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 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 (will need to change if we keep 30 nm foil) 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 +/- 1 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 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. A simultaneous high precision measurement of the beam polarization with a different polarimeter, clearly possible at the CEBAF accelerator, 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 inferred from measurements of the fine structure of atomic spectra. 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 number 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 (G-1, B-1). The development of polarized electron sources began in the 1960s, and required polarimetry to quantify and improve their performance (S-3). Mott scattering at modest energies was universally employed for these studies. All of these early Mott polarimeters operated at energies well below 1 MeV. The experimental challenges, and the problems in computing the Sherman function at these relatively low energies, are decidedly different than those encountered with few MeV energies, and will not be discussed here.

Detection of Mott scattered few MeV 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 very large scattering angles, while the cross section drops dramatically at larger scattering angles – facts which become ever more pronounced with increasing 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. If one detects only electrons independent of their origin, it is essentially impossible to assure that the detected electron arises from a single large angle scattering, or from 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 quasi-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 MeV energy 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 electron sources, precision experimental study of Mott polarimetry at accelerator energies in the MeV range becomes practical. Beam from these accelerators has RF time structure, offering the powerful prospect of time-of-flight discrimination against electrons that do not originate from the primary scattering foil. The RF time structure and high average beam current make continuous, precision monitoring of the beam current and position on the target foil 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. Finally, the scattering foils can be considerably thicker than those used at lower energies without introducing overwhelming plural scattering problems.

Along with these experimental advantages, calculation of the Sherman function with good precision at MeV energies is also practical. 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). Each 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. Inelastic scattering in the target foil makes a negligible contribution. The two leading order (Z) radiative corrections, vacuum polarization and self-energy, grow with both Z and energy, and are difficult to calculate. They are, however, believed to be of comparable magnitude and opposite sign, leading to some cancellation. The vacuum polarization contribution can be calculated in a reasonable approximation, and is about 0.5% at our 5 MeV beam energy. The total radiative corrections give the largest contribution to the theoretical uncertainty in the Sherman function in the few MeV energy range, and is estimated to be about 0.5% (R-1). 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. These favorable experimental and theoretical 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 well above 1 MeV was first employed in a search for possible time-reversal violation in the beta decay of 8Li (A-1, S-4). 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-5). 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 dependence of the analyzing power on target thickness arising entirely from double scattering in the target foil with no net polarization dependence. These double scattering events must belong to one of 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 relatively 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. Only events from category (b) above have useful analyzing power.

The 5 MeV polarimeter we describe here has been in use for twenty years, and has proven to be a readily available, easily used, and reliable monitor of beam polarization in the low energy region of the injector. For much of the full beam energy range covered by the present CEBAF accelerator, the beam polarization is not significantly degraded during multiple acceleration passes through the full accelerator, and remains essentially entirely in the horizontal plane between the polarized injector and the experimental hall targets (G-4). Thus polarization measured in the low energy region of the injector is directly relevant to the polarization measured at full energy in the experimental halls over much of the full energy range of the present accelerator.

Since our original development of this 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 (29, 47, and 79) 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 at three different beam energies (2.75 MeV, 5.0 MeV, and 8.2 MeV) made with the original polarimeter with the addition of time-of-flight background rejection 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-6, W-1). The entire three energy data set was 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. Finally, it should be noted that no radiative corrections were included in the computation of the Sherman function at these three energies. Given the dependence of the leading order radiative corrections on energy, this result provides strong circumstantial support that the two leading order radiative corrections largely cancel, as theoretically anticipated.

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 microtron accelerator at Mainz. It employed two double focusing spectrometer magnets followed by scintillation counters, with a fixed scattering angle of 164o, corresponding to the maximum analyzing power at 2 MeV. They reported 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 contribute to reducing 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 asymmetry in the scattering of longitudinally polarized electrons 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. The high precision Mott polarimeter described here not only provides an independent measurement of the beam polarization from the injector, but is a very useful instrument to normalize the polarization measured by various polarimeters in the experimental halls (G-2).

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