The Verdet Constant of Light Flint Glass

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(Dated: May 1, 2003)

Some optically inactive materials can become optically active by placing them in a high magnetic field. The optical activity of the material causes planes of polarized light to rotate. The angle of rotation is proportional to the product of the magnetic field, path length through the sample and a constant known as the Verdet Constant. The goal of the lab was to measure the Verdet Constant for a sample of light flint glass and to compare its value to a theoretically calculated value. The experimental value was $V = (4.13 \pm 0.04) \cdot 10^{-6} cm^{-1} G^{-1}$ while the theoretical value was $V = 1.18 \cdot 10^{-5} cm^{-1} G^{-1}$. A literature value for 578.0 nm was found to be $V = 1.00 \cdot 10^{-5} cm^{-1} G^{-1}$. Discrepancies between the three values can be attributed to a non-uniform magnetic field in the area where the sample was placed and play in the cross-polarizer/analyzer used.

I. INTRODUCTION

Chiral compounds are compounds in which their molecular mirror image is not superimposable on itself. For carbon compounds this usually results from a carbon atom having four different substituents bonded to it. Many introductory organic chemistry textbooks describe how a chiral compound will rotate a plane of polarized light through a given angle and that can be used as an identification technique between enantiomers (same molecular formula but they differ in their chirality). One enantiomer will rotate the plane of light in a positive direction while the other enantiomer rotates the light the same magnitude of degrees but in the opposite direction. [1]

Rotations of polarized light are not just limited to chiral compounds. Michael Faraday discovered in 1845 that when some optically inactive materials are exposed to high magnetic fields they will rotate the plane of polarized light. Unlike chiral compounds the rotation in the positive or negative direction is dependent on whether the incident light is traveling parallel or anti-parallel to the direction of the magnetic field. This effect can be seen in solids, liquids or in gases but is exaggerated the most in gases. [2, 3]

One of the concepts to understand behind the Faraday Effect is the Verdet Constant which is specific to each sample (much the same way that the molar absorptivity of a substance is specific to the substance). The Verdet Constant "is defined as the rotation per unit path per unit field strength." [3] It also acts as a proportionality constant between the angle of rotation and the product of the magnetic field and path length through the sample. The goal of the experiment was to measure the Verdet Constant for the light flint glass sample and compare it to a theoretically calculated value.

II. THEORY

The Faraday Effect is a magnetoptical effect in which a plane of polarized light is rotated as it passes through a medium that is in a magnetic field. The amount of rotation is dependent on the amount of sample that the light passes through, the strength of the magnetic field and a proportionality constant called the Verdet Constant. The Verdet constant is the proportionality constant between the angle of rotation θ of plane polarized light and the product of the path length l through the sample and the applied magnetic field B. More explicitly, the Verdet constant is the proportionality constant in Eq. (1).

$$\theta = VlB \tag{1}$$

The theory underlying why the Faraday Effect works lies in the quantum mechanical realm but can be understood on a more basic level using classical electrodynamics. The precession of the angular momentum of an electron orbiting the nucleus leads to different indices of refraction for rightly or leftly polarized light. This leads to a rotation of plane polarized light. To understand better how the Faraday Effect works, a classical electrodynamics approach gives an expression for the Verdet constant that is a function of the wavelength of light used in the experiment (the wavelength in a vacuum) and the change in index of refraction per change in wavelength. Thus our end-goal is Eq. (2) where e is the charge on an electron, m is the mass of an electron, c is the speed of light, λ is the wavelength of light and n is the index of refraction of the medium. [4]

$$V = \frac{e}{2mc} \lambda \frac{dn}{d\lambda} \tag{2}$$

III. EXPERIMENTAL

To determine the Verdet constant for light flint glass a 38 mm sample of the glass was placed in a high magnetic field and the rotation of plane polarized light measured. This was accomplished using a pair of Cenco electromagnets that were powered by a Kepco ATE 100-10M Power Supply. A Keithley 175 Multimeter was connected in series to the electromagnets to monitor the current output of the power supply and thus be able to determine a relationship between the current and the magnetic field throughout the sample. A Melles Groit HeNe laser beam of 632.8 nm wavelength passed through a polarizer, the magnets with the sample in the center and through the cross-polarizer/analyzer as seen in Fig. 1. The poles had a hole of approximately 6 mm that allowed the laser light to pass through. A sheet of white paper placed close to the cross polarizer was used to help detect the minima in the transmitted light.

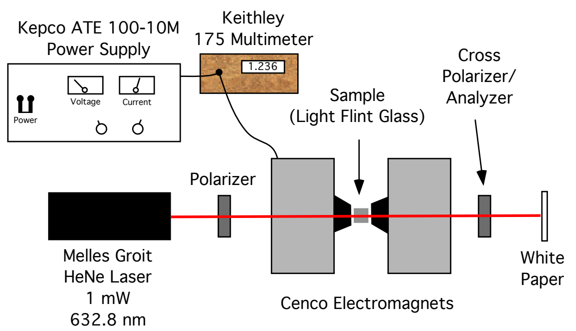

FIG. 1: A schematic of the setup used to measure the Verdet Constant.

The electromagnets did not produce a uniform magnetic field throughout the space in which the sample was placed. To determine the magnetic field that the sample experiences an Applied Magnetics Laboratory, Inc. Gaussmeter GM1A was used to measure the magnetic field in Gauss at the center of the two poles for several currents and for two currents, 3 A and 7 A, the magnetic field was characterized at nine points throughout the space between the two poles. This was then used to determine an average magnetic field experienced by the sample.

The light flint glass data was taken by first centering the glass between the poles. Then the laser was turned on and the alignment checked to make sure that the beam did not hit the cylindrical hole present in the center of the piece of glass. The water used to cool the electromagnets was turned on so that a steady flow of water was flowing. The power supply was turned on and the current was slowly raised to the desired value. At each current value, from 1 A to 8 A, the rotation of the plane of polarized light would be measured by the cross-polarizer by rotating it until a minimum in the transmitted light could be determined on the white sheet of paper.

IV. RESULTS

Since electromagnets are used to generate the magnetic field for the experiment, a correlation between the current supplied to the electromagnets and the measured magnetic field in the space between the poles needed to be deduced. The magnetic field at the center of the poles was measured at each integer current between 1 and 8 A (known to 1 mA) and an unweighted linear curve was fit to the field strength vs. current data:

$$B = -51.8 \pm 11 + (747 \pm 2.1)I \quad (3)$$

This equation was used to convert the applied current data into magnetic fields.

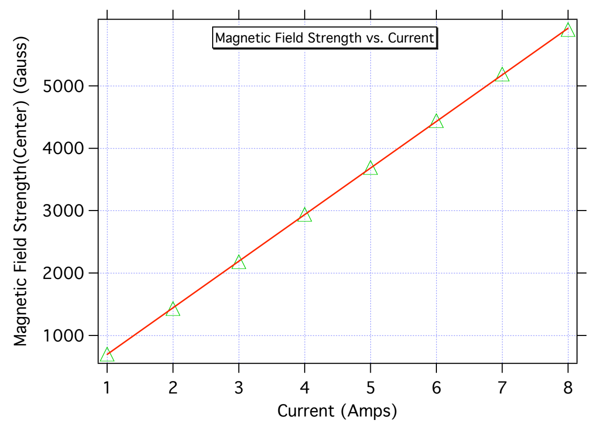

FIG. 2: A plot of the field strength vs. the current.

The magnetic field between the poles is not constant and so to characterize the variations in the magnetic field, at two currents, nine data points were taken at equal spacings between the poles. A plot of the relative field strength B/B_o where B is the field strength at the position it was measured (for example, 10mm to the left of center) and B_o is the field strength in the center of the poles. This plot showed that for most of the distance between the poles, the relative field strength followed a parabola with a minimum near the center of the poles. This plot, Fig. 3 shows the two sets of relative field strengths as a function of position and that they are close to being coincident which indicates that the magnetic field varies the same percentage independent of the current applied. To find an average value for the magnetic field that the sample experiences, a parabola was fit to the 3 A data. The data used was those in between $x = -15\ mm$ and $x = 15\ mm$ since the two outer edge points show that the field levels off and since most of the sample lies within the cursors, a curve fit to those data points is justified. By integrating the resulting function over the spatial interval and dividing by the interval an average value for the magnetic field experienced by the sample is 1.08 times the value of the magnetic field in the center. An uncertainty of 0.07 was assumed for the average value of the magnetic field.

The data for the angle of rotation vs. the current applied lends insight into whether or not the Faraday Effect is being observed. This data can be found in Table I. Since the angle of rotation increases as the current is increased and as current is increased the magnetic field increases linearly, the Faraday Effect has been observed in this experiment.

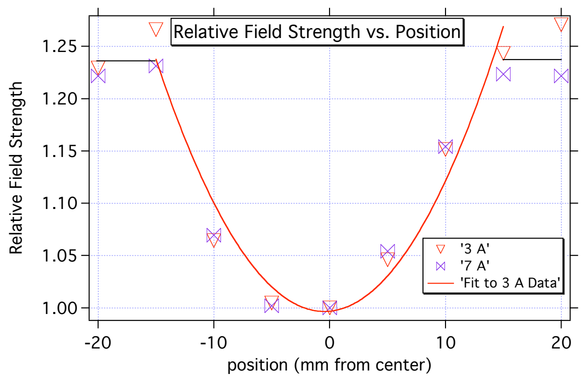

FIG. 3: A plot of the relative field strength $B(x)/B(0)$ vs. position between the poles used to find an average value of the magnetic field experienced by the sample.

TABLE I: Table of applied currents and the measured angle of rotation.

Current (A)	θ (rad)
1.000	1.10
2.000	1.10
3.000	1.13
4.000	1.15
5.000	1.16
6.000	1.17
7.000	1.17
8.000	1.19

V. ANALYSIS AND DISCUSSION

With a relationship between current and magnetic field established with Eq.(3), the current values from Table I can be converted to magnetic fields with an associated error. The uncertainty in B comes from the averaging of the magnetic field over the space between the poles. The uncertainty in the θ measurements was taken to be a constant value of 0.01 radians (a good estimate of the play in the cross analyzer) and magnetic field error was not propagated into the theta error. Error in the current supplied by the power supply is negligible as drifts of less than a milliamp were noted. A plot of the angle of rotation vs. the magnetic field is seen in Fig. 4 along with the error and associated unweighed linear fit. The equation that fits the theta vs. magnetic field data is found in Eq. (4).

$$\theta = 1.091 \pm 0.006 + \left((1.57 \pm 0.15) \cdot 10^{-5}\right) \overline{B} \qquad (4)$$

The Verdet Constant can be evaluated from the slope of the line.

$$V = \frac{1}{l}\left(\frac{\Delta\theta}{\Delta\overline{B}}\right) \qquad (5)$$

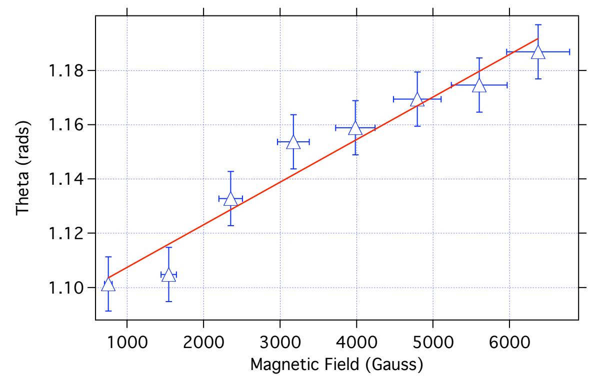

FIG. 4: A plot of the angle of rotation of the plane of polarization vs. the magnetic field with an associated linear fit.

Thus by multiplying the slope by the inverse of the path length $l = 3.8cm$ yields the Verdet Constant.

$$V = (4.13 \pm 0.04) \cdot 10^{-6} cm^{-1} G^{-1} \qquad (6)$$

A relative uncertainty of 9.6% was obtained thus making the uncertainty in $V = 0.40 \cdot 10^{-7} cm^{-1} G^{-1}$. This value can be compared to a theoretical value by evaluating Eq. (2) with determined values for the index of refraction at a given wavelength. The type of glass used in the experiment was light flint glass but the magnitude of the calculated Verdet constant for light flint glass $V = 1.18 \cdot 10^{-5} min/G\ cm$. This value was determined by plotting known indices of refraction vs. the wavelength of light used. [5] An unweighted power curve fit was done for the data to get an equation to describe the behavior of the index of refraction n_d as a function of the wavelength of light λ.

$$n_d = 1.56 + 8083.6\lambda^{-2} \qquad (7)$$

To arrive at the Verdet constant from Eq. (7) the derivative of Eq. (7) was calculated and evaluated at 632.8 nm. This value of the derivative was substituted into Eq. (2) and then converted from minutes of rotation per Gauss centimeter $(min/G\ cm)$ to radians per Gauss centimeter $(rad/G\ cm)$. A value for $e/2mc$ was taken from source [4] as 1.0083. This theoretical value is $1.18 \cdot 10^{-5} min/G\ cm$. The CRC value for the Verdet Constant of light flint glass was not listed for 632.8 nm but was present at 578.0 nm which yields an approximation of the actual value of V at 632.8 nm. This value for the Verdet Constant was $V = 1.00 \cdot 10^{-5}\ rad/G\ cm$. [5]

VI. CONCLUSIONS

The effects of the rotation of plane polarized light are used everyday especially by organic chemists who use the optical properties of chiral compounds for identification purposes. Less used is the magnetically induced optical activity seen in the Faraday Effect. In the lab, the Faraday Effect was demonstrated in a sample of light flint glass and the value of the Verdet Constant established to be $V = (4.13 \pm 0.04) \cdot 10^{-6} cm^{-1} G^{-1}$. The application of a magnetic field cause the glass to become optically active and as the magnetic field increased the angle of rotation increased.

In the future, the Faraday Effect could be explored in a number of different ways. The first would be to choose a different sample such as a liquid, for which the Verdet Constant is known and find a way to increase the accuracy and precision of the apparatus used in order to get experimental values to match better with known values. Besides measuring the Verdet Constant of another material, it would be interesting to measure the index of refraction of a material by knowing its Verdet Constant but using different wavelengths of light (different color lasers) to determine $\lambda(dn/d\lambda)$.

VII. REFERENCES

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