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Colours in your pocket: smartphone-based spectrometers to investigate the quantum world

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Colours in your pocket: smartphone-based spectrometers to investigate the quantum world

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Abstract. We designed a low cost spectrometer to be used by groups of students with an inquiry approach. This simple equipment allows to investigate the additive and subtractive models of colour formation, to study the selective absorption of a material and explain it from a microscopic point of view. The home made apparatus was used in several experiments showing the quantum nature of the absorption and production of light with the aim of bridging optics and modern physics.

1 Introduction

One of the aims of the recent researches carried out by the Physics Education Research Groups at the Physics Departments of the Universities of Pavia and Trento (Italy) is to design and test approaches and materials for introducing basic concepts of modern physics. In our approach, some experimental activities play a central role. Since these activities are mainly focused on optics and specifically on spectroscopy [1-8], we designed and tested low-cost spectrometers to be assembled and used by high school and undergraduate students.
The simple equipment was tested with high school and undergraduate students in the context of activity sequences bridging optics and modern physics.

Initially our spectrometers were used to study light transmission, both to investigate the additive and subtractive models of colour formation and to study the selective absorption of a material.
Then, aiming at bridging optics and modern physics the simple equipment assembled by students was used by groups of students with an inquiry approach in several experiments showing the quantum nature of the absorption and production of light.
In particular students compared the spectrum of light emitted by an incandescent bulb (continuous spectrum) and the discrete spectrum emitted by a fluorescent lamp. The comparison highlights the different mechanisms underlying light emission.
Students can also measure the wavelengths of visible lines of Balmer series, the ones of colored LEDs and the fluorescent emission spectrum of commercial materials.

2 Description of the apparatus

A first kind of spectrophotometer (see Figure 1) is based on the use of diffraction gratings and a smartphone [1-4]. Such spectrometer can be assembled by the students very quickly (about one hour) using inexpensive materials (black cardboard) allowing measuring wavelength and light intensity with good accuracy. A slit is opened at one end of a collimating tube, resulting in a narrow beam of light entering the tube. A low-cost transmission grating is placed on the opposite side and disperses the beam of light into spectral lines with different colours at different angles.
The tube, in combination with the slit, acts to ensure that the camera lens on the smartphone focus only approximately collimated light. After a simple calibration procedure [4], the spectrophotometers can be used

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to obtain quantitative measurements of spectra from different sources, thus allowing exploration of the physical mechanisms governing light emission.

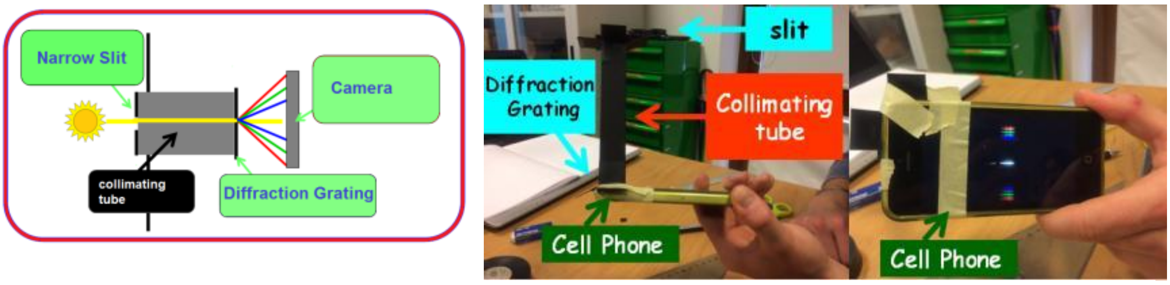

Figure 1 The experimental apparatus first proposed in ref. [1]

The second kind of spectrophotometer [10] employs the ambient light sensor of a smartphone and usual commercial low intensity LEDs with different peaks' wavelengths. We assembled the apparatus using two lenses to increase the light arriving on the sensor. This addition allows the employment of usual commercial low intensity LEDs.

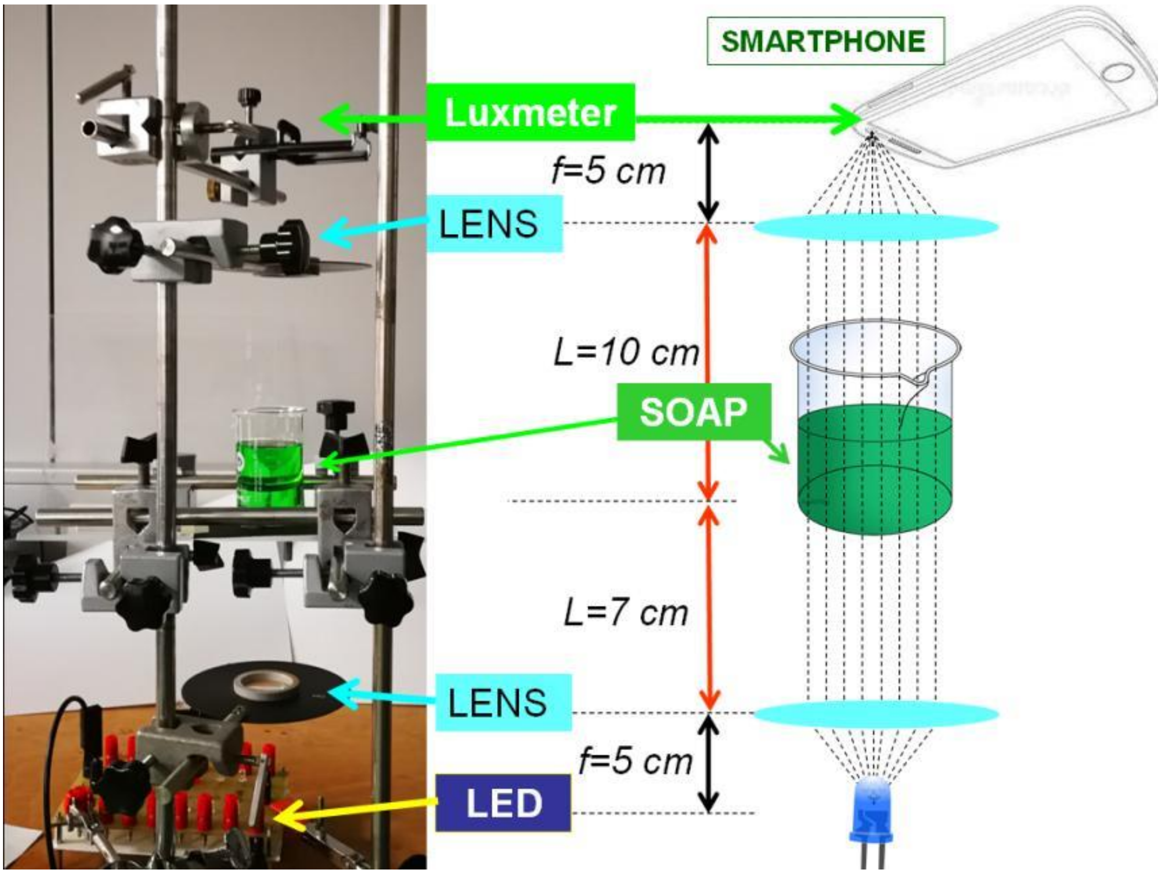

Figure 2 The experimental apparatus first proposed in ref. [10]

Figure 2 shows how the apparatus was assembled with a Plexiglas sheet, black cardboard, and a small beaker. The light emitted by the LED is collimated by the first lens, then it goes through the liquid contained in the beaker. A square window with a width of approximately 2 cm was opened in the black cardboard placed on the bottom of the beaker. The transmitted light is then focalized by the second lens on the smartphone ambient light sensor. Light intensity is finally obtained by using an app, Physics Toolbox,

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devoted to data extraction, calibration, storage and condivision. Thus the setup allows students to investigate the wavelength dependence of transmission and is very suitable to analyse the absorption spectrum of different samples, and in particular liquid ones.

3 Studying colours

The spectrophotometers were used by students to study light transmission with two different aims:

- to investigate the additive and subtractive models of colour formation
- to study the selective absorption of a material

Regarding the first point, the spectra of RGB colours emitted from a LCD screen and the transmission spectra of CMY pigments of a laser printer have been studied [4]. Knowledge of spectra is needed for a conceptual understanding of colours perception. In fact, some basic concepts such as the spectral composition of light, its intensity, the partial transmission/absorption/diffusion by a pigment, are essential to reconcile typical school knowledge about colours (additive/subtractive mixing mechanisms) and observation of daily life phenomena [4,5].
The typical spectra of RGB colour emitted from an LCD screen are reported in Figure 3 where the photos are compared with the luminance versus wavelength measured using the spectrometer.

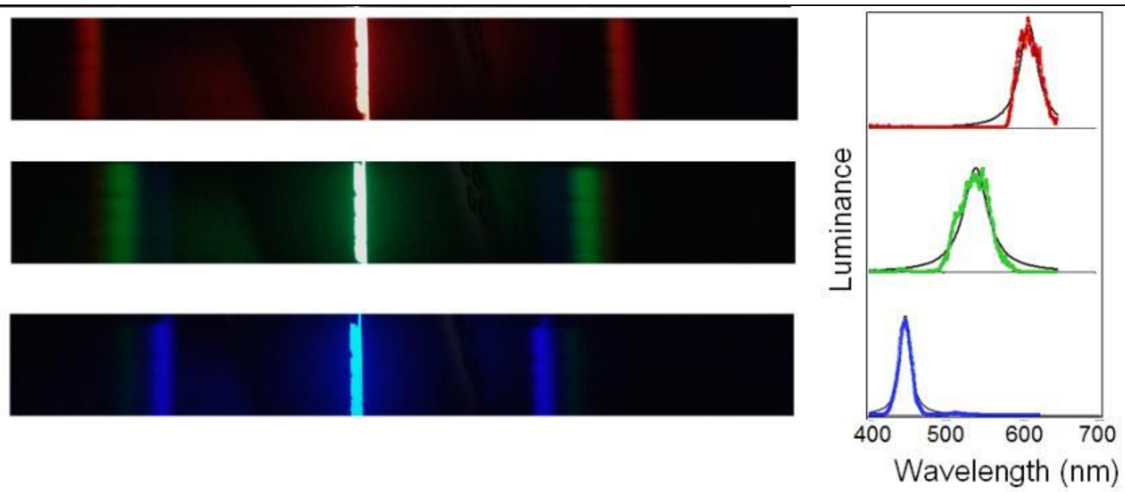

Figure 3 The luminance of photoemission measured with the spectrometer of Figure 1 for the different colours on the monitor. (Left) Collage of the acquired photos used for the measurements. Strips R, G, B come from photos of the spectra when the screen produces definite colours. (Right) The measured luminance versus wavelength is reported in arbitrary units.

The spectrometer can be used also to analyse the subtractive model [4]. In order to detect light transmission by ink pigments of a laser printer, coloured strips were printed on white paper, which is placed on top of the collimating slit, and sunlight is used as the source. We noted that when light passes through the coloured strips some colours disappear and a reduced transmission band is evident: the yellow pigment will absorb blue and transmit red and green, magenta pigment will absorb green, the green pigment will absorb blue and so on.
The selective absorption/transmission of wavelengths is the basic block of the subtractive colour model, which explains how the mixing of a limited set of pigments creates a wider range of colours.
However, the selective absorption of a material is a really relevant effect to be considered also in designing teaching/learning sequences about many other different topics such as the greenhouse effect (i.e. selective absorption/transparency – molecules absorbing radiation over a particular range of wavelengths only).
In ref. [10] we presented how the equipment in Figure 2 can be employed as spectroscope by using LEDs of different colours. In Figure 4 the transmittance versus wavelength is reported for a green liquid soap for three different thicknesses.

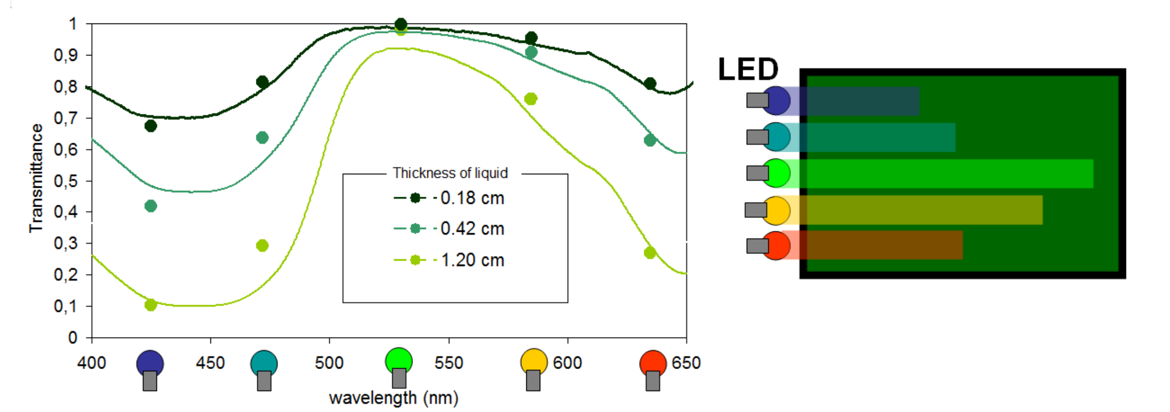

Figure 4. Absorption spectra of green soap in the visible light region. The solid lines are processed starting from data obtained with AvaSpec-2048™, a commercial spectrophotometer. Solid circles are transmittance values obtained from the measurements with our apparatus for the five LEDs used in the experiment.

4 Emission spectra

The analysis of spectra emitted by different light sources (incandescent bulb, fluorescent lamp, gas lamps) helps students understand the different physical mechanisms that govern the production of light. A deep and quantitative analysis of the spectra stimulates a discussion that involves the quantum nature of things, e.g.:

- The spectrum of an incandescent bulb measured at different temperature shows the typical features of the blackbody emission [8] see Figure 5.
- The spectrum of fluorescent lamp highlights the two mechanisms underlying light emission, the de-excitation of gaseous Hg atoms and the fluorescent emission of the lamp's coating [1], see Figure 5.

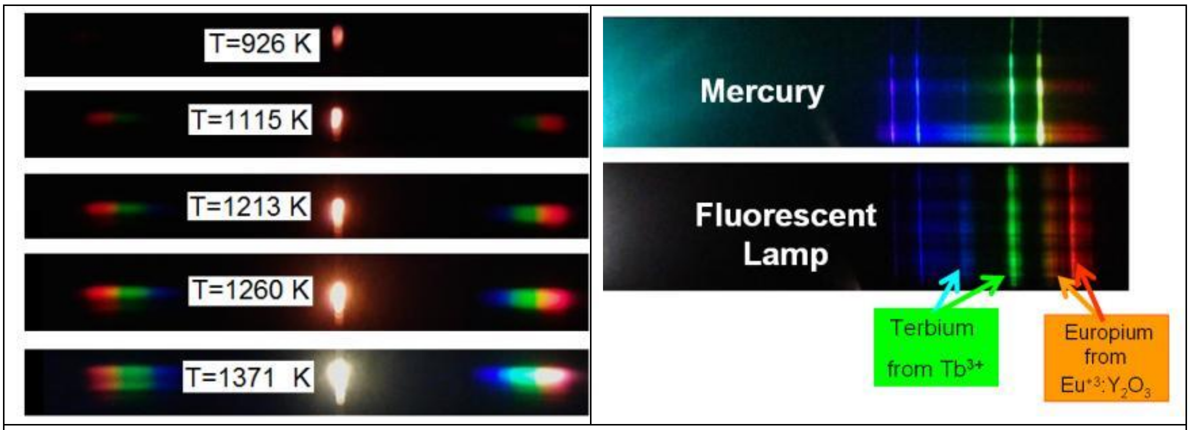

Figure 5 (Left) Photos of continuous spectra of tungsten light bulb at different temperatures (Right) Comparison between the spectra of a commercial fluorescent lamp and a spectral Mercury lamp, showing the effects of the coating materials which emit fluorescent light.

- The fluorescent emission spectrum of commercial ink highlights the quantum nature of light emission and allows a discussion about elastic and inelastic scattering of photons on materials [3,8].
- The wavelengths of visible lines of Balmer series can be measured, and the obtained values allow to estimate the value of Rydberg's constant with an error difference of few tenths [2,7,8].

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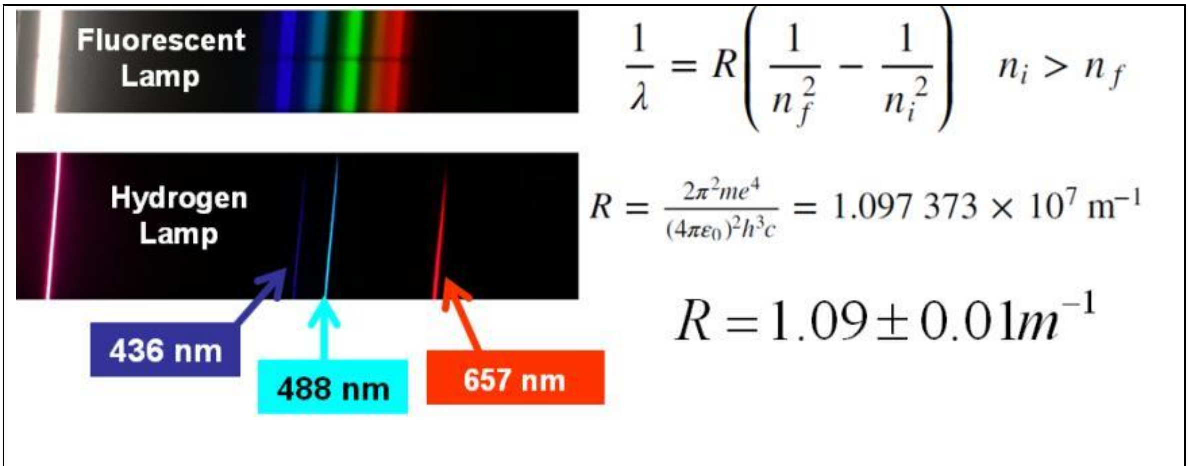

Figure 6. Spectrum lines (red, cyan and blue) clearly visible in the photographs obtained using a transmission grating. The spectra are compared with that of the fluorescent lamp used for calibration. From the measured values of the wavelengths we can estimate the experimental value of Rydberg's constant. The percentage difference of this value from the accepted one is less than 1%.

5 Planck constant

The home-made spectroscope was also employed to evaluate the wavelength of the light emitted by diodes of various colours in measurement of the Planck's constant. During this activity, usually combined with measurements of photoelectric effect, students estimated the ratio *h/e* using the emission wavelengths and the "turn on" voltages of LEDs. [8]

The latest experimental activity, introductory to modern physics, has been carried out for two consecutive years at the University of Pavia with final year students from science-intensive high school (Liceo Scientifico). According to our data, the activity may help students gain a better understanding of the Planck-Einstein relationship, and improve their ability to distinguish the respective roles of the frequency and intensity of light. The activity, based on LEDs and the photoelectric effect, heavily brings into play as a prerequisite students' knowledge of the structure of the electromagnetic spectrum, in particular the visible band and its bordering zones. Both the direct experience of the researchers, based on discussion with students, and quantitative data, from a test given to students at the end of the activity, reveal that students' knowledge is largely insufficient in this area.

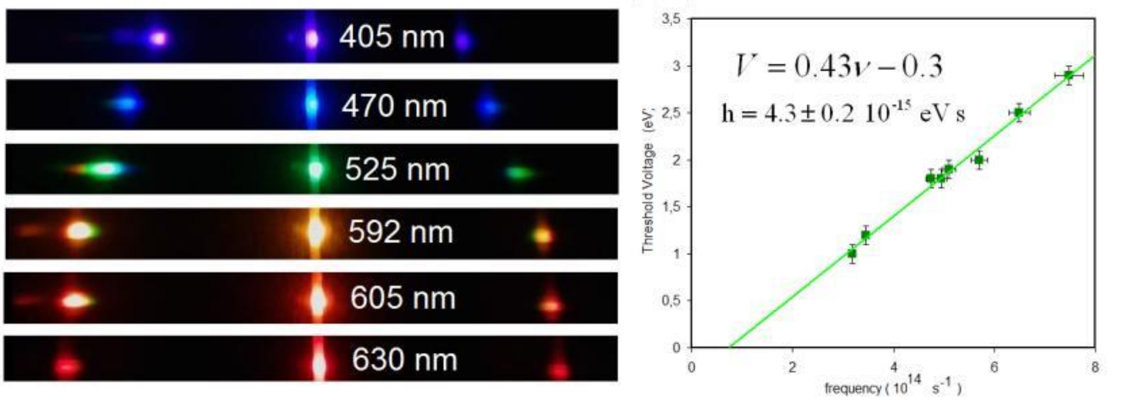

Figure 7 Spectrum of 6 LEDs with different wavelengths. (Right) Threshold voltage versus frequency plot enables us to estimate the Plank constant.

6 Conclusions

We have described home-made apparatuses which provide a simple way to perform quantitative measurement of the frequency and energy properties of light. Their use has been tested with high school students, undergraduates and with student teachers in a postgraduate course for physics teacher education. Our results testify a deep satisfaction of students, who were able to discuss relevant topics in physics and to carry out significant measurements and analysis of their data.

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