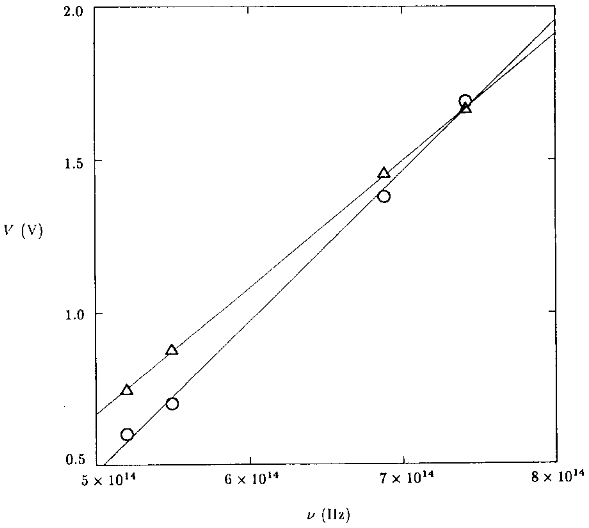

Fig. 1. Potential V across the phototube as a function of the frequency ν of the light. The circles are from Bobst and Karlow (Ref. 1), and the triangles are from a typical data set from one of our students. The straight lines are least-squares fits to the data.

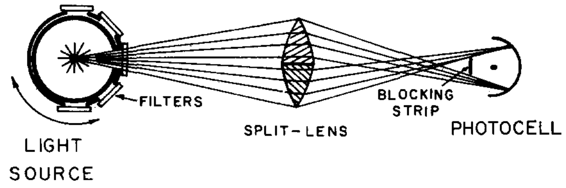

Fig. 2. Essential features of the light-gathering system illustrating the filter mounting and the split lens for focusing two images on the emitter of the phototube.

(2) We carefully cleaned pertinent electrical terminals and elements and mounted them such that students could not touch and contaminate them.

(3) We used an air-cooled, high-intensity, high-pressure Hg arc lamp (with small concentrated arc).

(4) We used narrow-band interference filters ($\approx$10-nm half-width).

(5) We mounted filters on a cover over the light source in such a way that by rotating the cover, students could easily change wavelength and still require all emitted light to pass through the filter (see Fig. 2).

(6) We focused the monochromatic light onto the phototube emitter using a "split lens." This split lens produced two focal spots, one on each side of the collector, and facilitated the elimination of light from the collector while optimizing the light intensity on the emitter. A "blocking strip" was still placed in front of the collector to further reduce this light level. The only light striking the collector in this configuration was that reflected from the emitter surface itself. The split lens was made by cutting a single lens along a diameter, removing a central region and remounting the two side pieces in contact with each other (see Fig. 2).

(7) We purchased a new GE 1P39 phototube. We compared h values measured using several tubes that had seen many years of use in student labs with a new tube when all other experimental parameters remained the same. Each older tube yielded a unique but consistently lower value of h relative to the new tube which gave excellent results. We attribute this condition to contamination with age of the high-work-function collector surface with material from the emitter.

(8) We installed a shorting switch across the capacitor to allow students to move from wavelength to wavelength in any desired order.

(9) We provided a close-fitting shield that covered the photocell and the split lens while measurements were being made, but could be easily removed for inspection of the detailed construction. This configuration allowed students to work in ambiant room light.

With these improvements, a typical student measurement is shown in Fig. 1 (the triangles). The slope of the line yields $h = 6.658 \times 10^{-34}$ J s, which is within 0.5% of the accepted value. This is a considerable improvement over the results of Bobst and Karlow.

This experiment was set up as a "walk-in" laboratory for an introductory physics course serving over 200 individual students. The equipment was made available for a week, during which time each student, at his own convenience, was required to "walk in" and do the experiment. The measurement of the four voltages for the specific wavelengths could be made in 10–15 min. During the first semester of operation, we analyzed the numerical results of the students by computer. We found that the scatter in their respective voltage measurements was 1% about the mean value of each of the four voltages. The students analyzed their own data using a graphical method. Most of them were able to obtain Planck's constant also to within approximately 1% of the accepted value. Computer fitting of the data obtained by each individual student yielded values of h with significantly less scatter. This result indicates the apparatus yields data that justifies computer fitting rather than graphical analysis.

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[1] R. L. Bobst and E. A. Karlow, Am. J. Phys. 53, 911 (1985).

Note on "Evaluating the effectiveness of an elementary undergraduate laboratory" [Am. J. Phys. 54, 702 (1986)]

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In his interesting discussion on undergraduate laboratories,[1] Buckmaster appears to have stated a problem in his Example that is too unstructured to be solved by students using slope-intercept methods. His example of graphing for analysis the cumulative amount of gas purchased (V) versus the odometer reading (x) did not assume that the car's gas tank was filled at each gas purchase, and the students who made this assumption were stated to be incorrect.