PROCEEDINGS OF SCIENCE

High-precision Møller Polarimetry at Jefferson Lab's Hall A

Eric King[a,*]

[a] *Temple University, Philadelphia, USA*

E-mail: ericking@temple.edu

The Thomas Jefferson National Accelerator Facility (JLab) operates the Continuous Electron Beam Accelerator Facility which produces a polarized electron beam which is delivered to four experimental halls and is utilized to probe the fundamental nature of matter. Parity-violating electron scattering experiments are one category of experiments that are run at JLab. For these experiments, knowledge of the beam polarization is a key source of systematic uncertainty. The Møller polarimeter, one of three polarimetry tools in experimental Hall A, operates by taking advantage of the QED spin asymmetry of Møller scattering of beam electrons on a magnetically saturated iron target foil. The upcoming MOLLER experiment has a high-precision polarimetry requirement of 0.42% or less. Here, I'll discuss the preparations underway and lessons learned during PREX-2 and CREX which will allow the Hall A Møller polarimeter to meet this requirement.

19th Workshop on Polarized Sources, Targets and Polarimetry (PSTP2022),
26-30 September, 2022
Mainz, Germany

[*] Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(PSTP2022)030

1. Introduction

Møller polarimetry is a method of extracting the electron polarization of a source by measuring the asymmetry in electron/electron scattering. The use of Møller scattering has proven effective for measuring the degree of polarization from polarized electron sources. The measured asymmetry, seen in Equation (1), is the difference over the sum of the coincidence scattering rates R when the beam and target polarization are parallel $R_{\uparrow\uparrow}$ and anti-parallel $R_{\downarrow\uparrow}$. This asymmetry is equal to the product of the beam polarization P_{beam} (an unknown), the target polarization P_{target} (a known value with an uncertainty) and the mean analyzing power (a value which we must compute).

$$A_{\mathrm{meas}} = \frac{R_{\uparrow\uparrow} - R_{\downarrow\uparrow}}{R_{\uparrow\uparrow} + R_{\downarrow\uparrow}} = -P_{\mathrm{beam}} P_{\mathrm{target}} \langle A_{zz} \rangle \tag{1}$$

During PREX-2 [1] and CREX [2] the Møller polarimeter achieved a systematic uncertainty of $< 1\%$. Details of these results can be found in a publication of the PREX-2 and CREX Møller polarimetry work [3]. Here, I will present a summary of achievements and lessons learned in preparation for the upcoming MOLLER [4] experiment which requires a 0.4% systematic uncertainty.

2. JLab Hall A Møller Polarimeter

The Hall A Møller polarimeter [5] is a double-arm polarimeter [6] which detects Møller electron coincidence pairs which have been successfully transported to the detectors. Covered here is a brief description of the JLab Hall A Møller polarimeter.

2.1 Physical Design

The polarimeter design, which can be seen in Figure 1 includes four quadrupole magnets which steer Møller electrons scattered from the magnetically saturated target downstream towards a dipole magnet which bends the scattered Møller electrons below the beam line where the Møller detector is located. The Møller target is magnetically saturated using a superconducting Helmholtz coil setup in the direction parallel to the beam line, and the foil plane is aligned perpendicular to the beam (except during certain systematic studies). Magnetically saturating the foil is informally known as the 'brute force' method of Møller polarimetry [7] and it eliminates some systematic uncertainties with regards to the spin polarization of the unpaired electrons in the foil.

The polarimeter detector is a lead/scintillating-fiber calorimeter [8] subdivided into four blocks. The fibers of the calorimeter are gathered into eight bundles with each bundle attached to a photomultiplier tube. This results in what are effectively 8 separate detector blocks—four on the left and four on the right. The division of these blocks can be seen on the lower left-hand side of Figure 1. The individual PMT signals feed into an analog-to-digital converter, are summed on both the left-hand and right-hand sides, and then fed into a timing discriminator to determine whether or not a Møller coincidence pair was detected.

2.2 Computing Analyzing Power

Computation of the analyzing power for the Hall A Møller polarimeter is done via Monte Carlo simulation. Our simulation, MolPol, is a Geant4-based [9] application and the geometry of the polarimeter in the simulation is built to physical survey specifications. Pairs of Møller electrons

PoS(PSTP2022)030

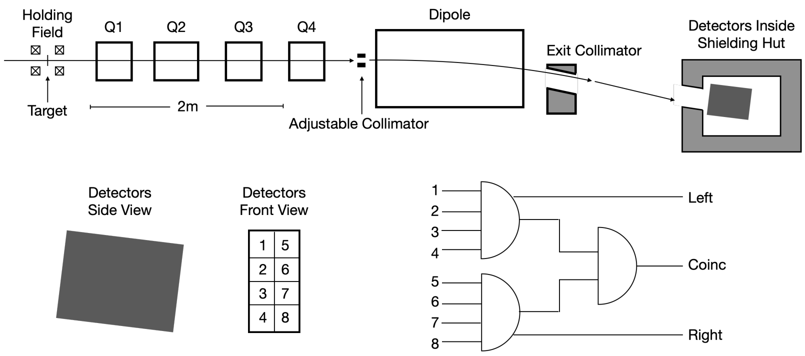

Figure 1: To-scale mock up of the Møller polarimeter as used in the PREX2 and CREX experiments in Hall A at JLab.

are generated in target foil which are then transported through the spectrometer where coincidence pairs, events for which both electrons make it to the detector, are counted and analyzed. The Møller electron generator in MolPol takes into account radiative corrections, target polarization, and, importantly, the Levchuk Effect [10] which alters the kinematics, and thus transportation, of Møller-scattered events in the spectrometer. Measurements were taken during PREX-2 and CREX to validate Levchuk modeling in the MolPol simulation. Discussion on improvements in our calculation of the Levchuk effect appears later in this proceeding.

3. Systematics

Polarimetry error for the Hall A Møller polarimeter is dominated by the systematic error. What follows is a brief review of the polarimeter systematics during PREX-2 and CREX, shown in Table 1, with plans on improving them for MOLLER in order to meet stringent systematics requirements shown in Figure 2. Detailed will be our main systematics: calculating the analyzing power uncertainty which is now considered well-constrained; our target polarization uncertainty which has made large improvements; measured systematic uncertainties; and extrapolation uncertainties.

3.1 Analyzing Power

The computation of the analyzing power presents uncertainties in and of itself. We have made noteworthy advancements have been made in the computation of the Levchuk Effect which is our dominant effect in the transportation of Møller electrons through the spectrometer. Figure 2 shows asymmetry data taken during CREX while altering magnetic optics. Modified-hydrogen momentum wavefunction modeling, detailed by Swartz [11] and which was used in our original modeling, did not provide a good fit to CREX experimental data. We commissioned Hartree-Fock calculated momentum wavefunctions for bulk iron to use in our simulations; the results, which can be seen in Figure 2, provide a much better match to the experimental data. This greatly reduces the uncertainty in our calculations for the Levchuk correction from 30% down to a conservative 10%.

*Extrapolation errors.

†Evaluated during polarization measurements.

‡'Laser Polarization' in Table 1 is same as 'Source Variation' in Figure 2.

**Foil Polarization in Table 1 broken down into Saturation Polarization and Degree of Saturation in Figure 2.

PoS(PSTP2022)030

Uncertainty	PREX2	CREX
$\langle A_{zz} \rangle$	0.20	0.16
Beam Trajectory	0.30	0.00
Foil Polarization**	0.63	0.57
Dead Time†	0.05	0.15
Charge Normalization	0.00	0.01
Leakage Currents*	0.00	0.18
Laser Polarization‡ *	0.10	0.06
Accidentals†	0.02	0.04
Current Dependence*	0.42	0.50
Aperture Transmission*	0.10	0.10
Null Asymmetry†	0.12	0.22
July Extrapolation	0.23	–
Total	0.89	0.85

Table 1: Systematic uncertainties for the Hall A Møller polarimeter during PREX-2 and CREX.

Uncertainty	CREX	MOLLER
$\langle A_{zz} \rangle$	0.16	0.15
Saturation Polarization**	0.28	0.24
Degree of Saturation**	0.50	0.15
Dead Time†	0.15	0.10
Leakage Currents‡*	0.18	0.00
Source Variation*	0.06	0.10
Accidentals†	0.04	0.10
Current Dependence*	0.50	0.10
Aperture Transmission*	0.10	0.10
Null Asymmetry†	0.22	0.10
Total	0.85	0.40

Table 2: Hall A Møller polarimeter systematic uncertainties achieved during the CREX experiment compared to the projected systematic uncertainties for the MOLLER experiment.

Additionally, in order to meet the demands of future high-precision experiments in Hall A there will be physical changes made to the polarimeter setup. The target magnet will be moved 30cm upstream to allow better Møller steering. A collimator at the entrance to the detector will restrict the acceptance to $\pm 7^\circ$ in order to further reduce analyzing power uncertainties.

3.2 Target Polarization

Uncertainty in the target foil polarization dominated the PREX-2 (0.63%) and CREX (0.57%) Møller polarimetry systematics. There are two components to the foil polarization systematic seen in Table 1—uncertainty in the saturation polarization of the iron foil and uncertainty in the degree of saturation. The polarimetry working group underwent an extensive literature review [12] on the saturation polarization of iron and nickel foils of which the details are too numerous to list here. Subsequent to the publication of the review the Møller polarimetry working group has revised the value from a 0.28% uncertainty to 0.23% uncertainty. The working group agreed on an assigned a 0.5% degree of saturation systematic for PREX-2 and CREX.

There is a dedicated plan in place to measure foil saturation and alignment during the commissioning period of MOLLER. Utilizing a combination of measurements taken at different holding field strengths and making use of rotary target motion we plan on convincing ourselves through extensive systematic studies that the foils are indeed saturated. There is an additional plan in place to ensure tighter and more taut mounting of target foils onto the target ladder.

3.3 Measured Systematics

The null asymmetry, accidentals, and dead time are measured during polarimetry measurements. These items are marked in Figure 2 with a dagger †. Details of how these measurements are used to correct the polarization data during analysis can be found in the author's thesis [15].

The null asymmetry measurement is performed with beam incident on a Cu foil for which the measured asymmetry should be consistent with zero. These measurements are performed with each pair or normal asymmetry measurements. We ultimately assign a systematic uncertainty equal

PoS(PSTP2022)030

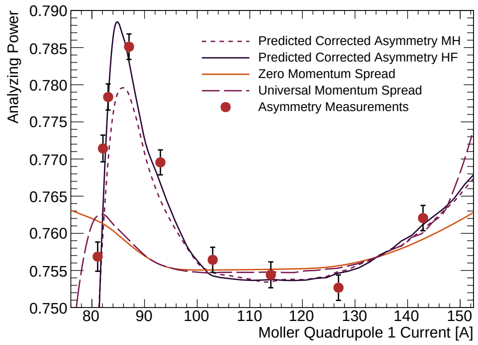

Figure 2: Results of asymmetry-measurements taken during CREX—red dots. Important to see here are: the expected results were the Levchuk Effect to not be taken into account "Zero Momentum Spread"; the Møller Asymmetry using modified-hydrogen wave-functions "Predicted Corrected Asymmetry MH"; and the Møller asymmetry using Hartree-Fock wave-functions "Predicted Corrected Asymmetry HF".

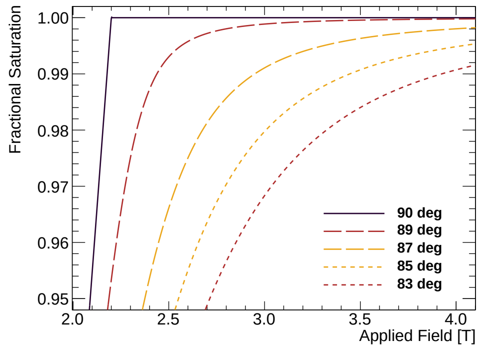

Figure 3: Stoner-Wolfarth magnetic saturation curves [13, 14] for a thin iron foil with target holding field strength listed on the horizontal axis and different target foil rotations (the angle being relative to plane of the foil). Planned target foil saturation studies will involve a series of measurements over a combination of different target holding field strengths and target rotations—$(0°, 1°, 2°, 5°, 7°)$ shown here.

to the mean value of the null asymmetries plus the error on the measurements. The size of this systematic uncertainty is therefore determined by the total amount of statistics that we accumulate. We anticipate this systematic to fall in line with expectations during MOLLER.

Dedicated measurements are made to determine the dead time of the data acquisition system (DAQ). The measurements utilize LED pulsers which have a known pulse rate. As the Møller rate on the detector increases the fractional losses of the LED pulser coincidences are counted—a missed pulser flash indicates the electronics were busy. During PREX and CREX a very conservative systematic uncertainty equal to 100% of the correction was assigned. Temple University has recently acquired a dual-channel detector emulator which will be used to test the DAQ system with regards to how the dead time is calculated. It is expected that this work will result in a large decrease in the size of the dead time systematic uncertainty during MOLLER.

3.4 Extrapolation Uncertainties

There are a variety of extrapolation uncertainties which are not directly measured—current dependence, source variation, leakage currents and aperture transmission. Evidence of source variation during PREX-2 was discovered during Møller polarimetry measurements. And while leakage currents are measured several times during polarization measurements they are not corrected for during analysis. Covered here are the current dependence—the polarimeter's dominant extrapolation systematic—and leakage current.

3.4.1 Current Dependence

Current dependence, also sometimes referred to as high-current extrapolation, derives from the simple fact of the matter that Møller polarimetry measurements are performed at currents typically around 1μA while main experiments in Hall A run closer to 100μA. There exist concerns over the possible relationship between beam polarization and heating of the source photocathode. In 2007, Hall C performed a dedicated study [16] using multiple techniques to deliver low current to the

PoS(PSTP2022)030

experimental hall while maintaining high laser currents on the source photocathode The results of this study were used to place an ~0.5% systematic uncertainty on the polarization measurement during PREX-2 and CREX. While a 0.5% systematic uncertainty isn't problematic for an experiment whose polarization uncertainty is >1%, a 0.5% systematic uncertainty isn't tolerable given the 0.4% uncertainty goal desired for MOLLER. The tough high-precision uncertainty goals of the MOLLER experiment therefore require a rigorously designed study, similar to that previously undertaken in Hall C in 2007, with the involvement of JLab source experts in order to limit this uncertainty from its current 0.5% down to the ~0.1% level.

3.4.2 Leakage Current

The JLab polarized source serves four experimental halls each to which it provides independent beam. An issue which arises is leakage current, also known as bleed through, which arrives into Hall A that was destined for other halls; a brief but thorough explanation of this phenomenon can be found in [3]. During PREX-2 there were no experimental halls operating at high currents and therefore leakage currents were virtually non-existent. However, during CREX, a considerable level of leakage current arrived while Hall C was operating. This led to an unanticipated sharp increase in a systematic (see Table 1) that we initially did not consider to be a problem. It is imperative that the leakage current be controlled during MOLLER.

4. Conclusion

The Hall A Møller polarimeter successfully measured the beam polarization during PREX-2 and CREX with a systematic uncertainty lower than 1% in spite of very conservative estimates made for a variety of uncertainties. On top of this, there was unprecedented agreement between the measurement made by the Møller polarimeter and the measurement made by the Compton polarimeter during CREX—Compton polarimetry was unavailable during PREX-2—and this gives us a great amount of confidence in our measurements. Meeting the strict requirements for 0.4% polarimetry for the MOLLER experiment seems within reach given the lessons learned during PREX-2 and CREX and planned modifications to the polarimeter. There is a need for some time-intensive systematic studies to further constrain poorly-understood uncertainties but the plans for these are being actively developed.

Acknowledgments

This work was supported under US Department of Energy grants DE-SC002042, DE-SC0012575, DE-FG02-07ER41522, DE-FG02-05ER41372, DE-AC05-06OR23177, and DE-FG02-84ER40146. Portions of the research presented here was performed using the Open Science Grid [17, 18], which is supported by the National Science Foundation awards #2030508 and #1836650.

Permissions

Certain figures contained in this conference proceeding are reprinted from Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment [NIM-A], Volume 1045, D.E. King, D.C. Jones, C. Gal, D. Gaskell, W. Henry, A.D.

PoS(PSTP2022)030

Kaplan, J. Napolitano, S. Park, K.D. Paschke, R. Pomatsalyuk, P.A. Souder, *Precision Møller Polarimetry for PREX-2 and CREX*, Copyright (2023), with permission from Elsevier—License Number 5550850487031.

References

[1] D. Adhikari et al. Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering. *Phys. Rev. Lett.*, 126:172502, Apr 2021.

[2] D. Adhikari et al. Precision Determination of the Neutral Weak Form Factor of ^{48}Ca. *Phys. Rev. Lett.*, 129:042501, Jul 2022.

[3] D.E. King et al. Møller polarimetry for PREX-2 and CREX. *NIM-A*, 1045:167506, 2023.

[4] MOLLER Collaboration. The MOLLER Experiment: An Ultra-Precise Measurement of the Weak Mixing Angle Using Møller Scattering, 2014.

[5] A. V. Glamazdin et al. Electron Beam Møller Polarimeter at Jlab Hall A, 1999.

[6] H. Frauenfelder et al. Parity and Electron Polarization: Møller Scattering. *Phys. Rev.*, 107:643–644, Jul 1957.

[7] L.V de Bever et al. A Target for Precise Møller Polarimetry. *NIM-A*, 400(2):379–386, 1997.

[8] D. Babusci et al. Lead/scintillating fiber electromagnetic calorimeters with $4.8\%\sqrt{E[\mathrm{GeV}]}$ energy resolution in the 20–80 MeV range. *NIM-A*, 332(3):444–458, 1993.

[9] S. Agostinelli et al. Geant4—a simulation toolkit. *NIM-A*, 506(3):250–303, 2003.

[10] L.G. Levchuk. The intra-atomic motion of bound electrons as a source of the systematic error in a möller polarimeter. *NIM-A*, 345(3):496–499, 1994.

[11] M. Swartz et al. Observation of target electron momentum effects in single-arm Møller polarimetry. *NIM-A*, 363(3):526–537, 1995.

[12] D.C. Jones et al. Accurate determination of the electron spin polarization in magnetized iron and nickel foils for møller polarimetry. *NIM-A*, 1043:167444, 2022.

[13] C.E. Stoner. Ferromagnetism. *Reports on Progress in Physics*, 13(1):83, jan 1950.

[14] E.C. Stoner and E. P. Wohlfarth. A Mechanism of Magnetic Hysteresis in Heterogeneous Alloys. *Phil. Trans. R. Soc. A*, 240(826):599–642, May 1948.

[15] D.E. King. *Utilizing Parity Violating Electron Scattering As a Probe to Measure the Neutron Radius of* ^{208}*Pb*. PhD thesis, Syracuse University, Syracuse, NY, USA, 2021.

[16] M. Poelker et al. Generation of electron bunches at low repetition rates using a beat-frequency technique. *Phys. Rev. ST Accel. Beams*, 10:053502, May 2007.

[17] Ruth Pordes et al. The open science grid. In *J. Phys. Conf. Ser.*, volume 78 of *78*, page 012057, 2007.

[18] I. Sfiligoi et al. Using GlideinWMS. In *2009 World Congress on CSIE*, pages 428–432, 2009.

PoS(PSTP2022)030