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Absolute calibration of a retarding-potential Mott polarimeter

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RICE UNIVERSITY

ABSOLUTE CALIBRATION OF A RETARDING-
POTENTIAL MOTT POLARIMETER

by

DAVID MICHAEL ORO

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IN PARTIAL FULFILLMENT OF THE
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MASTER OF SCIENCE

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by

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ABSTRACT

Mott polarimeters are used in many areas of physics to determine the spin polarization of electrons in studies of processes dependent on the electron's intrinsic spin angular momentum and associated spin magnetic moment. Mott polarimeters work by measuring the left-right asymmetry in the spatial distribution of electrons scattered from high-Z nuclei. This asymmetry, which was first recognized in theory by N. F. Mott in 1929 and demonstrated experimentally by Shull, Chase and Myers in 1943, is due to the "spin-orbit" interaction between the electron's spin magnetic moment and the magnetic field in its rest frame due to the "motion" of the scattering nucleus. The polarization of the incident electrons is related to the measured asymmetry via a parameter known as the effective asymmetry (Sherman) function, S_{eff} , which must be determined through calibration.

This work describes a novel technique for calibrating a Mott polarimeter that makes use of electrons of accurately known polarization obtained through Penning ionization reactions involving electron spin polarized He(2^3S) metastable atoms. This technique has been used to calibrate a compact retarding-potential Mott polarimeter, and the values of S_{eff} are presented for both gold and thorium target foils under a variety of operating conditions. They are compared to results from previous calibrations using different techniques.

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CHAPTER 1.

INTRODUCTION

The study of processes dependent on the electron's intrinsic spin angular momentum and associated spin magnetic moment has become increasingly important in recent years, primarily in atomic, molecular, solid state, high energy and nuclear physics (Kessler 1985, Feder 1985, Heller 1989). Many of these experiments require the measurement of the spin polarization of an ensemble of electrons (*i.e.* the relative number of electrons in the two magnetic substates, $m_s = \pm 1/2$). A widely used technique for measuring the spin polarization of electrons is based on the work of Mott, who believed (from arguments he attributed to Niels Bohr) that the spin magnetic moment of a free electron could not be observed directly (*e.g.* with a magnetometer or by the Stern-Gerlach effect) due to the uncertainty principle (Mott 1929)*. This belief motivated Mott to investigate the feasibility of determining the polarization of a beam of electrons by measuring the asymmetry in the distribution of electrons scattered at high energies from high-Z nuclei in a target foil (Mott 1929, 1932). The scattering asymmetry is a result of the interaction between the electron's spin magnetic moment and the transformed magnetic field in the electron's rest frame due to the electric field of the scattering nucleus, the so-called spin-orbit effect (discussed in detail in the following chapter). Devices that exploit this effect to measure electron spin polarization are known as Mott polarimeters, and consist of an acceleration region, scattering target, and electron detectors to measure the scattering asymmetry. Mott polarimeters are

* See Dehmelt (1990) for a discussion of recent experiments that have directly measured the spin magnetic moment of a free electron.

currently in use in studies of spin-dependent effects in atomic collisions (Kessler 1985, Baum *et al.* 1989), surface magnetization of solids (Feder 1985, Abraham and Hopster 1989), parity violations in high energy nuclear scattering (Prescott *et al.* 1978, Hughes 1990), studies of ferromagnetic surfaces by spin-polarized photoemission spectroscopy (Erskine and Fink 1990), spin polarized electron-microscopy (Robins *et al.* 1988, Vanzandt *et al.* 1991) and precision measurements of the Z^0 mass (Lowenstein 1989).

Traditionally, the scattering asymmetry is related to the incident electrons' spin polarization through an asymmetry function, S , known as the Sherman function. Sherman, following the work of Mott, computed the asymmetry function for relativistic electrons scattering from the point Coulomb fields of gold and other nuclei (Sherman 1956, Sherman and Nelson 1959, Lin *et al.* 1963). However, the fact that electrons scattering from a target foil can undergo several scattering events before being detected degrades the scattering asymmetry, and the values measured, S_{eff} , are typically less than the theoretical single atom scattering value, S . Many investigators have determined values of S_{eff} , the effective asymmetry, for foil targets by measuring the scattering asymmetry using foils of different thickness and extrapolating to zero thickness where single atom scattering occurs (see the review by Gay and Dunning 1992, and references therein). This value is then normalized to the theoretical result. However, as pointed out in the review, there does not exist a consensus on what is the best method for extrapolating to the zero thickness value.

A similar technique for measuring S_{eff} for foil targets involves determining the scattering asymmetry for different inelastic energy losses of the scattered electrons. The motivation for this method is the expectation that the thickness of the region from which scattering is observed decreases as the allowed energy loss is reduced due to discrimination against multiply and plurally scattered electrons*. The experimental results are extrapolated

* The average energy loss for 20 keV electrons in Au is $\sim 1 \text{ eV } \text{\AA}^{-1}$ (Campbell *et al.* 1985).

to zero energy loss and normalized to single atom scattering theory. However, this method suffers from the same uncertainty in the extrapolation procedure as the method described above. Also, since both techniques involve normalization to theoretical calculations, they are susceptible to uncertainties in the calculations.

The effective asymmetry, S_{eff} , can be directly determined by measuring the scattering asymmetry for electrons of independently known polarization. The advantage of this technique is that it does not rely on extrapolation or normalization to theoretical calculations. The first experiments of this type used electrons produced from β -decay assuming a polarization of v/c , a result of parity violation (Curtis and Lewis 1957). This technique has been recently employed to calibrate a Mott polarimeter used in β -emission experiments with β -decay electrons from ^{60}Co (Gauder *et al.* 1988). Another method involves using polarized electrons from a GaAs source. The polarization of the electrons is independently determined by an optical technique involving the observation of radiation emitted by an atomic target excited by the electron beam (Uhrig *et al.* 1989).

In the present work, S_{eff} for a small retarding-potential Mott polarimeter is determined using electrons of known polarization that are produced through Penning ionization reactions involving electron-spin-polarized metastable $\text{He}(2^3\text{S})$ atoms. The polarization of the electrons equals that of the original $\text{He}(2^3\text{S})$ atoms which can be determined with a Stern-Gerlach apparatus. The motivations for this work are two-fold. The first is to compare the values of S_{eff} for a gold target foil using this method to those obtained earlier using extrapolation techniques. The second is to compare the Sherman function for a gold ($Z = 79$) target to that for a thorium ($Z = 90$) target, which is expected to be larger due to the larger Z of thorium. Also, this technique was chosen over the other methods of directly determining the Sherman function because of the ease with which the current experimental apparatus could be adapted to make such a measurement.

The remainder of this thesis is divided into four parts. Chapter 2 discusses the theory of Mott scattering and of the production of polarized electrons through the ionization of polarized $\text{He}(2^3\text{S})$ atoms. Chapter 3 describes the experimental apparatus and familiarizes the reader with the measurement techniques used. Chapter 4 presents the results from this experiment. Chapter 5 provides some concluding remarks.

CHAPTER 2.

THEORY

A. Mott Scattering

As mentioned in the introduction, the asymmetry in the scattering of electrons from an atomic nucleus is due to the spin-orbit interaction which can be derived from first principles in Dirac's relativistic generalization of Schrödinger's equation. The effect can be understood semi-classically, however, by considering the interaction between the electron's spin magnetic moment and the magnetic field the electron experiences as it moves through the electric field of the scattering nucleus, as illustrated in Figure 2.1.

Fig. 2.1. Electric and magnetic fields experienced by an electron scattering to the left or right of a nucleus.

In the electron rest frame, this magnetic field is given by

$$\mathbf{B} = -\frac{1}{c} \mathbf{v} \times \mathbf{E}, \quad (2.1)$$

where $\mathbf{v}$ is the electron velocity. The electric field of the scattering nucleus is

$$\mathbf{E} = \frac{Ze}{r^3} \mathbf{r}, \quad (2.2)$$

where $\mathbf{r}$ is the nucleus-electron separation, and Z is the atomic number of the nucleus. Thus, $\mathbf{B}$ may be written as

$$\mathbf{B} = \frac{Ze}{cr^3} \mathbf{r} \times \mathbf{v} = \frac{Ze}{mcr^3} \mathbf{L} \quad (2.3)$$

where $\mathbf{L} = m\mathbf{r} \times \mathbf{v}$ is the electron orbital angular momentum about the nucleus. The energy of the interaction between this field and the electron spin magnetic moment, μ_s , is given by $V'_{SO} = -\mu_s \cdot \mathbf{B}$. Using the relation between the the electron spin, $\mathbf{S}$, and spin magnetic moment, $\mu_s = -\frac{g_s e}{2mc} \mathbf{S}$ ($g_s \cong 2$ and is the electron gyromagnetic ratio), V'_{SO} then becomes

$$V'_{SO} = \frac{Ze^2}{m^2 c^2 r^3} \mathbf{L} \cdot \mathbf{S}. \quad (2.4)$$

However, this result has been evaluated in the electron rest frame. Transforming back into the nucleus rest frame reduces the energy by a factor of 2 due to an effect in the relativistic transformation of the velocities known as Thomas precession. Thus, the spin-orbit interaction potential is

$$V_{SO} = \frac{Ze^2}{2m^2 c^2 r^3} \mathbf{L} \cdot \mathbf{S}. \quad (2.5)$$

This term represents a spin-dependent perturbation to the coulombic scattering potential. The magnitude of the effect is largest when $\mathbf{L}$ and $\mathbf{S}$ are parallel (or anti-parallel), and V_{SO} can be positive or negative. Figure 2.2 shows the scattering potential without spin-orbit

coupling and with spin-orbit coupling for spin-up electrons ($e\uparrow$) and spin-down electrons ($e\downarrow$) as the scatter to they left and right of the nucleus.

Fig. 2.2. Potential curves with (---) and without (—) spin-orbit coupling for electrons with spins up $\uparrow$ and spins down $\downarrow$ scattering to the left or the right of the nucleus.

This perturbation to the scattering potential introduces a spin-dependence in the differential scattering cross-section, $\sigma(\theta)$, which may be written as (Kessler 1985):

$$\sigma(\theta) = I(\theta) (1 + S(\theta)\mathbf{P}\cdot\mathbf{n}) \quad (2.6)$$

where $S(\theta)$ is the Sherman (asymmetry) function, $\mathbf{P}$ is the polarization of the incident electron beam*, and $\mathbf{n}$ is a unit vector normal to the scattering plane, parallel to $\mathbf{L}$. If the

*See Kessler (1985) for a detailed discussion on the description of polarized electrons. Briefly, $\mathbf{P}$ will have a magnitude between 0 and 1 and point in the direction of net polarization. If one measures the number of electrons with spins parallel to some direction z , $N\uparrow$, and the number with spins anti-parallel to z , $N\downarrow$, then

$$P_z = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}.$$

wavevectors for the incident and scattered electrons are expressed as $\mathbf{k}$ and $\mathbf{k}'$, respectively, $\mathbf{n}$ can be defined as

$$\mathbf{n} \equiv \frac{\mathbf{k} \times \mathbf{k}'}{|\mathbf{k} \times \mathbf{k}'|}. \quad (2.7)$$

It should be noted that only the component of the polarization transverse to the scattering plane contributes to an asymmetry in the cross-section. The differential cross-section for a beam of electrons with no transverse polarization is, simply, $I(\theta)$. Figure 2.3 shows the general characteristics of $S(\theta)$ for scattering from gold nuclei.

Fig. 2.3. Angular and energy dependence of Sherman function for scattering from gold. (Motz *et al.* 1964)

To see how the scattering asymmetry can be used to measure the polarization of an ensemble of electrons, consider a double scattering experiment which initially starts with a beam of unpolarized electrons, as illustrated in Figure 2.4. For the initial scattering through an angle θ_1 , the unit vector $\mathbf{n}_1$ is directed upward. The unpolarized beam can be

considered to consist of an equal number of electrons with spins up, parallel to $\mathbf{n}_1$ ($m_s = +1/2$), and spins down, anti-parallel to $\mathbf{n}_1$ ($m_s = -1/2$). From Eq. 2.6, it is apparent that the number of spin-up electrons, $N_\uparrow$, scattered through θ_1 is proportional to $(1 + S(\theta_1))$, while the number of spin-down electrons, $N_\downarrow$, scattered through θ_1 is proportional to $(1 - S(\theta_1))$. Thus, the polarization of the scattered beam can be written as

$$P(\theta_1) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{(1 + S(\theta_1)) - (1 - S(\theta_1))}{(1 + S(\theta_1)) + (1 - S(\theta_1))} = S(\theta_1), \quad (2.8)$$

or, in vector notation,

$$\mathbf{P}(\theta_1) = S(\theta_1)\mathbf{n}_1. \quad (2.9)$$

Fig. 2.4. Schematic diagram of a double scattering experiment.

Now consider scattering the electrons from a second target through an angle θ_2 to the left and to the right. Since the electrons are polarized normal to the scattering plane due to the first scattering event, there will be an asymmetry in the number scattered to the left, N_L , and the number scattered to the right, N_R , that can be written as

$$A(\theta_2) = \frac{N_L - N_R}{N_L + N_R}. \quad (2.10)$$

Using Eq. 2.6 and Eq. 2.9, it can be written that N_L is proportional to $(1 + S(\theta_2)P(\theta_1))$ and N_R is proportional to $(1 - S(\theta_2)P(\theta_1))$. Substitution into Eq. 2.10 results in

$$A(\theta_2) = \frac{(1 + S(\theta_2)P(\theta_1)) - (1 - S(\theta_2)P(\theta_1))}{(1 + S(\theta_2)P(\theta_1)) + (1 - S(\theta_2)P(\theta_1))} = S(\theta_2)P(\theta_1). \quad (2.11)$$

This equation forms the basis for Mott polarimetry. It shows that the scattering asymmetry is simply related to the incident polarization through the Sherman function. In practice, for scattering from foils, the Sherman function is replaced by the effective asymmetry, S_{eff} , to account for plural and multiply scattered electrons as discussed in the introduction. With knowledge of the S_{eff} for a Mott polarimeter the polarization of an incident electron beam can be determined. Or, as done in this work, the effective asymmetry of a polarimeter can be determined by measuring the scattering asymmetry for a beam of electrons of known polarization.

B. Production of Polarized Electrons

Free electrons of known polarization are produced using electron-spin-polarized metastable $\text{He}(2^3\text{S})$ atoms in Penning ionization reactions of the type

where the arrows represent the spin orientation of the electrons involved in the reaction and X represents the target gas species. These free electrons are then directed into the Mott polarimeter and the effective asymmetry is measured. In order to assure that the spin-polarization of the free electrons equals that of the $\text{He}(2^3\text{S})$ atoms, closed-shell, spin-

singlet, negative-electron-affinity species such as CO₂ and Ar are used as the ionizing target gas.

Fig. 2.5. Diagram of electron orbitals demonstrating the two-electron exchange mechanism for Penning ionization.

Penning ionization with such targets proceeds via the exchange mechanism illustrated in Figure 2.5. A target electron tunnels to fill the He(2³S) 1s vacancy with simultaneous ejection of the 2s electron (Hotop and Niehaus 1969, Niehaus 1981). Morgner (1982) argues that the actual transition in the Penning reaction conserves spin, therefore any spin degradation will be due to interactions that occur during the approach of the metastable He(2³S) with the target. The narrow widths of the various features in the energy distribution of electrons from Penning ionization of CO₂ and Ar (see Figure 2.6) show that the ionization occurs out of the covalent channel (Hotop *et al.* 1979). Thus, as is expected for negative-electron-affinity targets, ionic molecular complexes with sufficiently long life times for magnetic interactions to perturb the electron spin states are not formed

(Keliher *et al.* 1975). Keliher *et al.* (1975) have confirmed conservation of the original He(2^3S) electron spin in Penning ionization of Ar, CO₂ and other closed shell targets in a flowing afterglow experiment.

The energies of the electrons ejected from Penning ionization of CO₂ and Ar with He(2^3S) are shown in Figures 2.6 (a) and (b), respectively.

Fig. 2.6. Electron energy spectra resulting from reaction of He(2^3S) with (a) Ar and (b) CO₂ (Hotop *et al.* 1979).

CHAPTER 3.

EXPERIMENTAL APPARATUS

Figure 3.1 is a schematic diagram of the apparatus used for this experiment. A thermal-energy beam of electron-spin-polarized metastable helium atoms is crossed with a focussed thermal-energy target gas beam. The electrons produced in the reaction are directed into the Mott polarimeter where the scattering asymmetry is measured. Beyond the interaction region, the metastable helium beam travels through a Stern-Gerlach apparatus where the electron-spin-polarization of the metastable beam is measured. This chapter briefly describes the production, polarization and characterization of the metastable helium beam and the target gas flow, the interaction region, the operation of the Mott polarimeter, and the data collection technique. A more complete description of several portions of the apparatus can be found in: Riddle *et al.* 1981, Tang *et al.* 1988, Hart *et al.* 1989.

Fig. 3.1. Schematic diagram of the apparatus.

The apparatus consists of three vacuum chambers connected along the beam line by small apertures. The first chamber holds the equipment used to produce the metastable helium beam. The second chamber contains the optical pumping region and electrostatic deflection grids. The final chamber houses the interaction region, Mott polarimeter and Stern-Gerlach analyzer. The separation of the apparatus into three chambers allows each to be pumped separately such that during operation the pressure in the source chamber is 5×10^{-6} torr while the pressure in the final chamber is $\sim 1 \times 10^{-9}$ torr. The final chamber can be completely isolated from the other chambers by a gate valve.

A. Production of the Metastable Beam

A thermal-energy ground-state helium beam is produced by effusion through a planar multi-channel array into the source vacuum chamber. The beam then travels through a coaxial electron gun, shown in Figure 3.2, made up of a filament and electron optics aligned along the axis of a solenoidal magnet.

Fig. 3.2. Metastable production region

Electrons emitted by the resistively heated tungsten filament are accelerated by the electron optics and are confined to travel mainly along the helium beam-line by the magnetic field generated with the solenoid. The collision between the accelerated electrons and the ground-state He atoms produces many excited states of He including two long lived metastable states. These are the metastable He(2^1S) state (radiative lifetime: 0.02 s (Van Dyck *et al.* 1971)) and the metastable He(2^3S) state (radiative lifetime: 9,000 s (Woodworth and Moos 1975)). Figure 3.3 shows a partial term diagram of the states of helium relevant to this discussion.

Fig. 3.3. Partial term diagram for parahelium ($S=0$) and orthohelium ($S=1$). The splitting of the 2^3P levels for different J states is not to scale. 2^3P_0 - $2^3P_1 \approx 10^{-4}$ eV; 2^3P_1 - $2^3P_2 \approx 10^{-5}$ eV (Bethe and Salpeter 1957).

The $\text{He}(2^1\text{S})$ atoms are eliminated from the beam by exciting transitions of the type $2^1\text{S} \rightarrow n^1\text{P} \rightarrow 1^1\text{S}$ using resonance radiation from a DC-excited, flowing-helium, discharge lamp. The lamp also excites $\text{He}(2^3\text{S})$ atoms into $n^3\text{P}$ states, but they can only decay back to the 2^3S state, the lowest energy state of the triplet system. After elimination of the $\text{He}(2^1\text{S})$ atoms, the beam passes into the optical pumping vacuum chamber and through a transverse electric field to deflect any electrons or ions out of the beam. The field also serves to ionize any long-lived highly-excited Rydberg atoms contained in the beam. At this point, the only impurities in the beam (*i.e.* non- $\text{He}(2^3\text{S})$ atoms that could interact with the target gas to produce electrons) are fast neutral helium atoms and photons produced in the source region.

Effects from these impurities are eliminated from the experiment by mechanically chopping the atomic beam into pulses and using time-of-flight techniques. As an atom beam pulse travels to the interaction region the impurities will be spatially separated from the $\text{He}(2^3\text{S})$ atoms due to their larger velocity. Data are recorded in the time interval after the impurities from the first pulse have passed the interaction region and before impurities from the next pulse reach the interaction region. This technique ensures that the data measured are the result of interactions with the $\text{He}(2^3\text{S})$ atoms and not with the impurities. During typical operation, the duty cycle (*i.e.* the ratio of the time during which data are collected to the total time) is 0.4 for a chopped beam as compared to 1 for an unchopped beam.

B. Polarization of the Metastable Beam

The $\text{He}(2^3\text{S})$ state has a total angular momentum of $J=1$ ($L=0$, $S=1$), and three magnetic sublevels: $m_j(m_s) = -1, 0, +1$. Under normal conditions each level is populated nearly equally according to Maxwell-Boltzman statistics. The $\text{He}(2^3\text{S})$ atoms are electron-spin-polarized (*i.e.* electron-spins oriented to increase the relative populations of $m_j = +1$ or

-1 sublevels) using the technique of optical pumping. In this technique the metastable beam is illuminated with circularly polarized $1.083\ \mu\text{m}$ resonance radiation from an RF-excited, flowing-helium, discharge lamp. When a $\text{He}(2^3\text{S})$ atom is illuminated with right hand circularly polarized (RHCP) $1.083\ \mu\text{m}$ light the $2^3\text{S} \rightarrow 2^3\text{P}$ transition will be excited with the selection rule $\Delta m_j = +1$. The excited atom will then spontaneously decay back to the 2^3S state with $\Delta m_j = -1, 0$ or $+1$ ($m_j = 0$ to $m_j = 0$ is not allowed if $\Delta J = 0$). Figure 3.4 shows the possible excitations (solid lines) and deexcitations (dashed lines) for RHCP light. From the diagram it can be seen that a $\text{He}(2^3\text{S})$ atom excited into a 2^3P state with RHCP light has the possibility of decaying into the 2^3S , $m_j = +1$ sublevel. Once in this sublevel, it can only be excited into the 2^3P , $m_j = +2$ sublevel with RHCP light and only decay back into the 2^3S , $m_j = +1$ state. Therefore, the effect of repeated excitation-deexcitation cycles with RHCP light is to transfer or "optically pump" $\text{He}(2^3\text{S})$ atoms from the $m_j = -1$ and $m_j = 0$ sublevels into the $m_j = +1$ sublevel. It should be noted that by simply reversing the sense of polarization of the resonance radiation to left hand circular polarization (LHCP) the excitation selection rule becomes $\Delta m_j = -1$, and the $\text{He}(2^3\text{S})$ atoms are pumped into the $m_j = -1$ sublevel.

Fig. 3.4. Optical Pumping with Right Hand Circularly Polarized Light.

The optical pumping radiation is circularly polarized by first passing it through a linear polarizer and then a quarter-wave plate. The quarter-wave plate can be rotated 90° , changing the polarization state from RHCP to LHCP or vice versa, via the apparatus' control computer.

A weak (~ 0.5 G) magnetic field is applied perpendicular to the beam axis, parallel to the resonance radiation to maintain a well defined quantization axis. Determination of the degree of beam polarization is discussed in the following section.

C. Characterization of the Metastable Beam

The polarization of the metastable $\text{He}(2^3\text{S})$ is measured using the Stern-Gerlach spin analyzer at the end of the beam line shown in Figure 3.5. The beam is collimated with a pair of slits and then passes through an inhomogeneous magnetic field. The field spatially separates the metastable beam into three components as a function of the spin sublevel m_j . Atoms with $m_j = +1$ or -1 are deflected in opposite directions in the inhomogeneous field, whereas atoms with $m_j = 0$ pass through undeflected. The $\text{He}(2^3\text{S})$ atoms are detected with a channel-electron-multiplier (channeltron) approximately one-half meter down stream from the magnet. The channeltron is scanned in the vertical direction to measure the distribution of atoms in each spin state.

Fig. 3.5. Schematic of Stern-Gerlach spin analyzer.

Figure 3.6 (a) is a diagram of a distribution of an unpolarized beam. The abscissa represents the position of the channeltron, and the ordinate represents the $\text{He}(2^3\text{S})$ count rate. The figure clearly shows the separation of the beam into three components. The relative area under each peak represents the relative population of $\text{He}(2^3\text{S})$ atoms in each ($m_j = -1, 0$ or $+1$) spin state.

Fig. 3.6. Stern-Gerlach profiles of an $\text{He}(2^3\text{S})$ beam that is (a) unpolarized, and $\text{He}(2^3\text{S})$ beams that are polarized by optically pumped with LHCP radiation (—) and RHCP radiation (---) from (b) a discharge lamp ($P_Z = 0.38$) and (c) a solid state laser ($P_Z = 0.98$).

By measuring the area under each peak the polarization of the beam, P_Z , is calculated using:

$$P_Z = \frac{n_+ - n_-}{n_+ + n_0 + n_-} \quad (3.1)$$

where n_+ , n_0 and n_- are the populations (areas) of the $m_j = +1, 0$, and -1 sublevels (peaks), respectively. Polarizations of ~ 0.38 are regularly achieved when using the helium discharge lamp as a source of resonant pumping radiation. Figure 3.6 (b) shows Stern-Gerlach scans obtained after optical pumping with RHCP and LHCP radiation. Optical pumping has also been performed using $1.08\mu\text{m}$ radiation from a solid-state laser. The increased intensity of the laser light allows much higher polarizations of ~ 0.98 to be obtained, as is evident from Figure 3.6 (c). Unfortunately, problems with the laser's stability precluded its routine use in the present experiment.

It should be noted that particles other than $\text{He}(2^3\text{S})$ atoms can pass through the Stern-Gerlach analyzer and potentially be detected. Thermal-energy, ground-state helium atoms (which comprise the majority of atoms in the beam) pass through the analyzer undeflected. Their energy is not sufficient to eject electrons when they strike the channeltron and will not be detected. However, sufficiently energetic, ground-state helium atoms and photons can eject electrons upon striking the channeltron and are detected. By comparing the area of the central peak and the areas of the side peaks for an unpolarized beam, it is estimated that only $\sim 2\text{-}3\%$ of the (unchopped) beam produced by the source is composed of these impurities (Hart 1985). Beam chopping and time-of-flight techniques (discussed above) reduce this amount to an undetectable level.

D. Production and Characterization of the Target Beam

The basic challenge of this experiment is to create a region of high density gas as a target for the $\text{He}(2^3\text{S})$ beam without increasing the background pressure in the final

vacuum chamber to unacceptable levels. This challenge is met by employing a focussed multi-channel array to admit the target gas into the vacuum chamber. The array consists of about 10^7 1.9 mm long glass capillary tubes fused into a disk 2.54 cm in diameter. The disk is concave so that the axes of the capillaries are directed to a point 5.08 cm from the array. The capillary channel diameter is 7×10^{-4} cm, and the channels occupy 50% of the area of the disk. Following the analyses of Lucas (1973a & 1973b), it is calculated that such an array produces at its focus a region of enhanced density of $\sim 10^{12}$ atoms per cm^3 for CO_2 and Ar with a background pressure of $\sim 10^{-6}$ torr ($\sim 3 \times 10^{10} \text{ cm}^{-3}$), given the final chamber pumping speed of 240 liters per second. The full-width at half-maximum (FWHM) intensity is calculated to be ~ 1.9 mm at the focus.

As shown in Figure 3.7, the multi-channel array (MCA) is mounted in a stainless steel holder that is attached to a precision three-axes translator at the top of the vacuum chamber. The target gas is delivered to the MCA through stainless steel tubing from a gas cylinder outside the vacuum chamber. The flow rate is controlled by a variable leak valve. The port to the chamber's turbo-molecular vacuum pump is directly down stream of the MCA, allowing maximum gas throughput with minimum increase in background pressure.

To assure that the MCA functions properly, the target gas beam profile at the focus was measured using the techniques of Lucas (1973b) and Hanes (1960). A stationary, stainless steel, capillary probe 0.8 mm in internal diameter and 2 cm long was positioned near the beam focus. The probe was connected via stainless steel tubing to a another vacuum chamber that housed a quadrupole mass spectrometer. The spectrometer was used as a mass specific pressure sensor. This arrangement allowed the MCA to be translated over the probe and the local target gas density measured as a function of position. Figure 3.8 shows the profile for CO_2 flowing through the MCA with a chamber pressure of 8×10^{-6} torr resulting in a FWHM intensity of 1.8 mm. The capillary probe was removed from the chamber before the Mott polarimeter calibration experiments.

Fig. 3.7. Cross-sectional view of the multi-channel array and the interaction region. The direction of travel of the $\text{He}(2^3\text{S})$ beam is out of the page. The capillary probe is removed before the Mott polarimeter calibration experiments.

Fig. 3.8. Intensity profile of CO_2 flowing from focussed multi-channel array. FWHM = 1.8 mm.

E. The Interaction Region.

The interaction region is the region where the $\text{He}(2^3\text{S})$ beam and the target beam intersect resulting in Penning ionization of the target gas (see Figure 3.7). The $\text{He}(2^3\text{S})$ beam has a square cross-section 4 mm on a side that is defined by apertures upstream. The MCA is positioned such that its focus intersects the $\text{He}(2^3\text{S})$ beam and the central axis of the Mott polarimeter. The polarimeter is oriented so its central axis is horizontal and perpendicular to both the $\text{He}(2^3\text{S})$ beam and the target beam. The aperture of the polarimeter is 1.78 cm in diameter and 1.27 cm away from the center of the $\text{He}(2^3\text{S})$ beam.

The electrostatic potential in the interaction region is defined by the Mott polarimeter's first lens and aperture and the reference grid. The reference grid is a disk of stainless steel mesh 2.29 cm in diameter that is located along the polarimeter's central axis

4.2 cm from the aperture. The first lens is maintained at 1.7 kV (see the following section), and the aperture and polarimeter's outer body are grounded. The potential of the reference grid is set so that only electrons produced in the interaction region can traverse the polarimeter and reach the target foil. This is done to prevent electrons produced by surface deexcitation of scattered $\text{He}(2^3\text{S})$ atoms from affecting the measurements.

The appropriate reference grid potential was determined by modelling the electrostatic fields of the Mott polarimeter and the reference grid using the electrostatic lens analysis and design program SIMION PC/PS2 (available from D.A. Dahl, Idaho National Engineering Laboratory). The program calculated the electrostatic field based on the potentials of the lenses, aperture and reference grid. From this field, the program could then trace the trajectory of a charged particle. To determine the correct potential, trajectories of electrons originating in the interaction region and on the nearby surfaces with energies of 18 eV or less were followed to determine if they would enter the polarimeter and hit the target foil. By analyzing the results for various reference grid potentials it was determined that a potential of +60 V was appropriate to prevent surface electrons from entering the polarimeter while allowing slightly less than 50% of the electrons generated in the interaction region to successfully reach the polarimeter's target foil. With the reference grid at this potential, the potential in the interaction region was ~24 V.

F. The Mott Polarimeter

Since 1943, when Shull *et al.* first observed the spin-dependent effects of Mott scattering, Mott polarimeters have been used for spin polarization measurements in many areas of physics. Conventional Mott polarimeters (Wainwright *et al.* 1978) typically function by accelerating the electrons to energies of ~100 keV with an accelerating column and scattering them from a gold target. Electrons scattered at $\theta = \pm 120^\circ$ (where the Sherman function has a broad maximum) are detected by two energy sensitive detectors,

and the scattering asymmetry is measured. Such polarimeters typically require a large space (several m^3) and are cumbersome to operate in part because the accelerating column, scattering chamber, detectors and associated electronics must be maintained at a very high potential.

Work in this laboratory produced the first significant simplification to the conventional Mott polarimeter design in 1979 (Hodge, Moravec *et al.*). In the simplified design, illustrated in Figure 3.9, the electrons are accelerated to ~ 120 keV in a radial field established between two cylinders and scattered from a gold foil located at the center of the inner cylinder. Electrons scattered at $\theta = \pm 120^\circ$ are then decelerated in the radial field to near their original energy before being detected with channeltrons. This design provides for good energy discrimination against inelastically scattered electrons since only those electrons that have suffered small inelastic energy losses can overcome the deceleration field and arrive at the detectors. A bias voltage applied to the detector entrance cone permits the allowed inelastic energy loss of the detected electrons to be varied. Also, since the detectors are operated near ground the shielding requirements for the detectors and associated electronics are significantly reduced. Analyzers of this type are called retarding-potential Mott polarimeters.

Fig. 3.9. Top view of the retarding-potential Mott polarimeter of Hodge, Moravec *et al.* (1979).

In this laboratory, over the years, evolutionary development of the Hodge, Moravec *et al.* design (Gray *et al.* 1984, Dunning, Gray *et al.* 1987) has led to the current compact low-energy Mott polarimeter (Tang *et al.* 1988) used in this work as shown in Figure 3.10. It is known as the " μ -Mott" polarimeter due to its small size when compared to previous designs.

Fig. 3.10. Schematic of the μ -Mott polarimeter. For the present work the retarding grids were removed.

Electrons are admitted into the polarimeter through the entrance aperture and pass through a series of copper mesh grids that form a retarding-potential energy analyzer. These grids allow energy resolved polarization measurements to be made during typical operation of the Mott polarimeter. However, for the present work, energy resolution was

not required. Thus, the grids were removed and the entrance aperture was enlarged to improve the counting efficiency of the μ -Mott polarimeter. After entering the polarimeter, the electrons pass through the first and second lens elements operated at 1.7 kV and 1.0 kV, respectively. Their function is to focus the electrons to a small spot on the target foil that sits at the base of the final lens element. The target foil and final lens element are operated at a potential of 20 kV, therefore the electrons strike the target with essentially 20 keV of energy scattering in all directions. Electrons that backscatter in the designated plane (determined by the orientation of the polarimeter about its central axis) at angles of $\pm 120^\circ$ to the incident trajectory enter a retarding electric field between the inner apertures (at 20 kV) and the outer apertures and bell-mouthed channeltron cones (at ~ 1 kV). Consequently, the scattered electrons are decelerated, and only those with enough energy to overcome the retarding field are detected. This feature sets an upper limit to the amount of energy that the detected electrons are allowed to lose in scattering. It is known as the inelastic energy loss window, ΔE , and is approximately equal in eV to the potential of the output apertures and channeltron cones in V*. With the polarimeter operating under these conditions, the count rate measured by the channeltrons with no external source of electrons (*i.e.* the dark-count rate) is < 1 Hz.

The effective asymmetry, S_{eff} , can be determined by measuring the asymmetry in the count rate of the two detectors for a beam of electrons whose polarization perpendicular to the scattering plane is known. From Eq. 2.6 the ratio of the count rates can be written as

$$\frac{\sigma_L}{\sigma_R} = \frac{R_L}{R_R} = \frac{1 + S_{\text{eff}}P}{1 - S_{\text{eff}}P} . \quad (3.2)$$

* An electron ejected from a $\text{He}(2^3\text{S})$ atom with 6 eV energy in a region with a potential of 24 V will have a kinetic energy of $\text{KE}_i = 20 \text{ keV} + (6 - 24) \text{ eV}$ when it strikes the gold foil target. If it loses δE energy in scattering, and is subsequently decelerated in the field between the inner aperture and the channeltron cone, operating at a potential of V_c , it will have an energy of $\text{KE}_f = 20 \text{ keV} - 18 \text{ eV} - \delta E - (20 \text{ keV} - eV_c)$ or $\text{KE}_f = eV_c - \delta E - 18 \text{ eV}$ when it reaches the channeltron cone. If $eV_c < \delta E + 18 \text{ eV}$ then the electron cannot reach the channeltron cone and will not be detected. For this case the inelastic energy loss window is $\Delta E = eV_c - 18 \text{ eV}$.

However, this equation assumes an equal detection efficiency for the left and right channels. In practice, there exists sources of instrumental asymmetry such as unequal detector response, misalignment of the beam and other factors. This instrumental asymmetry can be included in the above equation as a term δ as follows

$$\frac{R_L}{R_R} = \left[\frac{1 + S_{\text{eff}}P}{1 - S_{\text{eff}}P} \right] \delta . \quad (3.3)$$

If the input beam's polarization is reversed ($P \rightarrow -P$) by reversing the sense of circular polarization of the optical pumping radiation the ratio of the counting rates becomes

$$\frac{R'_L}{R'_R} = \left[\frac{1 - S_{\text{eff}}P}{1 + S_{\text{eff}}P} \right] \delta . \quad (3.4)$$

Eliminating δ between Eqs. 3.3 and 3.4 and solving in terms of S_{eff} results in

$$S_{\text{eff}} = \frac{1}{P} \left[\frac{X - 1}{X + 1} \right] \quad (3.5)$$

where

$$X \equiv \sqrt{\frac{R_L R'_R}{R_R R'_L}} . \quad (3.6)$$

This result shows one of the major benefits to being able to reverse the sense of electron-spin-polarization simply by reversing the sense of the optical pumping radiation polarization. It allows measurements to be made independent of the instrumental asymmetry. A data run typically consists of measuring the counts in the left and right channels for one polarization sense for ten seconds, reversing the polarization and

measuring the count rate again. This cycle is then repeated, accumulating measurements for as long as desired under computer control.

As mentioned in the introduction, measurements were made for both a gold target foil and a thorium target foil. The gold foil target was a disk 0.025 mm thick and 15.2 mm in diameter. Tang *et al.* (1987) determined that for the gold target, with $\Delta E = 1.3$ keV, the scattering efficiency I/I_0 , where I is the total scattered current detected and I_0 is the current incident on the gold target, is $\sim 2 \times 10^{-3}$.

The thorium target used in the experiment was a disk 0.09 mm thick and 12.7 mm in diameter. Before it was installed into the Mott polarimeter, the black oxide layer on the target was removed by following a recipe of McClelland *et al.* (1989). The target was etched in concentrated sulfuric acid at 230 °C for 2 h, followed by passivation for 30 s in a ~30% solution of nitric acid at room temperature, rinsing after each step with deionized water. Following the treatment, the target had a shiny metallic appearance that did not visibly deteriorate after several days exposure to air.

An important parameter in with regard to the performance of Mott polarimeter is the so-called figure of merit, f , defined as :

$$f = \frac{I}{I_0} S_{\text{eff}}^2. \quad (3.7)$$

The quantity f is inversely proportional to the square of the statistical error in the measurement of the polarization P of an incident electron beam (Kessler 1985). Maximizing f , minimizes the error in the measurement of P for given number of incident electrons. The figure of merit for the μ -Mott polarimeter with the gold target is $\sim 2 \times 10^{-5}$ (Tang *et al.* 1987), about 2 orders of magnitude greater than that of the Hodge, Moravec *et al.* (1979) design.

G. Data Collection

The collection of data proceeded in the following manner. The $\text{He}(2^3\text{S})$ source was warmed up for a period of three hours before each data run to ensure stable operation. First, the $\text{He}(2^3\text{S})$ beam's polarization was determined by measuring the Stern-Gerlach distributions for optical pumping with LHCP radiation and RHCP radiation. Then, the target gas was admitted into the final chamber and the variable leak valve was adjusted for the desired pressure. The dark count rate of the polarimeter's detectors was measured (the rate was always < 1 Hz, typically ~ 0.5 Hz). Then the $\text{He}(2^3\text{S})$ beam was admitted into the final chamber, and electrons from the Penning reactions between the $\text{He}(2^3\text{S})$ atoms and the target gas were collected with the Mott polarimeter, and the scattering asymmetry was measured. Counts were accumulated for ten seconds with LHCP radiation and then ten seconds with RHCP radiation. Under computer control, this cycle was repeated accumulating counts until the statistical uncertainty was typically $\leq 5\%$. Data runs usually lasted for about one hour. At the end of the data run, the dark count rate was again measured, the target gas flow was stopped, and the polarization of the $\text{He}(2^3\text{S})$ was remeasured to make sure that it had not drifted during the run. Several data runs were performed for each of the desired conditions, and the results of the runs were combined in a weighted average.

CHAPTER 4.

RESULTS AND DISCUSSION

Values of the effective asymmetry, S_{eff} , for several inelastic energy loss windows, ΔE , using both gold and thorium targets and CO_2 as the target gas are shown in Table 4.1.

Table 4.1. Measured values of S_{eff} .

Target	Inelastic energy loss window ΔE		
	$\Delta E = 500 \text{ eV}$	$\Delta E = 900 \text{ eV}$	$\Delta E = 1300 \text{ eV}$
Gold ($Z = 79$)	–	0.121 ± 0.006	0.103 ± 0.005
	$0.148 \pm 0.023^{\text{a}}$	$0.125 \pm 0.018^{\text{a}}$	$0.105 \pm 0.016^{\text{b}}$
	0.14^{c}		
Thorium ($Z = 90$)	0.176 ± 0.009	0.141 ± 0.008	0.115 ± 0.006
	0.17^{c}		

^aResults from Zhang (1988).

^bResults from Tang *et al.* (1988).

^cResults from McClelland *et al.* (1989).

Also included in the table are values from an earlier calibration of the same Mott polarimeter by Zhang (1988) and Tang *et al.* (1988) and values from a calibration of a cylindrical Mott polarimeter by McClelland *et al.* (1989). The calibrations of Zhang and Tang *et al.* were referenced to a high energy (120 keV) cylindrical Mott polarimeter using the Rice flowing helium afterglow polarized electron source (Hodge, Dunning and Walters 1979) following the techniques of Gray *et al.* (1984). The effective asymmetry of the cylindrical polarimeter was determined by extrapolation to zero foil thickness and normalizing in this limit to the theoretical value for pure elastic scattering (Hodge, Moravec

et al. 1979). The calibrations of McClelland *et al.* were performed using a cylindrical Mott polarimeter based on the Hodge, Moravec *et al.* (1979) design. The effective asymmetries were determined by measuring the scattering asymmetry as a function of inelastic energy loss window, extrapolating to zero energy loss and normalizing to the theoretical value for pure elastic scattering. It should be noted that the results from the present work do not depend on extrapolation or normalization to theory. The agreement between the present and earlier results suggests that extrapolation and normalization can provide reliable calibrations of S_{eff} , at least at the few percent level.

From Table 4.1, it can be seen that the effective asymmetry for the thorium target foil is 19%, 17% and 12% larger than that for the gold target foil at $\Delta E = 500$ eV, 900 eV and 1300 eV, respectively. McClelland *et al.* (1989) found that the S_{eff} for a thorium target was 30% and 21% larger than that for a gold target at $\Delta E = 25$ eV and 500 eV. McClelland *et al.* attribute the faster drop off of S_{eff} with ΔE for thorium to the thickness of the thorium target. The thickness of their thorium target is the same as the one used for the present work, 0.09 mm, however their gold target is only 0.000125 mm whereas the one used in this work is 0.025 mm. They claim that multiple scattering is much more significant for a thick target, and hence that the degradation of S_{eff} should be more drastic as ΔE is increased. However, this conclusion is not consistent with the data of this work which shows that S_{eff} for thorium continues to drop faster with ΔE even when compared to a gold target of similar thickness. Also, Dunning, Tang and Walters (1987) showed that for an accelerating voltage of 20 kV and $\Delta E \leq 1300$ eV, S_{eff} was the same for gold targets 0.0001 mm and 0.025 mm thick. This is a result of the tight energy discrimination, afforded by retarding-potential polarimeters, which limits the thickness of the target region from which scattered electrons are detected. The maximum critical thickness from which scattered electrons can be detected for a given ΔE can be estimated from the mean energy loss per

unit distance, dE/dx , of electrons scattering in the target. For scattering at 120° , the path length is 3 times the scattering depth and the critical thickness is:

$$t_c = \frac{1}{3} \Delta E \left(\frac{dE}{dx} \right)^{-1}. \quad (4.1)$$

For 20 keV electrons in Au dE/dx is $1.2 \text{ eV } \text{\AA}^{-1}$ (Campbell *et al.* 1985), therefore for $\Delta E = 1300 \text{ eV}$, $t_c = 361 \text{ \AA}$. This should only be considered an estimate since the energy loss proceeds in discrete events. (The mean free path for inelastic scattering of 20 keV electrons in Au is $200 \text{ \AA}$ (Misell 1973).) The target foils considered here are much thicker than this value, thus the thickness of the scattering region will be governed by ΔE and not the physical size of the target. In light of this result, it is not reasonable to expect that the faster drop of S_{eff} with ΔE of thorium is due to the size of the target. More likely, it is a result of differences in the efficiency of producing inelastically scattered electrons between gold and thorium.

From the data of the present work, the scattering efficiency of thorium (I/I_0) is estimated to be about 35% greater than that of gold for both $\Delta E = 900 \text{ eV}$ and 1300 eV . However, uncertainties in the exact repositioning of the Mott polarimeter after installation of the thorium target foil, causing a change in the polarimeter's collection efficiency, may have resulted in a systematic error in this value. McClelland *et al.* (1989) determined the scattering efficiency of thorium to be about 15% higher than that of gold. Their larger cylindrical polarimeter allowed the targets to be changed *in situ*. Using the measured increase in S_{eff} and the McClelland *et al.* value for the increased scattering efficiency, the resulting increase in the figure of merit for thorium as compared to gold can be calculated using Eq. 3.7. The results are shown in Table 4.2.

Table 4.2. Ratio of the figures of merit of thorium and gold.

	Inelastic energy loss window ΔE		
	$\Delta E = 500 \text{ eV}$	$\Delta E = 900 \text{ eV}$	$\Delta E = 1300 \text{ eV}$
$f_{\text{Th}}/f_{\text{Au}}$	1.63	1.56	1.43

The experimental uncertainty of the present results is primarily associated with the determination of the $\text{He}(2^3\text{S})$ beam polarization, P_Z . While the $m_j(m_s) = +1, 0$ and -1 states could be well resolved by the Stern-Gerlach analyzer (see Fig. 3.6), the possibility exists that a small fraction of the $m_j(m_s) = \pm 1$ atoms might strike the pole faces of the magnet leading to an underestimate of the size of these populations. To examine this possibility, beam polarizations were measured using different magnetic field strengths in the analyzer and the data were analyzed using several different procedures. These tests indicated that the systematic error in the measurement of P_Z is $\leq \pm 0.03 P_Z$.

To determine if there existed any systematic effects in the results due to the pressure of the target gas, measurements were made at various pressures. Figure 4.1 is a plot of S_{eff} versus CO_2 pressure for the thorium target foil. As can be seen from the figure, there were no statistically significant variations in S_{eff} as a function of pressure in the range measured.

Limited measurements were also performed with Ar as the target gas. Table 4.3 lists the results along with the results of CO_2 for comparison. The uncertainties in the values are larger for Ar due to the lower count rate for Ar (see Table 4.4), resulting in a larger contribution from spurious background electrons to the total detected signal. The lower count rate is the result of the smaller Penning ionization cross-section of Ar with $\text{He}(2^3\text{S})$ atoms as compared to that of CO_2 (see Table 4.5).

Fig. 4.1. S_{eff} vs. CO_2 pressure for the thorium target.

Table 4.3. Measured values of S_{eff} for different target gases using the thorium scattering target.

Target Gas	Inelastic energy loss window ΔE	
	$\Delta E = 900 \text{ eV}$	$\Delta E = 1300 \text{ eV}$
Ar	0.133 ± 0.014	0.098 ± 0.010
CO_2	0.141 ± 0.008	0.115 ± 0.006

Table 4.4. Measured count rates for different target gases with the thorium target.

Target Gas	Inelastic energy loss window ΔE	
	$\Delta E = 900 \text{ eV}$	$\Delta E = 1300 \text{ eV}$
Ar	15 Hz	29 Hz
CO_2	79 Hz	119 Hz

S_{eff} for Ar are 6% and 15% lower than CO_2 for $\Delta E = 900$ eV and $\Delta E = 1300$ eV, respectively. The probable explanation for this is that the actual polarization of the electrons measured for Ar was lower than the $\text{He}(2^3\text{S})$ beam polarization as a result of contamination of the Penning electrons by electrons from another source. This source is the result of electrons produced from the deexcitation of scattered $\text{He}(2^3\text{S})$ atoms by collisions with the metal surfaces inside the chamber. Even though the polarization of such electrons is large, $\sim 75\%$ of the $\text{He}(2^3\text{S})$ polarization (Hart *et al.* 1989), if sufficient numbers are detected by the polarimeter they could reduce the measured scattering asymmetry. Table 4.5 lists the center of mass collision energies, the total scattering cross-sections, σ_{TS} , and the Penning ionization cross-sections, σ_{PI} , for the reactions of interest. For the same gas densities, it is expected that the number of electrons produced by scattered $\text{He}(2^3\text{S})$ atoms colliding with surfaces will be similar for both CO_2 and Ar given the similarity between the two gases total scattering cross-section. However, the number of electrons produced in Penning ionization reactions will be much less for Ar given its smaller Penning ionization cross-section. Thus, the fraction of the total number of electrons detected by the polarimeter that originate from surface collisions will be larger for Ar than for CO_2 , and the reduction in the effective scattering asymmetry will be greater.

To test this hypothesis, measurements were made with He and Ne as target gases, neither of which produce free electrons by Penning ionization. At the same densities as for the Ar and CO_2 measurements, the count rate detected by the Mott polarimeter for $\Delta E = 1300$ eV was ~ 5 Hz for Ne and ~ 3 Hz for He. This indicates that, contrary to what was expected based on the electron trajectory modeling (see Chap. 3, sec. E), a small fraction of the electrons produced by surface deexcitation of scattered $\text{He}(2^3\text{S})$ atoms could be detected by the Mott polarimeter introducing the possibility of a systematic error especially in the case of Ar for which the count rates were very low. However, reanalysis of the CO_2 data taking into account this source of electrons resulted in the calculated S_{eff} increasing only by

$\leq 2\%$, within the error quoted for the data. Thus, it is concluded that electrons from surface deexcitation do not contribute a significant systematic error to the results.

Table 4.5. Center of mass collision energies, total scattering cross-sections, σ_{TS} , and Penning ionization cross-sections, σ_{PI} , for reactions of interest.

Reaction	E_{CM} (meV)	σ_{TS} ($\text{\AA}^2$)	σ_{PI} ($\text{\AA}^2$)
He(2^3S) – CO ₂	46	$\sim 480^a$	$55 \pm 5\%^b$
He(2^3S) – Ar	45	$460 \pm 10\%^c$	$6.8 \pm 5\%^b$
He(2^3S) – Ne	44	$187 \pm 10\%^c$	–
He(2^3S) – He	41	$151 \pm 10\%^c$	–

^aEstimated from Li – CO₂ data of Dehmer *et al.* (1973). The total scattering cross-section of Li – atom and Li – molecule collisions have been shown to be very similarly to that of He(2^3S) – atom and He(2^3S) – molecule collisions, respectively (Rothe *et al.* 1965, Trujillo 1975, Harper and Smith 1977, Ohno *et al.* 1991).

^bResults from Koizumi *et al.* (1986).

^cResults from Fiering *et al.* (1982).

CHAPTER 5

CONCLUSIONS

This work has provided a novel technique for calibrating a Mott polarimeter based on producing electrons of known polarization through Penning ionization reactions between a beam of electron-spin-polarized $\text{He}(2^3\text{S})$ atoms and a target gas. Unlike the other calibration techniques discussed in this work, this method does not require the extrapolation of data, or the normalization to theoretically determined parameters. Gay *et al.* (1992) have concluded that the current upper limit of the precision to which calibrations can be done using extrapolation methods is $\sim 1\%$. They point out that the ultimate precision may be $\sim 0.5\%$. When this is coupled with theoretical accuracy to which the Sherman function is known, about 2% , the overall uncertainty of the method is $\sim 3\%$. The calibration method presented in this work does not have either of these limitations. Its precision is currently limited by the uncertainty in the determination of the polarization of $\text{He}(2^3\text{S})$ atom beam. This uncertainty can significantly be reduced, however, by the use of laser-induced optical pumping (which can achieve beam polarizations approaching unity) and an improved Stern-Gerlach apparatus.

Recently, a variation of the present calibration method has been demonstrated in which a target composed of gas condensed onto a refrigerated substrate is substituted for the thermal energy target gas beam (Oró *et al.* 1992). A $\text{Cu}(100)$ substrate was cooled to $\sim 40^\circ\text{K}$ and exposed to Xe gas which was adsorbed onto the cold surface. This surface was then used as a target for the polarized $\text{He}(2^3\text{S})$ atom beam and produced electrons through Penning ionization of Xe on the surface. Preliminary results of this method have

yielded the value $S_{\text{eff}} = 0.110 \pm 0.003$ for $\Delta E = 1300$ eV with the thorium scattering target. This is in good agreement with the value obtained in the present work, but the experimental uncertainty is significantly reduced. The reasons for this are two-fold. First, the detected count rate from the frozen gas target is about 20 times greater than with the gas beam target reducing the statistical uncertainty in the collected counts. Second, the He(2^3S) atom beam was optically pumped using light from Ti:sapphire laser resulting in a beam polarization > 0.9 . The potential exists for decreasing the uncertainty even more with the use of an improved Stern-Gerlach apparatus. It should be noted however, that while calibration of Mott polarimeters to high precision appears possible, the value of S_{eff} may not be directly transferable, with the same precision, to other polarimeters operating under similar conditions (*i.e.* with the same electron scattering energy and the same ΔE) due to variations in design of the polarimeters.

REFERENCES

- Abraham, D. L. and H. Hopster, 1989, Spin-Polarized Electron-Energy-Loss Spectroscopy on Ni, *Phys. Rev. Lett.*, **62**, 1157-1160
- Baum, G., M. Fink, W. Raith, H. Steidl and J. Taborski, 1989, Polarized Electron-Impact Ionization of Metastable Helium, *Phys. Rev. A*, **40**, 6734-6736
- Bethe, H. A. and E. E. Salpeter, 1957, *Quantum Mechanics of One- and Two-Electron Atoms*, Springer-Verlag, Berlin
- Campbell, D. M, C. Hermann, G. Lampel and R. Owen, 1985, A Compact Cylindrical Mott Electron Polarimeter Operating in the Range 20 - 100 kV, *J. Phys. E*, **18**, 664-672
- Curtis, R. B. and R. R. Lewis, 1957, Electron Polarization in Beta Processes, *Phys. Rev.*, **107**, 543-547
- Dehmelt, H., 1990, Experiments on the Structure of an Individual Elementary Particle, *Science*, **247**, 539-545
- Dehmer, P., G. Ury and L. Wharton, 1973, Absolute Total Cross Sections for Li-Molecule Scattering, *J. Chem. Phys.*, **58**, 4724-4732
- Dunning, F. B., L. G. Gray, J. M. Ratliff, F.-C. Tang, X. Zhang and G. K. Walters, 1987, Simple and Compact Low-Energy Mott Polarization Analyzer, *Rev. Sci. Instrum.*, **58**, 1706-1708
- Dunning, F. B., F.-C. Tang and G. K. Walters, 1987, Use of Thick Gold Foils in Retarding-Potential Mott Polarimeters, *Rev. Sci. Instrum.*, **58**, 2195-2196
- Erskine, J. L. and R. L. Fink, 1990, New Opportunities in Spin-Polarized Photoemission Spectroscopy, *J. Appl. Phys.*, **67**, 5699-5703
- Feder, R., ed., 1985, *Polarized Electrons in Surface Physics*, World Scientific Publishing Co., Singapore
- Fiering, K. B., S. R. Ryan and W. H. Wing, 1982, A Crossed-Beam Time-of-Flight Study of Metastable Helium in Collisions with Helium, Neon and Argon, *J. Phys. B*, **15**, 3841-3851
- Gauder, R., K. W. Hoffman, A. Hilscher, U. Zierer, E. Speller and O. Boslau, 1988, Measurement of the Longitudinal Electron Polarization in Nuclear Beta-Decay, *Z. Phys. A*, **330**, 423-429

- Gay, T. J., and F. B. Dunning, 1992, Mott Electron Polarimetry, *Rev. Sci. Instrum.*, in press
- Gay, T. J., M. A. Khakoo, J. A. Brand, J. E. Furst, W. V. Meyer, W. M. K. P. Wijayaranta and F. B. Dunning, 1992, Extrapolation Procedures in Mott Polarimetry, *Rev. Sci. Instrum.*, **63**, 1-17
- Gray, L. G., M. W. Hart, F. B. Dunning and G. K. Walters, 1984, Simple, Compact, Medium-Energy Mott Polarization Analyzer, *Rev. Sci. Instrum.*, **55**, 88-91
- Hanes, G. R., Multiple Tube Collimator for Gas Beams, 1960, *J. Appl. Phys.*, **31**, 2171-2175
- Harper, S. F. W. and A. C. H. Smith, 1977, Absolute Cross Sections for the Scattering of Metastable Helium and Neon Atoms from Rare Gas Atoms and Diatomic Molecules, *International Conference on the Physics of Electronic and Atomic Collisions, 10th, Abstracts of Papers*, 82, Commissariat a L'Energie Atomique, Paris
- Hart, M. W., 1985, Spin-Polarized Metastable Atom Deexcitation Spectroscopy: A New Probe of Surface Magnetism, M. A. Thesis, Rice University, unpublished
- Hart, M. W., M. S. Hammond, F. B. Dunning, and G. K. Walters, 1989, Spin-Polarized Metastable-Atom Deexcitation Spectroscopy: A New Probe of the Dynamics of Metastable-Atom-Surface Interactions, *Phys. Rev. B*, **39**, 5488-5491
- Heller, K. J., ed., 1989, *High Energy Spin Physics*, AIP Conference Proc. No. 187, AIP, New York
- Hodge, L. A., F. B. Dunning and G. K. Walters, 1979, Intense Source of Spin-Polarized Electrons, *Rev. Sci. Instrum.*, **50**, 1-4
- Hodge, L. A., T. J. Moravec, F. B. Dunning and G. K. Walters, 1979, Mott Electron Spin Polarization Analysis System of Novel Design, *Rev. Sci. Instrum.*, **50**, 5-8
- Hotop, H., E. Kolb and J. Lorenzen, 1979, The Temperature Dependence of Penning Ionization Electron Energy Spectra: He(2^3S)-Ar, N₂, NO, O₂, N₂O, CO₂, *J. Electron Spectrosc. Relat. Phenom.*, **16**, 213-243
- Hotop, H., and A. Niehaus, 1969, Reactions of Excited Atoms and Molecules with Atoms and Molecules, *Z. Phys.*, **228**, 68-88
- Hughes, V. W., 1990, High-Energy Physics with Polarized Electrons and Muons, *Nucl. Phys.*, **A518**, 371-388
- Keliher, P. J., F. B. Dunning, M. R. O'Neill, R. D. Rundel, and G. K. Walters, 1975, Spin Conservation During Chemi-Ionization and Surface-Electron Ejection by He(2^3S), *Phys. Rev. A*, **11**, 1271-1278
- Kessler, J., 1985, *Polarized Electrons*, 2nd edition, Springer-Verlag, Berlin

- Koizumi, H., M. Ukai, Y. Tanaka, K. Shinsaka and Y. Hatano, Temperature Dependence of the Deexcitation of $\text{He}(2^3\text{S})$ by Atoms and Molecules as Studied by Pulse Radiolysis Method, *J. Chem. Phys.*, **85**, 1931-1937
- Lin, S.-R., N. Sherman and J. K. Percus, 1963, Elastic Scattering of Relativistic Electrons by Screened Atomic Nuclei, *Nucl. Phys.*, **45**, 492-504
- Lowenstein, D. I., 1989, Spin Facilities in North America, *High Energy Spin Physics*, K. J. Heller ed., AIP Conference Proc. No. 187, 863-865, AIP, New York
- Lucas, C. B., 1973a, The Production of Intense Atomic Beams, *Vacuum*, **23**, 395-402
- Lucas, C. B., 1973b, Measurements of the Atomic Beam Formed by a Focusing Capillary Array, *J. Phys. E*, **6**, 991-994
- McClelland, J. J., M. R. Scheinfein and D. T. Pierce, 1989, Use of Thorium as a Target in Electron-Spin Analyzers, *Rev. Sci. Instrum.*, **60**, 683-687
- Misell, D. L., 1973, Image Formation in the Electron Microscope with Particular Reference to the Defects in Electron-Optical Images, *Advances in Electronics and Electron Physics*, L. Marton ed., **32**, 64-193, Academic Press, New York
- Morgner, H., 1982, Symmetry Considerations in Penning Ionization, *Comments At. Mol. Phys.*, **11**, 271-285
- Mott, N. F., 1929, The Scattering of Fast Electrons by Atomic Nuclei, *Proc. R. Soc. A*, **124**, 425-442
- Mott, N. F., 1932, The Polarisation of Electrons by Double Scattering, *Proc. R. Soc. A*, **135**, 429-458
- Motz, J. W., H. Olsen and H. W. Koch, 1964, Electron Scattering without Atomic or Nuclear Excitation, *Rev. Mod. Phys.*, **36**, 881-928
- Niehaus, A., 1981, Spontaneous Ionization in Slow Collisions, *Adv. Chem. Phys.*, **45**, 399-486
- Ohno, K., T. Takami and K. Mitsuke, 1991, State-Resolved Collision Energy Dependence of Penning Ionization Cross-Sections for N_2 and CO_2 by He^*2^3S , *J. Chem. Phys.*, **94**, 2675-2687
- Oró, D. M., Q. Lin, P. A. Soletsky, X. Zhang, F. B. Dunning and G. K. Walters, 1992, Absolute Calibration of a Mott Polarimeter, *Rev. Sci. Instrum.*, submitted for publication
- Prescott, C. Y., et al., 1978, Parity Non-Conservation in Inelastic Electron Scattering, *Phys. Lett.*, **77B**, 347-352
- Riddle, T. W., M. Onellion, F. B. Dunning and G. K. Walters, 1981, Polarized $\text{He}(2^3\text{S})$ Thermal Metastable Atom Source, *Rev. Sci. Instrum.*, **52**, 797-801

- Robins, J. L., R. J. Celotta, J. Unguris, D. T. Pierce, B. T. Jonker and G. A. Prinz, 1988, Domain Images of Ultrathin Fe Films on Ag(100), *Appl. Phys. Lett.*, **52**, 1918-1920
- Rothe, E. W., R. H. Neynaber and S. M. Trujillo, 1965, Velocity Dependence of the Total Cross Section for the Scattering of Metastable He(3S_1) by Helium, Argon, and Krypton, *J. Chem. Phys.*, **42**, 3310-3314
- Sherman, N., 1956, Coulomb Scattering of Relativistic Electrons by Point Nuclei, *Phys. Rev.*, **103**, 1601-1607
- Sherman, N., and D. F. Nelson, 1959, Determination of Electron Polarization by Means of Mott Scattering, *Phys. Rev.*, **114**, 1541-1542
- Shull, C. G., C. T. Chase and F. E. Myers, 1943, Electron Polarization, *Phys. Rev.*, **63**, 29-37
- Tang, F.-C., X. Zhang, F. B. Dunning and G. K. Walters, 1988, Compact Low-Energy Mott Polarimeter for use in Energy- and Angle-Resolved Polarization Studies, *Rev. Sci. Instrum.*, **59**, 504-505
- Trujillo, S. M., 1975, Absolute Total Velocity Dependent Scattering Cross Sections for He(2^3S_1) from He, Ne, Ar, and Kr for Velocities Between 5×10^2 and 2.2×10^4 m/sec, *Electronic and Atomic Collisions, Abstracts of Papers of the IXth International Conference on the Physics of Electronic and Atomic Collisions*, J. S. Risley and R. Geballe eds., 437-438, Univ. of Washington Press, Seattle
- Uhrig, M., M. Sohn, J. Kessler, K. Jost, G. F. Hanne, A. Beck, J. Goeke and F. Eschen, 1989, Calibration of a Mott Detector Using Circularly Polarized Impact Radiation from Helium, *Rev. Sci. Instrum.*, **60**, 872-878
- Van Dyck, R. S., C. E. Johnson and H. A. Shugart, 1971, Radiative Lifetime of the 2^1S_0 Metastable State of Helium, *Phys. Rev. A*, **4**, 1327-1336
- Vanzandt, T., R. Browning, and M. Landolt, 1991, Iron Overlayer Polarization Enhancement Technique for Spin-Polarized Electron-Microscopy, *J. Appl. Phys.*, **69**, 1564-1568
- Wainwright, P. F., M. J. Alguard, G. Baum and M. S. Lubell, 1978, Application of a dc Fano Effect Polarized Electron Source to Low Energy Electron-Atom Scattering, *Rev. Sci. Instrum.*, **49**, 571-585
- Woodworth, J. R. and W. H. Moos, 1975, Experimental Determination of Single-Photon Transition Rate Between 2^3S_1 and 1^1S_0 of HeI, *Phys. Rev. A*, **12**, 2455-2463
- Zhang, X., 1988, Design and Testing of Compact Mott Polarimeters for use in Energy- and Angle-Resolved Polarization Measurements, Masters Thesis, Rice University, unpublished