Electron Beam Polarimetry*

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Abstract. Along with its well known charge and mass, the electron also carries an intrinsic angular momentum, or *spin*. The rules of quantum mechanics allow us to measure only the probability that the electron spin is in one of two allowed spin states. When a beam carries a net excess of electrons in one of these two allowed spin states, the beam is said to be *polarized.* The beam polarization may be measured by observing a sufficient number of electrons scattered by a spin-dependent interaction. For electrons, the useful scattering processes involve Coulomb scattering by heavy nuclei, or scattering from either polarized photons or other polarized electrons (known as Mott, Compton, and Møller scattering, respectively). In this tutorial, we will briefly review how beam polarization is measured through a general scattering process, followed by a discussion of how the three scattering processes above are used to measure electron beam polarization. Descriptions of electron polarimeters based on the three scattering processes will be given.

INTRODUCTION

Along with its well-known charge and mass, the electron also carries an intrinsic angular momentum, or *spin*. The magnitude of the angular momentum carried by each electron is an exact number –3h/8π, where h is Planck's constant. Sensibly enough, the electron also has a magnetic moment directly proportional to the spin. However, the electron spin is a quantum mechanical quantity—there is no classical analog for electron spin.

Just as in classical mechanics, there is a direction as well as a magnitude associated with the angular momentum. In classical mechanics the angular momentum may be oriented in any direction in space, while in quantum mechanics, only certain discrete possibilities are allowed for this orientation. For electrons there are only two allowed orientations for the spin. The projection of the spin along a quantization axis may be only + or –h/4π. The quantization axis is defined by the physical situation at hand, as will become clear later. The two possible spin orientations are often referred to as "parallel" or "up," and "antiparallel" or "down."

In a beam of electrons from a conventional electron source (e.g., a thermionic emission cathode), the numbers of electrons with positive and negative spin

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projections along *any* axis are equal, with the result that the beam electrons carry no net angular momentum along any axis. Such a beam is said to be *unpolarized*. If, by some means, an electron beam is created with a net difference in the numbers of positive and negative spin projections along some axis, the beam is said to be *polarized* along that axis. The polarization of an electron beam along an axis is measured by counting the difference between the numbers of electrons with positive and negative spin projections along that axis, divided by the sum, i.e.:

$$P = \frac{n_+ - n_-}{n_+ + n_-} \tag{1}$$

in an obvious notation.

The rules of measurement in quantum mechanics tell us that it is *fundamentally impossible* to measure the orientation of the spin of an individual electron. Rather, one can only measure the *probability* that an electron is in one or the other of the two allowed spin orientations. Thus, the measurement of beam polarization implies that we must measure, or sample, the spin projection probabilites of a sufficiently large number of the beam electrons.

The physics programs at almost all electron accelerators dedicated to basic research in nuclear and high-energy physics demand polarized beams. In general, they require longitudinal beam polarization—i.e., an electron spin orientation either parallel or antiparallel to the beam momentum. The methods employed to produce polarized electrons do not provide a precisely known beam polarization. Furthermore, the orientation of the electron beam polarization does not stay fixed with respect to the beam momentum as the beam moves through the electromagnetic fields of an accelerator and its transport lines. Measurement of both the magnitude and the orientation of the beam polarization is thus essential. To date, essentially all electron beam polarimeters have been developed by the research groups using the polarized beams. This is true in part because the techniques involved in measuring electron polarization are very similar to those employed in the physics experiments themselves—i.e., clean identification of scattered electrons or photons and the rejection of scattered particle backgrounds from unwanted sources.

Rather than provide references for statements made throughout the text of this tutorial article, an annotated bibliography is provided at the end. The references in this bibliography cover in some detail all material presented in this article.

Electron Polarization Measurement by Scattering

All techniques devised to date for the measurement of electron beam polarization at accelerator energies involve measuring a difference in the scattering rate of electrons in the two possible polarization states. Three different scattering targets have been used—heavy nuclei, magnetized materials, and optical photons from a laser—and the three scattering processes are known as Mott, Møller, and Compton scattering, respectively. Before describing polarimeters based on these scattering processes, it is useful to work through the algebra underlying polarization measurement by scattering.

Consider scattering an electron into a detector by a process which has a spin dependent scattering probability; that is to say a scattering probability which depends on the spin orientation of the incident electron. In general, only a fraction of the total scattering probability depends on the spin orientation, so we split the total scattering probability into two pieces, one spin independent, S_0, and the other spin dependent, AS_0. Thus the probability of scattering an electron with a positive or a negative spin projection into the detector is $S_+ = S_0(1+A)$ and $S_- = S_0(1-A)$, respectively.

Now consider scattering of a beam of polarization *P*. We assume that we are able to reverse, or "flip" the polarization of the beam in some way, and that on reversal, the number of positive and negative electrons are simply exchanged, i.e., the polarization *P* is simply changed in sign. It is easy to show that the number of positive and negative electrons in the beam are given by:

$$n_+ = \frac{n_0}{2}(1+P) \text{ and } n_- = \frac{n_0}{2}(1-P), \quad \text{where } n_0 = n_+ + n_- \tag{2}$$

When the beam polarization is +|*P*|, we detect scattered electrons in the detector, and when the polarization is reversed to –|*P*|, we detect scattered electrons, where:

$$R_+ = S_0(1+A)(1+P)\frac{n_0}{2} + S_0(1-A)(1-P)\frac{n_0}{2}$$

$$R_- = S_0(1+A)(1-P)\frac{n_0}{2} + S_0(1-A)(1+P)\frac{n_0}{2}. \tag{3}$$

A little algebra then shows that:

$$\frac{R_+ - R_-}{R_+ + R_-} = AP. \tag{4}$$

Thus, by measuring the difference in counting rates in a single detector as the polarization is reversed in sign, we can measure the magnitude of the polarization. The counting rate difference is often called the asymmetry, and the quantity *A* is known as the "analyzing power" of the particular scattering process. Clearly a larger *A*, which gives a greater difference in the two counting rates, is desirable. It is also worth noting that we could have obtained the same result if we were able to reverse the sign of *A*, instead of reversing the beam polarization.

In assessing the precision with which the polarization is measured, one needs to consider both statistical and systematic uncertainties. An obvious statistical uncertainty is the counting statistics associated with measuring and . A quick estimate of the number of counts required to obtain a particular statistical error in *P* can be made by assuming that $AP = 0$. This makes and equal. If we accumulate a total number of counts *N*, equally divided between the two cases, it is easy to show that the statistical uncertainty in *P* is *P* is $\delta P = (1/A)N^{-1/2}$. Thus, for example, if *A* were 0.10, and one wanted a measurement of polarization with a statistical uncertainty of 0.01, 10^5 counts would be required. More often, it is necessary to measure *P* to a certain fraction of itself. To measure a *P* of 0.1 with a statistical precision 3% of itself, again with an *A* of 0.1, would require over 10^7 counts. Measuring polarization with good statistical precision can require large numbers of counts in practice, and, in some cases, the uncertainty in a polarization measurement is dominated by counting statistics.

In measuring polarization by scattering, it is important that the detector count only electrons scattered by the desired process. Electrons scattered by other processes are “backgrounds” which, in general, have a different, or even no, analyzing power. Good polarimeter designs allow the user to measure how well contributions from background are eliminated, thereby reducing the systematic uncertainties arising from background contributions.

Mott Scattering Polarimeters

In Mott polarimeters, electrons are scattered by the Coulomb field of a heavy nucleus. The scattered electrons have an orbital angular momentum about the scattering nucleus. The scattering probability depends upon whether the electron spin is parallel or antiparallel to this orbital angular momentum. Since the orbital angular momentum is perpendicular to the scattering plane, Mott scattering analyzes only the component of the spin which is also perpendicular to the scattering plane, and thus transverse to the electron momentum. One measures the difference in scattering rate for electrons scattered to the left and to the right. This difference is largest for electrons scattered at large angles from high-charge nuclei.

The calculated analyzing power for Mott scattering from single free-atoms is known as the Sherman function. This is shown in Figure 1 as a function of laboratory scattering angle and electron energy. At the present time, Mott scattering is the only practical way to measure electron beam polarization at the beam energies typical of electron guns (~50 to 100 keV) and electron injectors (a few MeV). Above beam energies of about 10 MeV, the Mott scattering probability is very small, and the scattering angle for maximum analysing power becomes impractially close to 180 degrees.

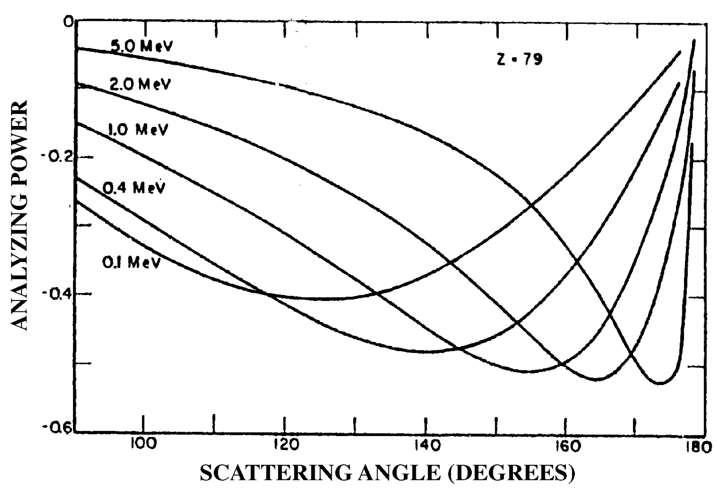

FIGURE 1. The Mott scattering analyzing power for gold as a function of scattering angle and electron energy, from J. Kessler, *Rev. Mod. Phys.* **41**, p. 3 (1969).

Mott scattering probabilities, particularly at lower beam energies, are very large, leading to the use of exceptionally thin scattering targets, and very low-average electron beam currents. Gold is the common scattering target, as it offers a high nuclear charge and is easy to fabricate into very thin targets. Target thicknesses from a few hundred to about 1000 angstroms are typical. Even with such thin targets, multiple and plural scattering is common, leading to substantial uncertainties in the analyzing power of the real target. It is normal to measure Mott scattering asymmetries for a range of target foil thicknesses, and use this information to extrapolate to zero target thickness. It was long believed that the theoretically calculated single atom analyzing power was the correct number to use for the zero target thickness extrapolation. More recently, it has been demonstrated that it is necessary to also verify that the electron has lost no energy in the scattering process for this theoretical analyzing power to be correct.

Small changes in beam steering on the Mott scattering target can cause large changes in counting rates. In low-energy Mott polarimeters, the usable beam current is too small to be monitored, either in position or intensity. To reduce the systematic effects associated with small changes in intensity or beam steering, one normally uses two nominally identical scattered electron detectors, located in the scattering plane at equal scattering angles, left and right, to the incident beam. Defining L_+ as the counting rate into the left detector with $|P|$ positive, with an obvious extension to the other three rates L_-, R_+, and R_-, one can show that:

$$\frac{X_+ - X_-}{X_+ + X_-} = AP \tag{5}$$

where $X_+ = \sqrt{L_+ R_-}$, and $X_- = \sqrt{L_- R_+}$, and A is the analyzing power. The advantage of using two nominally identical detection channels is that the polarization calculated from the above relation is insensitive, in first order, to systematic effects arising from beam steering and intensity fluctuations and target foil inhomogeneities.

Low-energy electrons scattered from heavy nuclei by Mott scattering have lost essentially no energy. The use of scattered electron detectors which give a signal proportional to the detected electron energy thus makes good sense. Such detectors provide one way to discriminate against background electrons which have lost energy, and background photons. At beam energies of a few tens of keV, silicon detectors are a good choice, while at MeV energies, a plastic scintillator makes a good total energy detector. The energy resolution of these detectors is not good enough to assure that the analyzing power of low-energy Mott polarimeters is undegraded by small energy losses.

Mott scattering polarimeters require only a modest vacuum—10^{-6} torr or so. However, vacuum venting and pumpdown must be done with great care to prevent destruction of the exceptionally thin target foils. It is useful to make the vacuum chamber walls and internal components from low-*Z* materials as much as possible, to minimize backscattering from these surfaces. Be, C, Al, and CH_2 are all useful. Collimators internal to the scattering chamber are commonly employed to define the detector acceptance for scattered electrons, and must be designed with care. The old maxim (attributed to Alvin Tollestrup) that, “You can’t collimate electrons; you can only make them angry,” must be understood and respected. A viewscreen which can be placed in the plane of the target foils is important for both steering and focusing the beam at the target. This is particularly important for low-energy Mott polarimeters, where the beam cannot be otherwise observed. Similarly, a no-target position, followed by a Faraday cup, is very useful in setup.

Until very recently, Mott polarimeters were routinely used only with beam energies no greater than 100 to 120 keV. Mott scattering at significantly higher energies—a few MeV—offers a number of advantages. The total scattering probability is much smaller, which greatly reduces plural scattering, making the results of the foil thickness extrapolation much less uncertain. The basic analyzing power is quite large, ~52%. The small scattering probability allows the use of much higher beam currents, which are easier to monitor. At MeV beam energies, there is typically rf micro-structure on the beam, permitting excellent monitoring of both beam position and current. At a few MeV, optical transition radiation produces a visible beam spot on the target foil. This spot may be measured with a CCD camera, and very small changes in spot size, shape, and position associated with polarization reversal can thereby be detected. It is even practical to consider measuring the beam polarization with foils of differing Z (e.g., Cu, Ag, and Au) to obtain an absolute calibration of the polarimeter.

At Jefferson Laboratory, we have constructed a 5 MeV Mott polarimeter. This is now in routine use for measuring beam polarization at the exit of the low-energy part of the injector. Its design is shown in Figure 2. The scattering angle for maximum analyzing power is ~172.5°, making it easy to incorporate four detectors to measure both transverse components of the polarization. Plastic scintillators coupled to photomultipliers are used as total-energy counters. Internal collimators are installed to assure that each scintillator detects electrons from only the central part of the target foil. The largest difficulty with a polarimeter like this is reduction of backgrounds. The Mott scattering probability is so low that a very large number of beam electrons must transit the target foil to produce a single useful scatter. Dumping the beam electrons may result in high background rates in the detectors. Since these background events must originate from the walls of the vacuum chamber, rather than the target foil itself, they arrive out of time with the good events. This allows time-of-flight analysis for separating signal events from the background. In tests with the Jefferson Lab 5 MeV polarimeter, this time-of-flight rejection has proven quite effective.

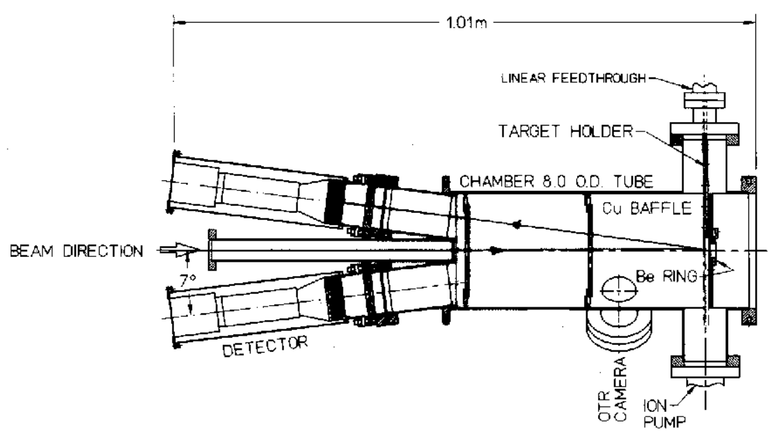

FIGURE 2. A schematic view of the Jefferson Lab 5 MeV Mott polarimeter.

MØLLER SCATTERING POLARIMETERS

Electron polarimeters based on Møller scattering are the “work horse” polarimeters for fixed target experiments at full accelerator beam energies. They have been used for beam energies between ~100 MeV to ~50 GeV. In these polarimeters, the polarized beam electrons are scattered from other polarized electrons in a target. To date, all Møller targets have employed magnetized foils. In such foils, only a small fraction of all the target electrons are polarized, leading directly to a small analyzing power.

The analyzing power of the Møller scattering process is exactly calculable in quantum electrodynamics. At high beam energies, both the analyzing power and the scattering probability in the center-of-mass system become constant, independent of beam energy. The maximum analyzing power for scattering longitudinally polarized electrons on longitudinally polarized electrons is 7/9, for scattering at 90° in the center-of-mass system. Similarly, Møller scattering of transversely polarized electrons can be used to analyze transverse beam polarization; although in this case the maximum analyzing power is only 1/9. These maximum analyzing powers are diluted by the fraction of the electrons in the target which are polarized, so the measurement of transverse beam polarization by Møller scattering is problematic in practice. The analyzing power as a function of center-of-mass scattering angle is shown in Figure 3.

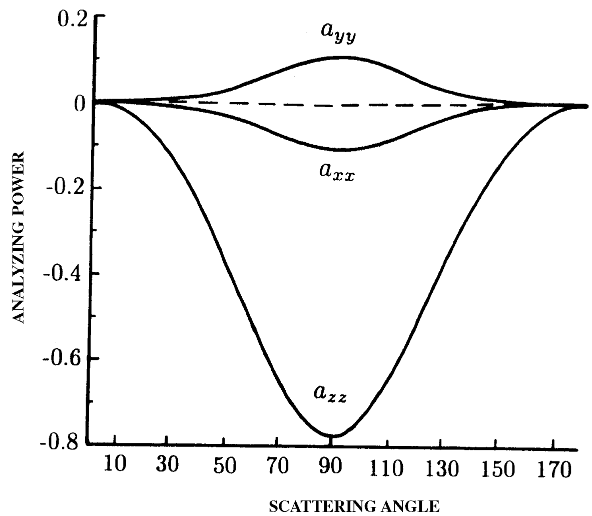

FIGURE 3. The Møller scattering analyzing power for transverse and longitudinal polarization from a single electron, as a function of center-of-mass scattering angle, from B. Wagner et al., *Nucl. Instr. Meth. A*, **294**, 541 (1990).

At the maximum analyzing power, the beam and target electrons are each scattered through 90° in the center-of-mass system. When we do the Lorentz transformation from the center-of-mass system to the laboratory system, the result is two electrons with equal energies (each having half of the incident beam energy), moving at equal and opposite small angles to the incident beam direction in the scattering plane. These facts lead very naturally to the use of magnetic fields to separate the scattered electrons from the beam electrons.

Two different magnet arrangements have been used to separate the scattered and beam electrons. In the first, one or more quadrupoles deflect the Møller scattered electrons to larger angles, while allowing the primary beam to pass through undeflected on the quadrupole axis. In the second, a dipole is constructed with a central magnetic shunt plate. A hole through the shunt plate allows the primary beam to pass through undeflected, while the scattered electrons are deflected by the full dipole field. Hybrid magnet arrangements, using both quadrupoles and dipoles, may also be used. All of these schemes clearly require locating the magnets sufficiently far downstream of the Møller target so that the small scattering angle has separated the scattered electrons adequately from the primary beam. Collimators are often utilized in front of and/or between the magnetic elements and the electron detectors. These serve to restrict the acceptance of the electron detectors to the center-of-mass scattering region with the highest analyzing power.

Once the Møller scattered electrons have been physically separated from the primary beam electrons, they are detected in counters. Counters which give unique signals for electrons, such as lead glass total absorption Cherenkov counters, are commonly used. The two-body kinematics of Møller scattering provides a strong correlation between the electron scattering angle and the electron energy. This correlation can be exploited by using position-sensitive detectors, such as scintillation counter hodoscopes or drift chambers, as part of the scattered electron detection package.

At low-duty-factor accelerators, it is common to detect just one of the two scattered electrons, while at high-duty-factor machines, coincidence detection of both electrons is essentially always employed. Coincidence detection has been employed at low-duty-factor machines, but the necessary low event rate required to obtain low accidental coincidence rates coupled with the relatively low analyzing power of Møller polarimeters means that it can be time-consuming to obtain good statistical precision. With coincidence detection at high-duty-factor accelerators, factors other than counting statistics usually limit the precision of the polarization measurement.

The primary background to Møller scattering is radiative Mott scattering from the Møller target nuclei. Though Mott-scattered electrons have energies very close to the beam energy, radiation allows them to lose enough energy to contribute to the counting rate in single-arm Møller polarimeters. It is possible to substantially reduce the radiative Mott background in coincidence Møller polarimeters through a combination of good coincidence timing, energy selectivity, and careful collimation.

All Møller polarimeter targets used to date have employed magnetized foils of either pure iron, or vanadium permendur. The analyzing power of these targets is not large simply because so few target electrons have their spins oriented. In iron, for example, only two of the 26 electrons per iron atom are spin-oriented in the magnetized material. This fact, along with the maximum single electron analyzing power of 7/9, leads to a net longitudinal analyzing power of about 0.06, and a transverse analyzing power below 0.01. In any of these targets, it is essential to know the relationship between the electron spin polarization in the target and the magnetic field applied to the target.

Two target configurations have been used. In the so-called “easy” magnetization method, the target foil is magnetized in its plane by a relatively low field. These fields, typically ~100 Gauss, are easily provided by Helmholz coils in air. In this arrangement, it is easy to reverse the magnetizing field, and thus the target polarization. The net magnetization in the foil is measured by placing pickup coils around the foil, and measuring the induced flux change with an integrating voltmeter as the magnetizing field is reversed. The foils are oriented at a small angle, typically about 20 degrees, to the beam direction, reducing the effective analyzing power by the cosine of this angle. The use of small magnetizing fields requires the use of magnetic materials which are easily saturated at low fields, such as vanadium permendur. Unfortunately, the relationship between the net electron-spin polarization and the foil magnetization is not well known in these materials, leading to a systematic uncertainty in the analyzing power of these targets. Corrections due to foil end effects and thickness inhomogeneities also lead to systematic uncertainties in the analyzing power. Finally, demagnetization from the beam heating the foil essentially goes undetected, since the area heated by the beam is very small compared to the total area of the foil.

In the "hard" magnetization scheme, the target foil is magnetized by the "brute force" application of a strong magnetic field perpendicular to the plane of the foil. The fields required are very large—several tesla—requiring the use of superconducting magnets. This magnetization scheme allows the use of pure iron foils, which, when magnetically saturated, have a well known net spin polarization. This is a considerable advantage, as it reduces a major source of systematic uncertainty. Furthermore, since the entire foil is fully magnetically saturated, it is not necessary to measure the magnetization in situ and variations in foil thickness are unimportant. Clearly the target magnetization is not easily reversible in this scheme. The depolarization caused by beam heating can, in principle, be measured by the Kerr magneto-optic effect. One observes the rotation of the plane of polarization of laser light reflected from the spot where the beam hits. This technique has yet to be implemented in an operating Møller polarimeter.

Only one hard-magnetization Møller polarimeter has been built to date, by a University of Basel group for use at Jefferson Lab. This is a coincidence polarimeter, employing two quadrupoles and a system of collimators to separate the Møller scattered electrons from both the primary beam and the radiative Mott background. With the systematic uncertainties associated with a fully saturated pure iron foil, and the high counting rate provided by the 100% duty factor CEBAF accelerator, this polarimeter should ultimately be capable of a combined statistical and systematic uncertainty in the measured beam polarization below 1%, and thus is the highest precision Møller polarimeter yet developed. It has an analyzing power of 0.06426 ± 0.00082, with all uncertainties included. The uncertainty in the analyzing power may be further reduced by use of the Kerr effect to measure the target polarization at the point of beam incidence. A schematic view of this polarimeter is given in Figure 4. The power of collimation and coincidence timing to separate Møller scattering events from backgrounds is illustrated in Figures 5 and 6, which clearly show the clean separation of signal and background.

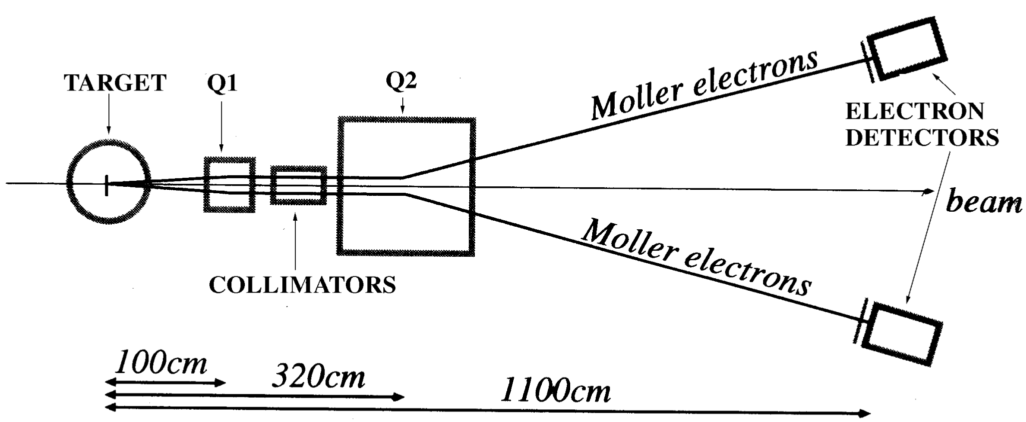

FIGURE 4. A schematic view of the hard-magnetization Møller polarimeter built by the University of Basel group for Jefferson Lab. Two quadrupoles are used to separate the Møller scattered and beam electrons, with a set of collimators between them to reduce backgrounds. The two Møller-scattered electrons are detected in time coincidence.

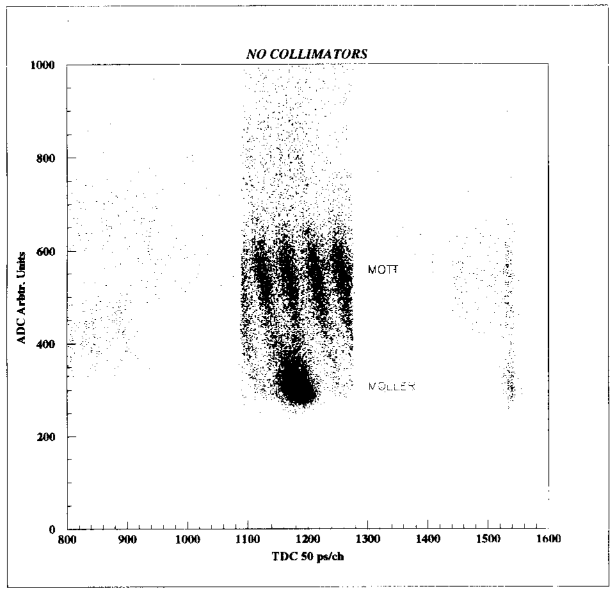

FIGURE 5. A plot of the pulse height versus the event time for one of the Møller electron detectors in time coincidence with the other electron detector, with the collimators fully open. Each scattering event is a dot on this plot. The pulse height is proportional to the detected electron energy. The incident electron beam had a 499 MHz time structure, so the beam bursts are 2 nsec apart, equal to 80 TDC channels. One can clearly see Møller scattered electrons in time coincidence with other Møller scattered electrons, and in accidental coincidence with Mott scattered electrons.

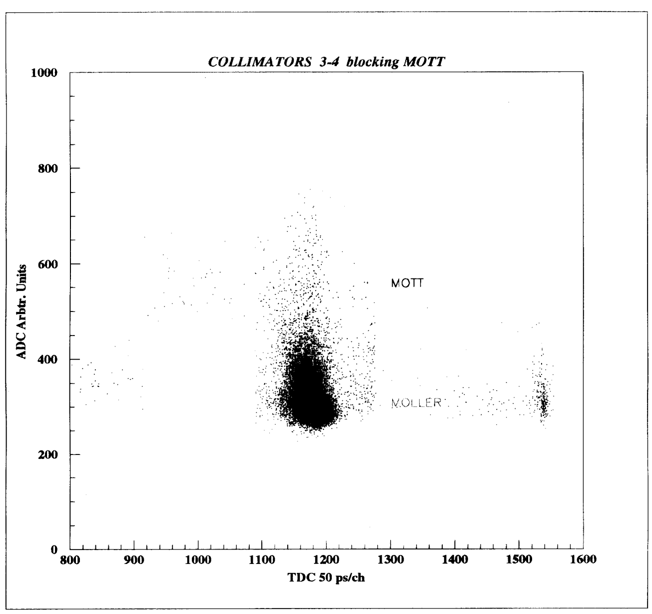

FIGURE 6. The same plot as in Figure 5, with the collimators moved to block the Mott-scattered electrons. The combination of pulse amplitude, time coincidence, and collimation is a powerful tool to separate Møller scattered electrons from backgrounds.

Møller scattering polarimeters had been in regular use for nearly two decades before a very important systematic effect was discovered and understood. This is the Levchuk effect, named after its discoverer. The effect is a result of the momentum carried by the atomic electrons in the Møller target. The tightly bound inner atomic electrons have quite large average momenta, while the loosely bound outer electrons have much smaller momenta. It is the outer atomic electrons which are polarized. The momentum of the atomic electrons broadens the laboratory angular distribution of the scattered electrons. For the case of the inner unpolarized electrons, this effect is quite significant. Depending upon the angular acceptance of the scattered electron detection setup, some beam electrons Møller scattered by the inner atomic electrons may be lost on collimators or fall completely outside the detector. Electrons scattered by the outer atomic electrons are much less likely to be lost by this effect. The net result is that, depending on the details of the detector and collimator arrangement, Møller scattering from the polarized atomic electrons is more likely to be detected than Møller scattering from the unpolarized electrons. This increases the effective analyzing power.

Values for electron beam polarization measured by Møller scattering prior to the understanding of the Levchuk effect are thus suspect. Since the change in the effective analyzing power is apparatus specific, no general statements can be made. The sign of the effect is always to increase the effective analyzing power, and thus decrease the true beam polarization from the measured value. Effects as large as 15% have been reported. Presently, the Levchuk effect is studied during the design stage of a Møller polarimeter by Monte-Carlo methods. The goal is to build a polarimeter in which the Levchuk effect is both small and sufficiently well-modelled that it is not a major contributor to the overall systematic uncertainty of the polarization measurement.

COMPTON POLARIMETERS

Compton polarimeters are the natural choice to measure the polarization of circulating beams in storage rings and stretcher rings, since they are “non-intercepting” devices; they do essentially no harm to the beam itself, so can be left on during accelerator operation. Their use is not restricted to ring applications, however. They have been successfully used with ordinary electron beams, most notably with the SLC at SLAC. In these polarimeters, polarized photons from a laser beam are backscattered by the beam electrons (or positrons). The backscattered photons are twice doppler-shifted, resulting in a laboratory backscattered photon energy distribution with a maximum photon energy given by:

$$E_{\max} = 4\gamma^2 E_\lambda \left(1 + 4\gamma E_\lambda / m\right)^{-1} \tag{6}$$

where E_λ is the energy of the laser photon, γ is the ratio of the electron beam energy to the electron mass m, and $E_{\max}$ is the maximum backscattered photon energy in the lab system. Typical electron beam energies give γ values from a thousand to very much greater. Thus, backscattering a few eV laser photon produces a continuous spectrum of gamma rays with a maximum energy of many MeV .

Compton scattering may be used to analyze either transverse or longitudinal electron polarization. To analyze transverse polarization, circularly polarized laser light is scattered off the polarized electrons. The backscattered gamma rate has a $\cos\phi$ dependence, where ϕ is the azimuthal angle of the backscattered gamma with respect to the polarization direction of the electron. This azimuthal dependence is usually measured by observing an up-down asymmetry, with respect to the scattering plane, in the backscattered counting rate. For longitudinal polarization analysis, circularly polarized laser light is scattered off the polarized electrons, and a difference is observed in the counting rate of the backscattered photons, depending on whether the laser and electron polarizations are parallel or antiparallel. The analyzing power for either transverse or longitudinal polarization depends strongly on the electron beam energy and the backscattered photon energy. High electron beam energies and high backscattered gamma energies give the largest asymmetries. This makes it desirable to use some form of energy discrimination in detecting the backscattered gammas.

In a storage ring, the electron and positron beams become transversely polarized (parallel or antiparallel to the magnetic guide field) by the Sokolov-Ternov effect. The ultimate polarization value is approached exponentially in time, and is exactly related to the polarization buildup time constant. This makes it possible to calibrate the analyzing power of a Compton polarimeter by measuring the asymmetry as a function of time. This is a very valuable characteristic of the beam polarization in storage rings.

The physics use of storage ring beam polarization requires longitudinal polarization. Some type of spin rotator must therefore be used in the storage ring to rotate the natural transverse polarization into longitudinal before the physics experimental interaction area, and back to transverse for transport around the ring. These spin rotators can be fairly complex from a beam optics standpoint, and may require a considerable amount of beamline space. In fact, although a number of Compton polarimeters have been built to measure the transverse polarization in storage rings, little use of the natural beam polarization has been made for lack of money and/or beamline space to install the necessary spin rotators. The major exception is the HERA storage ring. Spin rotators have been installed, a transverse Compton polarimeter is used to tune the storage ring for mazimum polarization, and a longitudinal Compton polarimeter is used to measure the beam polarization at the physics interaction point.

In stretcher rings, the beam does not stay in the ring long enough for the Solokov - Ternov effect to give significant polarization. Instead, one injects polarized electrons directly from a polarized source. Some form of "Siberian Snake" spin rotator is used to preserve the polarization in the ring. In this case, the beam polarization is measured with a Mott polarimeter before acceleration and injection into the ring, and the polarization in the ring is measured with a Compton polarimeter.

The laser and the electron beams collide in or very close to a "head on" geometry. The backscattering rate is related to the spatial and temporal overlap between the laser and electron beams. The diffraction limit of the laser beam determines the product of its diameter and divergence angle, and is often a real limitation on the maximum obtainable overlap of the two beams. The emittance of the electron beam is rarely a similar limitation. It is important to choose the interaction point between the laser and electron beams to be at a location where the storage or stretcher ring lattice parameters are optimized for the laser and detector used. For transverse polarimeters at high energies, where small position differences must be observed, this is essential.

Detectors for Compton polarimeters are very similar to detectors for Møller scattering. Counters sensitive to the total energy of the backscattered photon are used. These are usually lead-glass, lead-scintillator, or lead-lucite total absorption counters coupled to photomultipliers. Such counters give a signal amplitude proportional to the absorbed photon energy. It is common to add a "veto" scintillation counter in front of the total absorption counter, to assure that a neutral particle is detected. For measuring transverse polarization, position sensitive information is required. For this, one uses a thin sheet of high-Z material (lead or tungsten) to convert the photon into an electron-positron pair, followed by a high-resolution position-sensitive detector such as a drift chamber. For very high electron beam energies, where the maximum backscattered photon carries away a significant fraction of the incident electron energy, it becomes practical to detect the scattered electron rather than the backscattered photon. This allows a magnetic separation of the lower-energy scattered electron from the beam electrons. In principle one could detect the backscattered photon in coincidence with the scattered electron, though this is yet to be done in any Compton polarimeter.

The polarized photon "targets" provided by lasers are not dense. This fact, and the relatively small Compton scattering probability, lead to modest backscattering rates in Compton polarimeters. The principal backgrounds to Compton scattering are gamma rays produced by bremsstrahlung on the residual gas in the vacuum system, and x-rays produced by synchrotron radiation in magnets close to the interaction point. In designing Compton polarimeters, it is necessary take some care to ensure that the desired backscattering rate is large compared with the backgrounds. Two methods are used to accomplish this. In one, a low-duty-factor laser produces short duration optical pulses of high peak intensity. In this case, the backscattered photons arrive in a "burst", and the detector signal is integrated to obtain a measure of the total backscattered energy. Veto counters are not useful in this case. Q-switched and frequency-doubled Nd:YAG lasers are a common choice for this scheme. This method is essential for use with low-duty-factor electron beams, and may be selected for the case of continuous electron beams in a storage ring. The vacuum pressure in the electron-laser interaction region must be low (10^{-9} mbar or below is a typical requirement) so that bremsstrahlung gamma rays do not contribute significantly to the integrated counter signal. Similarly, the edges of nearby magnets must be magnetically "softened" with low field regions, or the detector must be shielded from line-of-sight to these magnets, to keep the synchrotron x-ray contribution small. These backgrounds may be measured by blocking the laser light.

Alternatively, a CW laser is used to continuously intercept the beam. If the beam current is low, as in accelerators like CEBAF, very high CW optical powers are required. Optical cavities with gains of 10^4 or greater have been proposed as a way to increase the CW optical power to yield adequate counting rates, though operation of these cavities in an accelerator environment is yet to be demonstrated. In this method, one detects individual backscattered photons or possibly scattered electrons. The vacuum requirements may be more demanding than in the pulsed laser case. The backscattered photon energy spectra is obtained, which is useful for discriminating between residual gas bremsstrahlung and Compton scattering. A variant of the CW scheme uses a cavity-dumped CW laser to produce a continuous train of moderate power optical pulses. The cavity-dumped laser choice is particularly appropriate for use with storage or stretcher rings, as the cavity dumping rate is well matched to the bunch revolution frequency in many rings. Argon-ion lasers are a common choice for the CW laser methods.

It is easy to reverse the sense of the circularly polarized light quite rapidly with a Pockels cell. This is an essential requirement for storage ring polarimeters, since the beam polarization is not reversible. However the circularly polarized optical beam is prepared, one must take care to keep the residual linear polarization components of the optical beam small, to avoid systematic effects. It is possible to slightly alter storage ring operating parameters to rapidly and completely depolarize the circulating beam. This latter trick also allows one to make very precise measurements of the storage ring beam energy. These techniques have been pushed to a point at the LEP storage ring where even the effects of Atlantic storms and electric railway currents are detectable!

SUMMARY AND SPECULATIONS

Three scattering processes have been used to date to measure electron beam polarization at accelerator energies. Mott scattering is uniquely suited to the measurement of beam polarization from polarized electron sources, and from the low-energy stages of electron injectors. Only transverse polarization can be measured. Fortunately, it is quite easy to rotate longitudinal polarization into transverse at low energy, so the longitudinal component can be measured fairly directly as well. While blessed with large analyzing power, Mott polarimeters, particularly at the lower energies, are subject to a number of difficult sources of systematic uncertainties. At energies of a few MeV, many of these uncertainties are greatly reduced. It appears possible to construct high-energy Mott polarimeters with well understood analyzing power and minimal systematic uncertainties, allowing high-quality polarization measurements to be made.

Møller polarimetry is the “work horse” instrument for polarization measurement at all fixed target electron accelerators. The effective analyzing power of all present Møller targets, based on magnetized foils, is low. Both longitudinal and transverse polarization can be measured, but the analyzing power for transverse polarization is smaller than for longitudinal by a factor of 7, making transverse measurements statistically challenging at best. With “easy” magnetization targets, there are significant systematic uncertainties in the knowledge of the effective target polarization. Such polarimeters are capable of giving polarization measurements with ~3–4% overall uncertainty. “Hard” magnetization targets have substantially lower systematic uncertainties, though they are moderately more expensive to construct and maintain. This type of polarimeter is capable of polarization measurements with better than 1% overall uncertainty

Compton polarimeters are universally used to measure the polarization of circulating beams in storage and stretcher rings, and are occasionally used in other circumstances. The analyzing power of Compton polaimeters is strongly beam energy dependent, growing with energy. Both transverse and longitudinal polarizations may be measured, with roughly equal ease. The laser “targets” are not dense, and the Compton scattering probability is not large, leading to a requirement for high-average-current electron beams and high-intensity lasers to obtain reasonable scattering rates. Compton polarimeters based on extremely high-gain CW laser cavities are under development for use in low-average-current CW accelerators. The time dependence of the polarization buildup in storage rings may be used to provide an absolute calibration for the analyzing power of Compton polarimeters.

By way of speculation, it has been suggested that the spin dependence of the intensity of synchrotron light may be developed into a circulating beam polarimeter for storage rings. Though very small, the effect has been observed at the VEPP-4 storage ring in Novosibirsk. The size of the effect increases with beam energy, so at higher-energy storage rings, such polarimeters become more practical. As with Compton polarimeters, the time dependence of the polarization buildup provides a calibration for the analyzing power.

Even more venturesome, some have suggested that it may be possible to detect the magnetic effects of a polarized beam directly by using SQUIDs. This certainly sounds exceptionally difficult with present technology. The magnetic fields due to the beam current itself are larger than those from the polarization, and there is presently not even a good SQUID based beam current monitor.

Møller polarimetry would be much more effective if one could develop a target with essentially 100% electron polarization. With much additional development, it might be possible to accomplish this with a jet of fully polarized atoms of hydrogen or helium. It is possible to completely polarize such atoms with optical pumping techniques. The difficulties arise in generating a sufficient target density of polarized atoms, and in avoiding dilution of the analyzing power with unpolarized atoms. Even more far out is the notion of using a low-energy electron beam of well-known polarization as a target for Møller scattering. Unlikely as these ideas seem, no doubt improvements in electron beam polarimetry will be developed in the future.

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