A High Precision Mott Polarimeter at 5 MeV

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 We report on the design and performance of a Mott polarimeter optimized for a nominal 5 MeV electron beam energy. Using beam with a 31 MHz time structure from the electron injector of the CEBAF accelerator, and incorporating time-of-flight in the electron detection, we can cleanly isolate electrons that originate from the scattering foil. This significant background reduction results in measured scattering asymmetries which are exceptionally stable over a very broad range of beam conditions, beam currents, and foil thicknesses. In two separate series of measurements from two different photocathode electron sources, we have measured the Mott scattering asymmetries produced by an approximately 86% transversely polarized electron beam incident on ten gold foils with areal densities between 96 g/cm2 and 1.93 mg/cm2. The statistical uncertainty of the measured asymmetry from each foil is below 0.25%. We confirmed that within this statistical precision, the measured asymmetry was unaffected by +/- 2 (3?) mm shifts in the beam position on the target, and by beam current changes and deadtime effects over a wide range of beam currents. A detailed simulation of the complete polarimeter using GEANT4 has confirmed that double scattering in the target foil is the sole source of the dependence of the measured asymmetry on foil thickness, and gives a result for the asymmetry versus foil thickness in good agreement with our measurements. Future measurements at different beam energies and with different Z target foils will seek to bound uncertainties from small effects such as radiative corrections. With a high precision measurement of the beam polarization using a different polarimeter, which is clearly possible at the CEBAF accelerator, simultaneous measurements with this polarimeter will allow a high precision comparison of our measured asymmetries with theoretical calculations of the Mott analyzing power.

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**INTRODUCTION**

Soon after the publication of Dirac’s revolutionary equation for the electron, Mott calculated the elastic scattering of electrons by the Coulomb field of the nucleus in this new formalism (M-1). His motivation was to determine whether the anticipated polarization of the scattered electron, produced by spin-orbit coupling and in principle measurable in a double scattering experiment, could be used to determine the magnetic moment of the free electron, with its then unusual g-factor of 2. It was understood at the time that the uncertainty principle precluded a direct measurement of the electron magnetic moment.

Mott’s solutions for the spin-flip and non-spin-flip scattering amplitudes are conditionally convergent series in which pairs of terms very nearly cancel, requiring the calculation of a very large number of terms to obtain reasonably precise values for the scattering cross section and scattered beam polarization. Although various mathematical transformations were employed to reduce the complexity of the calculations, they remained tedious. Before the advent of digital computers, calculated values for the cross section and polarization were restricted to a limited range of electron energies at a 90o scattering angle. The first extensive computer calculations of the cross section were done by Doggett and Spencer, and by Sherman, who also calculated the scattered beam polarization, which is transverse to the plane of scattering (D-1, S-1). Since that time, the analyzing power of Mott scattering has been known as the Sherman function.

Several early attempts to demonstrate electron polarization in a double scattering experiment gave negative or inconclusive results prior to the first successful measurement by Shull et al. (S-2). As Mott scattering was the only known method for producing polarized electrons at the time, experiments using them were uncommon. One early application was a measurement of the free electron g-factor with 0.5% precision, satisfying Mott’s original motivation, (though not in the way he envisioned) (L-1). Following the experimental demonstrations of parity violation in the weak interactions in 1957, Mott polarimeters, coupled with spin rotators, were developed in a number of laboratories to measure the longitudinal polarization of beta decay electrons. This led to a much improved understanding of the experimental technique, and to several well-designed polarimeters, capable of achieving percent level precision in polarization measurement. Good examples of such polarimeters are given by Greenberg et al., who measured the asymmetry of 194 keV electrons from 60Co beta decay with about 6% uncertainty in 1960, and Brosi et al., who measured 616 keV electrons from 32P beta decay with about 1% uncertainty in 1962 (G-1, B-1).

The development of polarized electron sources for accelerators began in the late 1960s, and required polarimetry to quantify and improve their performance. Mott scattering at modest energies, typically 60 to 120 keV, was universally employed for these studies. The early polarized sources delivered average currents in the A range, and peak currents of many mA. These average and instantaneous beam currents are much too large for Mott polarimetry at such low energies, requiring that they be greatly reduced – to the point where it is effectively impossible to monitor the average beam position or current with meaningful precision during a polarization measurement, to say nothing of observing any possible dependence of the beam polarization on these beam properties. Even the very thinnest gold scattering foils are “thick” in the sense that plural scattering is a significant problem at these low beam energies. Inelastic scattering also presents difficulties, particularly given the relatively poor energy resolution of the detectors used, although careful electrostatic design of a polarimeter can reduce the uncertainty associated with inelastic scattering. Screening of the nuclear potential by the atomic electrons is large at these low energies, and adds uncertainty to the calculated analyzing power. The result of these difficulties is that the uncertainty in the polarization measured by Mott scattering at such low energies is a few percent at best.

Detection of Mott scattered electrons for precision electron transverse polarization measurement is not experimentally easy, as a quick examination of the cross section and analyzing power reveals. High Z scattering foils must be used to provide a large spin-orbit effect. The analyzing power is largest at larger scattering angles, while the cross section drops significantly from small to large scattering angles – facts which become ever more pronounced at higher incident electron energy. As a result, for every scattering event providing useful polarization information, a much larger number of electrons scattered at smaller angles are also generated. Unfortunately one can detect only electrons, independent of their origin. It is essentially impossible to assure that a detected electron arises from a single large angle scattering, or from more scatterings from the far more prolific smaller angle scattering events coupled with additional scattering from the apparatus walls, target supports, etc. Since each scattering is primarily elastic or near-elastic, the electron energy is not a very useful discriminant in these latter cases, particularly when the energy resolution of typical detectors is incorporated. Thus a typical Mott scattering asymmetry measurement generally includes an uncertain and potentially significant contamination from the detection of electrons which did not arise from a single large angle elastic scattering in the target foil, and which have a very different scattering asymmetry.

With the high average current available from contemporary polarized sources in use at accelerators, it becomes practical to study Mott polarimetry at beam energies in the MeV range. Beam from these accelerators has RF time structure, offering the possibility of time-of-flight discrimination against electrons that do not originate from the primary scattering foil. The RF time structure and higher average current of the beam make continuous precision monitoring of the beam position and current possible. The detailed beam profile incident on the scattering foil is made visible by optical transition radiation (OTR), which can be measured continuously for each polarization state during a polarization measurement. The scattering foils can be thicker than those used at lower energies without overwhelming plural scattering problems. Screening effects are very small at few MeV energies, while the energy is still low enough that nuclear size effects are also quite small (Z-1, U-1). Both of these effects can be calculated with ample precision at the beam energies in question, and contribute very little to the uncertainty in the calculated Sherman function. Radiative corrections, though believed to be small, are difficult to calculate, and are the largest contribution to the theoretical uncertainty in the Sherman function in the few MeV energy range. By measuring the Mott asymmetry from foils of several different Zs, and at several different energies, it may be practical to place bounds on this theoretical uncertainty. All of these considerations led us to develop a Mott polarimeter capable of high statistical precision measurements for the injector of the CEBAF accelerator, which operates at a nominal 5 MeV beam energy. (More recently, this energy has been increased to 6.2 MeV.)

Mott polarimetry at energies above 1 MeV was first employed in a search for possible time-reversal violation in the beta decay of 8Li (A-1, S-3). The success of this experiment led some of its participants, with collaborators at the MAMI accelerator at Mainz, to make detailed measurements of the analyzing power of 208Pb foils at 14 MeV (C-1, S-4). Their measurements were the first to convincingly show the reduction in analyzing power from the nuclear size effect, in agreement with the calculations of Ungincius et al. (U-1). These measurements are consistent, within their approximately 3% statistical uncertainty, with the thickness dependence of the analyzing power resulting entirely from a second scattering with no net polarization dependence. These double scattering events must belong to one to two categories, viz. (a) a first scattering very close to 90o, followed by a second scattering making the remainder of the total large scattering angle (or vice versa), or (b) a first relatively large angle scattering followed by a second small angle scattering completing the net large scattering angle (or vice versa). The very thin target foils, and the strong dependence of the differential cross section on angle, effectively restricts events from other than these two classes from meaningful contributions at few MeV energies.

The 5 MeV polarimeter we developed has been in operation for twenty years, and has proven to be an easily used and reliable monitor of beam polarization at the exit of the injector. As the beam polarization is not degraded during multiple acceleration passes through the full CEBAF accelerator, and remains completely in the horizontal plane between the polarized injector and the experimental targets, polarization measurement in the injector is very relevant to the full energy physics measurements. Since our original development of the polarimeter, significant improvements to the shielding, detectors, electronics, time-of-flight system, and beam dump have been made, resulting in the current version of the polarimeter presented below. A very early result reported asymmetry measurements from foils of three different Zs in reasonable agreement with expectations, as well as OTR measurements showing that the beam profile was independent of the beam polarization to a high degree (P-1). Detailed measurements of a beam with constant polarization and three different beam energies (2.75 MeV, 5.0 MeV, and 8.2 MeV) made with this polarimeter following the addition of time-of-flight rejection of background have been presented, along with fits to the asymmetry versus target foil thickness at each energy using a semi-empirical model based on Wegener’s study of the double scattering problem (S-5, W-1). The entire data set is fit very well with this model, as shown in figure 1, and is consistent with the polarization at all three beam energies being the same within about 0.3%. It is worth noting that foil thicknesses spanning a factor of 100, from 0.05 m to 5 m were used in these measurements. Using an unpolarized beam, it was determined that the instrumental asymmetry of the polarimeter was (4 +/- 6) x 10-4.

One other polarimeter operating in the MeV range at an accelerator has been reported (T-1). This device was operated between 1 and 3.5 MeV at the MAMI accelerator. It employed two double focusing spectrometer magnets followed by scintillation counters, with a fixed scattering angle of 164o, the angle of maximum analyzing power at 2 MeV. They achieved a reproducibility better than 1% in their asymmetry measurements, and believe they reach an absolute accuracy for the measured polarization of about 1%.

The primary motivation for this work has been to reduce the statistical uncertainty of the measured polarization of longitudinally polarized electron beams used for parity violation studies. At the present time, the dominant uncertainty in the measured parity violating polarized electron scattering asymmetry comes from the uncertainty in the beam polarization. Consequently, a meaningful reduction in the electron beam polarization uncertainty will directly impact the physics interpretation of high energy parity violation measurements. The statistical and systematic uncertainties associated with electron beam polarization measurement are discussed below.

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