Planck's constant determination using a light bulb

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I. INTRODUCTION

Black-body radiation is a familiar phenomenon even though the name may seem mysterious. When the heating element of an electric stove is turned on, it emits radiation. This radiation can be detected by placing one's hand at some distance above the heating element. As the power is increased, the stove element will begin to glow first red, then white, and at higher temperatures even blue. This change in color is evidence that the frequency distribution of the radiation emitted by the hot body changes with temperature.

Although there are many methods available to determine the Planck's constant[1–4] the procedure presented here is easier to implement than earlier reported ones. Moreover, the cost of the required apparatus is modest since a commercially available 40 W–220 V clear glass lamp with a coil shaped tungsten filament is used as the light source.

It was assumed in the experiment that the electrical power dissipated by the filament was emitted entirely as radiation and that the filament was a perfect black body. A digital multimeter was used to measure the voltage and current of the light bulb filament whereas the emitted light intensity was determined with a phototransistor at a fixed frequency ν. Actually, the light intensity was measured over a narrow range of frequencies since a filter was employed. A cardboard tube was used to keep stray room light from reaching the phototransistor.

II. THEORY

Planck's law gives the intensity of radiation I at a single frequency ν as[5]

$$I(\nu,T)=\rho(\nu,T)dV=\frac{8\pi h}{c^3}\frac{\nu^3}{e^{h\nu/kT}-1} \tag{1}$$

where c is the speed of light, k is the Boltzmann constant, T is the absolute temperature of the emitter, and h is the Planck's constant.

The intensity ratio, measured at the same frequency and at two different temperatures T_1 and T_2, is expressed as follows:

$$\frac{I_1(T_1)}{I_2(T_2)}=\frac{e^{h\nu/kT_2}-1}{e^{h\nu/kT_1}-1}. \tag{2}$$

When $h\nu \gg kT$, then $\exp(h\nu/kT)\gg 1$, so Eq. (2) can be now expressed as follows:

$$\frac{I_1(T_1)}{I_2(T_2)}\approx\frac{e^{h\nu/kT_2}}{e^{h\nu/kT_1}}. \tag{3}$$

The approximate formula (3) holds for the visible range of frequencies ν and for the filament temperatures used in this experiment (up to 2500 K). In order to use relationship (3), it is necessary to select a narrow and well known range of frequencies, to measure the absolute temperature and to determine the intensity of radiation. It would be helpful to use a relationship between R and T to avoid direct filament temperature measurements. This relationship may be achieved by the laboratory student empirically. The student should make voltage V_i and current I_i measurements of the light bulb. Then the filament resistance R and power dissipation P can be easily calculated. The following discussion will clarify the procedure.

For a black-body the emitted power P is given by Stefan's law:[5]

$$P=A\sigma T^4 \tag{4}$$

where σ is known as the Stefan's constant and A is the surface area of the emitter. Assuming a power law $T\propto R^{\gamma}$, the power dissipation P can be written as

$$P=I^2R=A\sigma T^4=\text{const } R^{4\gamma}, \tag{5}$$

then the empirical $R-T$ relation is given by

$$T=\left(\frac{R}{R_0}\right)^{\gamma}T_0 \tag{6}$$

where R_0 is the resistance of the bulb filament at temperature T_0 and γ is a power to be determined from a log plot of Eq. (5). The fact that such logarithmic plot does indeed yield a straight line provides the justification for the assumption of a power-law relationship between T and R.

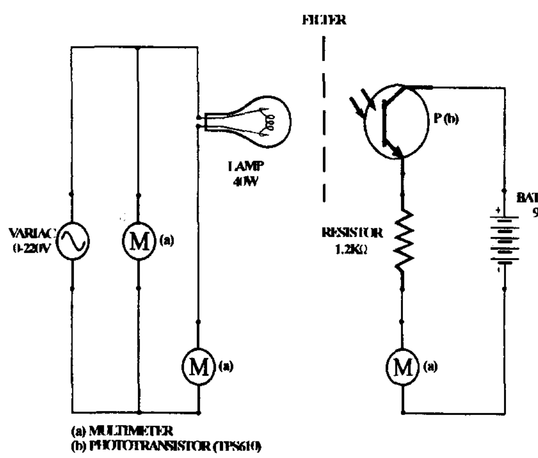

Fig. 1. Experimental setup and electric circuit.

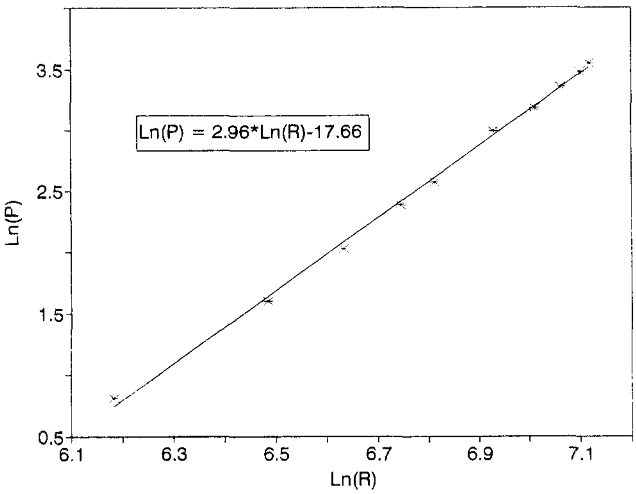

Fig. 2. Graph of $\ln P$ (total power) against $\ln R$; γ=0.741.

Table I. Experimental data and calculated resistance, power, and temperature.

		$(R_0=197\ \Omega;T_0=473\ \mathrm{K})$			
V (Volt)	I (A)	$R=V/I$ (Ω)	$P=I^2R$ (Watt)	T(K)	I (photocurrent, mA)
33	0.068	485	2.24	922	0.0019
57	0.087	655	4.96	1150	0.0565
76	0.100	760	7.60	1286	0.2420
96	0.113	850	10.85	1396	0.6980
109	0.120	908	13.08	1468	1.2050
143	0.140	1021	20.02	1601	3.1151
164	0.148	1108	24.27	1701	4.6501
183	0.157	1166	28.73	1767	6.0094
198	0.164	1209	32.47	1814	6.7502
207	0.168	1232	34.78	1840	6.8503

III. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. A commercially available incandescent lamp (40 W) is used as a source of "blackbody" radiation. Any single color filter is suitable for the purpose of selecting a frequency in the UV–V range from $4.232\times10^{14}\ \mathrm{s}^{-1}$ to $3.747\times10^{14}\ \mathrm{s}^{1}$. Though it is not the best filter available, the red cellophane film used in the experiment has a modest cost. This filter is interposed in order to have the phototransistor irradiated essentially by one "fixed" frequency ν (the numerical value used in the calculations was $3.990\times10^{14}\ \mathrm{s}^{-1}$).

A simple electrical setup, which includes an autotransformer, is used for voltage variations. As the ac voltage increases the filament resistance R and temperature T also increase. Relationship 6 is used to calculate the temperature. T_0=473 K is selected to measure R_0 by heating the light bulb in an electrical furnace until thermal equilibrium is reached. The empirical power γ can be determined from a linear regression fit to the logarithmic $P-R$ plot, whose slope is equal to 4γ (see Fig. 2).

The last quantity to be measured is the emitted light intensity coming from the incandescent lamp. Instead of darkening the laboratory room, a blackened-inside cardboard tube is used to setup the light bulb and the intensity detector in order to avoid any other source of radiation. As shown in Fig. 3 a bulb socket is fixed at one of the ends while a circle of cellophane is glued at the other. A similar tube with an attached phototransistor is fixed by its free end to the previous setup. Any object with similar shape could also be used, e.g., an aerosol tube and its caps or a plastic bottle.

The resulting light intensity that reaches the phototransistor generates a photocurrent that is measured with a digital multimeter as a voltage drop across the resistor (1.2 kΩ).

An appropriate polarization voltage (9 V) is applied to the phototransistor to assure different intensities for a given pair of illumination powers. The applied dc voltage depends on the characteristic $V-I$ of the phototransistor used. The sequences of photocurrent measurements are then repeated for a second setting of lamp voltage which in turn results in another filament temperature.

IV. RESULTS AND DISCUSSION

Typical experimental data and calculated resistance, power and temperature are summarized in Table I.

Planck's constant can be obtained with any pair of temperatures and the associated pair of photocurrents by apply-

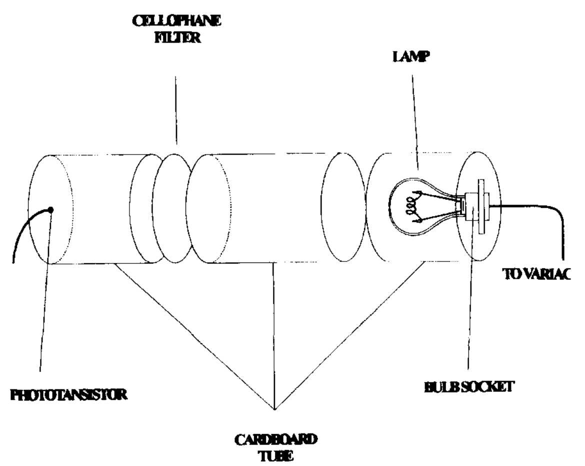

Fig. 3. Apparatus scheme.

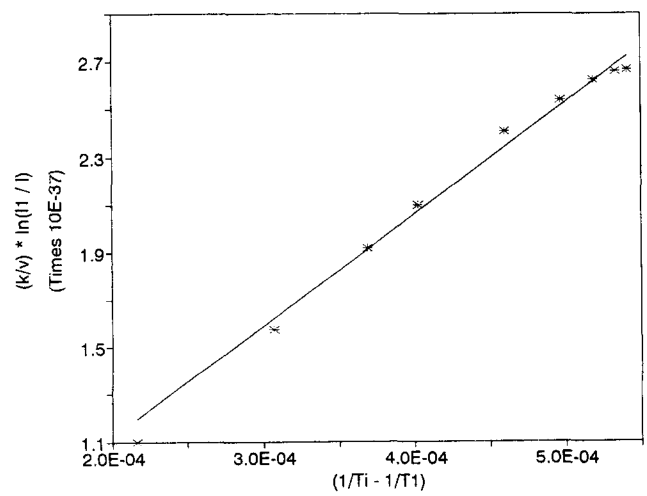

Fig. 4. Equation (3) plotting with a linear fit.

ing Eq. (3). As an alternative, the first temperature T_1 and the corresponding photocurrent I_i can be taken as a reference. Then the quantity $(k/\nu)\ln(I_1/I_i)$ is plotted vs $(1/T_i - 1/T_1)$, as shown in Fig. 4. *A linear regression fit to the data* is used to determine $h = 4.71 \times 10^{-34}$ Js from the slope with a standard error of coefficient of 1.8×10^{-35} J s. Any other temperature taken as a reference will bring a similar value for h in the range $(4.7\text{–}6.0) \times 10^{-34}$ J s.

The value obtained for Planck's constant is reasonably close to the accepted value, within an accuracy of 17%. Some of the sources of this discrepancy are the ignored convection loss corrections for glass filled lamps, some heat energy that heats up the glass itself, and the fact that a light filament is not a perfect black body. At large $(1/T_i - 1/T_1)$, the plotted points vary from linearity because a saturation photocurrent appears in the phototransistor at higher filament temperatures.

The original method proposed by Crandall and Delord[3] has the disadvantage of requiring filament area calculation. On the other hand, a rather cumbersome method has been proposed by Dryzek and Ruebenbauer,[4] in which an optical pyrometer is used to determine a calibration curve for the filament resistance dependence upon temperature.

The procedure presented here is less accurate than the one reported by Dryzek and Ruebenbauer, but it is more adequate for reproduction in the laboratory.

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OVEREMPHASIS ON PREDICTION

That again is a sign of a certain attitude to physics, which says that the essential point about physics is to predict something. Why do you want to predict? You would think that there is a predictive instinct which must be satisfied. But this is obviously not the case. The reason why people want to predict is just to confirm that their ideas are on the right track. I am trying to say that in some cases you cannot predict; some things are ambiguous.

Trying to see the weakness of a theory in a traditional way is inadequate. The traditional scientific method is to say: wait until your experiments clearly show that you are wrong. But if you are going along with confused methods, no experiment will clearly show that you are wrong, because you can always modify your theory. This has often been done.

We must look at it differently, realizing that there is something wrong, which the present theory does not have in it, which requires understanding, namely, there is an actual individual event—the decay of the radioactive nucleus—which is simply not accounted for in the present theory. We must put in new concepts to account for it, and see what happens, even if we can't use them to predict anything more at the moment. I think that there is an overemphasis on prediction, on getting results, which is stifling physics. Many people don't fully and deeply realize that there *is* something missing. They are so used to doing statistical calculations, and saying that only statistics matters, that they do not notice that there is an actual, individual fact which is not accounted for.

David Joseph Bohm, in *A Question of Physics: Conversations in Physics and Biology*, conducted by Paul Buckley and F. David Peat (Routledge and Kegan Paul, London 1979), p. 148.