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Suzie Protière and Emmanuel Fort

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Tribute to an exemplary man: Yves Couder

Teaching, arts

Experimental teaching — A tribute to Yves Couder by the example: stroboscopy and fluorescence lifetime with a fan

Antonin Eddi[*], [a, b], **Paul Baconnier**[a], **Matthieu Blons**[a], **Samuel Pautrel**[a], **Suzie Protière**[a, c] and **Emmanuel Fort**[a, d]

[a] Projets Scientifiques en Equipe (PSE), ESPCI Paris, 10 rue Vauquelin, 75005 Paris, France

[b] PMMH, CNRS, ESPCI Paris, Université PSL, Sorbonne Université, Université de Paris, F-75005, Paris, France

[c] Institut Jean Le Rond D'Alembert, Sorbonne Université, 75005 Paris, France

[d] Institut Langevin, ESPCI Paris, CNRS, PSL University, 1 rue Jussieu, F-75005 Paris, France

E-mails: antonin.eddi@espci.fr (A. Eddi), paul.baconnier@espci.fr (P. Baconnier), matthieu.blons@espci.fr (M. Blons), samuel.pautrel@espci.fr (S. Pautrel), protiere@ida.upmc.fr (S. Protière), emmanuel.fort@espci.fr (E. Fort)

Abstract. Yves Couder created "PhyExp" at Paris Diderot University in 80s. This undergraduate course was meant to introduce experimental physics to students through projects. This approach proved fruitful both for students and teachers and has been replicated Ecole Supérieure de Physique et Chimie Industrielles (ESPCI). As a tribute to Yves, we report here the results obtained during this course about a specific project, namely the measurement of fluorescence lifetimes using stroboscopy and a fan. We obtain quantitative measurements for both Europium and Terbium that are commonly used in fluorescent tubes and we further study the variation of the lifetime with temperature.

Résumé. Durant les années 80, Yves Couder a introduit une nouvelle méthode d'enseignement à l'Université Paris Diderot à travers le module "PhyExp". Au cours de projets expérimentaux, les étudiants découvraient des problèmes originaux de physique ainsi que les méthodes permettant d'y apporter des solutions. Ce module a été reproduit à l'Ecole Supérieure de Physique et Chimie Industrielles (ESPCI) depuis 2014. En forme d'hommage à l'approche d'Yves Couder, nous pésentons ici les résultats obtenus par un groupe d'étudiants dont le projet consistait à mesurer des temps de vie de fluorescence avec des moyens limités (un ventilateur et un spectromètre). En utilisant une méthode stroboscopique, nous avons pu obtenir des mesures quantitatives pour les raies visibles de l'Europium et du Terbium, deux éléments présents dans les tubes fluorescents. Nous avons également évalué la variation de ces temps de vie avec la température.

Keywords. Teaching, Physics, Experimental approach, Observations, Fluoeresence lifetime.

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[*] Corresponding author.

1. Introduction

During the 80s, Yves Couder with colleagues introduced a new experimental course at Paris Diderot University for the undergraduate level. During this course, students in groups of two or three, must build a new experiment from scratch. The course is based on a few simple but central principles. The course is independent of any theoretical course. Each experiment is performed only once. This implies that each group of students has a different project and that all the projects must be renewed each year. The supervising professors have not performed the experiments before and there is no specific supervisor for a given project. This approach has proven extremely fruitful for the students who had the opportunity to discover the scientific approach to question the world and often ended up considering their project as their masterpiece. This experimental course has also triggered new discoveries in research and several experiments have been transferred to the research lab. One of the best example is given by Yves' own research on "walkers" which are self-propelled droplets bouncing on the surface of a bath vibrated vertically [1, 2]. The discovery that vertical vibration could prevent coalescence was done during the experimental course [3]. This finding opened up a complete new field of research with the discovery of a classical non-quantum wave-particle duality which soon became Yves' major field of research in the following years. He supervised 4 PhD on the subject, wrote about 20 articles on the subject [4–24], performed several groundbreaking experiments and opened up the new branch of hydrodynamics quantum analogs. These experimental courses have been continued with success for more than 30 years now.

Yves wanted to pass on this teaching philosophy to other institution. Being part of the advisory education board of the Ecole Supérieure de Physique et Chimie Industrielles (ESPCI), he proposed to introduce a course based on the same principle in the engineer training program. This course, entitled "Projets Scientifiques en Equipes" was introduced in 2014 at ESPCI and soon became central in the student program. The course spans over an entire scholar year. All the students, by groups of three, choose a project in various scientific domains, mainly in physics, including (fluid) mechanics, optics, micro-fabrication or acoustics but also in chemistry or biology. Over the past years, around 100 projects have been conducted in physics. One of the output of the projects is a short videos presenting each project to a general public (https://pse.espci.fr/accueil-22/).

Here, we chose to report about a specific project which summarize the philosophy of this experimental course, namely that new interesting phenomena can be found in the observation of our everyday environment. In this paper, we show how to measure the fluorescence lifetime of the rare-earth elements present in common fluorescence light tubes.

2. Experimental observation and hypothesis

The genesis of this project is interesting in itself. Students in the experimental course from the previous year which were studying the gliding mechanisms that take place in ice skating (as compared to skiing) were using fans from dismantled computers to avoid the freezing of some parts of their experimental setup. They observed two phenomena: first that for some rotating speeds the fans appeared still and second that some colors could be observed when looking through the fan at the light of the white fluorescent light tubes used in the classroom (see Figure 1a and the Supplementary movie where the same phenomenon appears using a HandSpinner). The still motion originates from the stroboscopic effect due to the well-known modulation of the light emission of these tubes to the AC electric power but the origin of the colors was unknown. This triggered a subsequent new student project.

To understand the origin of the color, we must first describe the principle of a fluorescent lamp, also called fluorescent tube. The lamp is a low-pressure mercury-vapor gas-discharge lamp

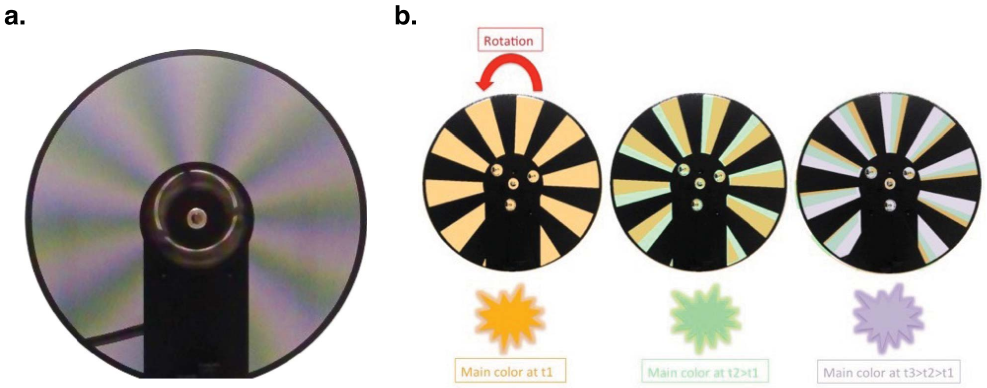

Figure 1. (a) Image of the color fringes obtained through a rotating optical chopper with rotation frequency ν_{chop} equal to the modulation frequency ν_{mod}. (b) Schematics showing the principle for color formation for various spectral line with associated delay times.

that uses fluorescence to produce visible light. An electric current in the gas excites mercury vapor, which produces short-wave ultraviolet light that then causes a phosphor coating on the inside of the lamp to glow. The gas mixture inside the lamp tube is composed of mercury with a rare gas (typically argon). The pressure inside the lamp is approximately 1% of atmospheric pressure [25] and the pressure of the mercury vapor alone is approximately 10^{-3}% of atmospheric pressure [26]. Light-emitting phosphors are applied as a paint-like coating to the inside of the tube. It is composed of small grain size around 10 micrometers. The spectrum of light emitted from a fluorescent lamp is the combination of spectral lines directly emitted by the mercury vapor and from the phosphorescent coating. The perception of colors results from the spectrum and its quality can be evaluated (color rendering index) by comparison with a reference light source such as daylight or a blackbody of the same color temperature [27]. Since the 1990s, fluorescent lamps based on europium and terbium ions have a higher-quality rendering.

The colors observed through the fan must thus be linked with the time response of the different emitting components inside the tube. While the emission of the mercury vapor can be considered synchronous with the electric excitation, this is not the case with the fluorescence emission of the rare-earth elements which presents a time lag. This average time τ_{fl}, called fluorescence lifetime, corresponds to the duration spent in the excited state after photon absorption. This lasts typically from microsecond to milliseconds, depending on the local chemical environment and bindings.

This could give an interpretation to the observed color pattern (see Figure 1a). Since the mercury excitation is modulated by the AC electric current, the fluorescence modulation at frequency $\nu_{\text{mod}} = 1/T_{\text{mod}}$ is also modulated. Because of the different fluorescence lifetime of the spectral lines associated to different elements, the fluorescence emission is phase shifted in time and its modulation contrast changes depending on the relative value of $\tau_{\text{fl}}/T_{\text{mod}}$. Hence, when the fan rotation is strobed near T_{mod}, colors appear at different positions depending on their relative delay and contrast. Note that the spectral lines associated to mercury also contribute to the global color pattern with a zero delay compared to the electric modulation. Figure 1b shows a schematics of the principle of color observation. At time t_1, the main color is orange. At time $t_2 > t_1$, the main color is green, thus two distinct fringes appear, one green and one resulting of the addition of green and orange. At time $t_3 > t_2$, the same process repeats itself with a new color.

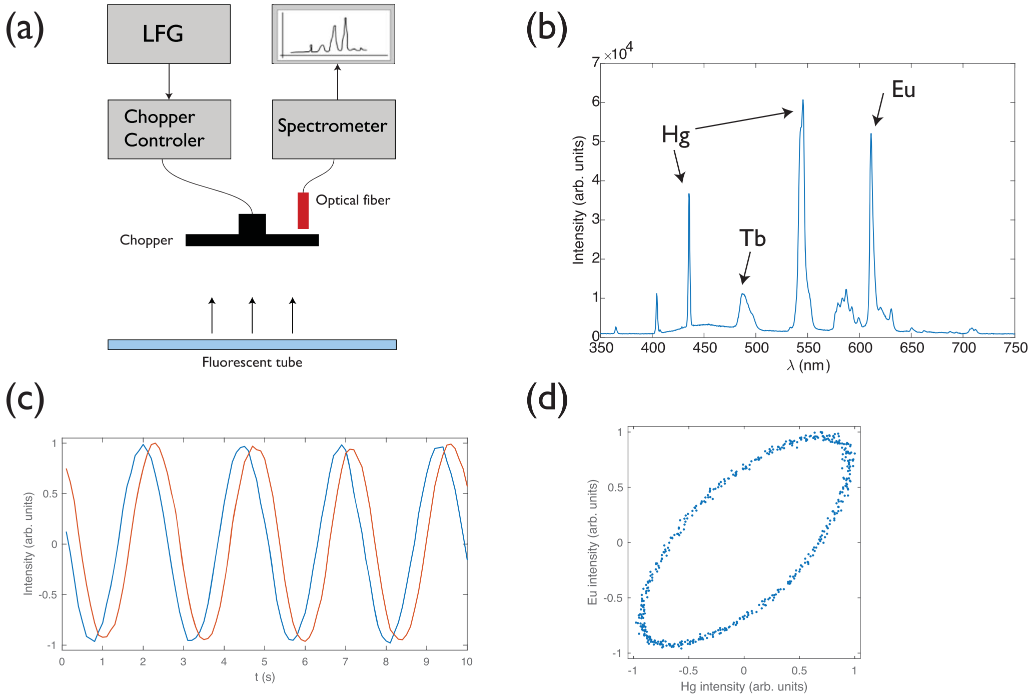

Figure 2. (a) Sketch of the experimental set-up. (b) Typical experimental spectrum. The main spectral lines are ascribed to the different elements (Hg, Eu and Tb). (c) Temporal oscillations of the Hg peak (λ_{Hg} @ 435 nm, blue) and the Eu peak (λ_{Eu} @ 611 nm, red) for a chopper frequency $\nu_{\mathrm{chop}} = 100.4$ Hz. (d) Lissajous curve obtained by plotting the Eu peak intensity as a function the Hg peak intensity from the entire temporal series.

This hypothesis can be tested with basic optical elements. This original experimental configuration should provide a quantitative measurement of the fluorescence lifetime associated to the rare-earth elements of a fluorescent lamp.

3. Experimental setup and fluorescence lifetime measurements

Figure 2a shows the experimental setup. An optical chopper with 10-blade wheel enables strobing at a precise frequency. It is connected to a low frequency generator to tune the rotating frequency ν_{chop}. The fluorescent lamp is plugged into the mains which results in a modulation of the light at $\nu_{\mathrm{mod}} = 100$ Hz. Figure 1a shows what can be observed through the chopper when tuned at $\nu_{\mathrm{chop}} = \nu_{\mathrm{mod}}$ with naked eyes. The fibber of a small spectrometer (OCEANOPTICS USB 2000+) collects the light after passing through the chopper.

Figure 2b shows a typical spectrum of the fluorescence lamp obtained with the spectrometer with the chopper stopped. The spectrum is characteristic of the one emitted by fluorescent tubes. The spectral lines can be associated to the mercury (Hg) gas for λ_{Hg} @ 435 nm and λ_{Hg} @ 546 and to the fluorescence of europium (Eu) for λ_{Eu} @ 611 nm and terbium (Tb) for λ_{Tb} @ 487 nm. The acquisition time of the spectrometer is limited because of the slow acquisition rate of the detector and its sensitivity (long exposure times are needed). Hence, the spectrometer cannot directly detect the modulation of the signal at $\nu_{\mathrm{mod}} = 100$ Hz. The stroboscopic effects enables to demodulate the signal and makes the acquisition compatible with a slow detection. The time demodulation can be made arbitrary slow by tuning the chopper frequency ν_{chop} close to the modulation frequency ν_{mod}.

Figure 2c shows temporal oscillations of signal for the Hg peak λ_{Hg} @ 435 nm (solid blue line) and the Eu peak λ_{Eu} @ 611 nm (solid red line) with the chopper set at frequency $\nu_{\text{chop}} = 100.4$ Hz. The phase shift ϕ between the two signals is clearly visible. This phase shift can be related to the fluorescence lifetime τ_{fl} by the simple relation [28–31] $\tan\phi = 2\pi\nu_{\text{mod}}\tau_{\text{fl}}$ under the hypothesis that there is only one exponential decay. The signal from the mercury spectral line can be used as a reference since the light emission of the mercury is synchronous with the electrical excitation hence all the mercury spectral lines are synchronous with the UV one which cannot be detected. Note that we checked that the two visible spectral lines associated to the mercury are indeed synchronous.

To measure ϕ, we build Lissajous curves by plotting the Eu light intensity as a function of the Hg light intensity (see Figure 2d). From these curves, one can directly extract ϕ by fitting the geometrical parameters of the ellipse. We obtain for the Europium lifetime $\tau_{\text{Eu}} = 1.4 \pm 0.2$ ms. Similarly, we obtain for the Terbium lifetime $\tau_{\text{Tb}} = 2.45 \pm 0.6$ ms. Both lifetimes are in good agreement with independently measured lifetimes using a pulsed lifetime spectrometer with $\tau_{\text{Eu}} = 1.21$ ms and $\tau_{\text{Tb}} = 2.82$ ms respectively.

4. Influence of temperature

The performance of fluorescent lamps is critically affected by the temperature of the bulb. Mercury condenses at the coolest spots in the lamp inducing changes in its partial pressure [26]. In addition, fluorescence lifetime can be very sensitive to temperature [32, 33]. Fluorescence lifetime-based thermometer have been proposed recently for biological applications [34,35]. We have thus decided to study the influence of the temperature on τ_{fl} for fluorescence tubes.

Figure 3a shows a schematics of the experiment. We repeat the same experiment while changing the working temperature. To do so, we immerse the light tube in a thermostatic bath whose temperature T can be varied from $T = 0$ °C to $T = 60$ °C. Below $T = 0$ °C, the tubes do not emit enough light, while the experiment becomes dangerous above $T = 60$ °C. In practice, we do not impose the working temperature of the fluorophores, just the surface temperature of the light tube, but these quantities are closely related. The spectral peaks associated to the mercury emission decrease sharply at low temperature as well as the intensity fluorescence spectral lines probably due to the condensation of the mercury. As expected the lamp is not working below $T = 0$ °C [36]. Figure 3b and 3c show the measured fluorescent lifetime for Terbium τ_{Tb} and Europium τ_{Eu} respectively as a function of the bath temperature T. τ_{Tb} slowly decreases with increasing T while τ_{Eu} presents a steeper decrease varying from about $\tau_{\text{Eu}} \simeq 2.5$ ms at $T = 0$ °C to $\tau_{\text{Eu}} \simeq 1.4$ ms at $T = 50$–60 °C. For the lowest temperatures, the uncertainty of the measurements increases due to the global decrease of light. The decrease of the fluorescence lifetime with temperature is expected due to the opening of additional relaxation processes.

5. Conclusion

This experimental project started with a simple but surprising observation: a rotating computer fan producing color fringes when enlighten with a fluorescent light tubes. In order to interpret it, we developed an original and low-cost apparatus that allowed us to extract the fluorescence lifetime of several rare-earth elements present in the light tubes. We also observed their dependence with temperature. The stroboscopic effect used in this implementation is original enabling the use of slow detectors. A variation of this idea has been proposed recently in the context of fluorescence lifetime imaging for super-resolution microscopy which needs a very sensitive camera

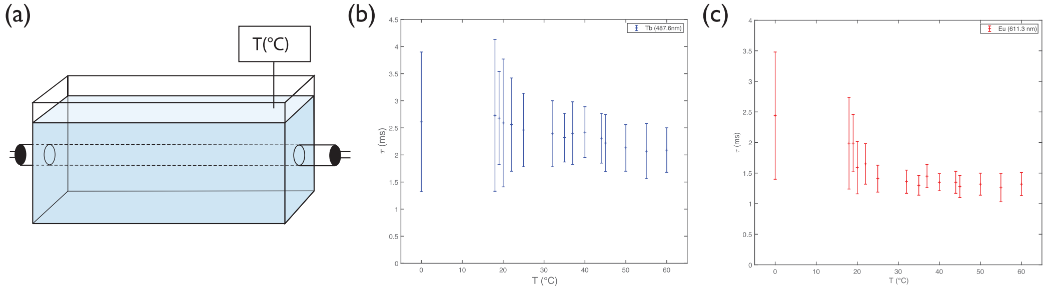

Figure 3. (a) Sketch of the experimental set-up with a thermostatic bath. (b) Evolution of τ_{Tb} with temperature T. (c) Evolution of τ_{Eu} with temperature T.

for the detection which cannot demodulate the megahertz frequencies needed for the nanosecond fluorescence lifetime to be detected. A fast electro-optical modulator is placed in from of the camera to perform the demodulation [37].

This paper is just one of the many examples showing the virtuous philosophy that Yves wanted to promote with the experimental projects. Great findings are inspired by everyday curiosity and within the grasp of every students.

Supplementary data

Supporting information (video) for this article is available on the journal's website under https://doi.org/10.5802/crmeca.39 or from the author.

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