Playing with Light: Adventures in Optics and Spectroscopy for Honors and Majors General Chemistry

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Vartkess Ara Apkarian
University of California, Irvine

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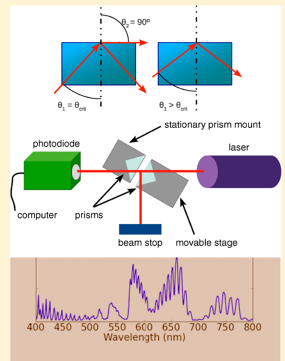
Playing with Light: Adventures in Optics and Spectroscopy for Honors and Majors General Chemistry

Marie N. van Staveren, Kimberly D. Edwards,* and V. A. Apkarian

Department of Chemistry, University of California, Irvine, California 92612 United States

Ⓢ *Supporting Information*

ABSTRACT: A lab was developed for use in an undergraduate honors and majors general chemistry laboratory to introduce students to optics, spectroscopy, and the underlying principles of quantum mechanics. This lab includes four mini-experiments exploring total internal reflection, the tunneling of light, spectra of sparklers and colored candles, and emission spectra of gases. These mini-experiments were of a mixture of styles, from open-ended inquiry, to more traditional cookbook experiments, and were chosen to echo current graduate research. In the accompanying lecture, students were given an overview of quantum mechanics and a primer on what type of information can be gleaned from a spectrum.



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A lab was developed to expose honors and majors general chemistry students to concepts in spectroscopy and quantum chemistry. The purpose of this lab was 2-fold. First, to give students a first-hand look at these conceptually difficult topics and ground the concepts in more accessible experience. Second, the lab was written with explicit connections to current research.

Although spectroscopy is a central tool for a chemist, many students lack understanding of the underlying concepts. The central goal of this lab is to rectify that. Concepts include a qualitative introduction to quantum mechanics, what information can be gleaned from a spectrum, basic concepts of optics such as index of refraction and total internal reflection, quantum tunneling, background subtraction, and emission spectroscopy.

Quantum mechanics is both conceptually and mathematically difficult for most students, leading it to be left for upper-division classes at many universities. This lab was written to complement a simple introductory unit on quantum mechanics in the general chemistry sequence. It is intended for a separate lab course that has a one hour lecture component. The lab lecture includes a simple discussion of the Heisenberg uncertainty principle, to impart to the students the founding principle of quantum mechanics: the more that is known about a particle's position, the less is known about its velocity. The experiment, then, allows them to see a consequence of the uncertainty principle when they see light tunnel.

■ DESCRIPTION OF EXPERIMENTS

This lab consisted of four mini-experiments. Students worked in groups of four to six, rotating through each experiment. They were given as long as an hour to complete each section, though some classes rotated in as little as half hour increments. These experiments were written to be exploratory, with several guess-and-check sections written in, allowing students to generate and test hypotheses. They were instructed to take pictures of important parts of each experiment, for inclusion in their lab report. Although most groups had several camera phones, disposable cameras were available for groups that needed them. Brief descriptions of the four experiments are given below and a detailed student handout is available in the Supporting Information.

■ TOTAL INTERNAL REFLECTION

In the first part of the experiment students are introduced to two basic principles of geometric optics: the index of refraction of a material and the critical angle. The index of refraction measures the speed of light in a given material relative to that in vacuum: n = (speed of light in vacuum)/(speed of light in medium).

The index in vacuum is defined to be one, and all other materials are defined relative to that. The index is inversely proportional to the speed of light in that material; that is, light travels slower in higher index materials.

The concept of the critical angle is fundamental to total internal reflection spectroscopy. When light passes through an interface between two materials, it bends according to Snell's law:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

n_i is the index in the material, and θ_i is the angle the light makes relative to the normal to the interface. This means that light bends away from normal when going from a high to a low index of refraction. At some incident angle, θ_2 will be 90°; that is, the light has bent so far that it is now traveling along the interface. This is called the critical angle. Past this angle, all light is reflected off of the interface.

Students were given a fish tank full of water containing a small quantity of starch solution to make the water slightly cloudy. The fish tank was placed in a fume hood where the light could be turned on and off easily. First, a pencil was half way emerged in water and observations were made at various angles. Next, students predicted and then tested out how a laser beam would be affected when directed at different angles through the back wall of the fish tank (Figure 1). Students found the critical angle experimentally and then calculated its value using indices of refraction. Finally, students were asked whether they thought the light interacted with the air outside the fish-tank, which sets up the next experiment. In order for the light to change direction, it must interact with the air outside the fish tank.

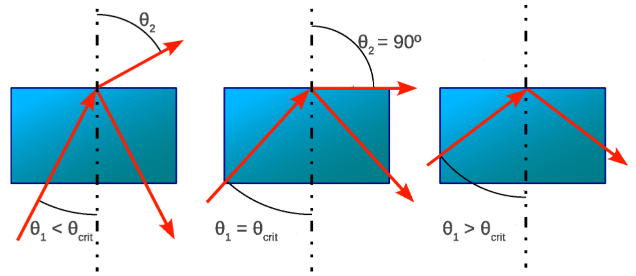

Figure 1. Reflection and refraction (transmission) of a laser in a tank of water at various angles. (left) The incident angle is less than the critical angle, resulting in a reflected and a transmitted beam. (center) The incident angle is at the critical angle, and the transmitted beam disappears. (right) The incident angle is greater than the critical angle, and the light cannot cross the glass/air interface.

TUNNELING OF LIGHT

Quantum tunneling is a counterintuitive but fundamental process. Although any object can tunnel, the effect is inversely proportional to the momentum of the particle. Therefore, it is most often seen in objects with little to no mass, and therefore little momentum, such as electrons and photons. The process exploits the uncertainty principle, that is, the probabilistic nature of a particle's location. The particle approaches some potential energy barrier that exceeds its kinetic energy; therefore, it does not have enough energy to cross it. If the uncertainty in the particle's position is large in comparison to the width of the barrier, then there is a probability for the particle to be on the other side even if it did not have the energy to go over. This can be demonstrated with light by showing that it has a tunneling probability that depends on the width of the barrier, a probability that can be measured to decay exponentially as a function of the barrier width.[1]

The tunneling demonstration is shown in Figure 2. It consists of a helium–neon laser, a pair of mirrors for alignment, two prisms where the actual tunneling occurs, and a photodiode to measure the signal. The first part of this activity was to fill in a set of diagrams, first confirming the behavior of light at an interface before and after the critical angle, then expanding to ask what happens when there is a second interface. The students are then shown the tunneling setup, with the diagrams they just filled in being related to the experimental design. The teaching assistant explained the experimental setup and showed them the tunneling light changing intensity with change in gap distance. Finally, students collected tunneling intensity as a function of distance, plotted this data, and determined the functional form. The worksheet asks students to think about how the uncertainty principle could cause this behavior, and the activity is explicitly described as the quantum answer to the previous, classical, activity.

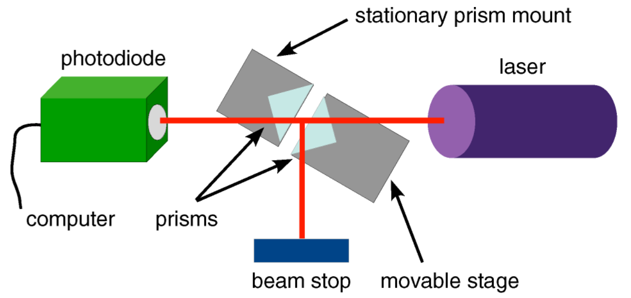

Figure 2. The setup of the tunneling activity. The laser is aligned such that it undergoes total internal reflection at the first prism. A translation stage allows the distance between the two prisms to be varied. The photodiode collects any tunneled light and sends the signal to the computer for recording.

SPECTRA OF EVERYDAY MATERIALS

The goal of this section was to introduce students to the basics of interpreting emission spectra and draws heavily on two previously published papers.[2,3] Students used hand-held spectroscopes to observe the spectrum of the classroom lights, which consists of five bands in the visible, and a white LED, which is continuous throughout the visible range. This also gave them the background that would be in each of their spectra. Next, they were asked to light candles with colored flames and draw the appearance of the spectra for each, as described previously.[2,3] These same steps were repeated with colored sparklers. Students were asked to use information given in the lab lecture to classify the spectra as being from single-electron elements, multielectron elements, molecules, or some combination. They were also asked if any of the candles and sparklers shared chromophores, and if there was any feature common to all spectra. The purpose of these questions was to encourage exploration of how to interpret spectra, rather than to get a right answer.

EMISSION SOURCES

This activity centered on a gas discharge power source loaded with three tubes: hydrogen, neon, and nitrogen. Students were asked to view each tube using a hand-held spectroscope and guess the identity of each tube based on the complexity of the spectrum. After checking their answers, students used a UV–vis spectrometer with a fiber optic attachment to record spectra of each sample. They were given instructions on optimization of the signal, including adjustment of the integration time. Finally, they were asked to use Rydberg's formula to determine which transitions they observed for hydrogen.

HAZARDS

The lasers used were class II and IIIa, which do not represent a health hazard unless directly stared at. The candles and sparklers were burned in a fume hood, standing up in a sand bath. Sparklers were carefully controlled by the teaching assistant, and used sparklers were dipped in water to cool before disposal.

CONCLUSIONS

To encourage students to think about the concepts they explored, and not to worry as much about quantitative results, the writeup of the lab was to make a magazine or newspaper article for a general audience. They were instructed to take pictures of the laboratory equipment and record data, and that their report must contain some of these pictures and figures. Lab reports showed student understanding of the major topics. For instance, in explaining the hydrogen emission spectrum, one group wrote "What causes the red light is most of hydrogen's electrons tending to be excited to just the right energy level so that when it falls back down to the ground state, the energy difference corresponds to a red light." Another group, describing tunneling, said "Though it seems impossible, some of the photons that make up the laser light are able to jump, or "tunnel" through to the other side...what makes this so strange is that the photons should not have the energy to make this jump; yet, the results of this experiment clearly indicate that this is apparently what happens."

Activities one, three, and four can be performed with easily accessible equipment. Although activity two requires some knowledge of optics and specialized equipment not normally used in general chemistry classrooms, the assembly is not that difficult and should be within reach of many classrooms.

ASSOCIATED CONTENT

Supporting Information

Student laboratory manual and notes for instructors. This material is available via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: kdmullen@uci.edu.

Notes

The authors declare no competing financial interest.

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