Precision electron polarimetry

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Abstract.

A new generation of precise Parity-Violating experiments will require a sub-percent accuracy of electron beam polarimetry. Compton polarimetry can provide such accuracy at high energies, but at a few hundred MeV the small analyzing power limits the sensitivity. Møller polarimetry provides a high analyzing power independent on the beam energy, but is limited by the properties of the polarized targets commonly used. Options for precision polarimetry at 300 MeV will be discussed, in particular a proposal to use ultra-cold atomic hydrogen traps to provide a 100%-polarized electron target for Møller polarimetry.

Keywords: Polarimetry

PACS: 29.27.Hj Polarized beams; 29.27.Pj Polarized and other targets

INTRODUCTION

Polarized electron beams in an energy range of $\sim 0.2 - 50$ GeV have been used in various single-spin and double-spin experiments. Modern beam sources provide polarization of about 86-89%. In the double-spin experiments the requirements for the electron beam polarimetry have been typically modest - of about 2-3%, since the target (nucleon) polarimetry accuracy has been the limiting factor. On the other hand, some single-spin experiments, such as precise measurements of Parity-Violating (PV) effects in electron scattering, require higher accuracy. Due to the improved techniques in PV experiments, the beam polarization uncertainty often dominates the systematic error.

A new generation of precise PV experiments[1, 2] at JLab will require a $\sim 0.4\%$ accuracy of electron beam polarimetry in an energy range of 6.6–11 GeV. Such experiments at JLab typically run at a beam current of 40-100 μA . Several features of the JLab accelerator should be taken into account. One is the spin precession in the machine. At 11 GeV a 0.1% change of the beam energy will turn the spin orientation on target by about 20%. Another feature is the multi-hall operation. The 1500-MHz machine accelerates three overlapped 500-MHz “beams”, each assigned for one hall. The “beams” may have different currents and polarizations. A small leakage from a differently polarized beam may introduce a considerable systematic error[3]. Variations of the electron polarization at the source is also a possibility. Because of these factors the polarimetry should be continuous throughout the experiment and should use just the same beam as the experiment.

This Workshop is dedicated to physics at the beam energies of 150-300 MeV. Such a machine is under construction at Mainz[4]. Polarimetry is a challenge for these experiments, in particular because the polarized Compton scattering is a less efficient tool at lower energies.

In order to achieve the required level of accuracy at least two polarimetry methods have to be applied and the results cross-checked. At least one method should provide continuous measurements.

METHODS USED FOR ELECTRON BEAM POLARIMETRY

Various methods to measure the electron beam polarization have been applied in a broad energy range from ~ 10 eV to 50 GeV. The atomic absorption has been used at very low energies of a few eV. In the energy range of 50 keV - a 10 MeV, the spin-orbital interaction in elastic electron scattering on unpolarized targets (Mott scattering) provides a large

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analyzing power. At energies >100 MeV the spin-spin interaction in scattering on polarized targets provides large polarization-driven asymmetries (let us consider the longitudinal polarizations only): $\frac{\sigma_{\uparrow\uparrow}-\sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow}+\sigma_{\uparrow\downarrow}} = A \cdot \mathcal{P}^b \mathcal{P}^t$, where $\sigma_{\uparrow\uparrow}$ and $\sigma_{\uparrow\downarrow}$ are the cross sections for the parallel and anti-parallel spins of the beam and the target, $\mathcal{P}^b$ and $\mathcal{P}^t$ are the beam and target polarizations, and A is the analyzing power of the process. The following description of the physics processes uses the formalism given in [5].

Atomic absorption

In a novel low energy polarimeter[6], a 50 keV beam from the gun is decelerated to 13 eV and absorbed in argon. The degree of the circular polarization of the emitted fluorescence (811.5 nm) is related to the electron beam polarization. Potentially, this method could provide a 1% systematic accuracy, a 1% statistical accuracy in a 20 s measurement, and be non-invasive. However, due to problems with handling the very low energy beam, the device has provided only relative polarization measurements and worked at low beam currents (40 nA). It was used for invasive, but fast monitoring of the relative beam polarization.

Mott scattering

Single Mott scattering

The standard polarimetry method used in the polarized electron injectors in the energy range of 0.05–10 MeV, is to measure the spacial (left-right) asymmetry of the Mott scattering of a transversely (vertically) polarized electron beam off heavy nuclei (see a review in [7]).

The differential cross section for a polarized electron elastically scattering from a heavy particle with a charge Z to an angle of θ is:

$$\sigma(\theta, \phi) = I(\theta)[1 + S(\theta)\vec{P} \cdot \hat{n}], \quad I(\theta) = r_e^2 Z^2 \cdot \frac{(1 - \beta^2)(1 - \beta^2 \sin^2(\frac{\theta}{2}))}{4\beta^4 \sin^4(\frac{\theta}{2})}, \quad (1)$$

where $\vec{P}$ is the incident electron polarization, $\hat{n} = \frac{\vec{k} \times \vec{k}'}{|\vec{k} \times \vec{k}'|}$ is the unit vector normal to the scattering plane where $\vec{k}$ ($\vec{k}'$) is the incoming (outgoing) electron momentum, and r_e is classical electron radius. The analyzing power $S(\theta)$ (so-called Sherman functions[8], see fig. 1) is calculable within QED, but the measured asymmetries are distorted by nuclear effects, spin rotation, plural scattering etc. The analyzing power depends on the scattering angle and reaches about 50% in the backward direction, closer to 180° at higher energies.

FIGURE 1. Left: Sherman function for gold for different kinetic energies commonly used. Right: Target thickness extrapolation for 3 beam energies with percent level precision [9].

The uncertainty of the Sherman function is a few percent at low energy due to electron cloud screening [10] or at the percent level above 1 MeV due to finite nuclear size penetration [11]. Plural and multiple scattering on thicker

targets dilute the measured asymmetry. Using several target foils allows to extrapolate the measured asymmetry to zero target thickness.

TABLE 1. Mott polarimeters at e^- accelerators.

Polarimeter	Energy (MeV)	Target / Thickness (Z) / (μm)	$\frac{\sigma P}{P_{\text{sys}}}$ (%)
[12] TU Darmstadt	0.1	Au,Ag / 0.04-0.5	3
[13] KPH Mainz	1-3.5	Au / 0.1-15	2
[9] JLab CEBAF	2-8	Au,Ag,Cu / 0.1-10	1.1

Existing Mott polarimeters are listed in Table 1. At lower energies (< 0.2 MeV) the larger Mott cross section limits the beam intensity to nA's and the target thickness to $< 0.1 \mu\text{m}$. Such thin foils are difficult to handle. The dilution by plural/multiple scattering remains significant. At higher energies (1-10 MeV) higher beam currents (μA 's) and thicker foils (μm 's) are used. The beam quality is better controlled. Plural scattering is significantly reduced. The target thickness extrapolation is done more accurately, including corrections for double elastic scattering (see fig. 1).

Double Mott scattering

Initially unpolarized electrons scattered off a heavy nucleus become polarized. The scattering of these secondary electrons to the same angle determine the square of the Sherman function $S(\theta)^2$. Such a method is applicable at relatively low energies of the initial electrons of ~ 0.1 MeV. It has been demonstrated[14] that the apparatus asymmetries can be largely canceled potentially allowing an accuracy as low as 0.3% to be achieved.

Application at 150-300 MeV

The Mainz group plans to use the double Mott scattering for accurate polarimetry at the injector. Since the method is invasive and measures the beam polarization at the injector only, alone it is not sufficient for the precision required. Still, it provides an important cross check and also helps to tune up the polarized injector.

Compton scattering

Compton back scattering on circularly polarized light can be used to measure both longitudinal and transverse components of the beam polarization. The analyzing power has been calculated up to second order in QED and the deviation from the Born approximation for the typical polarimeter acceptance is about 0.1%[15]. The unpolarized differential Compton cross section can be expressed as,

$$\left(\frac{d\sigma}{dx d\phi} \right)_{\text{unp}} = r_e^2 y \left\{ \frac{x^2(1-y)^2}{1-x(1-y)} + 1 + \left[\frac{1-x(1+y)}{1-x(1-y)} \right]^2 \right\}, \quad y = \left(1 + \frac{4E_0\omega_0}{m_e^2} \right)^{-1}, \quad x = \frac{\omega}{\omega_{\text{max}}} = \frac{\omega}{E_0(1-y)} \quad (2)$$

where r_e is classical electron radius and the dimensionless x, y -scattering parameters are defined in terms of the incident (scattered) electron and photon energies, E_0 and ω_0 (E and ω). The back scattered photon energy can be expressed as a function of the photon angle θ_γ (here θ_γ is relative to the electron direction),

$$\omega = E_0(1-y) \left[1 + y \left(\frac{E_0\theta_\gamma}{m_e} \right)^2 \right]^{-1}. \quad (3)$$

The polarized cross section is:

$$\frac{d\sigma}{dx d\phi} = \sigma_{\text{unp}} (1 - \mathcal{P}^\gamma [\mathcal{P}_z^e A_z(x,y) + \mathcal{P}_t^e \cos \phi A_t(x,y)]), \quad (4)$$

where ϕ is the azimuthal angle of the outgoing photon with respect to the electron transverse polarization, $\mathcal{P}^\gamma$ is the incident photon's circular polarization, $\mathcal{P}_z^e$ and $\mathcal{P}_t^e$ are the incident electron's longitudinal and transverse polarization,

FIGURE 2. Left: the Compton longitudinal analyzing power dependence on the scattered photon energy, for three beam energies: 10, 1 and 0.3 GeV. Right: the dependence of the maximum energy of the scattered photon on the incoming electron energy.

and the longitudinal and transverse analyzing powers are given by,

$$A_z(x, y) = \frac{r_e^2 y}{\sigma_{unp}} [1 - x(1 + y)] \times \{1 - [1 - x(1 - y)]^{-2}\}, \quad A_t(x, y) = \frac{r_e^2 y}{\sigma_{unp}} x(1 - y) \frac{\sqrt{4xy(1 - x)}}{1 - x(1 - y)}. \quad (5)$$

A_z is maximal at the kinematic endpoint $E_{min} = yE_0 = E_0 + \omega_0 - \omega_{max}$, corresponding to 180° back scattering in the center-of-mass (CM) frame; it is zero for 90° scattering in the CM. Both final state electrons and photons can be used for longitudinal polarization measurements. $\mathcal{P}_t^e$ can be determined from measurements of the position asymmetries of the final state photons.

The analyzing power strongly depends both on the beam energy and on the relative energy of the scattered photon (fig. 2, left). Therefore, the energies of the particle detected should be accurately measured, or the energy response of the integrating detector should be well understood. The maximal longitudinal analyzing power increases with the beam energy, from 0.35% at 0.1 GeV to 30% at 10 GeV (for “green” laser light of $\lambda = 532$ nm). The maximal photon energy at the Compton edge $x = 1$ also increases with the beam energy from 0.35 MeV at 0.1 GeV to 2.6 GeV at 10 GeV (fig. 2, right).

TABLE 2. Compton polarimeters. Notes: column A: L - linear accelerator, S - storage ring; column P: L / T - longitudinal / transverse polarization; column EGCI: E - electron measurement, G - γ measurement, C - counting mode, I - integrating mode, while “+” or “-” indicates whether the method was or was not used. The cartoon at the right presents the schematics of the JLab Hall A Compton polarimeter [19] which uses a Fabry-Pérot cavity.

Polarimeter					Beam GeV	$\frac{\sigma P}{P_{sys}}$
ref	Lab	A	P	EGCI		
[16, 17]	MIT-Bates	S	L	+++	0.3-1	5-6%
[18]	NIKHEF	S	L	+++	< 1	4.5%
[19, 20]	JLab, A	L	L	+++	1-6	1%
[21]	HERA LPOL	S	L	+++	27.5	1.6%
[22, 23]	HERA TPOL	S	T	+++	27.5	2.9%
[24, 25]	SLD SLAC	L	L	+++	45.6	0.5%

Table 2 lists results and references for several Compton polarimeters. In general, the systematic errors improve at higher beam energies and are better for longitudinal measurements than for transverse measurements. However, Compton polarimeters are increasingly in use at lower energies of a few GeV with good precision. The way to improve the performance is to use a shorter wavelength and a higher power of the incoming light. A Fabry-Pérot cavity was used successfully in Hall A of JLab at 1064 nm[19] amplifying the power of the laser by a factor of ~ 4000 . Later, the system was upgraded to 532 nm[20] with the amplification factor of about ~ 2000 . The polarimeter built for QWEAK experiment in Hall C (see the presentation by D.Gaskell at this Workshop) uses a higher power 532 nm laser (10 W) and a lower gain (~ 200) cavity. Using a cavity complicates the measurement of the light polarization. This polarization becomes a significant source of the total systematic uncertainty.

A cartoon in Table 2 shows the schematics of the polarimeters with cavities. The scattered electrons must be measured from the Compton endpoint $E = E_0 - \omega_{max}$ to about $E = E_0 - 0.5\omega_{max}$. The magnetic chicane should

FIGURE 3. Left: Møller cross section dependence on the scattering angle in CM, for a 1 GeV beam; Right: Møller longitudinal analyzing power dependence on the scattering angle in CM

provide enough separation between the unscattered beam and the scattered electrons (typically ~ 20 mm). At lower beam energies a smaller energy fraction goes to the scattered photons and a larger magnetic separation is needed.

Compton polarimetry is not invasive and can run continuously with the experiment. Along with a nearly 100% polarization of light it makes it the most accurate and convenient tool at high energies and at high beam currents, in spite of the large variations of the analyzing power.

Application at 150-300 MeV

With 150 MeV electrons and 532 nm light the Compton edge is at $\omega_{max} = 0.8$ MeV and $A_Z = 0.5\%$. A 45° magnetic bend and a ~ 10 m drift distance would provide a 20 mm minimal separation from the beam. Such a large floor space may not be available within the existing facilities. Extrapolating the experience of the Hall C (1 GeV, $A_Z = 3.5\%$) polarimeter one may expect that a 1% statistical accuracy can be achieved in about 24 h. Because of the lower analyzing power various false asymmetries will be relatively more significant in comparison with the QWEAK conditions.

Møller scattering

Møller polarimetry makes use of polarization asymmetries in the e^-e^- scattering cross section [26, 27], calculated up to second order in QED. The deviation from the Born approximation for the typical polarimeter acceptance is about 0.3% [28, 29]. Both longitudinal and transverse components of the beam polarization can be measured.

$$\frac{d\sigma}{d\Omega} = r_e^2 \frac{m_e^2}{s} \frac{(3 + \cos^2 \theta)^2}{\sin^4 \theta} \left[1 - \mathcal{P}_{\parallel}^b \mathcal{P}_{\parallel}^t A_{\parallel}(\theta) - \mathcal{P}_{\perp}^b \mathcal{P}_{\perp}^t A_{\perp}(\theta) \cos(2\phi - \phi_1 - \phi_2) \right] \quad (6)$$

where θ, ϕ = CM electron scattering angles, ϕ_1, ϕ_2 = azimuths of transverse polarization vectors, $\mathcal{P}_{\parallel, \perp}^{b, t}$ = beam and target longitudinal/transverse polarization states. The analyzing power is defined by the longitudinal and transverse asymmetry functions $A_{\parallel, \perp}$ (max for 90° scattering in CM):

$$A_{\parallel} = \frac{(7 + \cos^2 \theta) \sin^2 \theta}{(3 + \cos^2 \theta)^2} \leq \frac{7}{9}, \quad A_{\perp} = \frac{\sin^4 \theta}{(3 + \cos^2 \theta)^2} \leq \frac{1}{9}, \quad (7)$$

The analyzing power does not depend on the beam energy and only weakly depends on the scattering angle around 90° in the CM frame (see fig.3). Møller polarimeters select secondary particles with energies close to half the beam energy and produced in a certain angular range. Various magnetic optics schemes are used: with dipole magnets [30], with quadrupole magnets [31, 32, 33] and with combinations of both [34]. Detecting both scattered electrons allows to reduce the non-Møller backgrounds to negligible levels.

The polarized electron targets in Møller polarimeters consist of thin ferromagnetic foils magnetized in external magnetic fields. The average polarization of electrons in saturated iron at room temperature is $\sim 8.04\%$ [35]. In the

FIGURE 4. Left: Hall C Møller polarimeter[31]; Right: Hall A Møller polarimeter[34, 38]

typical scheme the foil oriented at a small angle ($\sim 20^\circ$) to the beam is magnetized along its surface by a field of 0.01-0.03 T parallel to the beam. Typically, only the longitudinal beam polarization is measured, but a transverse component of the target polarization allows determination of the transverse beam polarization as well. In a different scheme the foil is oriented perpendicular to the beam and is magnetized to saturation by a 3-4 T field perpendicular to its surface[35]. The latter method reduces the target polarization uncertainty from 2-3% to sub-percent level[31].

The spectrometer acceptance may depend on the initial momentum of the target electron (comparable to e^-e^- rest mass for inner shells of iron atoms), which changes the effective target polarization and requires a correction [36], in some cases as large as 10% [37] (Levchuk effect). This correction is another major source of systematic error, along with the target polarization (about 0.3% for the most precise Møller polarimeter up-to-date[31]).

Fig. 4 shows two JLab Møller polarimeters. Parameters of several polarimeters are summarized in Table 3.

TABLE 3. Møller polarimeters. The magnetizing field is shown in the second column.

Polarimeter	Field, T	Arms	Optics	$\sigma P/P_{\text{sys}}$	
				target	full
[30] SLAC	0.010	1	D	1.7%	2.7%
[32, 33] Bates	0.015	2	Q	1.5%	2.9%
[34] JLab, A	0.025	2	QQD	2.0%	3.0%
[38] JLab, A	3.9	2	QQD	0.3%	0.8%
[31] JLab, C	3.9	2	QQ	0.3%	0.5%

Ferromagnetic targets can not stand continuous beam currents higher than several μA because of their heating and depolarization. Also, foils thinner than $\sim 1 \mu\text{m}$ are difficult to use. This excludes their application in storage rings. In extracted beams, Møller polarimetry typically has to use beam currents much lower than the PV experiments need. Extrapolation of the results to the experimental conditions introduces a systematic error, which is sometimes hard to evaluate, in particular in case of JLab where the beam in a certain hall may contain a leakage from a differently polarized beam for another hall[3]. Møller polarimetry with these targets is invasive and typically requires a different beam tuning.

There were attempts in Hall C at JLab to overcome the beam current limitation (see the presentation by D.Gaskell at this Workshop) by using a low duty cycle beam. The target foil in a ~ 4 T field was perpendicular to the beam with its edge close to the beam orbit. A kicker magnet moved the beam spot over the edge in and out of the foil. It occurred that in this configuration it was difficult to provide mechanical stability of the foil in the field. This approach may eventually work but for various reasons it has not succeeded so far.

In comparison with Compton polarimetry, Møller polarimetry has an advantage of a nearly constant analyzing power, independent on the beam energy. The disadvantages as the beam current limitation, a low target polarization and the Levchuk effect, are associated with the target material used in these polarimeters.

Since at low energy electron accelerators Møller polarimetry is potentially more promising than Compton polarimetry, there are incentives for overcoming the limitations of the former. A major improvement could come from replacing the ferromagnetic targets with electron-spin-polarized atomic hydrogen.

A jet of polarized deuterium atoms[39] with a density of about $5 \cdot 10^{11} \text{ cm}^{-2}$ was used in a storage ring at $\sim 100 \text{ mA}$. The polarization of the atoms was about 100% (the accuracy has not been discussed). So far, a 1% statistical accuracy could be reached in $\sim 100 \text{ h}$. Because of a low target density of the jet this method is hardly applicable for $\sim 100 \mu\text{A}$ extracted beams.

Another possibility discussed[40, 41] is to use an ultra-cold storage cell for 100% polarized atomic hydrogen. This method could be used for CW beams up to $200 \mu\text{A}$ in a non-invasive way. It would remove the sources of the main systematic uncertainties as the target polarization, the Levchuk effect and the beam current extrapolation.

The technique of storage cells was perfected in 1980[42], and later a density as high as $3 \cdot 10^{17} \text{ atoms/cm}^3$ was achieved [43] in a small volume. Hydrogen atoms from a dissociator are cooled to about 0.3 K and differently polarized states are separated by the field gradients of a $\sim 8 \text{ T}$ solenoidal magnet. The central part of the solenoidal field acts as a trap for the atoms with a certain electron polarization. The technique was applied to build jet targets of polarized protons. Fig. 5 shows a working prototype cell[44]. So far, the storage cell itself has not been put in a high-intensity particle beam.

The effective length of such a target is about 20 cm. A gas density of $3 \cdot 10^{15} \text{ cm}^{-3}$ was obtained experimentally[45], for a similar design, which would be enough to obtain a 1% statistical accuracy in about 15 minutes.

Several sources of potential depolarization caused by a high power beam have been identified and ways to control them proposed[41]. If successful, such a method may reduce the systematic uncertainty of Møller polarimetry to $\sim 0.2\%$.

FIGURE 5. A sketch of the storage cell

SUMMARY

Precise polarimetry for 150-300 MeV electron beams is a challenge. Compton polarimetry provides continuous measurements of the beam close to the experiment, but is difficult at low energies because both the back-scattered photon energy and the analyzing power are very low. The energy of the scattered electrons is close to the energy of the beam and in order to detect them a rather large magnetic chicane is needed. Møller polarimetry as it exists can not provide continuous measurements and has to use a beam current much lower than the typical PV experiment. Replacing ferromagnetic targets with polarized hydrogen can provide continuous measurements and reduce the systematic uncertainties to a $\sim 0.2\%$ level, but would require a considerable R&D work². Both the high-field ferromagnetic target and the hydrogen trap require a solenoidal magnetic field of 4–8 T along the beam. Such a field if misaligned strongly steers the low energy beam and makes the beam tune a challenge. A remotely controlled fine positioning of the magnet

² The Mainz group working for MESA started an R&D work using existing parts of a prototype hydrogen storage cell[44]. See the presentation by P.A. Bartolome at this Workshop

may help to mitigate this problem. The MESA group also plans to cross calibrate the continuous polarimeter with a double-Mott polarimeter at the injector, which can potentially reach a 0.3% accuracy.

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