NOTES AND DISCUSSIONS | FEBRUARY 01 2024

Developing a low-cost experimental apparatus to observe the Tyndall effect using an Arduino and 3D printing FREE

Luiz Américo Alves Pereira ; Rozane de Fátima Turchiello ; Sergio Leonardo Gómez

Am. J. Phys. 92, 154–156 (2024)
https://doi.org/10.1119/5.0146499

Developing a low-cost experimental apparatus to observe the Tyndall effect using an Arduino and 3D printing

Luiz Américo Alves Pereira[a)]
Physics Department, State University of Ponta Grossa, Ponta Grossa, CEP 84030-900, PR, Brazil

Rozane de Fátima Turchiello[b)]
Physics Department, Federal University of Technology of Parań, Ponta Grossa, CEP 84017-220, PR, Brazil

Sergio Leonardo Gómez[c)]
Physics Department, State University of Ponta Grossa, Ponta Grossa, CEP 84030-900, PR, Brazil

(Received 14 February 2023; accepted 10 August 2023)

The Tyndall effect describes light scattering by suspended solid particulates with sizes smaller than or comparable to the wavelength of light. This work describes the design and construction of an instructional kit for observing the Tyndall effect. The kit consists of a 3D printed holder that can be combined with low-cost and readily available materials to enable student laboratory experiments.

https://doi.org/10.1119/5.0146499

I. INTRODUCTION

Scattering of incident light on objects is one of the processes that makes them visible. It is also responsible for phenomena such as the color of the sky and the glare produced when fog is illuminated by the headlights of a car. Scattering depends on the wavelength (λ) and polarization of light, as well as on the size and concentration of scattering objects.[1] Previous papers in this journal have described methods of measuring light scattering and have presented models to explain the results.[2] In a typical experiment, a laser that is linearly polarized along the x-direction and propagates along the z-direction induces an oscillating electric dipole oriented along the x-direction of a molecule or a nanoparticle (NP) in the path of the beam. Far from the object, the scattered field is zero along the dipole direction and a maximum at 90° from the x-direction, having axial symmetry (doughnut-shaped). Light scattering has interesting applications in biological and biopharmaceutical sciences[3] and is also the basis of the dynamic light scattering technique for determining the size of NPs dispersed in a fluid. The scattering of light by nanosized objects dispersed in a fluid is called the Tyndall effect. Hence, light scattering is scientifically relevant and fundamental for students of biology, chemistry, and physics, making it desirable to develop a low-cost instructional kit to demonstrate its fundamental characteristics. Previous work used research laboratory equipment to explore the characteristics of light scattering, which is not accessible in many undergraduate laboratories.[2,4] In this paper, we propose a simple and low-cost experimental setup for demonstrating basic aspects of the Tyndall effect and light scattering.

II. EXPERIMENTAL SETUP

The proposed experimental setup for analyzing the Tyndall effect is shown in Fig. 1 and comprises the following: a linearly polarized laser pointer, an unpolarized laser pointer, the Arduino Uno board, the Adafruit TSL2591 luminosity sensor, a computer, a cuvette, colloid of silver NPs, distilled water, Pasteur pipette, test tubes, a linear polarizer film, a 3D printed holder, and a protractor.[5] Figure 1(a) shows an image of the complete experimental setup, and Fig. 1(b) shows an expanded view of the holder, which was 3D printed and designed for measuring the intensity of the light scattered in a direction perpendicular to the laser propagation direction.[6] It contains a cubical cavity for a 1 cm pathlength cuvette and a cylindrical cavity to secure the laser pointer. It also has a removable lid containing the light sensor. The design of the holder prevents ambient and unscattered light from reaching the light sensor. The experimental setup includes a protractor fixed to the holder. An advantage of this geometry is that the position of the laser beam that crosses the cuvette remains unchanged from one measurement to another; only the polarization is changed. An unpolarized laser pointer can be used if a polarizing film is placed at its output, although this polarizer will reduce the intensity by 50%. The orientation of the film's polarization axis can easily be determined by remembering that when unpolarized light is reflected specularly from a surface, as in the glare spots that may be seen on a shiny floor or table, the reflection is preferentially polarized parallel to the surface.

The laser pointers, protractor, cuvette, Pasteur pipettes, test tubes, and Arduino board are commonly found in an undergraduate laboratory or can be purchased online. The proposed scattering medium is a colloid of silver NPs, a nanofluid that can be purchased in chemical suppliers,[7] or synthesized following a photochemical route.[8] A red beam is recommended for the laser pointer due to the optical properties of the colloid of silver NPs. The output of the TSL2591 luminosity sensor can be connected to the Arduino, and its values can be recorded. The technical information about the TSL2591 sensor and the code for controlling the sensor using the Arduino board can be freely obtained on the Internet.[9,10] Samples are prepared by diluting aliquots of the stock colloid with distilled water. It is suggested to prepare samples with different concentrations. In commercial colloids of nanoparticles, concentrations are usually of the order of 0.01–0.02 mg/ml ($\approx 10^{15}$/ml), and the sizes of nanoparticles are

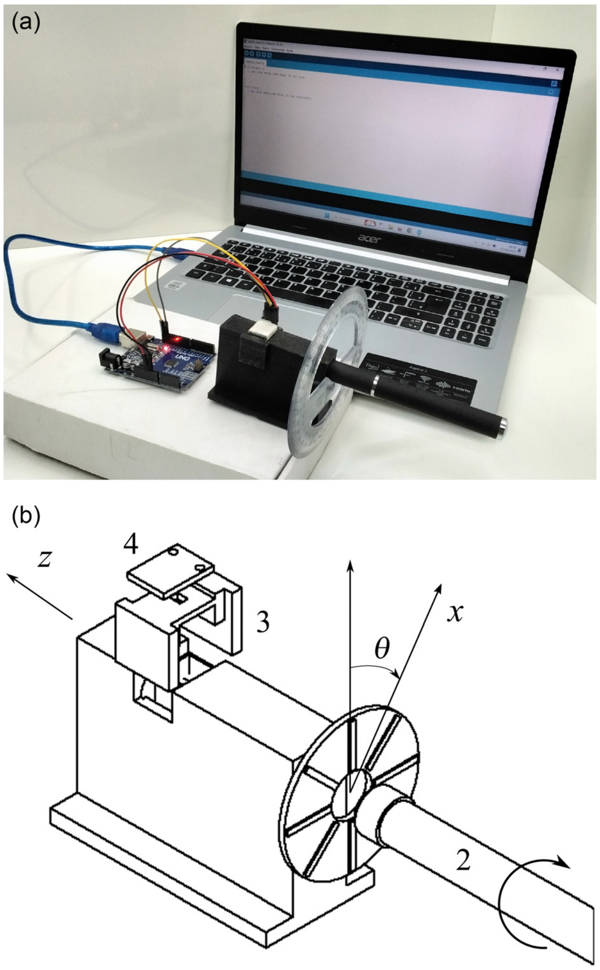


Fig. 1. (a) Complete experimental setup; (b) scheme of the holder: (1) protractor; (2) laser pen; (3) removable cover that holds the light sensor; (4) light sensor. The polarization direction defines the x-axis.

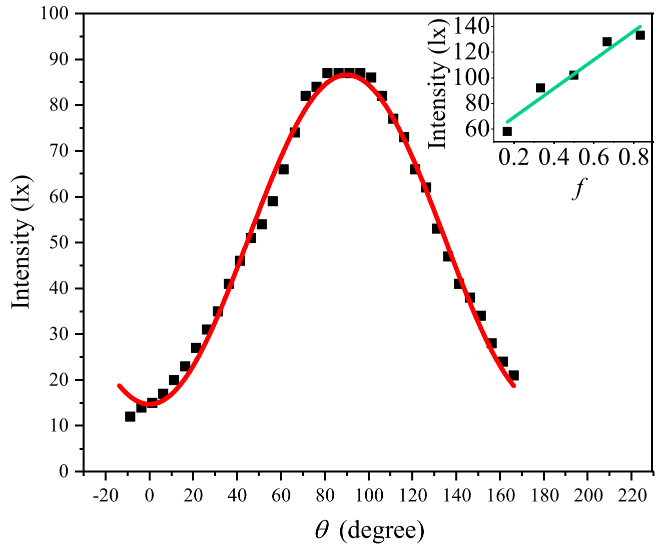


Fig. 2. (Color online) Graph of red laser light intensity scattered at $\theta = 90^\circ$ as a function of angle θ. The solid red line represents a fitting to the function $a + b\ \sin^2\theta$, where parameter a is introduced to take into account a residual scattering. Inset: Graph of the intensity of red laser light scattered at $\theta = 90^\circ$, measured as a function of the fraction f of the initial concentration of NPs. The solid green line is a linear fitting of data.

in the range of 10–20 nm. The available concentrations are rather high, so it is recommended to start with solution containing half the concentration of the stock solution. From this diluted solution (sample 100%), prepare successive samples diluting progressively with distilled water (samples 90%, 80%, etc.).

III. EXPERIMENTAL PROCEDURE

The following experimental procedures are suggested for an introductory student experiment on scattering.

(1) *Measure the angular dependence of the scattering of a linearly polarized laser*. The incident laser polarizes the NPs along the same direction as the laser polarization, so the intensity of the scattered light (re-radiated by the dipoles) is proportional to $\sin^2\theta$ (see Eq. (12) of Ref. 2). In this experiment, the direction of the laser polarization is rotated, while the position of the detector remains fixed vertically above the sample. When the laser polarization is rotated from vertical to horizontal, the angle θ increases from 0° to 90°, and the intensity should be observed to increase from a minimum to a maximum, with additional minima and maxima alternating and separated by 90°. Figure 2 shows a typical result obtained with the kit. The intensity is nonzero at $\theta = 0$ due to scattered light reaching the detector after being reflected by the walls of the cell. The scattering at position $\mathbf{r}$ from an electric dipole $\mathbf{p}$ is characterized by an electric field $\mathbf{E}$ whose direction is parallel to that of the vector $(3/r^2)\mathbf{r}(\mathbf{r}\cdot\mathbf{p}) - \mathbf{p}$.[11] So, at $\theta = 90^\circ$, the polarization directions of the scattered light and the laser beam are parallel. This can be confirmed removing the lid and observing the beam through a linear polarizer.

(2) *Measure the scattering as a function of NPs concentration.* For widely spaced scatterers, such as the nanoparticles in the liquid medium, scattering is incoherent. So, the scattering at $\theta = 90^\circ$ of N scatterers that radiates individually with intensity I_0 is NI_0; i.e., the scattered intensity is a linear function of the concentration.[12] With the linearly polarized laser at a fixed θ, proceed to measure the intensity of light scattered by the previously prepared samples containing different concentrations of NPs. The scattered intensity should decrease with reduced nanoparticle concentration. The inset of Fig. 2 shows the maximum intensity (observed at $\theta = 90^\circ$) as a function of the concentration of nanoparticles and a linear fitting of data.

(3) *Observe the polarized character of the scattered light of an unpolarized laser beam*. When θ is varied, the intensity of the scattered light should remain constant. However, by removing the lid and using a linear polarizer, it can be verified that the scattered light is linearly polarized, with its polarization direction perpendicular to the longitudinal axis of the laser pointer.

Another aspect of light scattering that can be explored is the dependence on the wavelength, although it may be necessary to control for the different power and polarization of the different lasers. Also, a small modification of the holder, placing a second detector to measure the transmitted intensity, could make it possible to explore the transmittance of an absorbing medium and arrive at the Beer-Lambert law.

IV. CONCLUSIONS

We expect that the affordable and low-cost arrangement proposed here for studying the characteristics of light scattering could improve teaching and can also be used for an initial research project for students.

ACKNOWLEDGMENTS

The authors thank the financial support from INCT-FCx, CAPES, Fundação Araucária, SETI-PR, and CNPq.

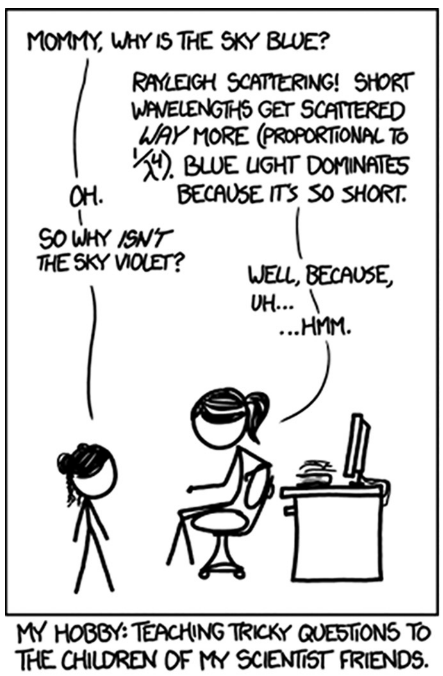
AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

[a]ORCID: 0000-0001-6915-1825.
[b]ORCID: 0000-0002-4039-0424.
[c]Electronic mail: sgomez@uepg.br, ORCID: 0000-0002-4945-3997.

[1]E. Hecht, *Optics, International Edition*, 4th ed. (Addison Wesley, San Francisco, CA, 2002), pp. 86–92.
[2]N. L. Sharma, E. R. Behringer, and R. C. Crombez, “A study of electric dipole radiation via scattering of polarized laser light,” Am. J. Phys. **71**(12), 1294–1302 (2003).
[3]A. L. Minton, “Recent applications of light scattering measurement in the biological, and biopharmaceutical sciences,” Anal. Biochem. **501**, 4–22 (2016).
[4]D. E. Shaw, M. J. Hones, and F. J. Wunderlich, “Quantitative, molecular light-scattering experiment,” Am. J. Phys. **41**(11), 1229–1232 (1973).
[5]The estimated cost of the materials for this project is around 70 USD, which includes the Arduino board, light detector, laser pointer, protractor, quartz cuvette, Pasteur pipette, polarizing film, test tubes, and PLA 3d printer filament. These items can be purchased from a popular e-commerce site. If a 3D printer is also needed, the cost will increase by about 150 dollars. Finally, 20 ml of a colloidal solution of silver nanoparticles can be purchased from 158 dollars.
[6]Files required for 3-D printing of the holder (STL files) are available at <https://cults3d.com/en/3d-model/various/holder-for-studying-light-scattering> and also in supplementary material online.
[7]Some chemical suppliers that sell colloidal silver and/or nanopowder for dilution are: Sigma Aldrich, American Element, NanoComposix, Nanocs, US-Nano, and SSNANO.
[8]S. K. Lin and W. T. Cheng, “Fabrication and characterization of colloidal silver nanoparticle via photochemical synthesis,” Mater. Lett. **261**, 127077 (2020).
[9]Hookup guide of the TSL2591 luminosity sensor <https://www.digikey.jp/htmldatasheets/production/1640736/0/0/1/tsl2591-guide.html>. The site also contains the code for reading the sensor via the Arduino board.
[10]Arduino Library for the TSL2561 Luminosity Sensor, <https://reference.arduino.cc/reference/en/libraries/adafruit-tsl2591-library/>
[11]J. D. Jackson, *Classical Electrodynamics*, 3th ed. (John Wiley, Castleton, 1998), p. 411.
[12]E. Hecht, *Optics, International Edition*, 4th ed. (Addison Wesley, San Francisco, CA, 2002), pp. 89 and 285.



Feynman recounted another good one upperclassmen would use on freshmen physics students: When you look at words in a mirror, how come they’re reversed left to right but not top to bottom? What’s special about the horizontal axis? (Source:https://xkcd.com/1145/)