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Smartphone experiments to study the radiation of a black body in a remote laboratory

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Summary. — In this article we present an experimental setup consisting of a smartphone and a simple home kit to study the law of thermal radiation of an incandescent light bulb. The measurement of the filament temperature is obtained indirectly from the temperature dependency of the resistivity. The light sensor of the smartphone is used to measure light intensity. By analysing the graph of the dependence of light intensity on the inverse of temperature, in the limit of the Wien approximation of the Planck distribution, it is possible to obtain an estimation of the spectral response of the sensor or, alternatively, if this is known, an estimation of Planck's constant.

1. – Introduction

Blackbody radiation is an important topic commonly taught in undergraduate university courses and also, with some simplifications, at high schools. Often, only a theoretical treatment of the subject is given [1, 2]. In this article we present a method based on smartphone sensors and a low-cost kit useful for a high school physics laboratory [3].

The kit, designed to remotely carry out experimental activities during the pandemic, contains several items (for a description of the kit, see the article by Caprara *et al.* in this issue) including those needed for the experiment described here: a commercial filament lamp, a universal power adapter, some resistors, and two multimeters. On smartphones, we used the light sensor, which is one of the most common components. In recent years, smartphone sensors have been used to propose a variety of scientific activities; among these, the light sensor is one of the most flexible applications and can be used to make measurements not only in the field of optics [4, 5], but also in the field of mechanics [6].

In the first part of the activity we worked on the classic experiment of the Stefan-Boltzmann law. The temperature of the filament of the incandescent lamp can be estimated by measuring voltage and current through the filament and using the data tables of resistivity as a function of temperature. At first this setup makes it possible to analyse how the absorbed power, calculated from the voltage and current measurements, depends on temperature and thus makes it possible to verify the validity of the Stefan-Boltzmann law. In the second part of the activity, by using the ambient light sensor of the smartphone it is possible to measure the illuminance emitted by the lamp and by working in the Wien approximation regime, we can study how the illuminance varies as the temperature changes. The activities were proposed to undergraduate students and are tailored to be carried out at home. Given the affordability of the kit, the activities can also be adapted for high school students. The students' understanding of this topic was explored with some test questions (selected from the Concept Inventories on Electricity and Magnetism [7]) before the activities took place during the laboratory course. It was found, in a particular question, and in line with what is known in the PER literature, that students, even those that would answer the other items relatively well, would tend not to consider that the resistance of a light bulb connected in series to a power supply would change if the potential difference increases.

2. – Experimental setup and theory

The experimental apparatus and the circuit diagram of the experiment is shown in fig. 1 (left and center). Two digital multimeters are involved, one to measure the potential difference V across the incandescent bulb and the other used as the ammeter to measure current I through the bulb. Usually, in a lab setting, a desktop AC/DC power supply is utilised. In this home experiment, we used a very cheap power supply with only a few voltages available (with nominal output voltages of 3/4, 5/6/7, 5/9/12 V). A resistor is placed on a breadboard in series with the lamp in order to obtain different voltages. To measure the intensity of the light emitted, a smartphone light sensor has been used through applications like Phyphox or Physics Toolbox [8, 9]. The application displays the value of illuminance, a photometry quantity, defined as luminous flux per unit area, measured in lux (with a sensibility of about 1 lux).

Briefly recalling Planck's energy distribution, power, $W(\lambda, T)$, emitted at the wavelength λ per unit surface and per unit wavelength is given by the equation

$$W(\lambda, T) = \frac{(2\pi\ hc^2)}{\lambda^5} \frac{1}{e^{(hc/kT\lambda)} - 1}, \tag{1}$$

where h is Planck's constant, k is Boltzmann's constant and c is the speed of light in vacuum. In the limit of $\lambda \ll\ hc/kT$, from eq. (1) with a few passages we get Wien's approximation: $W(\lambda, T)\mathrm{d}\lambda = (2\pi\ hc^2)/(\lambda^5\ e^{hc/kT\lambda})\ \mathrm{d}\lambda$. This approximation is well satisfied in our experiment, being the filament temperature equal to about 3000 K, and the sensor's detected wavelength being $\lambda \ll\ hc/kT \approx 4800$ nm. Based on the reasoning illustrated by Monteiro in [10] light intensity J_S measured by the light sensor of the smartphone can be approximated as:

$$J_S \approx \int_{\lambda_L}^{+\lambda_U} W(\lambda, T)\mathrm{d}\lambda, \tag{2}$$

where λ_L and λ_U are the lower and upper limits of the spectral response of the used light sensor. Applying the mean value theorem of the Calculus [3] one can come to the following relationship:

$$J_S \approx Ae^{C/T} \tag{3}$$

with $C = -hc/k\lambda_0$. By graphing the logarithm of J_S as a function of temperature, the value of the coefficient C can be estimated. This value of C, assuming the other parameters of the formula are known, leads to an estimation of the average wavelength

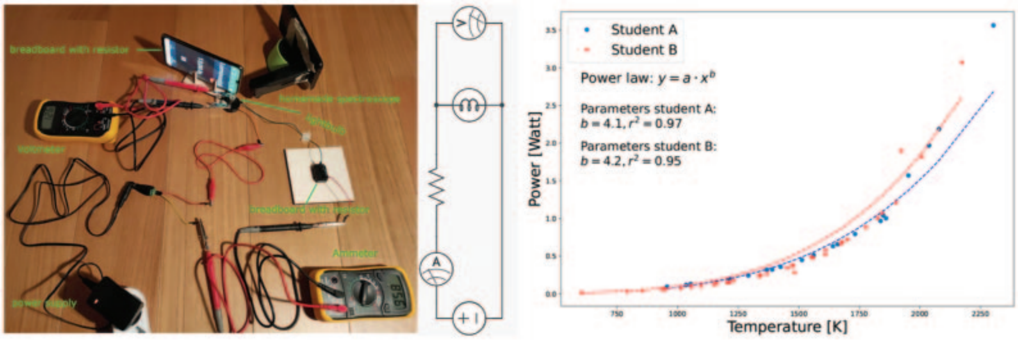

Fig. 1. – Left: experimental apparatus; Center: circuit diagram; Right: electric power as a function of T. The fit with a power law is shown in good agreement with the Stefan-Boltzmann law.

λ_0 of the light sensor. The spectral response of the ambient sensor of the smartphones used goes from about 350 nm to 1100 nm, thus including a part of the infrared region (the sensitivity of the human eye has a much narrower wavelength range, approximately from 400 nm to 700 nm). From the graph of the spectral response, it is possible to estimate an average spectral response λ_0 for the corresponding light sensor.

3. – Measurements and results

From the data tables [11] it is possible to derive a phenomenological relationship linking the temperature of the tungsten filament to the measured resistance: $T(R) \approx 295(R/R_{ref})^{0.83}$ K where R_{ref} is the resistance of the lamp at room temperature (about 295 K). By measuring V and I, students can get the electric power and plot it as a function of T. By applying a power law fit a good agreement is obtained with the Stephan-Boltzmann law (fig. 1, right) [12, 13]. The Wien approximation of the Planck law described above allows connecting the measured illuminance to the temperature of the filament. By applying a linear fit, it is possible to obtain the estimation of the parameter C from which λ_0 can be obtained, in good agreement with the spectral responses of the smartphone used. The following figure shows the data of two students, each performing the experiment during the distance learning laboratory course. The students managed, with trial and error, to achieve consistent results. The parameter C corresponds to the slope of the lines of best fit in fig. 2. We can thus obtain an estimate of λ_0 and its uncertainty for the two experimental set-ups: Student A: $\lambda_0 = (620 \pm 50)$

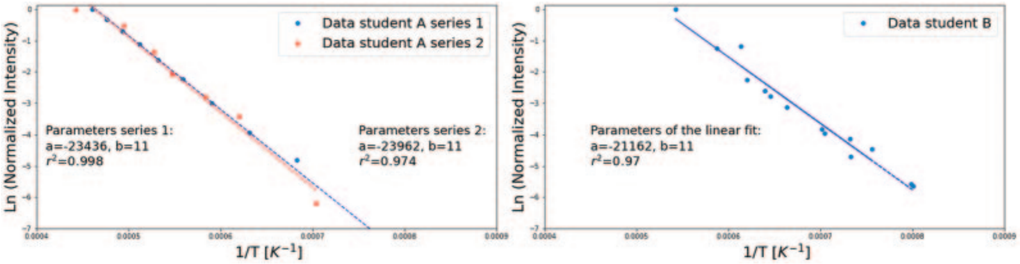

Fig. 2. – Logarithm of light intensity measured with the light sensor as a function of the reciprocal of temperature. Two sets of data are shown acquired from student A (left) and one set from student B (right).

nm; Student B: $\lambda_0 = (680 \pm 40)$ nm. It should be noted that the two estimates are not strictly comparable because the light sensors of the two smartphones did not have the same spectral response. The good agreement with the specifications of the sensors used is a confirmation of the correctness of the method. Another method applied by the students to measure the intensity of light was the use of a homemade grating spectrometer coupled to the smartphone camera and the video analysis tool. For a comparison of the two methods, see [3].

4. – Conclusions

We discussed an experiment useful to analyse the thermal radiation law which can be made at home with easily available materials and the ambient light sensor of a smartphone. The commitment required of students is not trivial and its implementation requires the development of useful experimental skills and inventiveness. Estimating the temperature of the bulb filament through the phenomenological relationship between temperature and resistance, it is therefore possible to verify the agreement with the Stefan-Boltzmann law. From the graph of the dependence of light intensity on the inverse of temperature, in the limit of the Wien approximation, it is possible to obtain an estimate with a good agreement of the spectral response of the sensor. Therefore, alternatively, if λ_0 is reliably known, it can be used as a method for estimating Planck's constant.

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