MEASUREMENT OF THE VERDET CONSTANT FOR A PREVIOUSLY UNCHARACTERIZED FUSED QUARTZ GLASS

By

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A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College.

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ABSTRACT

SAMYUKTA KRISHNAMURTHY: Measurement of the Verdet constant for a previously uncharacterized fused quartz glass.
(Under the direction of Dr. R. Kroeger)

The objective of this experiment is to measure and analyze the Verdet constant for Corning 7980, a fused quartz glass with no previously published Verdet constant data. This quartz glass is being used at the Belle II experiment at Tsukuba, Japan.

The Verdet constant is measured using the Faraday effect – a magneto-optical phenomenon that describes the rotation of the plane of polarization of light within a medium in the presence of an external magnetic field. This experiment quantifies the rotation of the plane of polarization with respect to the wavelength and the magnetic field. Data collected through this experiment depicts a linear relation between the angle of rotation and the magnetic field. A linear relationship is also established between the Verdet constant and $\lambda \frac{dn}{d\lambda}$ where λ is the wavelength and n is the index of refraction for the glass rod. The Verdet constant is determined to be:

$$V = -\left[-0.6787 \pm 0.1400 + 0.81195 \pm 0.0152 \times \frac{e}{2mc}\lambda\frac{dn}{d\lambda}\right]$$

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

1. MICHAEL FARADAY

Born on September 22nd, 1791, Michael Faraday was a British physicist and chemist who contributed significantly to the study of electromagnetism and electrochemistry. Raised in a relatively poor family, Faraday only received basic education; at the age of 14, he became an apprentice to a bookbinder. This gave him an opportunity to read about a wide range of scientific subjects. After seven years, upon completing his apprenticeship, he was appointed by Humphry Davy to the position of a chemical assistant at the Royal Institution. He worked on several experiments with Davy and other scientists at the Royal Institution. In 1821, he published his work on electromagnetic rotation. Ten years later he discovered electromagnetic induction. During his lifetime, he rejected the offer to become the president of the Royal Society twice and turned down a knighthood, both on religious grounds. However, he did accept a house in Middlesex, England that was later known as the Faraday House. He lived there for 19 years, until his death in 1867. (Gladstone 1872)

2. THE FARADAY EFFECT

The first experimental evidence that showed that light and electromagnetism were related to each other was the Faraday Effect. On September 13th, 1845, Michael Faraday, in his diary[1] recorded his discovery:

"BUT, when the contrary magnetic poles were on the same side, *there was an effect produced on the polarized ray*, and thus magnetic force and light were proved to have relation to each other. This fact will most likely prove exceedingly fertile and of great value in the investigation of both conditions of natural force." (#7504, September 13th, 1845)

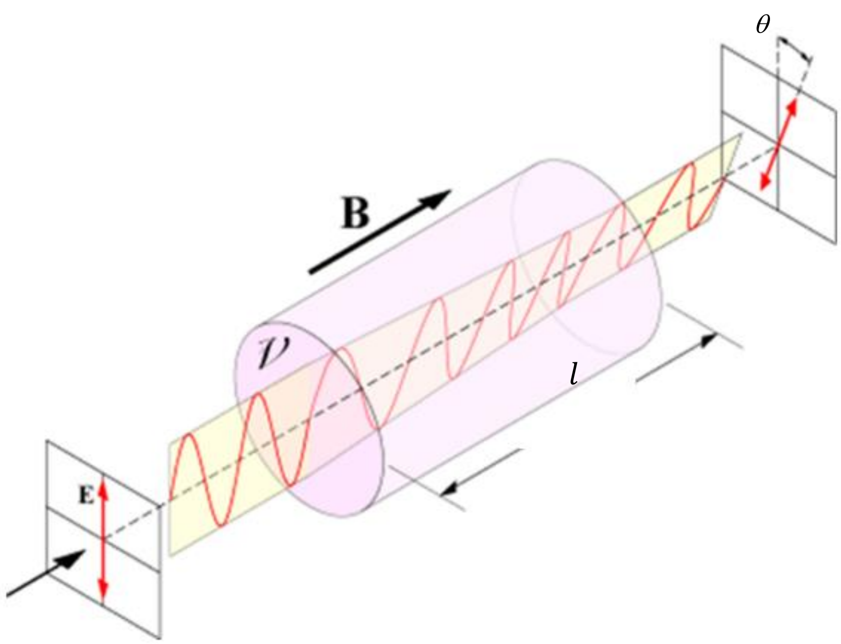

Figure 1 Rotation of the plane of polarization of light within a medium due to an external magnetic field. (Holmarc Opto-Mechatronics Handbook for the Faraday apparatus)

[1] Faraday kept an extensive record of all his experimental findings and wrote numerous letters to fellow physicists and chemists, manuscripts of which have been fortunately preserved by the Royal Institution of Great Britain.

Faraday discovered that when ‘heavy glass’ is subjected to an external magnetic field it becomes optically active. When plane-polarized light passes through this glass, parallel to the external magnetic field, there is a rotation in the polarization angle (Figure 1).

This rotation depends on the strength of the magnetic field and the distance traveled by the light within that medium. It is given by the simple relationship

$$\theta = B\ l\ V \qquad (1)$$

Where θ is the angle by which the plane of polarization of the light rotates (in radians), B is the uniform external magnetic field (in Tesla), l is the length of the glass (in meters) and V is the Verdet constant. The Verdet constant is characteristic of the medium and is defined as the rotation of the plane of polarization per unit length per unit magnetic field (Jenkins and White 1976).

II. MOTIVATION: THE BELLE II EXPERIMENT

The Belle ll Experiment is a particle physics experiment conducted by the Belle Collaboration, an international collaboration of more than 400 physicists that are investigating charge-parity violation (CP violation) at the High-Energy Accelerator Research Organization in Tsukuba, Japan (KEK). The experiment allows us to probe for new laws of physics and the mystery behind the disappearance of anti-matter from the early universe.

1. THE BELLE II DETECTOR

Electrons and positrons collide to form B mesons that decay into a large number of lighter particles including kaons, pions, electrons, muons and photons. This decay is recorded by the Belle detector, which is eight meters in height, depth, and width (The Quest for New Physics 2014). Following is a list of the various sub-detectors:

- Vertex Detector: To assist in tracking; to provide information on the location of the primary interaction point and the location of decay points or vertices for heavy quarks.
- Central Drift Chamber: To track charged particles and measure their charge and momentum.
- Electromagnetic calorimeter: To measure the energy of incident particles and identify electrons and photons.

- Aerogel Ring imaging Cherenkov Counter: Particle identification by Cherenkov radiation.
- Time of Propagation (iTOP) counter: Particle identification by Cherenkov radiation.

In order to identify new particles or to study new physics, reconstruction of the entire event is extremely crucial. To do this, one must be able to identify all the long – lived daughter particles produced in the interaction. A common method to identify a particle is through its mass which is possible if the velocity and the momentum of the particle are known.

2. THE IMAGING TIME OF PROPAGATION DETECTOR

One of the sub-detectors, the iTOP counter, works specifically towards the identification of kaons and pions. The iTOP counter is a quartz bar that is 2.7 m long, 0.45 m wide and 2 cm thick. It is instrumented with 16 micro-channel plate photomultipliers (MCP-PMTs) on a prism at the readout end of the bar (Figure 2) (The Quest for New Physics 2014).

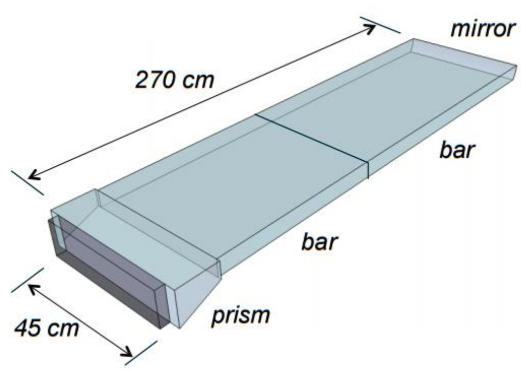

Figure 2 iTOP Quartz bar

When kaons and pions travel through the iTOP they give off Cherenkov photons. When charged particles travel faster than the speed of light within a medium, they give off Cherenkov radiation at a particular angle known as the Cherenkov opening angle (Figure 3) given by the equation:

$$\cos\theta_c = \frac{1}{\beta n} \quad \text{Where } \beta = \frac{v}{c} \tag{2}$$

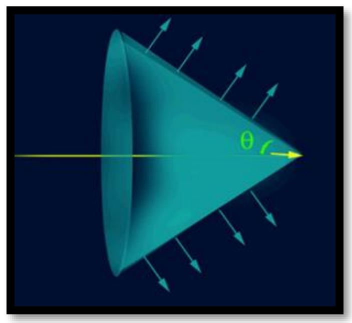

Figure 3 Cherenkov Angle θ_c (Courtesy of the Belle II collaboration)

The kaons and pions have different masses and hence have different velocities as they travel through the quartz glass. The Cherenkov radiation given off by these particles is at different Cherenkov opening angles depending on the speed of the particle. As the radiation travels through the quartz glass it is trapped and channeled by total internal reflection. It reaches the MCP-PMTs at different times depending on the opening angle (Figure 4).

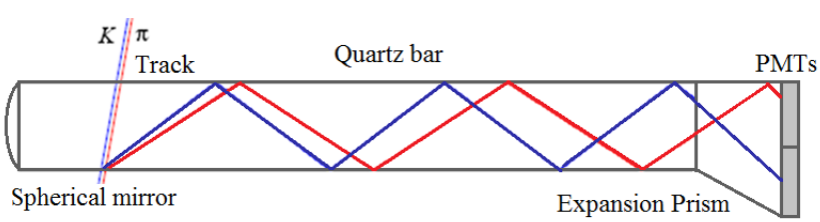

Figure 4 Cherenkov radiation as it travels through the quartz bar

The counter detects the time of propagation of the radiation with remarkable precision and thus distinguishes between the two particle species (Figure 5). The red arrow in Figure 5 indicates the path of the particle as it passes through the TOP counter.

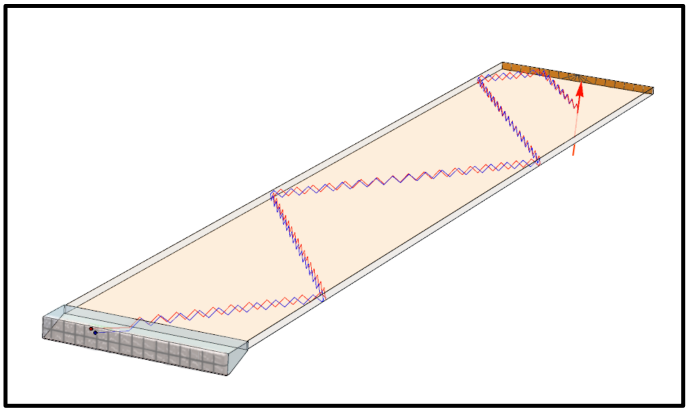

Figure 5 Cherenkov photons propagating through the quartz bar given off by the kaons and pions with different times of propagation.

A 1.5 Tesla magnetic field exists within the iTOP that causes a change in polarization angle of these Cherenkov photons. The collection efficiency of the MC-PMTs in the iTOP has a strong dependence on the polarization state of the photons. To achieve a better understanding of the photon collection efficiency, the polarization state of theses photons need to be considered. This research project determines the rotation of the polarization angle of the Cherenkov photons, within the iTOP, due to the external magnetic field.

3. THE EFFECT OF THE FARADAY EFFECT

When plane polarized light enters the quartz glass – in the presence of an external magnetic field, it is decomposed into two elliptically polarized states that rotate in the opposite directions (right-handed and left-handed). The two elliptically polarized states have different indices of refraction and travel through the quartz glass at different velocities. The vector sum of the two states is still linearly polarized, but they undergo a net rotation due to their different velocities (Jenkins and White 1976) (Kroeger, et al. 2015).

The dependence of the Verdet constant on the different indices of refraction of the counter rotating elliptically polarized states is given by:

$$V_B = \frac{\omega}{2n_0cB}(n_-^2 - n_+^2) \tag{3}$$

Where V_B is the Verdet constant, ω is the frequency of the light, n_0 is the refractive index of the medium, B is the magnetic field, $n_+$is the refractive index of the right-handed polarization state and n_- is the refractive index of the left-handed polarization state (Jenkins and White 1976).

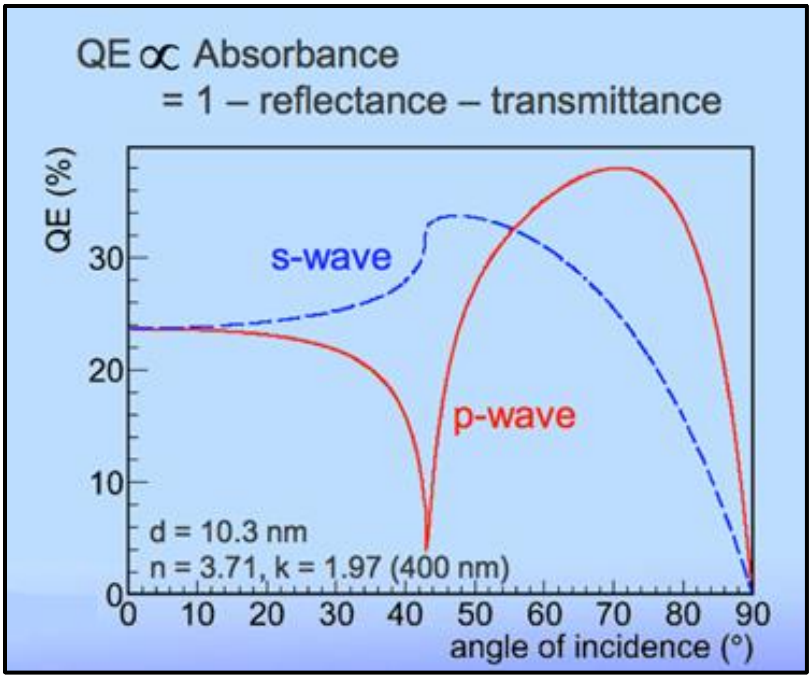

Figure 6 The polarization dependence of the collection efficiency of the Micro Channel PMTs as a function of incidence angle (Courtesy Belle II Collaboration)

As the graph suggests (Figure 6), the change in incident angle has a drastic effect on the collection efficiency of the MC-PMTs. There also exists a strong asymmetry for the transverse electric and transverse magnetic component of the photon polarization for the collection efficiency of the MC-PMTs. Since most photons that are detected by the PMTs undergo total internal reflection, their incident angles are close to the critical angle. This critical angle, unfortunately, is 43^{o} , the angle close to which the collection efficiency (%QE) falls to 7% for the transverse magnetic wave (Kroeger, et al. 2015).

Monte Carlo analyses that have been developed by the Belle II Collaboration to date do not account for the Faraday effect. Knowing the polarization states of the photons and integrating it into the Mote Carlo analysis will give us a better understanding of the photon collection efficiency, therefore aiding in very precise particle identification.

III. METHODOLOGY

1. EXPERIMENTAL SETUP

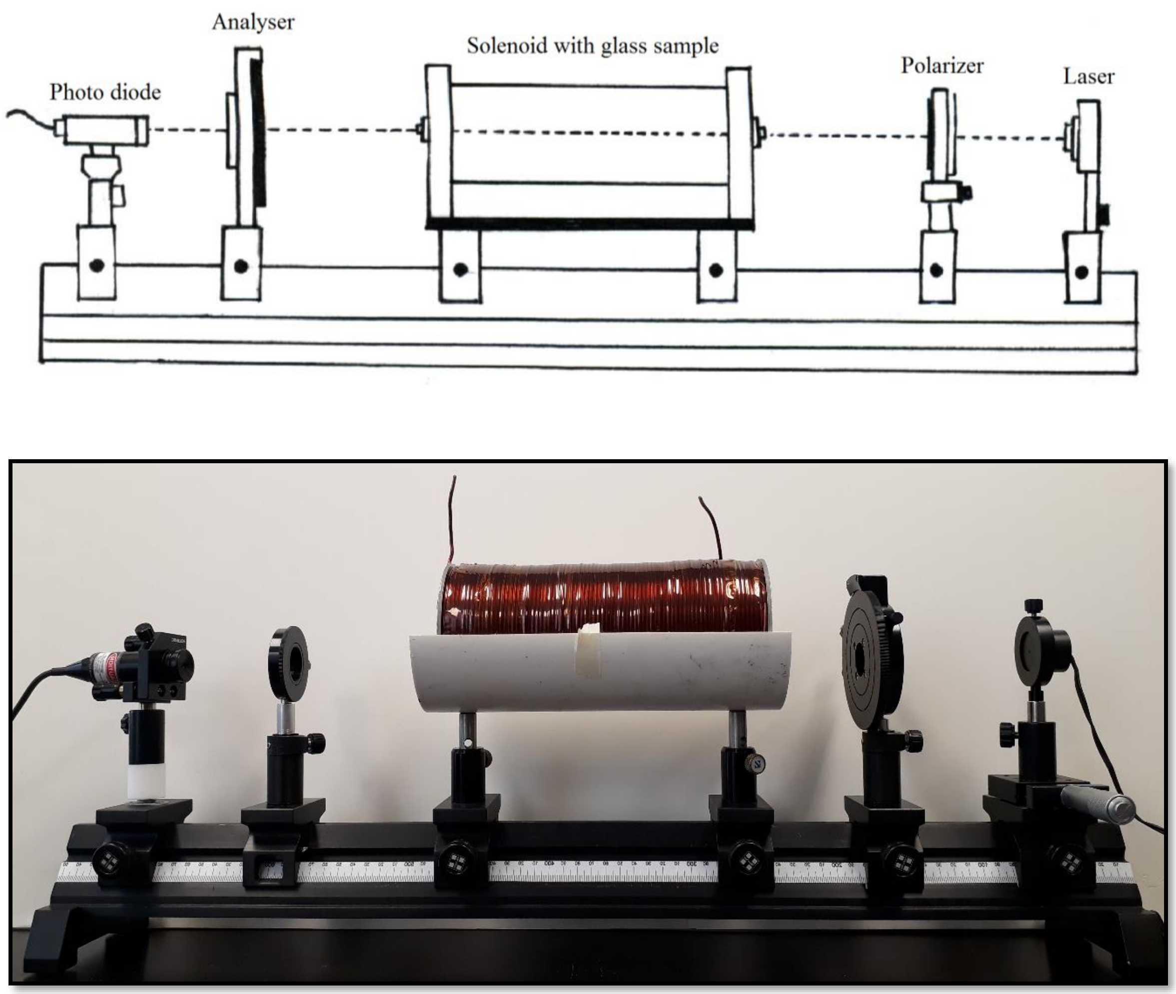

Figure 7 (Top) Graphical representation of the setup. (Bottom) Actual Experimental Setup

The experimental setup (Figure 7) used to accurately measure the Verdet constant was partially constructed by the machine shop at the physics department. An apparatus set was purchased from Holmarc Opto Mechatronics Pvt. Ltd and parts of the apparatus were replaced to improve the experiment's precision.

The experimental setup is comprised of the following parts:

a. Lasers

   Four different lasers were used to study the wavelength dependence of the Verdet constant. Two of the diode lasers (650 nm and 532 nm) were provided as a part of the apparatus. The two other diode lasers were purchased from Thor Labs (447 nm and 405 nm). The study of the Faraday effect in the shorter wavelengths is crucial since most of the photons detected in the iTOP are near the ultraviolet region of the spectrum.

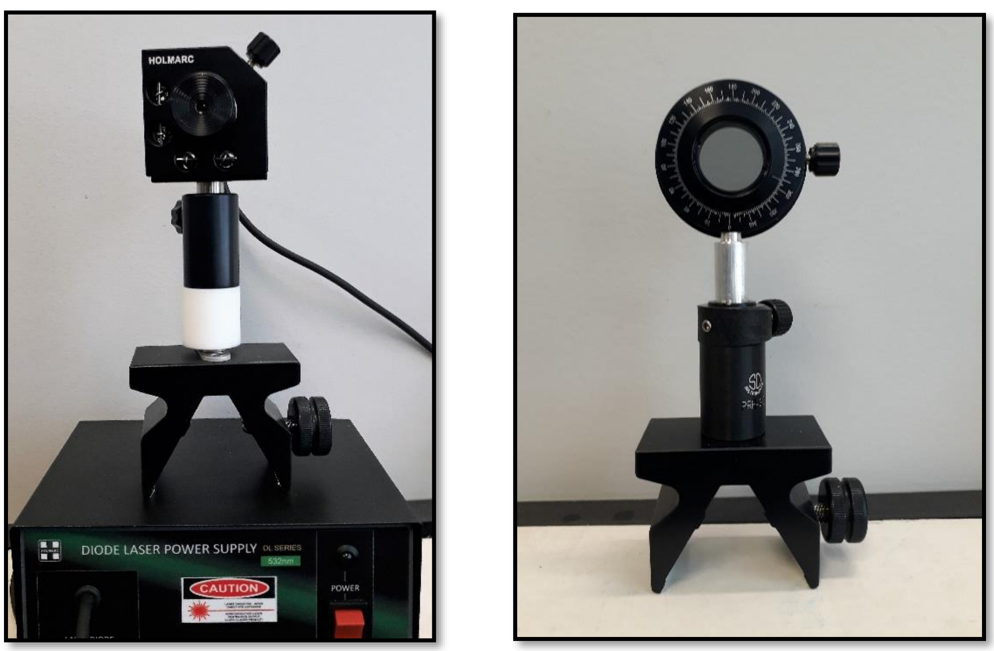

Figure 8 (Left) Diode Laser. (Right) Polarizer

b. Polarizer

The polarizer was used to plane polarize the light before it entered the quartz rod. Since the diode lasers were slightly polarized, the angle of the polarizer was chosen such that maximum amount of light was allowed to pass through the glass.

c. The Solenoid

Two solenoids (Figure 9), approximately 21 cm in length were constructed in the machine shop in the Physics Department. For the smaller solenoid, 22-gauge wire was tightly wound around the metal spool with an average of 150 turns per row. There were 15 rows, each insulated from the next using temperature resistant Kapton tape. This was to prevent the quartz glass from heating up. The larger solenoid was built similarly, this time using 10-gauge wire. The solenoid created a relatively uniform magnetic field and the quartz glass was placed within it.

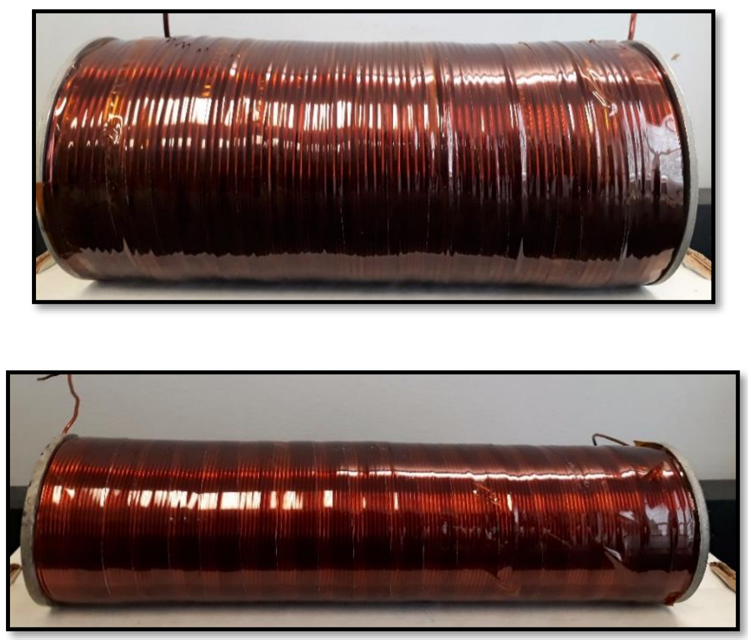

Figure 9 (Top) Large Solenoid built with 10 - gauge wire. (Bottom) Small solenoid built with 22- gauge wire

d. The Quartz Sample

The quartz sample is a very specific fused silica – Corning 7980, the same material with which the iTOP is built. This specimen was bought from Creator Optics Inc. (China). This material was chosen by Belle due to its properties such as uniformity in refractive index, low stress birefringence values, large size capabilities, exceptional transmittance from the deep ultraviolet through the infrared region, and an ultra-low thermal expansion coefficient. The quartz glass sample was wrapped in black paper for thermal isolation and to prevent light from leaking.

Figure 10 Corning 7980 quartz glass wrapped in black paper

e. The Analyzer

The analyzer is another polarizer with a precision angular adjustment disk with a least count of 0.1 degrees per division and was used to measure the polarization angle of the light after the light passes through the quartz glass. Although the analyzer was equipped with a Vernier scale, it was not used for making the measurements. This is further discussed in the error analyses section of the paper.

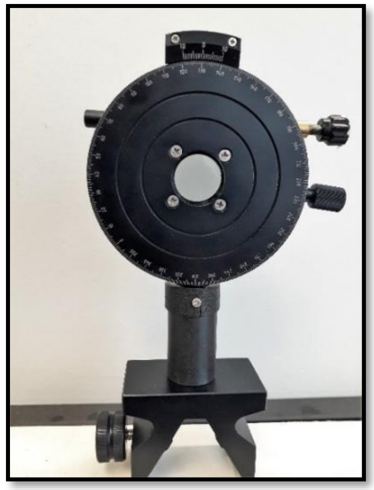

Figure 11 Analyzer

f. Pin-Hole Photo Diode and Output Instrument

The Pin-Hole photo diode is used to measure the intensity of light after it passes through the analyzer. Due to the lack of perfectly efficient polarizers, the minimum output recorded was never equal to zero. It ranged from 0.3 – 0.8 mA according to the pin-hole laser diaphragm and laser used.

Figure 12 Pin-hole Photo Diode with output instrument

g. Constant Current Power Supply

A precision constant current power supply was connected to the solenoid to produce a constant uniform magnetic field. The precise constant current mode on the power supply played a crucial role in data collection; without this mode, it would have been difficult to obtain a constant magnetic field. This instrument was a significant upgrade compared to the one provided in the apparatus set by Holmarc.

As the current that passes through the solenoid was changed, the magnetic field changed proportionally causing a rotation in the polarization angle of the light within the quartz glass. Further details of the experimental procedure are discussed in the next section.

2. EXPERIMENTAL PROCEDURE

The entire setup is aligned such that the light from the laser passes through the center of the quartz sample to the pin-hole photo diode. With the magnetic field turned off, the laser light is polarized by the polarizer and the analyzer is adjusted such that the photodiode shows minimum intensity. From the law of Malus, which states that ‘transmitted intensity varies as the square of the cosine of the angle between the two planes of transmission’:

$$I = I_0\, cos^2 \theta \tag{4}$$

where I is final intensity, I_0 is initial intensity, and θ is the angle between the polarizer and analyzer (Jenkins and White 1976). In theory, when the polarizer and analyzer are at 90^{o} to each other the transmitted intensity must be zero, however, due to the lack of perfectly efficient polarizers, this does not hold true. Hence the angle corresponding to the minimum intensity is chosen. This angle for the analyzer is recorded as $\theta_{0.}$ Now, when the current is turned on, there is a magnetic field within the solenoid causing the plane of polarization of the light to rotate. θ_0 is no longer the angle of minimum intensity; the analyzer is rotated to find the new minimum angle called θ. The difference between θ and θ_0 gives the rotation of the polarization angle in the presence of the magnetic field ($\Delta\theta$). This procedure is repeated multiple times for a particular magnetic field and the average is obtained. The average rotation is calculated for different currents and hence different magnetic fields. The process is repeated for the remaining lasers.

IV. RESULTS

1. ROTATION OF PLANE OF POLARIZATION VS. CURRENT

A plot of the change in rotation of the polarization angle with respect to current shows a very linear relationship between current and rotation of polarization angle. Since the current is directly proportional to the magnetic field, this graph (Figure 9) is in very good agreement with equation (1) $\theta = B\ l\ v$.

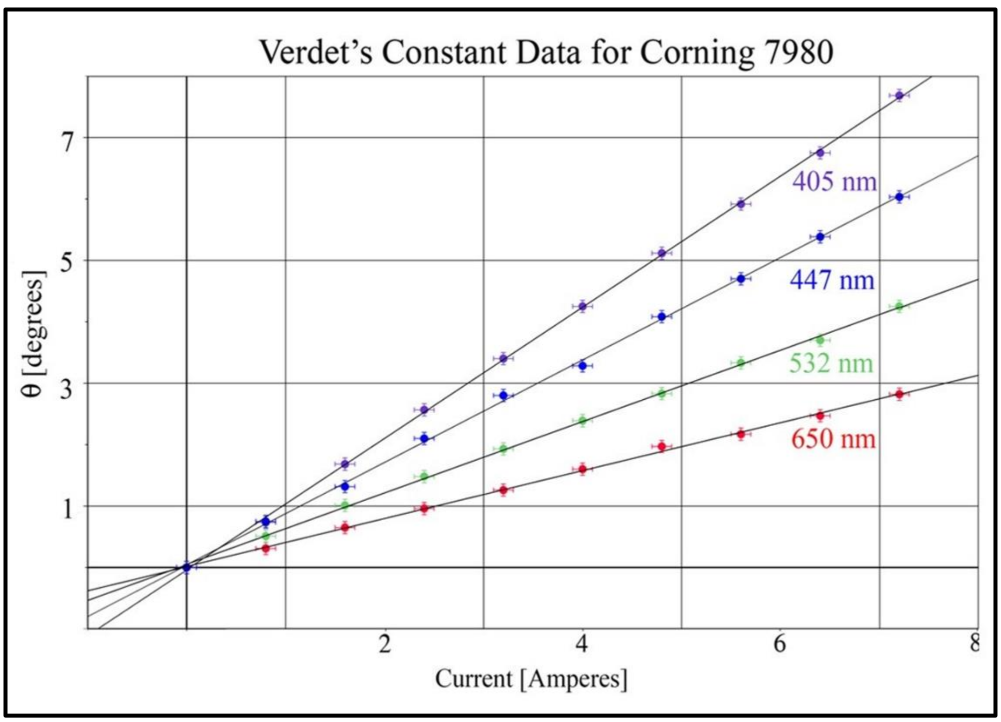

Figure 13 Rotation of polarization angle vs. current

The Verdet constants for the blue-violet laser (405 nm), blue laser (447 nm), green laser (532 nm) and red laser (650 nm) in Corning 7980 were calculated.

To determine the rotation more precisely, $\theta = B\ l\ \nu$ is replaced by

$$\theta = \nu \int B \cdot dl \tag{5}$$

Since the solenoid is not infinite, the equation $B = \mu n I$ needs a small correction for edge effects. Here B is the magnetic field, μ permeability of the medium, n is the number of turns of the coil per unit length and I is the current passing through the coil.

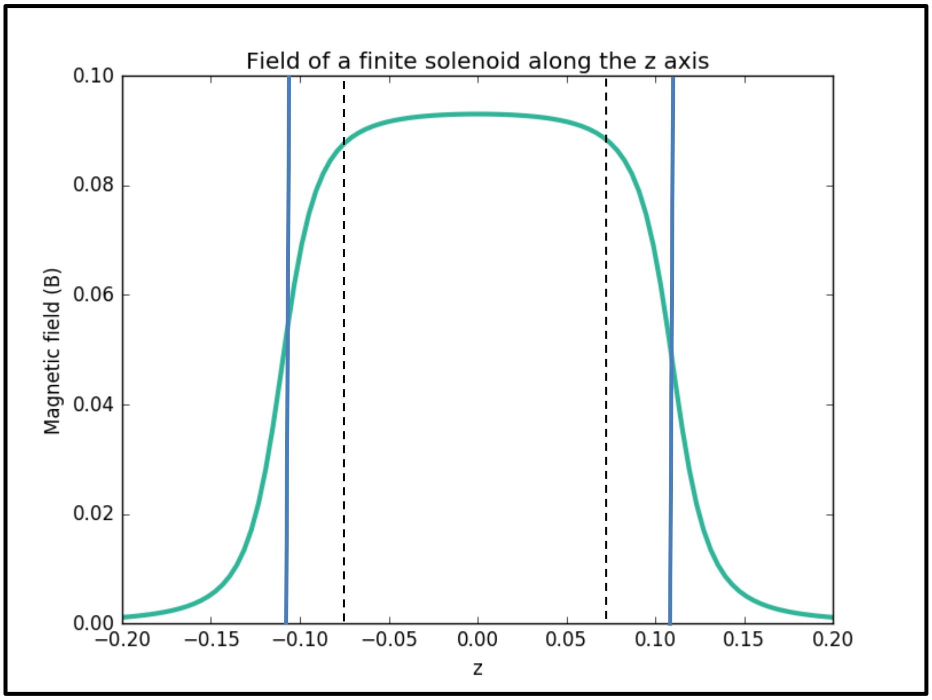

Figure 14 The magnetic field within the solenoid for the smaller solenoid along the z-axis. Blue lines indicate the length of the solenoid. Dashed lines indicate the length of the glass sample.

The graph shows a very uniform magnetic field along the z-axis except at the ends of the solenoids (Figure 14). The magnetic field within the solenoid was determined using the results observed in the paper by Muniz, Bhattacharya and Bagnato. A downward correction of 3.3% was made to our value $\int B \cdot dl$ using the equations found in the same paper.

The equations provided by Muniz et al. are adapted to this experiment and the magnetic flux is calculated for each of the fifteen layers of the small solenoid and summed up to obtain the $\int B \cdot dl$. This is also repeated for the larger solenoid where the flux is summed up for the 14 layers.

2. BECQUEREL FORMULA

In the Faraday Effect section of this paper, we attributed this rotation in the plane of polarization of the light to the different indices of the left and right-handed components of light. This difference in indices can be explained using the Zeeman effect. Using this analysis Henry Becquerel derived an equation for the Verdet constant:

$$V = \frac{-e}{2mc} \lambda \frac{dn}{d\lambda} \tag{6}$$

Where V is the Verdet constant, λ is the wavelength, e is the charge of an electron, m is the mass of an electron, n is the index of refractive index of the medium. The magnitude of the Verdet constant is better predicted if a material dependent fudge factor γ is used in the Becquerel Equation. This is called the 'magneto-optic anomaly' with values close to 0.7 - 0.8 for fused quartz glass (Kroeger, et al. 2015).

$$V = \gamma \frac{-e}{2mc} \lambda \frac{dn}{d\lambda} \tag{7}$$

The Verdet constants were plotted with respect to λ, as shown in Figure 15. The magneto-optic anomaly is assumed to be 0.75. Since the data falls below the prediction in the longer wavelengths, a newer form for the Verdet constant equation has been explored. (This deviation of measured Verdet constant from the prediction in the longer wavelength has also been observed by other authors such as Tan and Arndt in their measurement of the Verdet constant for a silica glass called Supracil W2).

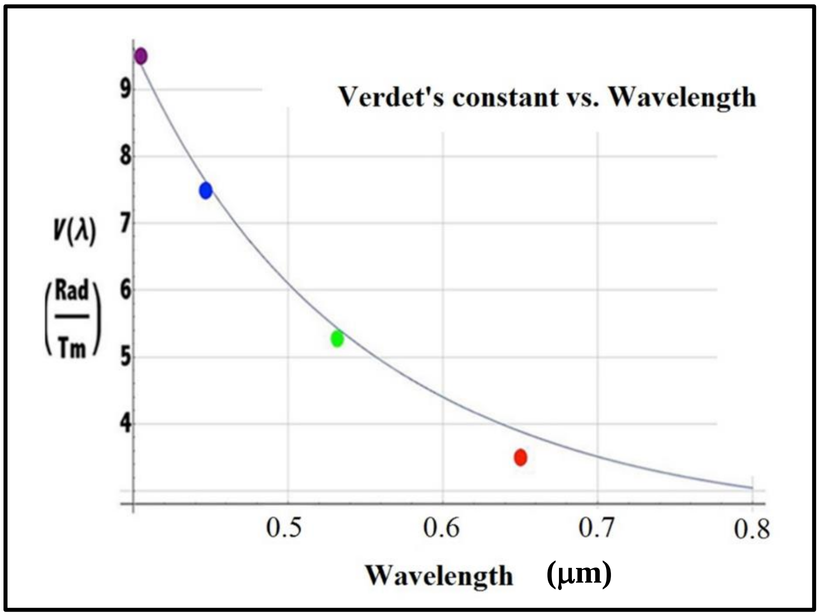

Figure 15 Verdet Constant vs. Wavelength

To find a better approximation, the Tan and Arndt model suggests an additional constant 'a' in the Becquerel equation.

$$V = a + \gamma \frac{-e}{2mc} \lambda \frac{dn}{d\lambda} \tag{8}$$

The Verdet constant is also plotted against $\lambda \frac{dn}{d\lambda}$. As predicted by equation (8), there is a linear relationship between the Verdet constant and $\lambda \frac{dn}{d\lambda}$ and a non-zero intercept term 'a' (Figure 16).

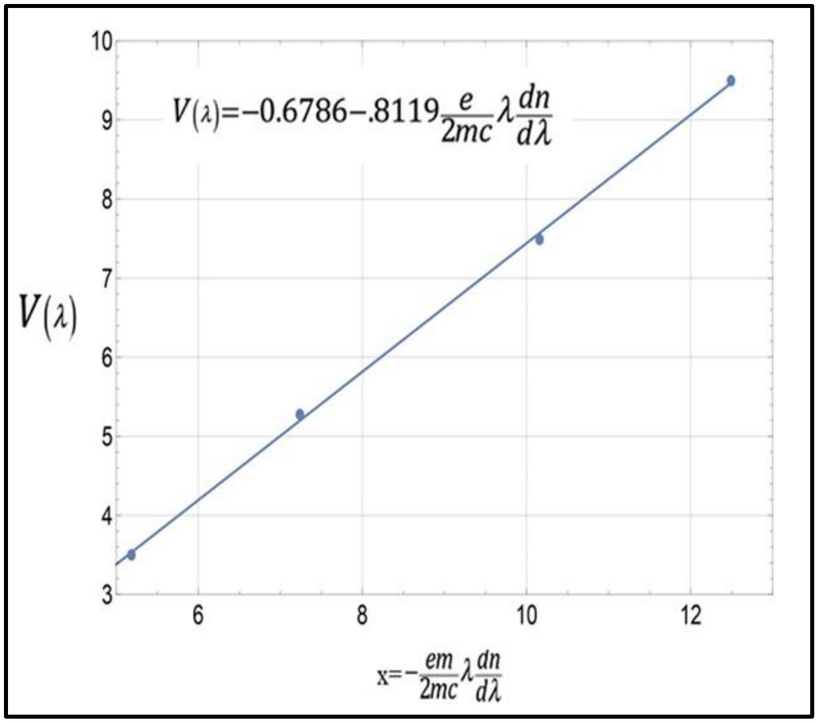

Figure 16 Quasi-empirical Equation as predicted by Tan and Arndt.

Verdet constant as a function of λ vs. λ dn/dλ

3. FINAL EQUATION

The paper by C.Z. Tan and J. Arndt yields a quasi-empirical equation for the approximate the rotation in the polarization axis in the iTOP. Using the Verdet constants data we obtain the following:

$$V = -\left[-0.6787 + 0.81195 \times \frac{e}{2mc}\lambda\frac{dn}{d\lambda}\right] \tag{9}$$

V. ERROR ANALYSIS

1. THE ANALYZER.

The precision rotation analyzer in the experimental setup was used to determine the angle of minimum intensity. The scale on the polarizer has a resolution of 0.1 degrees. The Vernier scale on the polarizer was not used; a camera was focused on the smaller Vernier scale (Figure 17) and the angle that coincided with the zero was recorded. This was because the Vernier scale was constructed incorrectly; 9.7 divisions on the Vernier scale corresponded to 10 divisions on the main scale instead of 9:10.

Unfortunately, the minimum detected intensity was spread over a range of angles. To determine the median angle, the lowest and highest angle for which the intensity remained a constant minimum value was recorded and the average was calculated. These were termed as θ_L (Left) and θ_R (Right) respectively.

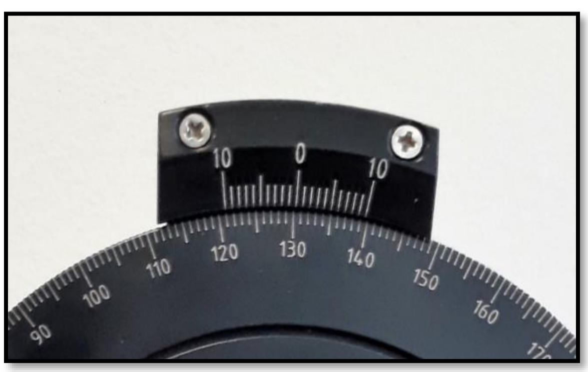

Figure 17 Vernier scale on the analyzer

2. TEMPERATURE DEPENDENCE OF THE VERDET CONSTANT

The larger solenoid was constructed with 10-gauge wire and each row was separated with heat resistant Kapton tape to prevent heat dissipation. When the current was increased to 25A or more and allowed to pass continuously, there was a significant increase in the temperature of the solenoid. Leaving the setup turned on for longer periods of time with higher currents may lead to a significant difference in the angle of rotation. In order to prevent this, all measurements were performed when the solenoid was 'cold'. The setup was allowed to cool for 10-15 minutes before the next measurement was taken and measurements that required higher currents were taken multiple times over several days to check for consistency.

3. ERROR PROPAGATION IN $\int B \cdot dl$

A part of the uncertainty in the measurement of the Verdet constant is due to the magnetic field within the solenoid. The main causes for error in the $\int B \cdot dl$ could be the following:

a. Efforts were made to place the sample in the center of the solenoid. Inevitably, there could be some degree of shift along the z-axis.

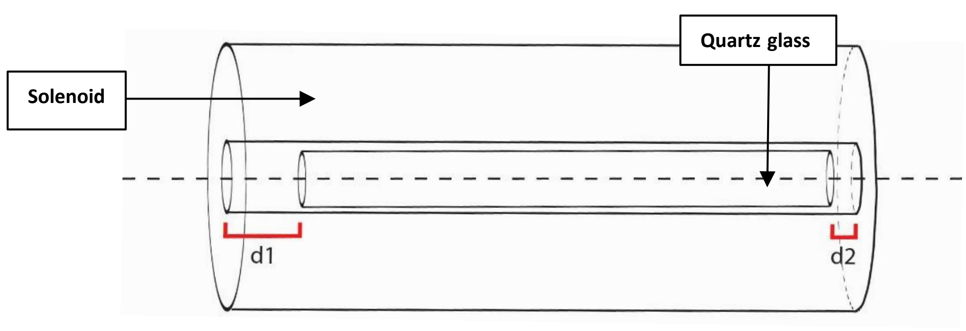

Figure 18 The sample is placed off center

b. The point at which the light enters and exists the glass rod is given by (s, z); where s is in the radial direction and z is along the axis. In an ideal experiment, the point of entry and exit would be (0, 0). However, a shift from this central position would contribute to the error in the magnetic field experienced by the light.

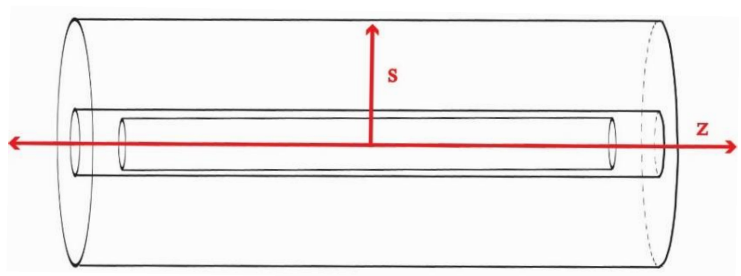

Figure 19 (s, z) coordinates to determine the points of entry and exit for light

The standard deviation in the $\int B \cdot dl$ is given by the following equation.

$$\sigma_{\int B \cdot dl} = \sqrt{2\left(-\frac{\partial \Phi_{in}}{\partial s}\right)^2 \delta s^2 + \left[-\frac{\partial \Phi_{in}}{\partial z} - \frac{\partial \Phi_{out}}{\partial z}\right]^2 \delta z^2} \qquad (10)$$

The partial derivatives of Φ are calculated using the equations provided by Muniz et al. The error due to offset in z is 1.35×10^{-2} %. The error due to offset in s is 1.7×10^{-3} % and the error due to alignment in θ is 1.16×10^{-2} %. This gives us a total error in the alignment and positioning of 1.79×10^{-2} %.

4. POWER SUPPLY:

The high precision power supply in the constant current mode has a less than ±10 mA error in the current output. This brings the error to 0.139% when a maximum current of 7.2 A was passing through the solenoid.

5. LIGHT FROM REFLECTION:

Light reflecting from the faces of the glass sample travel through the sample two extra times before hitting the photo-diode and hence have a different polarization angle. About 4% of the light is reflected at each surface. The maximum rotation observed is about 7 degrees for 7.2 amps, this implies that the light after reflecting twice has rotated 21 degrees. The rotation due to the Faraday effect does not unwind on reflection. The error due to the light from reflection can be calculated as follows:

$$\frac{I_{contaminate}}{I_{desired}} = \frac{cos^2(21)\times 0.04\times 0.04}{cos^2(7)} \tag{11}$$

This value is calculated to be 0.142% of the light passing through the glass sample.

6. TAN AND ARNDT MODEL

The statistical errors in the calculation of the Verdet constant for the individual wavelengths are propagated into the Tan and Arndt model. The χ^2 for this linear fit is 2.90 with 2 degrees of freedom.

7. FINAL ERROR CALCULATION

The most significant sources of systematic error include the inaccuracy of the current supply and the light from reflections. When added in quadrature this sums up to a total of 0.199 % systematic error in the measurement. Taking the statistical error into account, the final equation now is given by:

$$V = -\left[-0.6787 \pm 0.1400 + 0.81195 \pm 0.0152 \times \frac{e}{2mc}\lambda\frac{dn}{d\lambda}\right] \tag{12}$$

VI. CONCLUSION AND FUTURE WORK

This research project successfully measured the Verdet constant for Corning 7980 at room temperature and verified that the Tan and Arndt model provides an excellent characterization of the Verdet constant for the Corning glass over the range studied.

There is a significant rotation in the plane of polarization especially in the shorter wavelengths. The following are figures are produced in a ray-tracing simulation indicating the difference in the predicted data in presence or absence of the magnetic field (Figure 20). Figure 20 (a) shows the model predictions for presence of kaon s (blue) and pions (green) with and without a magnetic field. Figure 20 (b) shows that the efficiency for photon collection at the prism end of the quartz bar and they have different polarization states when the magnetic field is on.

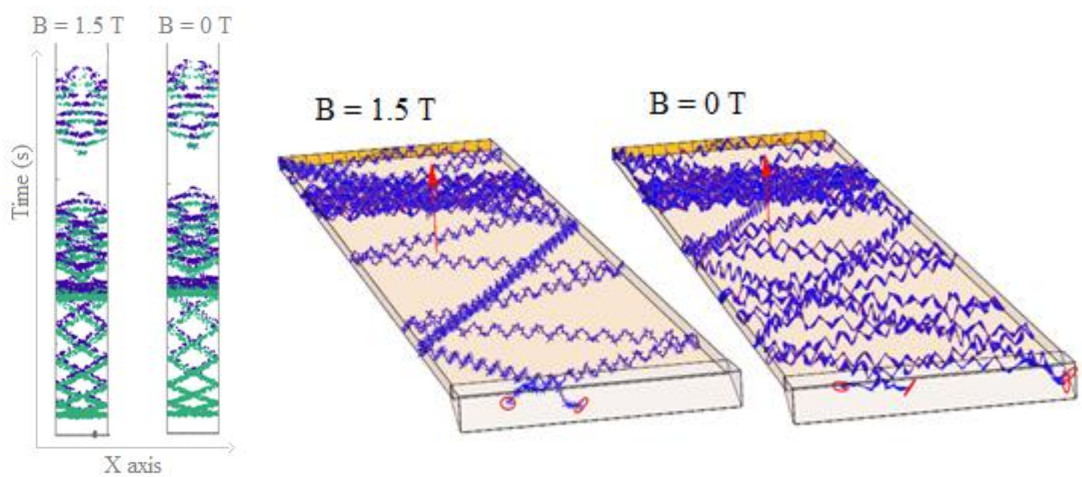

Figure 20 (a) – left and (b) – right. Comparing the data with and without magnetic field. (Courtesy Dr. R. Kroeger)

Considering the final polarization angle of the photons as they reach the photomultiplier tubes would certainly improve the understanding the efficiency with which the photons and hence the particles can be detected.

The future goal of this experiment is to extend the experimental setup in wavelengths as low as 340nm. Most photons in the glass bar in the iTOP are in this region of the spectrum, measuring the Verdet constant in the ultra-violet region of the spectrum to a tenth of a percent would be the goal.

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