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Low cost experimental proposals to bridge from classical to modern physics

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Abstract. Simple experiments with diffraction gratings allow us to build a bridge between classical and modern physics. A LED, a diffraction grating and a screen are sufficient to measure the wavelength of the light emitted by the LED. The energy E of the emitted photon is inversely proportional to wavelength of the light λ , $E = hc/\lambda$, where h is Planck's constant. By a simple multimeter and a volt-ampere connection we can obtain the characteristics voltage-current curves of the LED. The threshold voltages of LEDs of different colours are easily measurable. When the LED emits light, we can assume that the electron of the current circulating in the LED when the voltage U transfers its energy eU to the photon and we can derive the Planck's constant by the relationship $h = \lambda eU/c$. The students of the Quadri Lyceum of Vicenza have successfully tested such an activity within a course on electrical conduction. With the data for the red LED the students obtain $h = 6 \cdot 10^{-34}$ Js. Now, by means of a CD-ROM we build a simple device to carry out the same measurement in reflection modality. The use of a simple and economic spectroscope enriches the experimental proposal in the perspective to build a path bridging from classical to modern physics. The intervention module based on this kind of lab in modern physics summer school for secondary students allows us to analyze its role in learning.

1. Introduction

Simple and quantitative experiments are important didactic activities that contribute to the learning process in two ways (Viennot *et al.* 2014) concerning:

- the specific contents;
- the methodological aspects regarding physics as a discipline (Holbrook & Rannikmae 2007).

These experiments give an even more significant contribution if they concern modern physics topics, employing high-tech devices, nowadays of common use: in this perspective, LEDs represent a unique context to develop lots of proposal (Planinšič & Etkina 2014). With this cheap and common piece of equipment, it is possible to treat, at different levels, various problems concerning electrical conductivity in solids, as well as the ones concerning physical optics or spectroscopy. In particular, optical spectroscopy represents a bridge between classical and modern physics, and it has been recently subject of research as concern learning processes (Ivanjek *et al.* 2015a, 2015b). Moreover, the study of optoelectronic properties of LEDs represents a fertile link with material physics, that student can directly deal with. These potentialities have been tested in a pilot proposal conducted in 2015 by professors G. Fera & D. Merlin, that inspired a new laboratory-based proposal, used as a didactical intervention in 2016.



2. The pilot proposal and the basis of our proposal

The pilot proposal and the learning results

A teaching intervention module on electrical conductivity in solids was carried out in 2015 at Lyceum Quadri of Vicenza (IT) with students aged 18-19 by means of IBL strategy to correlate macro quantities (U-I-R) with microscopic processes by means of Drude's model. An experimental problem solving was used to face the interpretative problem of the emission of light by a LED to bridge from classical to quantum model (energy bands). Characteristics curves U-I are measured for different LEDs (Fig. 1) in order to correlate the threshold voltage U to the frequency ν or the wavelength λ of the emitted light, measured with the apparatus described in Fig. 2.

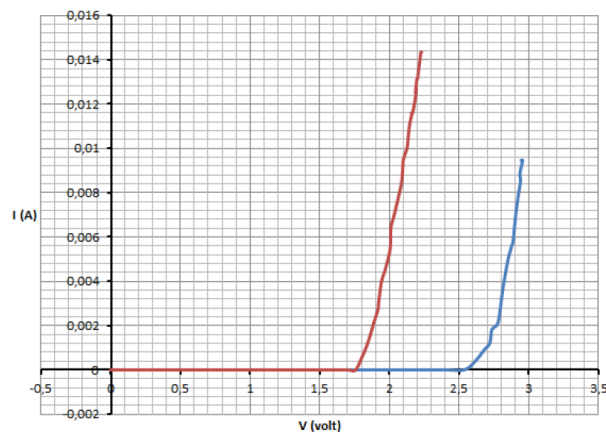


Fig. 1. U-I characteristics of a red and a blue LED

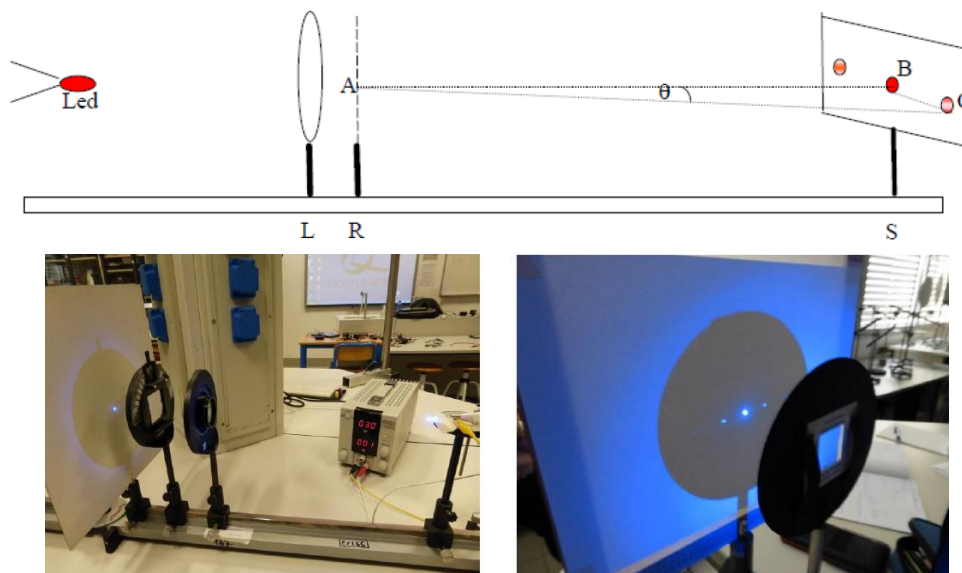


Fig. 2. Measurement of wavelength: experimental setup. L is the lens, used to make the light collimated, R is the diffraction grating, and S the screen

Data obtained according to the table 1 allow an evaluation of the Planck's constant h .

Table 1. Data acquired by students in order to evaluate Planck's constant h

θ (rad)	d (μm)	$\lambda = d \sin\theta$ (μm)	$\nu = c/\lambda$ (s^{-1})	U (V)	$E = eU$ (eV)	$h = eU\lambda/c$ (Js)
0.38	1.75	0.65	$4.62 \cdot 10^{14}$	1.75	1.75	$6.07 \cdot 10^{-34}$

The monitoring of students' reasoning evidenced the following aspects:

- Drude's model is no more valid for the interpretation of the emission of a LED (10/11) because: LED is a semiconductor (7/11); there are no metallic bonds (2/11); LED is not a metal (1/11);
- Activation energy is correlated to the color of the LED (6/11); in order to produce a current, electrons have to overcome a limit (1/11);
- The activation energy is inversely proportional to the wavelength (3/11);
- The relation between energy and frequency of the emitted light is supposed to be a direct proportionality (5/11).

Our experimental proposal: basis and research questions

Two main needs emerged from this experience:

- To simplify the apparatus to offer each student the opportunity to carry out a personal analysis of the phenomenon;
- To focus on the relationship between energy levels interpretative model and the emitted spectra of a source.

For the first need we developed the two experimental apparatuses (see next section). The former make use of a CD to carry out the measurement in reflection modality, the latter make use of a cheap diffraction grating and a ruler. In both cases the images are virtual. No lenses are needed. For the second goal we used the second version during a summer school (see section 4). Research questions were:

- RQ1: How does experimental activity contribute in identifying: the specific spectral characteristics, the role of a diffraction grating, the relationships between diffracted spectra and energy model of the emitting systems?
- RQ2: Which are the operative and conceptual difficulties encountered by students in the proposed activity?
- RQ3: How do students sketch and compare the energy structure of a gas-discharge lamp (used in another experiment) and of a LED correlating them to the emitted spectra?

3. Experimental proposals

Proposal 1: CD in reflection modality

A CD works as a reflection grating. Placing a light source above its surface (Fig. 3) allows to see the first-order maximum (Fig. 4). In a simplified model (Fig. 5) the angle θ can be determined by geometric measures, and thus $\lambda = d \sin\theta$ ($d = 1.67 \mu\text{m}$ for CDs). A potentiometer varies the voltage on the LED; when the LED starts emitting light, it is possible to measure its threshold voltage by means of a voltmeter (Fig. 3). Data concerning red and green LEDs are summarized in table 2.

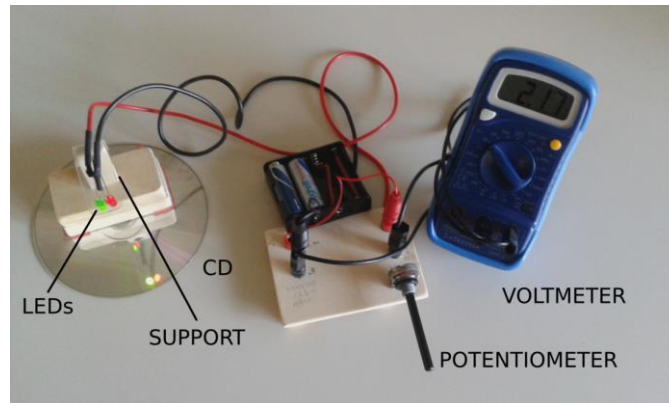


Fig. 3. The prototype used to measure λ of LEDs by means of a CD

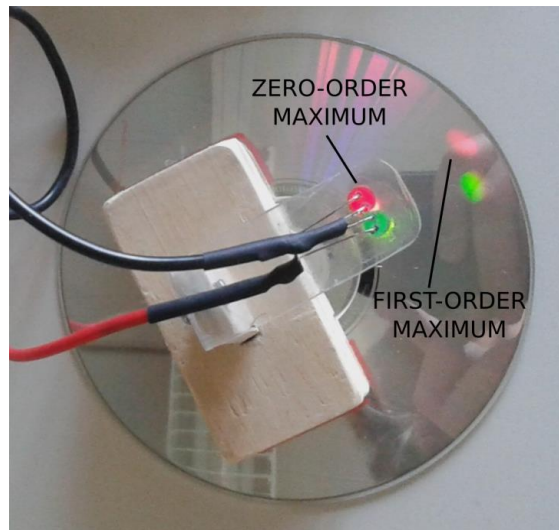


Fig. 4. The CD seen from above

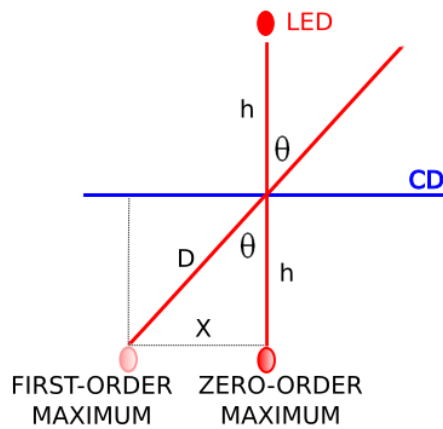


Fig. 5. Oversimplified geometric model for measuring θ

Table 2. Red and green LEDs: evaluation of λ using a CD and simple geometric measurements⁷

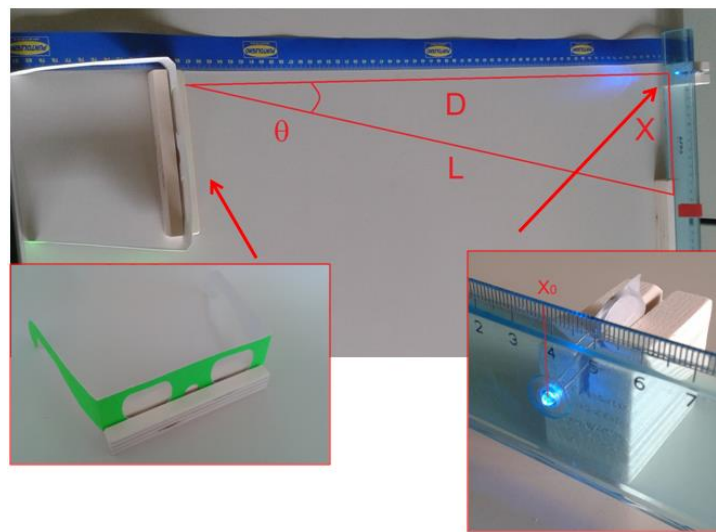
colour	h (cm)	u(h) (cm)	X (cm)	u(X) (cm)	$D = \sqrt{X^2 + h^2}$ (cm)	u(D) (cm)	$\sin\theta = X/D$	u(sin θ)	$\lambda = d \sin\theta$ (nm)
Red	7.000	0.058	2.800	0.058	7.500	0.058	0.3733	0.0082	653 ± 29
Green	7.000	0.058	2.300	0.058	7.400	0.058	0.3108	0.0082	544 ± 29

Proposal 2: grating and ruler

The setup in Fig. 6 allows students to measure the dominant wavelength emitted by a LED in transmission modality. Looking through cheap rainbow-glasses, used as a diffraction grating, it is possible to see the spectrum of a LED along a ruler. Simple geometric measures allow to obtain the angle θ of the emission peak and thus its wavelength (Figs 6, 7). The implementation of this kind of setup in a didactical proposal is described in the next section.

4. The proposal for the summer school 2016 in Udine

In the 2016 Summer School in Modern Physics at University of Udine (IT) for 32 selected talented secondary school students, two experiments about spectroscopy have been proposed. In the first experiment, students measure wavelengths of a discharge lamp through an optical goniometer, in the second experiment, students see and measure the spectrum of a LED using setup presented in Fig. 6 Learning processes were monitored by means of test-in, test-out, tutorials and interviews. Here we report a case study carried out by means of detailed analysis of the experimental reports written by 4 students and the results coming from two questions from the test-out submitted to the whole group of students.

**Fig. 6.** The low-cost apparatus: with rainbow glasses and a ruler it is possible to see and measure the spectrum of a LED

⁷ The combined standard uncertainties $u_c(y)$ of the measurement results y have been evaluated using the formula $u_c(y) = \sqrt{\sum_i \left(\frac{\partial y}{\partial x_i} \cdot u(x_i) \right)^2}$ (the law of propagation of standard uncertainties) where $y(x_i)$ is the evaluated (dependent) quantity and $u(x_i)$ is the standard uncertainty of the measured (independent) variable x_i . The uncertainty of λ is the expanded uncertainty.

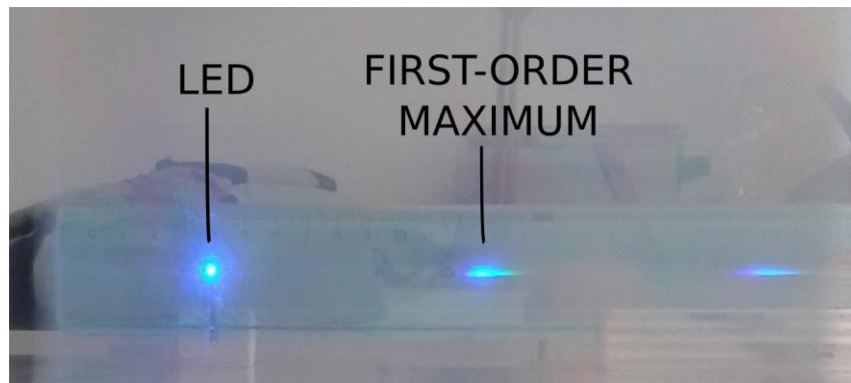


Fig. 7. The grating of the rainbow-glasses allows to see the virtual image of the spectrum of the LED along the ruler

The case study on the lab activity

We analyzed the detailed reports of 4 students concerning this low-cost experiment. We provided them a synthetic sheet for the experimental procedure. Students structured independently the reports in the following sections: introduction, goal, theoretical aspects, material used, procedure, data, discussion and conclusions.

Main learning outcomes

- The energy of the emitted radiation (3 students) is associated to the observed peak (2) or the measured wavelength (1) with specification concerning the energy changes in the emitting system (3) and relative energy level model (1);
- Non-perfect monochromatic nature of the light emitted from a LED (4): the spectrum of a LED consists of a main peak superimposed on a sort of continuum (3), white light spectrum (2) or waves and colors associated (1);
- Intensity decreases with the order, so that the first order is the brightest (2);
- The diffraction grating splits the light (2) in the different wavelength (1);
- Even with simple materials it is possible to obtain reliable measurements of wavelength (3).

Explicit operative difficulties pointed out

- To sight the exact position of the first-order peak;
- To measure the exact LED-grating distance;
- To quantify the uncertainty in measuring λ .

General conclusions: conceptual limits

- The way in which spectral features allow to find the energy levels of the emitting system;
- The way in which students look at the experiment, remaining on observational/operative plans;
- The lack of analysis and argumentations in using formal relationships;
- The relationships between light wave model, energy and colors observed and/or the role of the different components of the apparatus.

Post-test questions submitted to the whole group of students

We analyzed the answers given by 32 students to the following two post-test questions:

- Q1) Compare the emission spectra of a LED and a gas-discharge lamp, pointing out similarities and differences.
- Q2) Make an hypothesis on the energetic structure of the LED and gas-discharge lamp by means of a sketch.

Q1 – analysis

Similarities pointed out by 12/32 students concern that both sources emit radiation (4) and both have a spectrum (4) that is not continuous (2), polychromatic (5), incomplete (1), with only certain energies (2). The spectra have certain common frequencies/wavelength (2). Differences pointed out by 22/32 students concern that the spectrum of the LED is a continuum (16) or with bands (2) but is monochromatic (4). One student states that the LED needs less energy than the lamp in order to emit. The lamp shows a discrete spectrum (3) characterized by sharp (2) and colored (1) lines (11) due to a superimposition of colors and frequencies (3).

Q2 – analysis

From drawings/statements by 19/32 students, the lamp has a discrete number of energy levels (16) in number of 4 (6) to account for 6 lines (3). Students draw also 3 levels (2) or 5 (2), 6 (2), 7 (1). Representations for the energetic structure of LED fall in 7 models (A-G), represented by the sketches in Fig. 8.

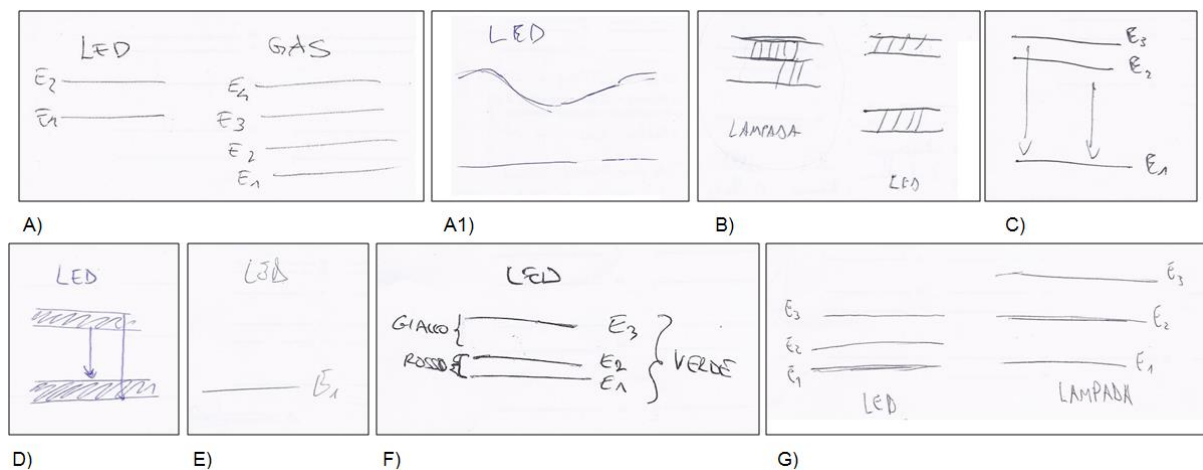


Fig. 8. Representations for the energetic structure of a LED: model A (2 students) and model A1 (1) make use of two energy levels; model B (3) shows transitions between couples of levels; model C (4) represents the left and right edge of the continuous spectrum; model D (3) shows bands; model E (1) makes use of a single level; model F (2) shows all the colors in the spectrum; in model G (1) the energy levels in the LED are more closely spaced than the ones in the lamp

5. Conclusions

Simple experiments, as the ones suggested here, are crucial for conceptual understanding of the relationship between diffracted spectra and energy models. No particular difficulties emerge in stimulating students to switch from a descriptive to an interpretative level. Questions asked are fertile in spontaneous production of energy-levels model for the emitting systems. The richness of the models used by students to describe the energy structure of a LED is a didactical resource as concern the way in which physicists use spectroscopic investigations to build an energy-level model of matter, and the way this knowledge allows to build high-tech devices, as LEDs, to obtain the desired quasi-monochromatic emission.

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