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MEASURING GLASS THICKNESS OF A REFERENCE CELL USED IN A POLARIZED ^{3}HE EXPERIMENT

Nathan Justis, Jian-ping Chen

ABSTRACT

Studies of the spin structure of the neutron are often conducted using a polarized ^{3}He target due to its close spin resemblance to that of a free neutron. Experiments are conducted by bombarding polarized ^{3}He nuclei with high-energy electrons from a linear accelerator. The polarized ^{3}He gas is contained in a glass tube-like cell called the *target cell*. In addition to the target cell, a *reference cell* is also used for calibration purposes. The thickness of each cell must be accurately determined for the analysis of the scattering data of the experiment. The thickness of a reference cell was determined by using a tunable infrared laser to create a thin-film interference pattern by reflecting the laser light off of the glass cell. The intensity of the pattern is known to vary sinusoidally as the wavelength of the laser changes. Such variation was recorded as an array of numbers by a LabView program at 26 different points on the cell. Each of the 26 sets of data were fit to an equation containing the thickness variable to determine the thickness of the glass. The cell side, or *wall,* thickness ranged from 1.42 mm to 1.65 mm, with an uncertainty of less than 5% in every case. End, or *window*, thickness measurements were also successfully taken, but have yet to be fitted to the derived equation.

INTRODUCTION

Reference cells in a polarized ^{3}He experiment are needed because electron scattering results from more than just the electron/^{3}He interaction. The total electron scattering must be described in terms of scattering due to the ^{3}He nuclei, the glass, and the small amount of N_2 molecules that are in the target cell.

During an experiment, the reference cell sits below the target cell on a mobile ladder system. By moving the ladder up and down, the system can move the target cell, the reference cell, or any other target into the beam line for measurements. In this apparatus, the reference cell is attached to a vacuum pump, as well as to ^{3}He and N_2 gas bottles, which allows the cell to be filled with either of the two gases, or placed in a vacuum state [1]. When the cell is filled with ^{3}He or N_2 gas, researchers can measure the amount of electron scattering due to these gases in a target cell. With the cell vented and evacuated, measurements reveal how much electron scattering is due to the glass itself.

In addition to assisting in the characterization of the scattering data, the reference cell can be used to interpolate the pressure in the target cell. Because the pressure can be varied when filling the reference cell with either of the two gases, and most importantly, the ^{3}He gas, the amount of electron scattering can be observed at many different pressures in the reference cell. The pressure at which the amount of scattering in the reference cell matches that of the target cell can be used to estimate the pressure in the target cell [2].

Radiative Corrections

The thickness of a reference cell must be known to correct for energy loss of both the incoming and scattered electrons. As an electron passes through matter, such as glass, it loses energy in the form of electromagnetic radiation. If one can characterize the type and amount of matter the electrons passed through before and after the scattering, the necessary mathematical corrections, or *radiative corrections*, are possible [3].

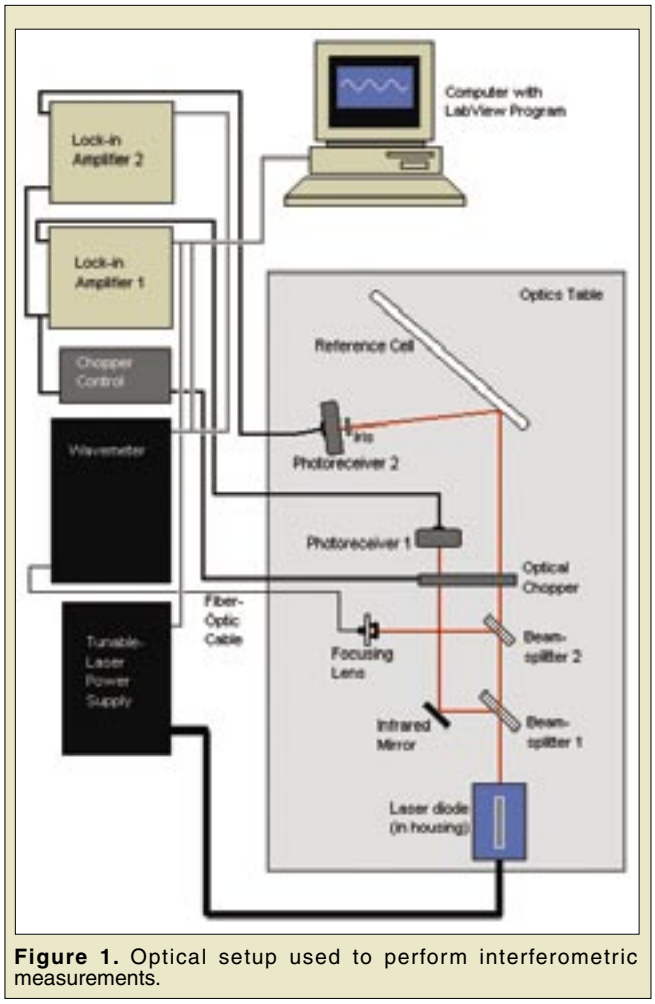

Figure 1. Optical setup used to perform interferometric measurements.

MATERIALS AND METHODS

Interferometry Review

When two sources of light are incident on the same surface, they interfere with each other either constructively, or destructively, depending on their relative phase. Interferometry is the application of coherent light interference principles to determine values such as thickness of a thin transparent material and surface integrity of a smooth surface.

In determining the thickness of a transparent material, or thin-film, laser light is set incident on the thin-film. As one wave front reflects off of the front surface, another will pass through the film and reflect off of the back surface of the film. This second wave front will then travel back through the film and the first surface and interfere with the first wave. Whether constructive or destructive interference occurs at a certain point depends on the optical path difference of the two waves, and hence, their relative phase [4].

Optical Setup

Applying principles of interferometry to actually measure the thickness of the glass cell was fairly complex and involved a number of steps. Twenty-six measurements were taken on the sides of the cell and analyzed. The instrumental setup used to take these measurements is shown in figure 1. This setup was used because of its previous success in measuring cell glass thickness at Jefferson Lab.

Infrared laser light from a tunable laser (New Focus 6300) was directed through a beam-sampler where ~10% was split off to an infrared mirror and then reflected through an optical chopper (New Focus 3501). The chopper converted the laser light to pulsed laser light with a pulse frequency of 1.4 kHz. After passing through the chopper, the light reached a photoreceiver (New Focus 2031) that was connected to a lock-in amplifier (PerkinElmer 7265) referenced to the chopper frequency. The remaining ~90% of the light was directed to a beam-splitter where ~50% of the light was split off and channeled down a fiber-optic to a wave-meter (Burleigh WA-1100) for wavelength measurement. The remaining ~50% from this beam-splitter continued through the same optical chopper set at 1.4 kHz. After passing through the chopper the light finally reached the glass cell.

An additional photoreceiver was placed in line of the interference pattern to measure its intensity. An optical iris was placed in front of this photoreceiver to assist in focusing on the small portion of the interference pattern desired for the measurement.

The signals from the two photoreceivers, each after passing through a lock-in amplifier, were sent to a computer and read by a LabView program. The measured wavelength of the light was also read by the computer through the wavemeter. Perhaps the key element of the setup was the tunable laser. As the wavelength of the laser was increased, the intensity of the interference pattern varied sinusoidally, going from wavelengths that provided for destructive interference to wavelengths that provided for constructive interference. A plot of Signal vs. Wavelength was created where "Signal" represents roughly the ratio of reflected light (measured by photoreceiver 2) to incident light (measured by photoreceiver 1) (see fig. 2).

The above setup was used to record data at 26 different points on the right and left walls of the cell. For each measurement, a location from the center of the cell was recorded in centimeters, as well as the angle of incidence used when taking the measurement. This angle was later used with Snell's Law to calculate the angle of refraction in the glass. Figure 3 displays the various points at which measurements were recorded.

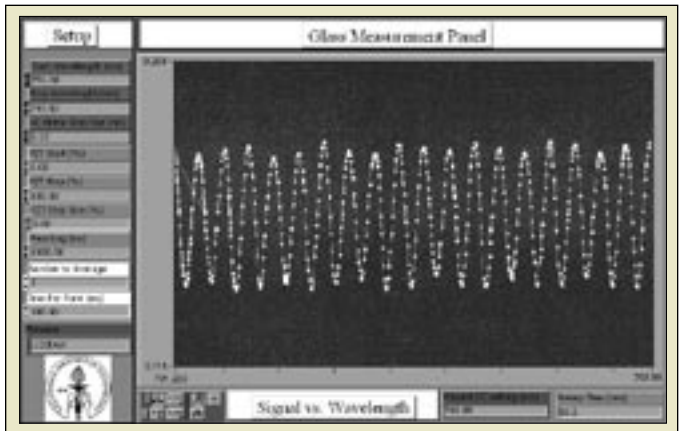

Figure 2. Graphical user interface of LabView program used to collect thickness data.

To take a measurement, many things had to be checked and verified in the system. For example, it had to be verified that the lock-in amplifiers were picking up and correctly reading the 1.4 kHz signals coming from the photoreceivers. This was done by checking that the amplifiers had settled on the signal of that frequency. Also, laser temperature stability had to be achieved before recording any data. Laser temperature was stable within 0.1 degrees Fahrenheit after just a few minutes of turning it on. The data collection software reminded the user to check for laser temperature stability before proceeding. Effects of changing the laser temperature were not studied.

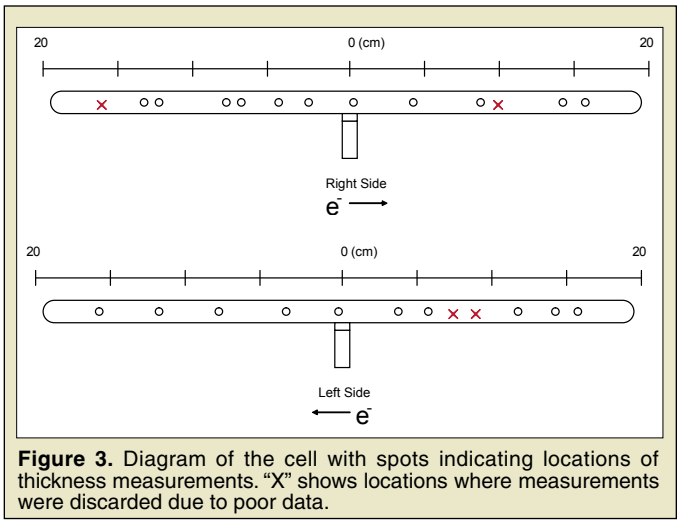

Figure 3. Diagram of the cell with spots indicating locations of thickness measurements. "X" shows locations where measurements were discarded due to poor data.

Once the instrumentation was functioning properly, preliminary measurements were taken. Because the search for a good signal often required many trials, the size of laser wavelength increments was increased to decrease the scan time required. To do this, a piezoelectric ceramic made from oxides of Lead (Pb), Zirconium (Zr) and Titanium (Ti), or PZT, step size was temporarily increased to 6.00%, and a DC motor step size to 0.30 nm [5]. The DC motor step size indicates the rough increment at which the wavelength was increased. The PZT step size is a percentage of the DC motor step size—basically a finer increment at which the laser wavelength was increased. When a final measurement was performed, the PZT step size was set at 3.00% and the DC motor step size at 0.15 nm. This final measurement took about 15-16 minutes to perform.

Obtaining a good signal required finding a good thin-film interference image. Clear interference images were found by slowly moving the cell in both a rotational and linear manner until distinct fringes in the image were discovered. The clearer the fringes were, the easier it was to obtain a good signal with the photoreceiver. The photoreceiver was placed in such a way that the fringes fell upon the photocell. Shifting the iris and photoreceiver around behind the image helped in discovering a section of the image that provided a good signal. When a good signal seemed particularly difficult to obtain, the iris and photoreceiver were pulled further away from the cell to allow the interference fringes to spread out. This way, the photoreceiver could be placed in a more specific area of the fringes. After each attempt, the iris and receiver were shifted a very small amount (approximately 1 mm) from left to right behind the image and a new practice signal was recorded.

Taking preliminary measurements involved taking a reading, shifting the cell and/or photoreceiver and iris, taking another reading, shifting again, taking another reading, etc., until the desired signal was discovered. A perfect signal would be one that is perfectly sinusoidal. Normally, however, an acceptable signal included some slight variation in the amplitude as the signal was recorded. A poor signal looked nothing like a sine wave. At this point, quality of a signal was simply determined by eyeballing it.

Once a good signal was found and recorded as a final measurement, the location measurements were recorded. A ruler was used to measure the location of the measurement from the center of the cell within +/- 0.3 cm, and a protractor was used to measure the angle of incidence within +/- 2 degrees. After the data were recorded along with a location and angle of incidence, they were fit to the following equation [4] by a computer program described below:

$$\frac{I_R}{I_i} = \frac{\dfrac{4\left(\dfrac{n-1}{n+1}\right)^2}{\left(1-\left(\dfrac{n-1}{n+1}\right)^2\right)^2}\sin^2\left(\dfrac{2\pi nd\cos\theta}{\lambda}\right)}{1+\dfrac{4\left(\dfrac{n-1}{n+1}\right)^2}{\left(1-\left(\dfrac{n-1}{n+1}\right)^2\right)^2}\sin^2\left(\dfrac{2\pi nd\cos\theta}{\lambda}\right)} \quad (1)$$

Here, I_R is the intensity of the reflected light, I_i is the intensity of the incident light, n is the refractive index of the glass, d is the thickness of the glass, θ is the angle of refraction, and λ is the wavelength. The refractive index for the cell, which was made of GE-180 Aluminosilicate glass, is known to be 1.536 [3].

The fit was improved by adjusting the thickness value in the programming code until the fit was reasonable; the fit was judged by the χ^2/ndf ratio. A fit was considered reasonable if this ratio was less than 6. Minimizing this ratio to improve quality of fit is a standard procedure in any fitting process. Using this method, the thickness associated with a measurement was determined to within 5% of the actual width.

Window Thickness Measurements

Only a few differences need to be noted concerning the measurement of the window thickness. Because the window thickness is about a factor of ten smaller than the wall thickness, the sinusoidal signal had a much longer period. The signal period for a window measurement was typically a little more than ten times the signal period for a wall thickness measurement. The original scanning range of 791 nm to 793.5 nm was increased to 791 nm to 799 nm in order to capture more than one signal wavelength. This

range typically provided for about four to five signal wavelengths in a window thickness measurement.

Another difference in measuring the window thickness involved the search for a good signal to record. The search for a good signal in performing a wall thickness measurement involved finding a clear vertical band of horizontal fringes, but the search for a good signal in performing a window thickness measurement required finding a circular pattern of interference fringes, which was expected because of the hemispherical shape of the windows. A clear circular pattern was discovered for each of the cell's two windows, and sinusoidal signals were obtained by placing the photoreceiver and iris at the center of these signals. Because the scan for a window thickness measurement covered 8 nm, as compared to the 2.5 nm for the wall measurements, recording signals took much longer—about 45 minutes. Practice scans were performed with a PZT step size of 40.0%, and a DC motor step size of 0.35 nm. Final measurements were performed using a PZT step size of 3.00%, and a DC motor step size of 0.15 nm, the same as when measuring the wall thickness.

Error Analysis

An uncertainty of less than 5% was desired to properly understand the error in calculating the radiative corrections for the associated experiments. Calculating the uncertainty required consideration of both systematic and statistical errors. The dominant systematic error involved determining the angle of incidence, and subsequently, the angle of refraction. The angle of incidence in (1) is the angle of refraction, however, so Snell's Law was used to calculate the angle of refraction. Afterwards the uncertainty was adjusted appropriately by finding the largest deviation in angle of refraction due to an increase or decrease of 2° in the angle of incidence. This value, 1°, was then used to find the largest deviation in thickness due to an increase or decrease of 1° in the angle of refraction when fitting the data. The largest deviation was 0.005 mm, or approximately 0.3% of the thickness. An uncertainty of 0.5% was used to be conservative.

Calculating the statistical error involved many steps. The data recorded by the optical setup was in a text file format. The program used to record the data performed two measurements with the laser at each step in the wavelength scan of the laser. A series of programs developed by Vince Sulkosky and Aidan Kelleher of the College of William and Mary, read the text files and output an array of the differences between the two values recorded at each wavelength and then produced a histogram of these differences and output a sigma value for the histogram. This sigma was later used as the signal error in the fitting the data to (1). Part of the fitting program found the minima and maxima of the fit and used these values to calculate the thickness. This was done by taking the difference between two adjacent minima (or maxima). The difference was then used to create another plot with all minima and maxima separated by this difference. The wavelength of this plot determined thickness. For example, a plot of the data with a fit equation containing five minima and five maxima would calculate eight different thickness measurements. A plot of these measurements with their statistical error bars was made and an average of these values was calculated. This average was the thickness of the glass at the specific location of measurement. The standard deviation of these values from the average was the statistical uncertainty of that thickness.

The systematic error was roughly 4% of the thickness, and the systematic error due to the angle measurement was 0.5%. Any other systematic error was considered negligible. When added in quadrature to give the overall error, the systematic error dominated. Only once was the overall error more than 5% of the thickness (see Table 1).

Wall Thickness Measurement Data

No.	File Name	Distance from center (cm)	Side	Thickness Uncertainty (mm)	Thickness Uncertainty (Percentage)	Notes
1	JanineL9up	8.6 up	L	-	-	discarded
2	JanineL8up	7.5 up	L	-	-	discarded
3	JanineL6up	5.5 up	L	-	-	discarded
4	JanineL6upII	5.5 up	L	1.421	0.056	
5	JanineL14up	14.4 up	L	1.55	0.048	
6	JanineL8down	8.0 down	L	1.484	0.061	
7	JanineL12down	11.8 down	L	1.517	0.058	
8	JanineL4down	3.7 down	L	1.437	0.059	
9	JanineL16down	15.7 down	L	1.497	0.073	
10	JanineLcenter	0.5 down	L	1.48	0.061	
11	JanineL12up	11.7 up	L	1.469	0.056	
12	JanineL16up	15.7 up	L	1.496	0.053	
13	JanineL3up	3.0 up	L	1.468	0.056	
14	JanineR14down	14.3 down	R	1.516	0.056	
15	JanineR2up	2.2 up	R	1.594	0.054	discarded
16	JanineR10down	9.8 down	R	1.556	0.149	discarded
17	JanineR9down	8.5 down	R	1.513	0.058	
18	JanineR4down	4.0 down	R	1.505	0.055	
19	JanineR16down	15.7 down	R	1.553	0.059	
20	JanineRcenter	0.0 up/down	R	1.603	0.055	
21	JanineR4up	4.4 up	R	1.605	0.055	
22	JanineR7up	7.0 up	R	1.555	0.057	
23	JanineR13up	12.5 up	R	1.654	0.055	
24	JanineR8up	8.0 up	R	1.571	0.06	
25	JanineR14up	13.5 up	R	1.622	0.056	

Table 1. Thickness measurements of the cell with associated locations.

RESULTS

Wall Results

Thirteen thickness measurements were taken on the left side of the cell, and thirteen were taken on the right side (see fig. 3). Five of these were not used due to the difficulty of fitting the sinusoidal equation to the data recorded at these five points. Wall thickness of the cell ranged from 1.421 mm to 1.55 mm on the left side, and

from 1.505 mm to 1.654 mm on the right side. Table 1 gives a complete listing of the thickness measurements acquired.

Window Results

Two thickness measurements were recorded on the down window of the cell, and one thickness measurement was recorded on the up window of the cell. These three sets of data have yet to be fit to the equation aforementioned. As displayed by the data recording program, the data recorded at these points appeared generally sinusoidal.

Comparison With Mechanical Measurements

Wall and window thicknesses of the cell had been previously measured mechanically at the University of Virginia (UVa) using a micrometer before the various sections of the glass tube were fused together. However, in order to make a more precise measurement, interferometric methods were required. The mechanical measurements give a range on the left side of 1.524 mm to 1.702 mm and an unweighted average of 1.592 mm (+/- 0.007 mm), whereas the interferometric measurements give a range of 1.421 mm to 1.55 mm and an unweighted average of 1.482 mm (+/- 0.058 mm). On the right side, the mechanical measurements give a range of 1.549 mm to 1.778 mm and an unweighted average of 1.676 mm (+/- 0.007 mm), whereas the interferometric measurements give a range of 1.505 mm to 1.654 mm and an unweighted average of 1.571 mm (+/- 0.064 mm). Furthermore, the mechanical measurements show that the right side is somewhat thinner near the down end. This difference is also seen in the interferometric measurements (see table 1). Difference between thickness on the right and left sides can be attributed to the different effects on the two sides from fusing the glass tubing together.

The window thickness measurements were also measured mechanically at UVa—0.137 mm on the upstream window (with unknown uncertainty), and 0.135 mm on the downstream window (with unknown uncertainty). No comparison is possible until the interferometric data taken on the windows is fit to the sinusoidal equation.

DISCUSSION AND CONCLUSION

Using interferometry and data-fitting to measure the thickness of thin glass is an adequately accurate method. Despite the uncertainty of the interferometric method, it still proves more reliable than the mechanical measurements taken before the completion of the cell because of the effects of the fusing during cell construction on glass thickness. This method involves many steps, however, and takes a fairly long time to complete. If a faster method were developed, just as accurate, it should be employed over the use of interferometry and data-fitting. However, the current setup at JLab can now be considered capable of performing both wall and window thickness measurements. This setup is highly convenient, since in the past cells were moved to another lab to perform window thickness measurements.

Finally, the author gives two simple recommendations. First, that the optics table upon which the measurements were performed be stabilized with pneumatic dampening legs in order to reduce vibration of the setup and background noise in the signal. Second, that a focusing lens be placed in the incident beam line to decrease the size of the beam spot and assist in obtaining a good sinusoidal signal for recording measurement data, especially when recording the window thickness, which is much smaller and more difficult to measure.

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