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Mott Scattering Measurements of the Spin Polarization of the NBS GaAs Electron Source

an internal report

by

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ABSTRACT

Measurements of the spin polarization of the GaAs electron source were carried out on the atom beam apparatus in the Electron Physics Group at the National Bureau of Standards. Both a cylindrical Mott analyzer operating at 100 kV ("Maximott") and a hemispherical Mott analyzer operating at 30 kV ("Minimott") were used. A calibration of the Minimott was carried out and compared with that of the Rice group. The following conclusions were arrived at:

(1) In December of 1986, the atom beam GaAs source had a polarization P_e of 0.2435 ±0.0074.

(2) Over a period of a year, from December 1985 to December 1986, the polarization fell by somewhere between 6 and 24% of its original value.

(3) Our calibration of the Minimott led to values of S_{eff}, the effective Sherman function, consistently lower than the Rice values, though there was marginal agreement considering the error estimates.

(4) Conclusion (3) is based on an absolute value for S_{gold} of 0.39 at 100 kV, 120° scattering angle, as used by the Rice group. This is a theoretical value, which has not been experimentally confirmed. Double scattering experiments have yielded a value for S_{gold} of 0.370 ± 0.008. This value for S_{gold} was used to determine the absolute source polarization.

(5) Taking into consideration the lack of knowledge of S_{gold}, the most conservative uncertainty estimate for P_e is ±0.015.

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I. Introduction.

The GaAs polarized electron source has been in use in the Electron Physics Group for almost 10 years. At present there are two operating sources - one used for surface studies (the polarized low-energy electron diffraction, or "PLEED" source) and one used for electron-atom collision studies (the "atom beam" source). The absolute value of the polarization of these sources has been a difficult but important concern since they were first put into use, though many useful results have been obtained which depend only on relative polarization measurements.

Historically, our knowledge of the polarization of the GaAs source has been rather strongly dependent on work originating in the polarized electron group at Rice University. The first measurements were done on the PLEED source using a "transfer standard" technique. The polarization of certain LEED spots from a tungsten crystal were measured at Rice and put on an absolute scale using Mott polarimetry. The same crystal was then installed in the NBS PLEED apparatus and the polarization of the source was inferred from the measured asymmetry. A polarization of 0.36 was obtained in this manner. This value was found to stay "constant" over a period of several years, independent of GaAs crystal changes and reactivations, as determined by periodically remeasuring specific values of scattering asymmetries.

A more direct way of measuring the electron beam polarization was clearly desirable, so an exact copy of a hemispherical, intermediate energy (20 - 40 kV) Mott analyzer from the Rice group[1] was constructed (the "Minimott"). This analyzer was installed on the PLEED apparatus and a polarization of about

0.27 was measured, using the calibration curves published by the Rice group. The difference between this value and the previous value of 0.36 remains unexplained.

The Minimott was then installed on the atom beam apparatus in May, 1985. A value of about 0.26 was obtained, again using the Rice calibration. After many reactivations and two crystal changes, the source was found to have a polarization of about 0.25 in December, 1985.

The various values obtained for the source polarizations led us to undertake the present study in the hope of explaining some of the differences observed. We constructed a 100 kV cylindrical Mott analyzer ("Maximott"), again based on a Rice design[2], and installed it on the atom beam apparatus. In principle, Mott scattering at 100 kV is "well understood", so one can hope to draw on established values of the Sherman function S_{gold} to obtain an absolute value of the electron beam polarization. Using the polarization obtained in this manner, a calibration of the Minimott was measured with the two analyzers connected in tandem.

This report contains a brief discussion of the operation of the atom beam GaAs source, a discussion of the Maximott measurements leading to an absolute determination of the electron beam polarization, a description of the use of the Minimott and its calibration, and some thoughts on the true value of S_{gold}. No attempt has been made to be brief, in the hope that by including as many details as possible the usefulness of this report will be enhanced. We apologize for any important details that may have been left out.

II. The Atom Beam GaAs Polarized Electron Source.

The GaAs polarized electron source installed on the atom beam apparatus was constructed on the basic principles outlined in the *Review of Scientific Instruments* article published by the Electron Physics Group in 1980[3]. A (100) GaAs crystal is heat-cleaned and then exposed to Cs and O_2 to create negative electron affinity at the surface. Photoemission is generated with circularly polarized light from a laser diode at 810 nm, and the resulting polarized electrons are formed into a beam with transverse polarization.

At the time the atom beam source was constructed, some minor "improvements" were included in the design. The resulting source has proven quite adequate for generating a large body of atomic scattering data, though its performance has not quite lived up to that of the PLEED source. The major difference between the two sources is that while the PLEED source requires reactivation only rarely (every six months or longer), the atom beam source needs to be reactivated about once every three to five days. The reason for this difference is still unknown and under investigation. Speculations as to the cause include vacuum contamination (the atom beam source has a base pressure of about 3×10^{-10} torr - quite adequate - but may have some unknown contaminant), or one or more of the minor modifications to the source geometry.

II.A Source activation.

Many (actually seven) activations were carried out over the period (10/22/86 - 12/30/86) during which the measurements described here were performed. All activations consisted of the same routine, and most resulted in roughly the same performance of the source. At no time was a single reactivation seen to significantly alter the polarization of the source.

The activations usually started with a pressure in the source of about 1×10^{-9} torr. During the period of the studies there was a little difficulty with outgassing from the transport electron optics coupling the Maximott to the main chamber, so the source chamber did not usually reach its ultimate base pressure. The GaAs cathode was radiantly heated by a filament (carrying about 4 A) to a temperature of 635°C, which took about 3-4 minutes. The temperature, measured with a thermocouple on the crystal mount, was strictly maintained at 635°C for five minutes by manually controlling the filament power supply and observing the temperature. During this time the pressure usually rose to somewhere in the range 0.5×10^{-8} to 3×10^{-8} torr. The cathode was then heated to 645°C and held there for two minutes, during which time the pressure usually rose by about another 20%. Heating was then discontinued and a flow of liquid nitrogen was passed through the cathode mount. This was continued until the cathode temperature reached 135°C (about 10 minutes), at which point the liquid nitrogen flow was replaced by a flow of dry nitrogen at room temperature.

When the cathode cooled to 50°C, the cesium reservoir (maintained at 90°C) was opened. After a minute or so, photoemission excited by a common high-intensity reading lamp aimed at the cathode began to be detectable. This

photoemission usually peaked at about 15 - 30 nA and then began to fall, after which the cesium was turned off and the oxygen was turned on to 9934 on the Granville-Phillips valve (this amount of oxygen was determined empirically as just sufficient to elicit a strong response in the photoemission current). The photoemission current then rose rapidly, and at this point an infrared pass filter (715 nm cutoff) was inserted between the light source and the cathode to make the measured current more sensitive to the degree of negative electron affinity. After going through several cycles of peaks with the oxygen on and subsequent peaks with the oxygen off, the photoemission current usually settled into a slow rise with a very small quantity of oxygen applied (9932 on the Granville-Phillips valve). In 30 - 45 minutes, the current usually levelled off at about 300 nA. At no time during the activation did additional cesium cause any increase in the photoemission.

The cathode was then moved into position over the laser diode and the photoemission current measured at 75 mA laser current, corresponding to about 1 mW of laser power. Typical emission currents ranged anywhere from 3 to 10 μA.

Without any further treatment of the cathode, the current could remain constant for several hours, though in some cases it was seen to fall within 20 minutes or so, and in others is was seen to last up to a day. There seemed to be some correlation between the lifetime of the cathode and the residual pressure in the chamber - the lower the pressure the longer the cathode lifetime.

After excessive decay of the photoemission current, good operation could usually be restored by heating a cesium dispenser channel mounted near the

cathode with about 4 A of current. In fact, the photoemission could routinely be held very constant for the better part of a day by contiuously heating the cesium dispenser with about 3.5 A. For the first 3 to 5 days after a reactivation, most of the original photoemission current could be maintained by leaving the cesium dispenser on during the day and turning it off at night. A current of 4 A first thing in the morning brought the current up to its nominal value (from an overnight low of essentially zero) and then a current of 3.5 A maintained it for the rest of the day. Each day the photoemission current reached when the dispenser was first turned on was a little less than the day before, until a reactivation was found to be necessary.

Though the cathode was reactivated periodically in a consistent manner, the variable nature of the resulting cathode performance made it impossible to ascertain that all measurements carried out on the polarization were conducted under exactly the same cathode activation condition. Nevertheless, at no time was the state of activation seen to cause any variation in the polarization of the electron beam. This was corroborated by earlier measurements on the PLEED source.

III. Maximott Polarization Analyzer.

The Maximott cylindrical polarization analyzer used in the measurements described here, shown in Figure 1, is based upon a design of the Rice group[2]. A similar design also has been used in Edinburgh[4]. It consists of two concentric cylinders with a gold foil scattering target at the center. The outer cylinder is maintained at about +1000 V with respect to the electron source cathode, and the inner cylinder is held at +100 kV. Incident electrons enter through apertures in the cylinders and strike the target normal to its surface with an energy of 100 kV. Electrons scattered through 120° pass through apertures in the cylinders on either side of the incident beam, and are detected by channeltron multipliers equipped with retarding apertures. Four gold foils of nominal thicknesses 750 Å, 1000 Å, 1250 Å and 1780 Å are mounted on a moveable stage to provide different scattering targets. The first three have a Formvar backing, and the thickest is free-standing.

Because of the Mott scattering effect[5], electrons with spin polarization "up" (i.e., parallel to the cylinders' axis) will scatter preferentially to the right, and electrons with spin "down" will scatter preferentially to the left. Thus the asymmetry in the detected count rates of the two multipliers, defined as

$$A = \frac{I^{left} - I^{right}}{I^{left} + I^{right}} , \qquad (3.1)$$

provides a measure of the polarization of the electron beam. A beam with polarization 1.0 will produce an asymmetry of S_{eff}, the effective Sherman

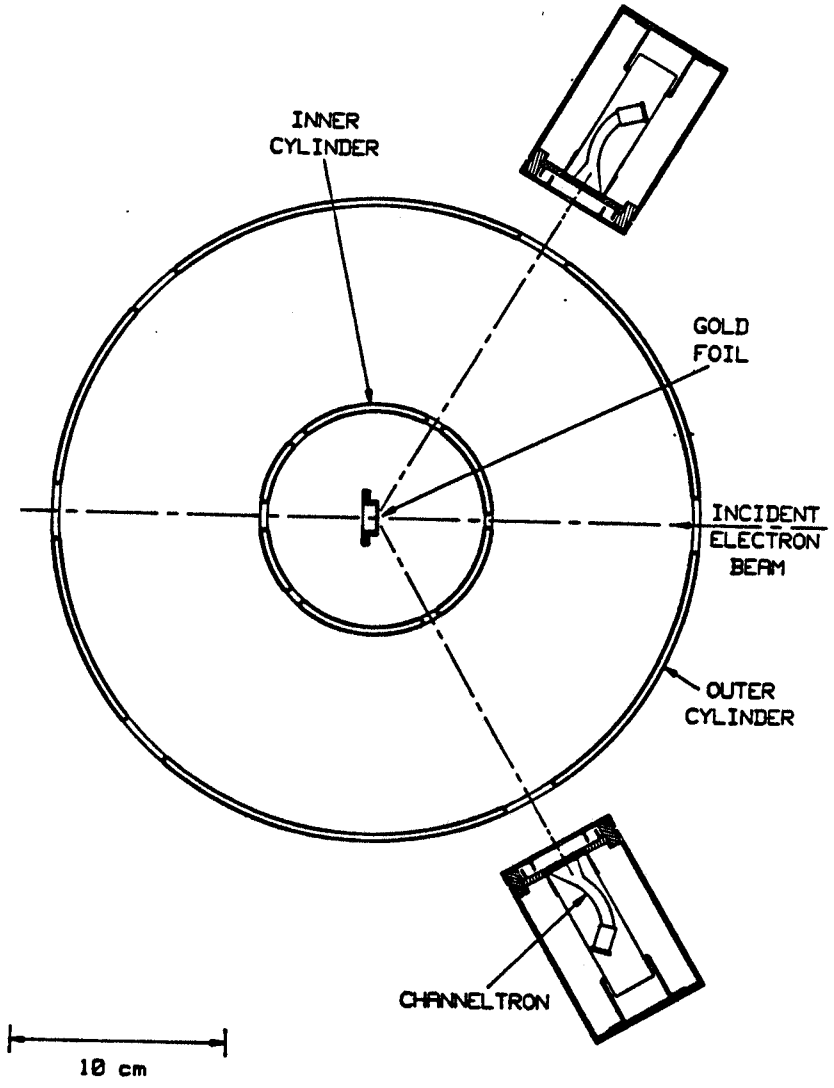

Figure 1. Maximott polarization analyzer.

function for the gold foil. A beam with polarization P_e will produce an asymmetry of $A = P_e S_{eff}$. Thus if S_{eff} is known, the polarization of the electron beam can be obtained.

At 100 kV, the Sherman function is considered "known" for pure elastic single atomic scattering (this will be discussed further in Section V). Thus in principle one can obtain an absolute value of the electron beam polarization. In real life, however, pure elastic single atomic scattering conditions are not attainable due to two major effects. Inelastic scattering occurs when electrons strike the gold foil with 100 kV but leave it with less energy, having caused atomic excitation, X-ray production, etc. Multiple scattering is a result of electrons scattering from more than one atom in the foil on their way to a 120° scattering angle. Each of these effects cause a reduction in the effective Sherman function of the analyzer, and must be accounted for in a measurement.

III.A Corrections for inelastic scattering.

Inelastic scattering can be effectively eliminated by biasing the detector retarding aperture with a voltage V_{bias} to allow in only elastic electrons. A voltage equaling the cathode potential with respect to ground will accomplish this. Electrons which enter the Mott analyzer are accelerated to 100 kV for scattering, but are decelerated on their way to the detector. An electron which suffers no energy loss will have zero kinetic energy in a region held at the cathode potential, and any electron that has lost energy will not be able to reach this region.

In practice zero energy loss usually means a very low signal, so a series of measurements of A are made at different voltages on the detector aperture. An extrapolation of A is then carried out to zero energy loss. In the measurements described in this report, a small ambiguity was encountered as to what voltage to extrapolate to. The value of V_{bias} which cut off the entire scattering signal differed from the cathode voltage by as much as 25 V, and was different depending on whether only the aperture was biased or the aperture and the multiplier cone were biased together. This was thought to be caused by field penetration through the aperture, which depended on the biasing configuration.

A decision had to be made on which biasing method to use in the actual measurements, and also whether to consider $V_{cathode}$ as the real zero energy loss voltage, or the value of V_{bias} that extinguished all signal. The biasing method was chosen based on the shape of the signal vs V_{bias} curves. As seen in Figure 2, when either the cone or the aperture was biased alone, a large peak appeared in the signal, which is probably attributable to focussing effects. Only when the multiplier cone and the aperture were biased together did the curves look smooth and well behaved, so this was considered the biasing method of choice. The real zero energy loss voltage was chosen to be the value of V_{bias} that extinguised the signal, as this was thought to be more realistic in light of field penetration effects.

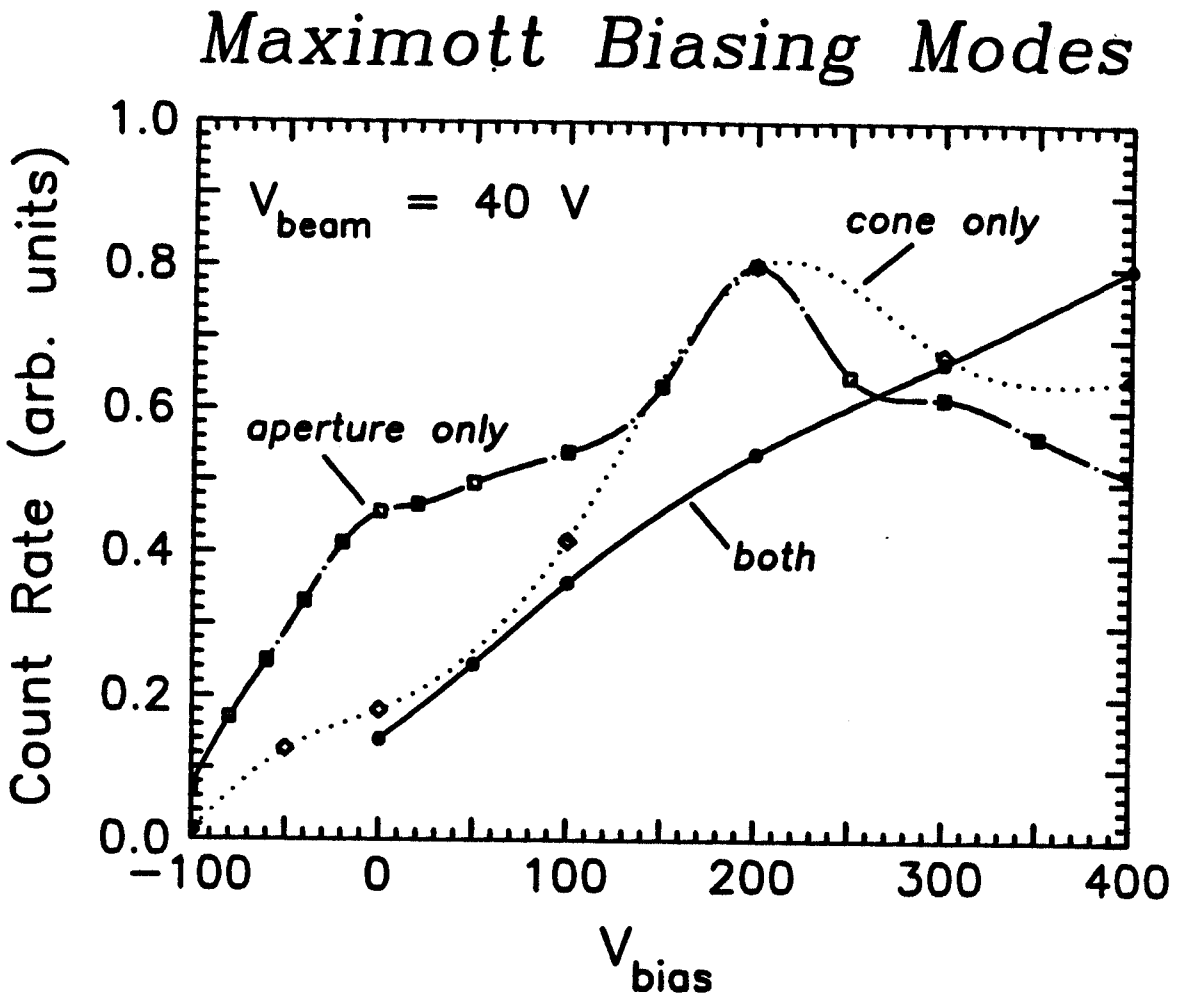

Figure 2. Maximott detector signal vs V_{bias} for different biasing modes.

III.B Corrections for multiple scattering.

Multiple scattering can be corrected for by measuring A with several foils of different thicknesses and extrapolating to zero thickness. This has been a significant source of error for Mott analyzers using surface barrier detectors for energy analysis[6], but it is apparently not a problem with cylindrical Motts. At 120° scattering angle, all multiple scattering seems to be inelastic, as will be seen in Section III.D. Measurements with four different foil thicknesses led to different values of A when V_{bias} was set to allow some inelastic scattering into the detector, but the extrapolation to zero energy loss in each case led to the same value of A for each foil. The strong dependence on foil thickness found in surface barrier detector Mott analyzers is probably a result of their poor energy resolution (about 10 kV).

III.C Instrumental asymmetries.

In any real Mott detector, there are instrumental asymmetries which cause the count rates in the two detectors to differ even if the electron beam is unpolarized. These may be caused, for example, by different detector efficiencies, by misalignments in the cylinders, detectors, or other mechanical components, or by a misaligned incident electron beam.

Clearly if the asymmetry as defined in Equation (3.1) were used, these instrumental effects could be serious. An asymmetry which is much less sensitive to these problems, and which gives the same result in the ideal case, is obtained by measuring the difference between count rates in one detector when the electron polarization is flipped:

$$A = \frac{I^{\uparrow} - I^{\downarrow}}{I^{\uparrow} + I^{\downarrow}} . \qquad (3.2)$$

The only major sources of error in this asymmetry arise if the electron beam intensity is modulated by flipping the spin, or if the beam actually moves when the spin is reversed. These effects have been investigated in the past, and were found to always be smaller than a part in 10^4. If the detector one chooses to use is badly misaligned, of course, an erroneous result can be obtained, but one can always measure with both detectors and check that both give the same asymmetry. This ability to make redundant measurements can be very useful, as will be seen in the discussion of the Minimott.

Another way of eliminating instrumental asymmetries is to measure, for spin up and spin down incident electrons, the ratios $R^{\uparrow}$ and $R^{\downarrow}$ of the count rate in one detector to the count rate in the other. By calculating

$$A = \frac{(R^{\uparrow})^{1/2} - (R^{\downarrow})^{1/2}}{(R^{\uparrow})^{1/2} + (R^{\downarrow})^{1/2}} , \qquad (3.3)$$

the same asymmetry is obtained as in Equations (3.1) and (3.2) (a proof of this is contained in Ref. [5]). This method of obtaining the asymmetry has the advantage that it effectively eliminates all instrumental asymmetries caused by misalignments and beam movement. Its major disadvantages are that there is no way to conveniently subtract a background signal, and that there are no measurements possible to check for proper operation of each detector separately.

III.D Use of the Maximott.

In the actual experiments, the Maximott was coupled to the atom beam chamber through an electron optic system equipped with an einzel lens for focussing and two sets of deflector plates. The electron beam, produced in the GaAs source, drifted approximately 25 cm across the atom beam scattering chamber with an energy of 40 - 100 V and entered the transport optics. The energy was increased to about 1000 V in the last stage of the optics, and the beam was focussed at the center of the Mott chamber. A phosphor screen was moved into the position of the gold foil and the electron beam spot was centered and focussed by eye with the Mott voltage at 100 kV. At this voltage the spot was reasonably sharp, but was vertically elongated, as expected because of the cylindrical geometry.

When the phosphor was observed, the electron beam current was kept below 1 nA. When the foil was moved into place, a beam current of about 10 nA and a V_{bias} of +400 volts produced a count rate of about 10 kHz in each detector.

Before a final set of measurements were performed, a series of checks were carried out to ascertain that both the Maximott and the GaAs source were operating properly.

With the electron beam aligned as described above, the instrumental asymmetry, as displayed in Equation (3.1), was measured with unpolarized electrons. This turned out to be about 0.08, the actual value depending somewhat on the exact deflector plate settings. This relatively low value indicated that the overall alignment was pretty good.

A problem in the Maximott that could affect the measured asymmetry, no matter whether Equation. (3.1), (3.2) or (3.3) is used to determine it, is a constant isotropic background. When the electron beam was turned off, the background count rate (due mostly to microdischarges on the 100 kV insulator) was less than 10 Hz. This was considered negligible. With the electron beam on and V_{bias} set to reject all electrons (i.e., much more negative than $V_{cathode}$), a background of about 200 Hz was observed. This background was independent of V_{bias} up to about -400 V, and is thought to be caused by desorbed ions from the gold foil, or possibly X-rays. The foil could not be biased with respect to the inner cylinder, as was the case with the Rice Maximott. This background, though small, could not be eliminated if Equation (3.3) was used to obtain the asymmetry, but it was a simple matter to subtract it if Equation (3.2) was used.

Other sources of background, possibly asymmetric, include scattering off the inner or outer cylinder, or backscattering from the beam dump where the primary electron beam is trapped. The background from these sources is most likely very dependent on the position and focussing of the electron beam. This possibility was investigated by purposefully moving the electron beam off-center and defocussing it. No significant change in the asymmetry, as derived from Equation (3.3), was observed. In addition, no change in the measured asymmetry was seen when the Minimott was later added in place of the beam dump, indicating that trapping of the beam was not a serious problem.

The polarization of the electrons entering the Maximott could have been affected by either improper source operation or depolarization of the beam during transport. Several checks were made for this and in each case no change in the polarization was observed:

(1) Several reactivations were done.

(2) The diode laser was run in a lasing mode instead of a fluorescence mode (its current was increased to 75 mA) and neutral density filters were used to keep the electron beam intensity low enough.

(3) The cesium dispenser channel, kept on at 3.5 A during most measurements, was turned off to see if its magnetic field was affecting the polarization.

(4) The degree of circular polarization produced by the Pockels cell was checked for both σ^+ and σ^- light and found to be better than 0.99 in each case.

(5) Magnetic field depolarization during transport was checked for by varying the transport energy from 2 eV to 100 eV, by adding conetic shielding outside the transport optics, and also by measuring the residual AC magnetic field, which turned out to be less than 2 mG.

Figure 3 shows the measured intensities for each foil as a function of $V_{inel} = V_{bias} - V_{cathode}$. The beam energy (numerically equal to $-V_{cathode}$) in this case was 100 eV. The intensities shown are averages over the left and right detector signals, and are also averaged over up and down incident spins. It is interesting to note that the overall intensity increases more or less linearly with foil thickness, except in the case of the 1000 Å foil curve. This indicates that the actual thickness of the 1000 Å foil is perhaps closer to 1250 Å.

The asymmetries were calculated from Equation (3.2) individually for the left and right sides, and it was seen that both sides agreed within the error bars. The intensities were then averaged, $I^{\uparrow}_{left}$ with $I^{\downarrow}_{right}$ and $I^{\downarrow}_{left}$ with $I^{\uparrow}_{right}$. The resulting average asymmetries are shown in Figure 4. As can be

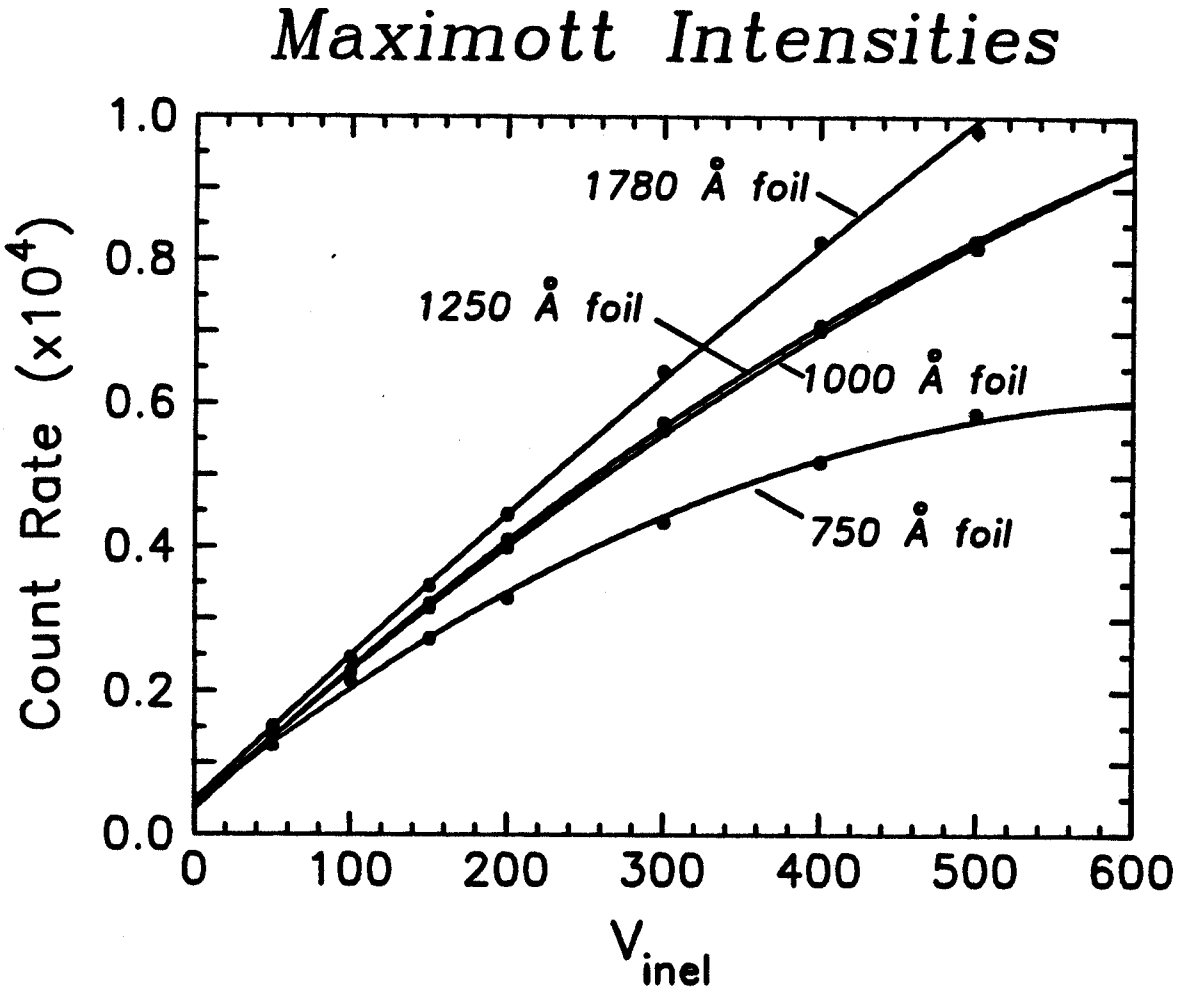

Figure 3. Maximott detector signal vs. bias voltage for the four foil thicknesses. Dots are measurements, and solid lines are least-squares fits to a quadratic.

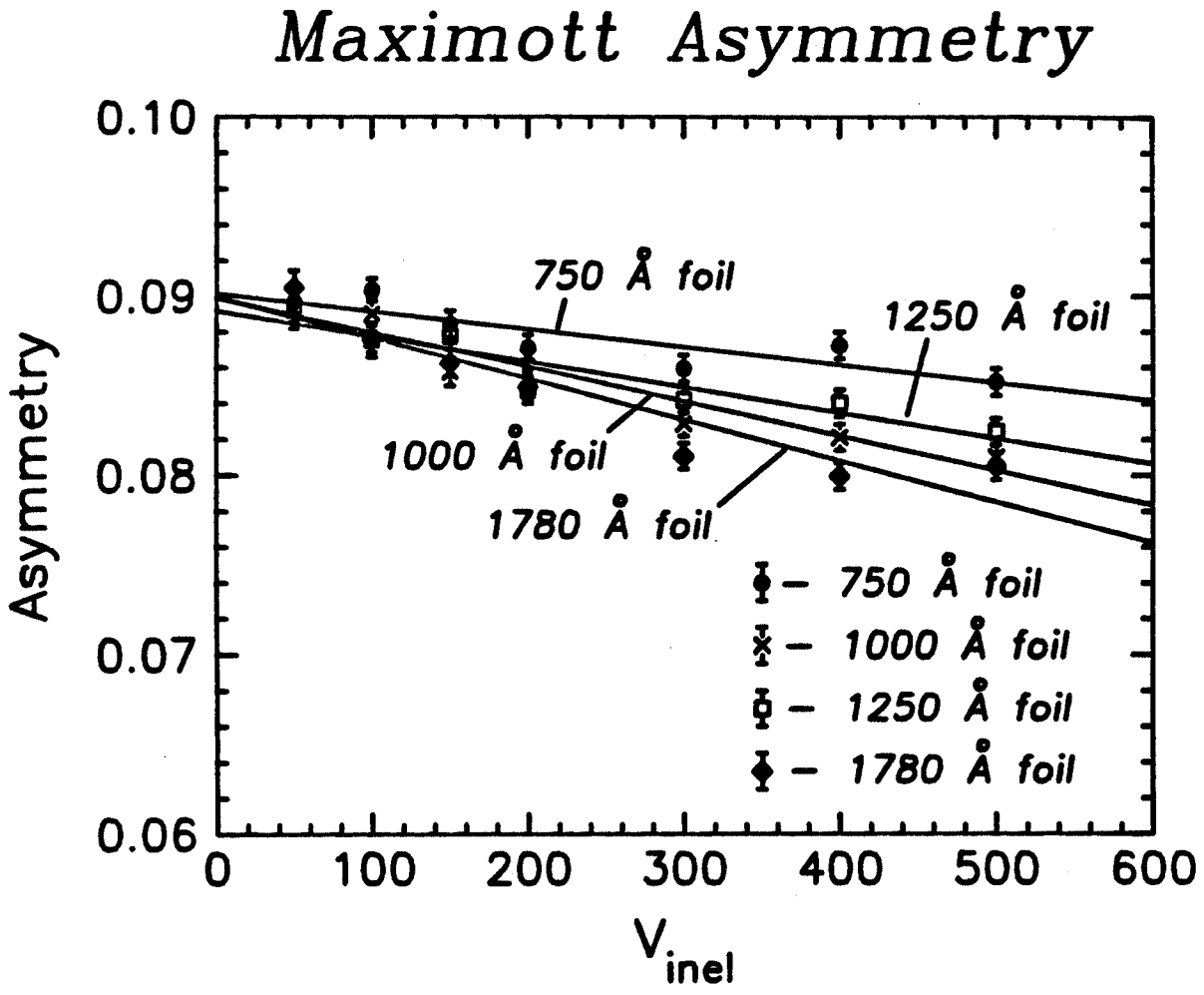

Figure 4. Maximott asymmetry vs maximum inelastic energy loss. Data for four foils are shown. Solid lines are least-squares fits to a straight line.

seen in the figure, progressively thicker foils have increasingly steeper slopes, with the exception of the 1000 Å foil. All curves seem to meet at zero energy loss, which is consistent with the claim that all multiple scattering is inelastic. It is interesting to note that the Rice measurements[2] of these curves show a much steeper slope, while the Edinburgh results[4] are closer to our measurements.

The procedure for determining the asymmetry at zero energy loss involved first extrapolating the intensity curves to zero. This was done by fitting the data for each foil to a quadratic curve (shown as the solid lines in Figure 3). The x-intercepts of the curves for the different foils along with their error estimates are listed in Table I. The error estimates are one standard deviation, and were obtained by propagating the one-standard-deviation errors for the coefficients of the fit through the expression for the intercept. The values for all foils agree within the errors.

Table I

Maximott Extrapolated Zero Energy Loss vs. Foil Thickness

Foil	Intercept (Volts)
750 Å	-25.19 ± 17.28
1000 Å	-16.67 ± 6.74
1250 Å	-19.75 ± 6.54
1780 Å	-22.84 ± 14.55

For each foil, the value of V_{inel} corresponding to zero energy loss was taken as an extrapolation point for the asymmetry curves, which were fittted to straight lines using least-squares. The resulting asymmetry values are shown in Table II. Note that all foil thicknesses are seen to yield the same zero-energy-loss asymmetry.

Table II

Maximott Zero-energy-loss Asymmetry vs Foil Thickness

Errors are 90% confidence intervals

Foil	Asymmetry
750 Å	0.0904 ± 0.0015
1000 Å	0.0902 ± 0.0015
1250 Å	0.0895 ± 0.0014
1780 Å	0.0905 ± 0.0022
Average	0.0901 ± 0.0008

The errors quoted in Table II arose from two sources: (1) Maximum and minimum extrapolations were calculated using the error estimates for the values of the intercept listed in Table I. These were assumed to be standard deviations, and 90% confidence limits[7] were calculated from these. (2) The standard deviations of the values of the asymmetry at the intercepts were assumed to be equal to the χ^2 of the linear least squares fit and 90% confidence intervals were calculated from those. The two errors were combined in quadrature to yield the errors shown in Table II. The final average value of 0.0901 ± 0.0008 was obtained by taking a weighted average of the values for the four foils.

This final value of A, when divided by S_{gold} (the single-scattering pure elastic Sherman function), gives the polarization of the electron beam P_e. Exactly what value of S_{gold} should be used is unfortunately somewhat ambiguous. Leaving the discussion of this for Section V, we simply quote in Table III two results for P_e, one based on a theoretical value of S_{gold} and one on an experimental one.

Table III

Electron Source Polarization P_e, Based on Two Values of S_{gold}.

	S_{gold}	P_e
Experiment	0.370 ± 0.008	0.2435 ± 0.0074[a]
Theory	0.391	0.2304 ± 0.0020

(a) the errors in S_{gold} and A have been added in quadrature.

IV. Minimott Polarization Analyzer.

The hemispherical Mott detector, or Minimott, is shown in Figure 5. Built according to a Rice design[1], it operates on essentially the same principle as the Maximott, the only differences being the hemispherical geometry and a lower operating voltage. Electrons pass through a hole in the outer hemisphere, are accelerated through the inner hemisphere to 30 kV, and strike a gold foil. The electrons which are scattered into 120° are decelerated as they pass out through the inner and outer hemispheres and are detected by two detectors. A scattering asymmetry is measured in the same way as in the case of the Maximott.

Since the true value of S_{gold} is much less certain at 30 kV than it is at 100 kV, the Minimott cannot be used alone to measure an absolute value of the electron beam polarization. Nevertheless, if the analyzer is calibrated by measuring the effective Sherman function S_{eff} as a function of V_{inel}, it can be used more or less reliably to measure P_e provided the gold foil is not changed. This latter requirement may not even be necessary. Since the Maximott extrapolated elastic asymmetry seems to be independent of foil thickness at 100 kV, this may also be true for the Minimott at lower energies.

A calibration of the Minimott was published in the original Rice group paper[1]. They presented values of S_{eff} as a function of V_{inel} for 20, 30 and 40 kV. These were measured using a set up very similar to the one described here: A polarized electron source (in their case an optically pumped He flowing afterglow source) was connected to a Maximott and a Minimott in tandem. The Maximott was used to determine the source polarization, and the Minimott was thereby calibrated.

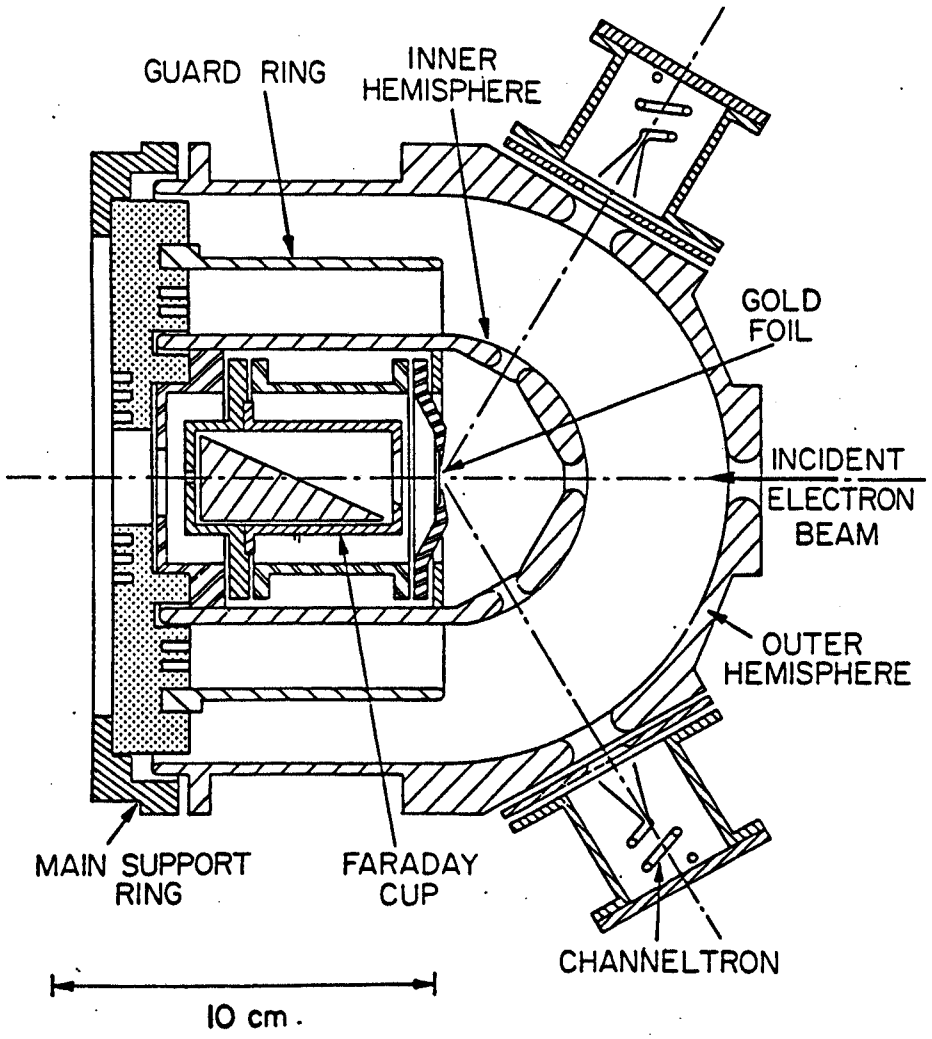

Figure 5. Minimott polarization analyzer.

The purpose of the present study was to recheck the Rice calibration to see whether two analyzers built to the same exact specifications could have the same calibration, and to see if the various discrepancies in measured source polarizations could be resolved. An unsupported foil of the same thickness (~1300 Å) was therefore used, and the Minimott was mounted directly behind the Maximott.

IV.A Installation and operation of the Minimott.

The Minimott was mounted in place of the beam dump on the Maximott, and a copper drift tube was installed between the two. The outer cylinder of the Maximott, the drift tube, and the outer hemisphere of the the Minimott were all electrically connected and held at about +1000 V with respect to ground. When the Minimott was operated, the foil stage in the Maximott was moved to an empty space (no signal in the Minimott could be obtained with the Maximott foil in place).

Some difficulty was found in ascertaining that the electron beam, after traversing the Maximott, was correctly aimed into the Minimott. First, the current reaching the outer hemisphere was measured in the hope that this would show a minimum when the beam passed cleanly through the hole in the outer hemisphere. The current was found to be always positive (at about 20% of the electron beam current), but did show a slight dip at deflector plate settings roughly corresponding to a straight beam. Setting the beam at the minimum of this dip, however, led to erroneous asymmetry measurements, as diagnosed by observing the spin asymmetry in the two channels of the Minimott separately. At large values of V_{inel}, the asymmetry in one channel dropped anomalously.

This we attributed to scattering off the edge of the hole in the inner hemisphere, since it could be altered by slight changes in the deflector plate voltages. We might note that this problem was only diagnosed after measuring the asymmetry as shown in Equation (3.2) - it remained undetected as long as Equation (3.3) was used.

After some experimentation, a good way to optimize the electron beam position was determined. A Keithley meter floated at 30 kV was connected between the Minimott Faraday cup and the rest of the inner hemisphere assembly. This meter only measured current that passed through all apertures and also the gold foil. The current measured in this way showed a distinct negative maximum at only one setting of deflector plates, and was very sensitive to this setting. It was also quite sensitive to the voltage applied to the Maximott inner cylinder, and showed a maximum with about 20 kV applied. With the electron beam aligned in this manner, count rates of about 6-8 kHz were seen in each detector with an incident current of about 0.2 nA and a V_{inel} of 200 V.

The correct choice of biasing mode, and the relation between V_{bias} and V_{inel}, were a slight problem in the Minimott as they were in the Maximott. Biasing with the retarding aperture alone gave very anomalous results because of very large field penetration, so the aperture and the cone of the channeltron were biased together. This was perhaps not ideal because different energy electrons struck the cone for different values of V_{bias}, but it was the best compromise in the given situation.

Intensity curves as a function of V_{bias} were measured, and are shown in Figure 6. The cut-off point is seen to differ for the two channels by 25

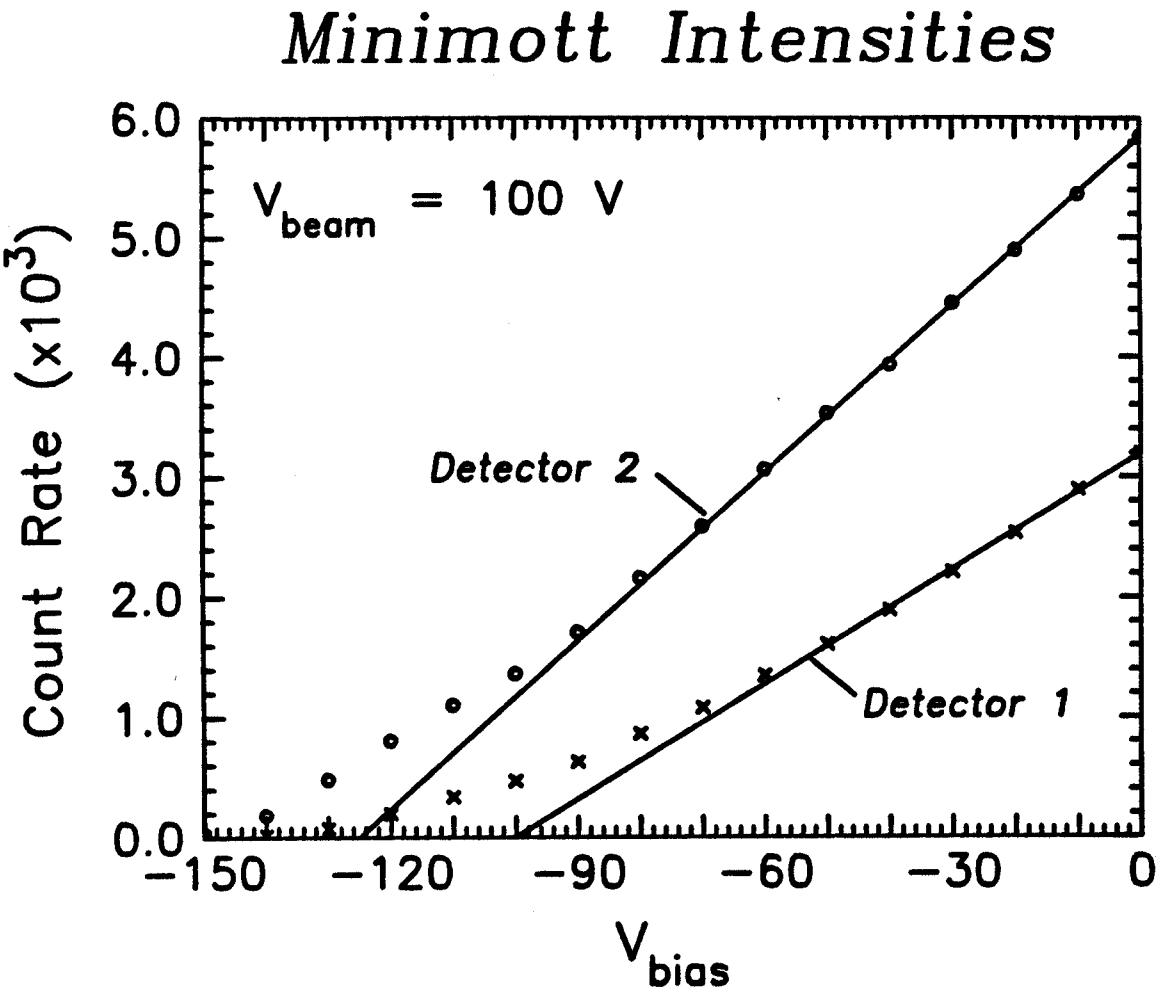

Figure 6. Minimott detector intensities as a function of bias voltage.

volts, which leads to some ambiguity as to what the correct value for V_{inel} is. As with the Maximott, we decided to take as the true zero of V_{inel} the observed cut-off voltage. Consequently, all measurements were carried out with slightly different values of V_{bias} for the two different channels: for a desired value of V_{inel}, we took

$$V_{bias}(1) = V_{inel} + V_{cathode} \tag{4.1a}$$

and

$$V_{bias}(2) = V_{inel} + V_{cathode} - 25 \ . \tag{4.1b}$$

As can be seen in Figure 6, the instrumental asymmetry in the Minimott is much larger than in the Maximott, reaching as much as 0.30. This is probably due to some basic misalignments or different detector efficiencies - no amount of electron beam movement could make it better. Because of the immunity to instrumental asymmetries inherent in the measurement method (see Section III.C), this was not considered a severe handicap.

Using polarized electrons, it was first checked that both sides gave the same spin asymmetry (Equation 3.2) for all values of V_{inel}. The intensities were then averaged, as in the case of the Maximott, "left-up" with "right-down" and "left-down" with "right-up". Average asymmetries were then calculated and divided by P_e to yield S_{eff}. The resulting calibration curves are shown in Figure 7, along with the Rice results[1]. Two calibrations are shown, corresponding to the two values of P_e shown in Table III. In order to

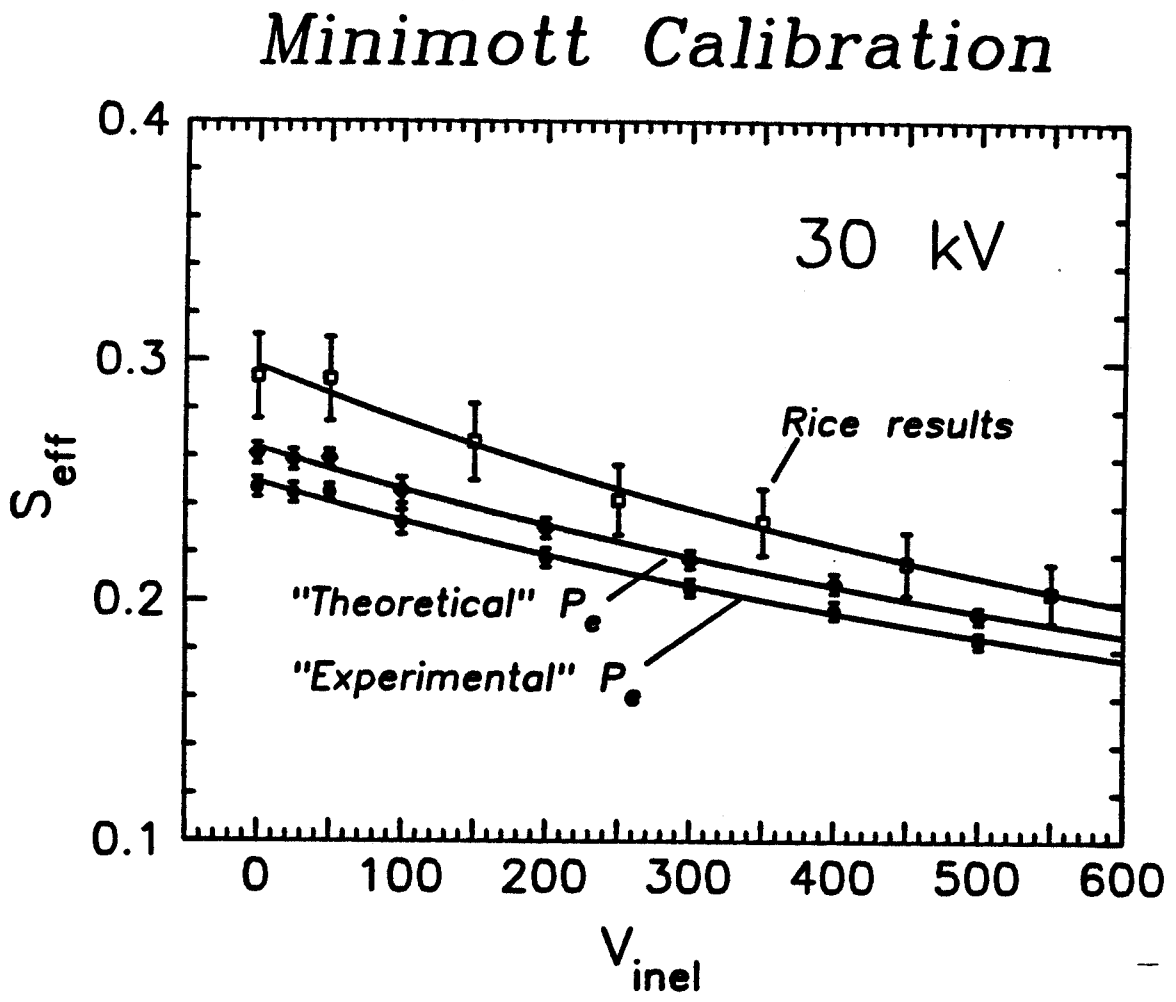

Figure 7. Minimott calibration. "Theoretical" and "experimental" curves are derived from the theoretical and experimental values for S_{gold} listed in Table III. Error bars on our results are one-standard deviation as derived from counting statistics. Solid lines are non-linear least squares fits to Equation (4.2).

provide a fair comparison with the Rice results, the "theoretical" value $P_e = 0.2304$ was used in the upper curve, since their source polarization was based on the theoretical S_{gold} of 0.39. The lower curve was calculated using the "experimental" value 0.2435. The upper curve and the Rice results compare favorably, although our results are somewhat lower. Taking into account the error estimates, agreement can perhaps be considered "marginal".

For convenience in the future use of the Minimott, the calibration data shown here have been least-squares fit to the functional form

$$S_{eff} = \frac{\alpha}{\beta + V_{inel}} \, . \tag{4.2}$$

Values for α and β have been determined for the Rice calibration, and for the present calibration using the "theoretical" and the "experimental" determinations of P_e. These values are given in Table IV.

Table IV

Coefficients for the Fit to Equation (4.2)

Calibration	α	β
Rice	357.56	1200.91
Present "theoretical"	379.13	1438.81
Present "experimental"	358.73	1438.81

IV.B Magnetic depolarization in the Minimott.

Because our measured calibration of the Minimott was a bit lower than the Rice results, there was some concern that the electrons were being depolarized during transport from the Maximott to the Minimott. The most likely cause for such a depolarization is a magnetic field; a field along the axis of the electron beam would cause the most problems because it would depolarize the electrons without deflecting the beam.

Magnetic fields cause spin depolarization by inducing a precession of the spin about the field. The amount of rotation φ for an electron traveling with energy E through a distance ℓ in an axial magnetic field B is given by

$$\varphi = 8.54 \frac{B\ell}{E^{1/2}} , \qquad (4.3)$$

where φ is in degrees, B is in Gauss, ℓ is in centimeters, and E is in volts. Let us take E to be 1000 V and ℓ to be 20 cm, and calculate how much magnetic field would be necessary to cause the difference between the Rice calibration and ours. The difference is about 9% at V_{inel} = 250 V, so $\cos\varphi \cong 0.91$, or $\varphi \cong 24^{\circ}$. This implies that B would have to be about 4.4 Gauss to cause the observed effect. This is significantly higher than any stray fields in the lab (the earth's field is about 0.6 Gauss), so it is unlikely that magnetic depolarization was a problem. As a further check of this, a solenoid of 5 turns was wound around the transport tube. A DC current of 5 A (a current calculated to create a field of 2 Gauss on the axis) was run through this solenoid. No significant change in the asymmetry was observed, even though 2 Gauss is believed to be significantly higher than any stray field in the laboratory.

V. Absolute Determination of the Sherman Function.

The use of the Mott analyzers discussed here, and in fact all Mott analyzers, depends ultimately on knowing the true value of the Sherman function for the particular analyzer in question. This quantity, which we call S_{eff}, depends on incident energy E and scattering angle θ, as well as foil thickness t, energy resolution ΔE and angular resolution $\Delta\Omega$.

The only way to obtain S_{eff} in a truly unambiguous way is to perform a double scattering experiment with two identical detectors. An unpolarized electron beam enters the first detector and scatters with a polarization equal to S_{eff}. The scattered electrons enter the second detector, and an asymmetry of S_{eff}^2 results. By taking the square root of the asymmetry in the second detector, one thus has a measure of S_{eff}.

Double scattering experiments are very difficult to perform, but in principle, if a double scattering experiment is done once with known values of E, θ, t, ΔE and $\Delta\Omega$, then any Mott analyzer built to the same specifications will have an absolute calibration. Analyzers almost always differ from each other in some way or another, though, so this is not practical. The best compromise is to try to do double scattering with t, ΔE and $\Delta\Omega$ as close to zero as possible over a range of values for E and θ. This provides a reference Sherman function, which we call S_{gold}, that not only can be approximated to a greater or a lesser degree by detectors of all kinds, but also can be compared with theoretical calculations of pure elastic scattering from single atomic targets. If E is in the range of 100 kV, there is some reason to believe that a good theory could be correct.

We thus must ask two questions when trying to determine S_{eff} for our analyzer. First, how closely does our analyzer approach the ideal conditions of $\Delta E = 0$, $t = 0$ and $\Delta\Omega = 0$, and second, how well do we know the true value of S_{gold}. The Maximott probably approaches $\Delta E = 0$ better than any other type of analyzer. The limit $t = 0$ is more difficult to approach, but it seems from the current work that this limit is achieved by getting ΔE as close to zero as possible. To get $\Delta\Omega = 0$ is of course a problem because the signal will become vanishingly small, but since the angular dependence of the Sherman function in the region of 120° is quite flat, a moderate size for $\Delta\Omega$ is acceptable. In the present set up, $\Delta\Omega \cong 0.037$, a value which is only approximate because the detector acceptance area is not accurately known and because different values of V_{inel} will change this.

The true value of S_{gold} can be obtained from the double scattering experiments in the literature or from theory. If both agree, then there is no difficulty in choosing a value. Unfortunately, this is not the case.

Actually, there have been very few double scattering experiments conducted in the energy range around 100 kV. In 1962, Apalin *et al*[8] made measurements in the range from 45 to 245 kV. A continuation of this work was published by Mikaelyan *et al*[9]. Van Klinken[10] made a similar set of measurements over the range 26 - 261 keV in 1965. All these experiments used solid state detectors with $\Delta E \cong 10$ kV, and various foil thicknesses to extrapolate to $t = 0$.

There have been a number of theories published, beginning with Mott's original paper[11]; the most widely used results are those of Holtzwarth and Meister[12], where a fully relativistic calculation is done using a properly screened potential.

Theoretical and experimental results in the energy region relevant to the present work are shown in Figure 8. A difference of about 5% - more than two standard deviations - is seen between experiment and theory. One is thus faced with a difficult decision: do we take the experimental value, since an unverified theory is always suspect, or do we conclude that the experiments do not have sufficient energy resolution to measure S_{gold}, so the theoretical value is closer to what would be measured with the Maximott. One might be tempted to think that a good extrapolation to zero foil thickness is as good as measuring with a small ΔE because of the correspondence between these two limits seen in the present work. On the other hand, there may be some basic limitations on the accuracy obtainable with foil thickness extrapolations and solid state detectors. A discussion of this is found in Reference (6), where it is shown that in most cases an accuracy of 6% is the best one can hope for.

The only safe conclusion that one can make at this point is that S_{gold} is simply not known to an accuracy better than 5 or 6%. If one must choose a number for a specific calibration, an experimental value is always better than an unverified theoretical one. We can only hope that in the future, the difference between the experimental and the theoretical results will be resolved, perhaps by doing double scattering with Maximotts, or by using other absolute polarization detection schemes such as scattering from helium[13].

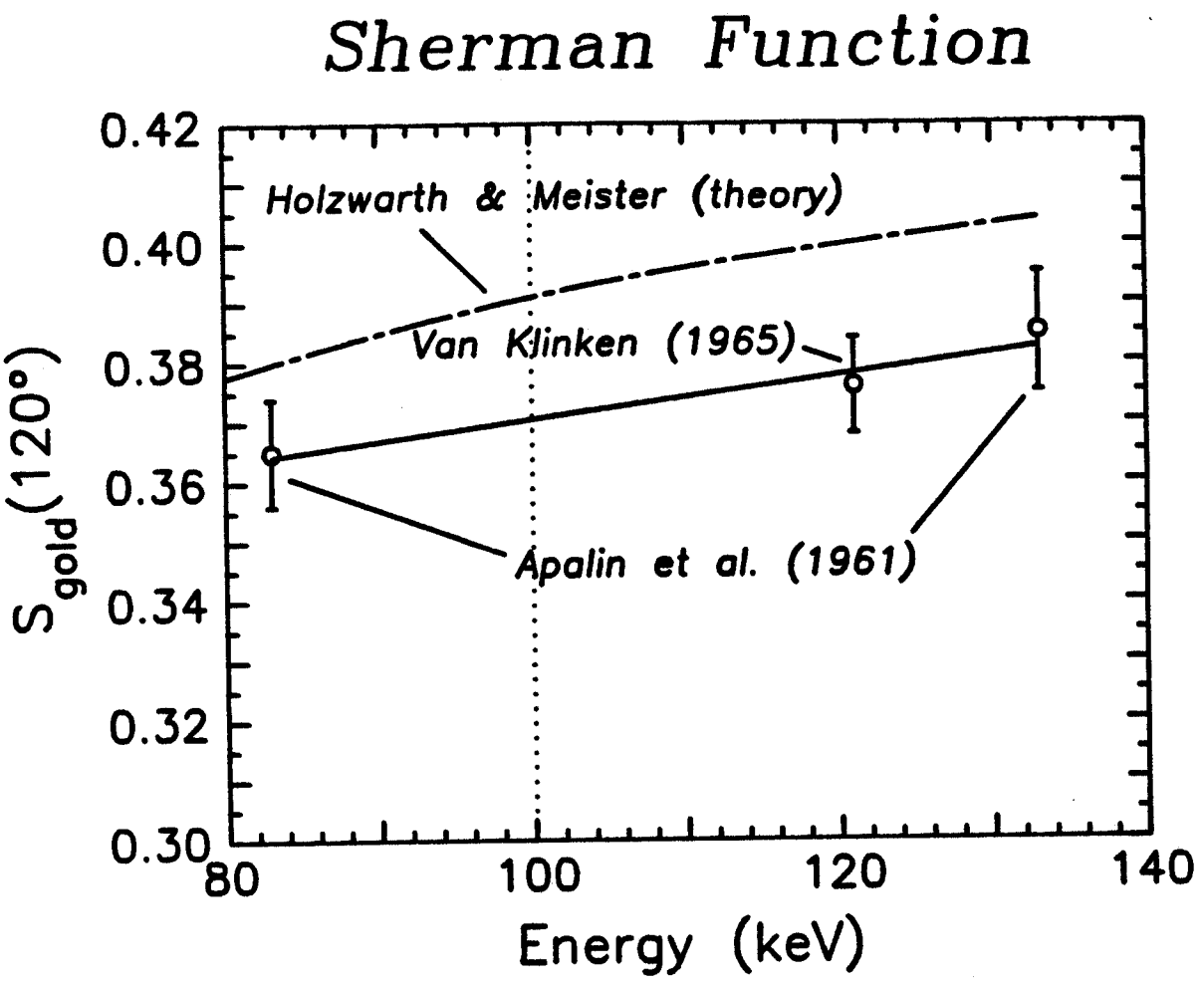

Figure 8. Theoretical and experimental values of the Sherman function at 120 degrees scattering angle vs incident electron energy. The solid line through the experimental data shows the least-squares fit to a straight line used to interpolate the value of 0.370 shown in Table III.

VI. Conclusion.

We have presented a discussion of the experiments that were undertaken over the 3 month period from October to December 1986 to determine the polarization of the GaAs polarized electron source. Though we have come up with some hard numbers in which we have a fair amount of confidence, this is by no means the end of the story. The long-term time dependence of the polarization has not been rigorously tested in enough different sources to allow us to make a general statement about any sort of fall off in the polarization. The differing behavior of the PLEED and the atom beam sources, though not significant enough to seriously affect operations, is troublesome. An explanation of the apparent discrepancy between the earlier PLEED polarization measurements of 0.36 and the more recent Minimott measurements of 0.27 is still not apparent.

More measurements are planned in the near future which will hopefully answer some of the dangling questions. A repeat of the PLEED measurements on tungsten will be done to see whether 0.36 is still the polarization of the PLEED source as measured by that method. The Minimott will be reinstalled on the PLEED apparatus at the same time. A new GaAs crystal will be installed in the atom beam source to see if a polarization of 0.26 is regained. A new wafer will be used to see if perhaps the original wafer, from which all the atom beam source crystals were obtained, has been decaying somehow over a long period of time.

In discussing all the "problems" with the GaAs electron source as we have been doing in this report, we should not lose perspective on the overall performance of the source. We could perhaps be accused of looking in this study at the polarization with more precision than the overall accuracy desired or attainable warrants. When one considers the figure of merit of the source, along with its relative ease of operation, it is still the most practical polarized electron source for a majority of the applications one can conceive of. As more measurements of the polarization are performed over a periods of years, we can expect that our knowledge of the source's performance will become more and more refined.

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