Tested Demonstrations

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A Classroom Demonstration of Rayleigh Light Scattering in Optically Active and Inactive Systems

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Optical activity is a property of molecules that causes the rotation of the electric field vector of light as it travels through an optically active medium. The concept of optical activity often remains vague to students. It often must be taken for granted by students because it is difficult for instructors to demonstrate the phenomenon in the classroom. A few overhead projector demonstrations have been developed that illustrate optical rotation by placing an optically active medium between initially crossed polarizers and using an overhead projector as the light source (*1–4*). In this type of demonstration light passes through the polarizers even though they are crossed, because the electric field vector of the light rotates owing to its refraction through the optically active medium. An improved approach may be to allow students to observe a sidewise view of the optical path of the polarized light as it travels through the optically active medium. A demonstration of this type would allow students to observe the rotation to the right or to the left (depending on whether the medium is dextrorotatory or levorotatory) of the electric field vector of the incident light as the light travels through the solution.

A demonstration has been developed that allows students to observe and manipulate the optical path of polarized light through optically inactive and optically active solutions. In the first part of the demonstration they observe the optical path of a laser beam through an optically inactive medium. After the scattered light intensity pattern is understood, the demonstration is repeated with the optically inactive solution replaced with an optically active solution. Now the students observe a spiral pattern of bright and dark areas. The light observed in these demonstrations is due to Rayleigh scattering. Therefore, basic principles of Rayleigh scattering and the spatial distribution pattern from an oscillating dipole are presented to explain the observed phenomena.

Theoretical Background

Unless we are looking directly at a light source such as a flame or light bulb, most of the light that reaches our eyes is scattered light. Rayleigh-type scattering occurs when the scatterers are smaller than the wavelengths of light being scattered. During Rayleigh scattering the frequency of the scattered light remains the same as the frequency of the incident light. There are direct observations of Rayleigh scattering that students can easily make, including the blue color of the sky and polarized sunlight at 90° from the Earth–Sun line.

In Rayleigh scattering theory the scattering probability is inversely proportional to the fourth power of the wavelength of the scattered light. Therefore, shorter wavelengths are scattered more efficiently than longer wavelengths. Violet is the shortest wavelength that our eyes can detect. However, our sky is not violet owing to the distribution of light in the solar spectrum and because our eyes are more sensitive to blue than to violet. The effects of Rayleigh scattering can also be directly observed by looking at the sky through a polarizer at 90° to the Earth–Sun line. When this is done, the blue color of the sky deepens. Although Rayleigh's theory predicts complete polarization at this viewing angle, the observed polarization is only ca. 50%. This "polarization defect" is caused by multiple scattering, large-particle scattering (Mie theory), and anisotropy of the macromolecules dispersed in air (these molecules are not spherical, as is assumed in Rayleigh theory) (*5*).

Scattering results from the interaction of matter with electromagnetic radiation. A complete description of this interaction requires a lengthy quantum mechanical treatment and will not be given here (such a treatment can be found in ref *6*). When electromagnetic radiation is incident upon a molecule (scatterer), the oscillating electric field of the incoming light induces the electron distribution of the molecule to oscillate. The result is an induced dipole in the molecule. The induced molecular dipole and the electric field of the incident radiation oscillate in the same plane (Fig. 1). The induced dipole emits radiation in a directional pattern, as shown in Figure 2. The maximum radiation (Fig. 2) is observed at right angles to the oscillating dipole axis and none is observed along the dipole axis. This is analogous to a radiating antenna. An antenna's electromagnetic radiation is caused by electrons oscillating along its radial axis. No radiation is emitted directly above or below a vertical antenna; rather, radiation is emitted perpendicular to the antenna. Similarly, in the case of a radiating dipole, no scattered light will be observed if one is looking directly down or up the induced dipole axis. The maximum scattered light intensity will be observed in the plane perpendicular to the induced dipole axis. The plane of maximum scattered light intensity is called the "scattering plane". In Figure 2 the induced dipole is oscillating along the *z*-axis, producing the

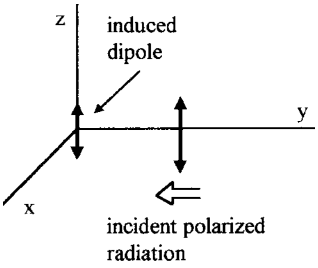

Figure 1. The incident polarized electromagnetic radiation is polarized in the *y–z* plane. The induced dipole is also polarized in the *y–z* plane.

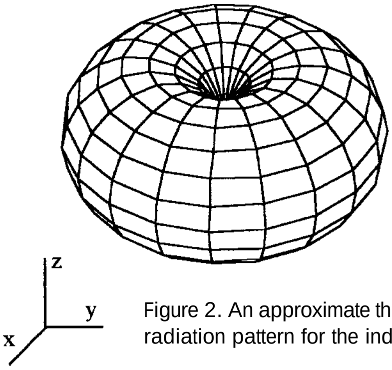

Figure 2. An approximate three-dimensional directional radiation pattern for the induced dipole in Fig. 4.

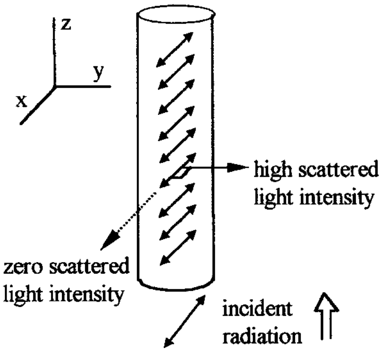

Figure 3. Incident light polarized in the *x–z* plane travels through an optically inactive medium in a vertical tube. The resulting induced dipoles are all polarized in the *x–z* plane.

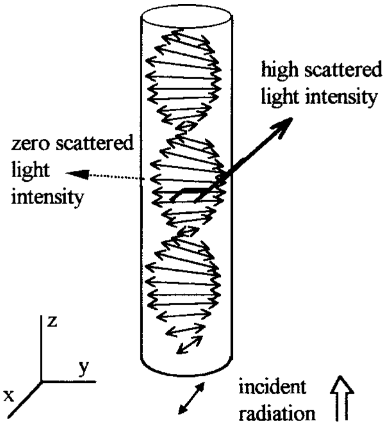

Figure 4. When polarized light travels through an optically active medium the induced dipoles created form a spiral pattern. In turn, the observed scattered radiation is a spiral band of light.

scattering plane oriented in the *x–y* plane. The scattered light intensity is zero directly above and below the radial axis of the induced dipole; therefore, no light is observed in either the +*z* or –*z* direction.

Figure 3 depicts polarized light traveling through a vertical column containing an optically inactive medium. The incident polarized light induces molecular dipoles as it travels through the medium. Since the medium is not optically active, the electric field of the incident radiation does not rotate as it travels up the column. Because the electric field of the incident radiation does not rotate, all the induced dipoles in the column oscillate in the same plane. Therefore, as shown in Figure 3, when viewing the column from a position perpendicular to the induced dipole axis (i.e., from a scattering plane), an observer will see an uninterrupted vertical “line” of maximum scattered light intensity as he or she looks up and down the vertical column. Moving 90° around the column in either direction, the observer would see the scattered light intensity change from maximum to zero. Upon completing a single revolution around the column, the observer would have passed through two positions (separated by 180°) where the scattered light intensity is at a maximum and two positions (separated by 180°) where the scattered light intensity is zero.

Figure 4 depicts polarized light traveling through a vertical column that contains an optically active medium. Because the medium is optically active, the polarization of the incident radiation rotates as the light travels up the column, leaving behind a three-dimensional spiral array of induced molecular dipoles. Owing to the radial distribution pattern of an oscillating dipole, the overall scattered light intensity appears like an optical “candy cane” of spiraling bright and dark areas. An observer could walk around the column and follow a bright or dark area as it wraps vertically upward or downward around the column.

The Demonstration

Materials

Diode laser[1]
Battery power supply for diode laser (available in most hardware stores)
Distilled water
64 fl. oz. of high-fructose light corn syrup (check ingredients for high fructose content)
Polarizer
Plumber’s Goop (sealant available in most hardware stores)
Nondairy creamer (e.g. Cremora, manufactured by Borden)
Two clean fluorescent lamp tube guards (available in most hardware stores)
Two 2.5-cm square glass plates
Two tall lab stands
Clamps[2]
Short lab stand
Two black rubber stoppers (size #9)
Flashlight
Weights

Setup

The glass plates are sealed with Plumber’s Goop to one end of each of the fluorescent tube guards. It is important for the glass plates to be clean and transparent. After a permanent watertight seal is made, clamp each tube vertically, with the sealed end down, to a separate lab stand (see Fig. 5). The tube should be clamped about six inches above the lab stand base. The lab stands used should be about as tall as the tubes. Optional weights may be used to stabilize the setups.

One tube is filled with the optically active medium (high-fructose corn syrup) and the other is filled with the optically inactive medium (distilled water). When pouring the corn syrup try to minimize the production of bubbles. Bubbles will only serve as distractions when the scattered light intensity pattern is viewed. They can be removed by letting the tube stand vertically for a few days. Each tube is topped with a #9 black stopper to help prevent extraneous light scatter during the demonstration.

The diode laser can be placed in a small clamp, which is attached to a short lab stand. Any diode laser module or laser pointer with fresh batteries should work well. Intensity and easy-to-see wavelengths are important criteria in choosing a laser for this type of demonstration. Best results were found with a 635-nm diode laser from Digi-Key (part no. 0220-832-00). Inexpensive He/Ne lasers cannot be used because their laser cavities usually do not contain a polarizing element and therefore the output polarization is not constant. To prevent damage to any diode laser be sure to use the correct voltage power supply and the correct polarity when powering up. The case should be grounded to prevent damage from buildup of static electricity. Grounding can easily be accomplished by removing any rubber from the laser-positioning clamp to allow the metal clamp to touch the metal case of the diode laser. Laser pointers, owing to their construction, have the added benefit of not needing to be grounded in this fashion. CAUTION: Laser light is intense. Do not look directly into a laser beam.

An ideal location for this demonstration is a room that can be made completely dark and that allows space for students to walk completely around the setups. The tube containing the optically inactive medium (distilled water) should be tested for scatter visibility in the classroom where it will be observed. Because of the need for complete darkness, this demonstration may only be visible in specific settings. The necessity of complete darkness may be avoided by using a 635-nm diode laser (part no. 0220-832-00 from Digi-Key). Although such a laser is more expensive, its high visibility allows the room to be partially lit.

Turn off the room lights and power the laser. Carefully orient the laser path so that the beam travels vertically up the column (Fig. 5). Be sure that the laser beam travels straight up the tube and does not bounce off the sides (internal reflection) as it travels upward. Owing to the need for complete darkness, a flashlight is a useful guide for orienting the laser and for movement around the room. Once the correct orientation is achieved, move around the tube until you can see a bright line of scattered light traveling all the way up the tube. Then move 90° around the tube, and a large portion of the line of light that is perpendicular to your line of sight will disappear. Continue to move around the column and after a further 90° the line will reappear. Therefore, with the optically inactive medium there will be two positions with respect to the column where an intense scattered line can be seen (separated by 180°) and two positions where no scattered light will be seen (also separated by 180°). The scattered light is most likely due to dust in the distilled water. To improve viewing of this part of the demonstration, an extremely small amount of nondairy creamer (a few granules per liter) can be added to the distilled water. Nondairy creamer is an excellent nonfluorescent scatterer and allows the typical Rayleigh light scattering pattern discussed above to be more easily seen.

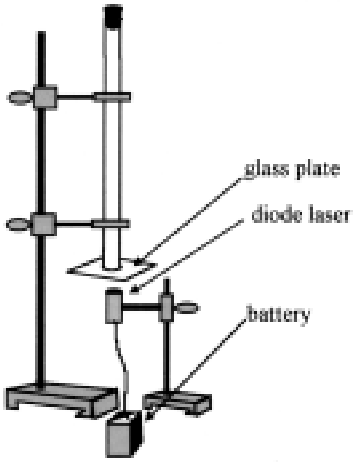

Figure 5. The sealed tube is clamped vertically and the diode laser is positioned vertically through the sealed tube.

The tube containing the optically active medium should also be tested for scatter visibility in the classroom where it will be observed. Turn off the room lights and turn on the laser. Orient the laser path in the same way as for the optically inactive setup. Once the correct orientation is achieved and your eyes have become accustomed to the dark, you should observe bright regions separated by about five inches as you view the tube from top to bottom. Because at first it is often difficult to see the bright and dark bands, we photographed the setup containing the optically active medium with the room lights on (Fig. 6) and off (Fig. 7). Allowing your eyes to become dark-acclimated and viewing perpendicular to the tube or from a few feet away may enhance viewing. Try walking slowly around the setup; a bright (or dark) band may be followed as it spirals around the tube.

Procedure

For instructional purposes this demonstration is divided into two parts. In part 1 students observe scattered light from the optically inactive medium. In part 2 they observe the scattered radiation pattern from the optically active solution. Before carrying out Part 1 it is beneficial to demonstrate that the diode laser is inherently highly polarized. Setting a single polarizer directly on top of the diode laser and rotating the polarizer may do this. The transmitted laser light can be observed to change from an intense maximum to a barely visible minimum. Indicate to the students that the polarizer is therefore not needed, since the diode laser light is highly polarized.

In Part 1 of the demonstration, students view and walk around the setup containing the optically inactive compound. Relate to them the predictions of the scattering intensity made by Figures 2 and 3 and what they actually observe. Have them stand in fixed positions around the setup. Ask them to predict

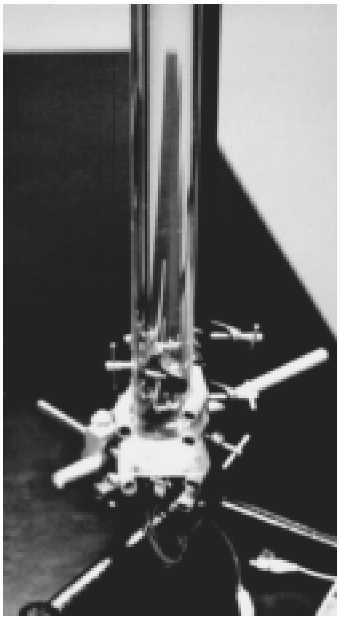

Figure 6. The bottom portion of the demonstration setup containing the optically active medium is shown in this photograph with the room lights on.

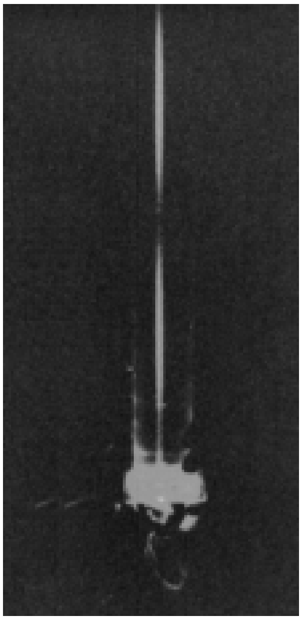

Figure 7. The bottom portion of the demonstration setup containing the optically active medium is shown in this time-resolved photograph with the room lights off.

what will happen if you rotate the laser. Does the direction of rotation matter? After getting a consensus, carefully rotate the laser to test their predictions.

In Part 2 of the demonstration, students view and walk around the setup containing the optically active compound. Relate to them the predictions of the scattering intensity made by Figures 2 and 4 and what they actually observe. With the students in fixed positions ask them what will happen if you rotate the laser. Is the direction of rotation an important factor? Test their predictions by carefully and slowly rotating the laser in the corresponding direction.

Discussion

Fluorescent tube lamp guards are clear and consist of polycarbonate. Lamp guards are used in this demonstration instead of glass tubing because they offer an inexpensive and accessible alternative to large-diameter glass tubing of similar size. The lamp guards used in this demonstration were approximately 117 cm long and 4 cm in diameter. Plumber's Goop was used instead of epoxy because Plumber's Goop was easier to work with and, in this case, made a better seal than epoxy.

The optically active medium chosen was a high-fructose corn syrup manufactured by Karo. While there are many more optically active compounds that could have been chosen, corn syrup was chosen because students are familiar with it, it is readily available, and it can remain in the column for long periods of time. The optically inactive medium chosen was distilled water. To save time it may be a good idea to have two diode lasers, one for each part of the demonstration. With two lasers, class time spent aligning the laser in the optically active medium can be avoided.

The purpose of the #9 stoppers placed at the end of the tubes is to enhance viewing by lowering the amount of scattered light. The stoppers can be removed to allow the laser light to pass through each solution and shine on the ceiling. The patterns seen on the ceiling reveal the expected planar and nonplanar nature of the light passing through the water and corn syrup, respectively.

This demonstration brings Rayleigh scattering directly into the organic or physical chemistry classroom. It allows students to observe and manipulate (through rotation of the laser) Rayleigh scattering in both optically active and optically inactive systems. It is an excellent tool for introducing students to the rotation of polarized light and the directional radiation pattern of an oscillating dipole.

Acknowledgments

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Notes

1. A variety of inexpensive diode lasers may be purchased from Digi-Key; call 800/344-4539 for a catalog.
2. Proper clamps may be purchased from Sargent-Welch, 800/727-4368, Part nos. WLS19226, WLA8304.

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