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

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Polarized Sources Targets and Polarimetry 2022
Johannes Gutenberg University – Helmholtz Institute Mainz

Important References

Papers:

PREX2	10.1103/PhysRevLett.126.172502
CREX	10.1103/PhysRevLett.129.042501
Fe/Ni Polarizations	10.1016/j.nima.2022.167444
PREX2/CREX Polarimetry	10.48550/arXiv.2207.02150

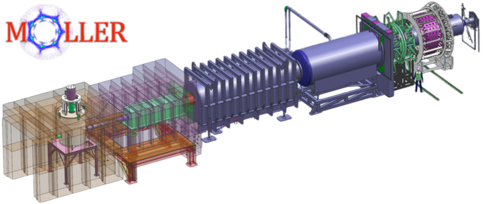
Data:

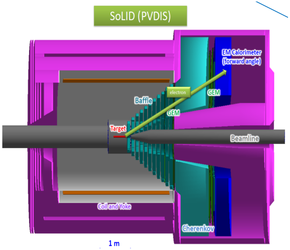
Hartree-Fock Calculated Momentum distributions for bulk Fe

Repository: gitlab.com/dhamil/levchuk-dft-corrections/-/tree/master/
File: data_files/Fe_BBB93_shell_decomposition.csv

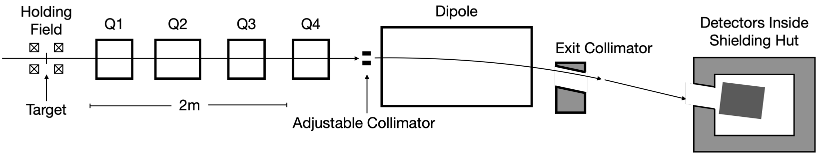
High-Precision Polarimetry for MOLLER and SoLID

- Stringent polarimetry requirements for two upcoming experiments to Hall A
- MOLLER: 0.40%
- SoLID (PVDIS): 0.40%
- The plan is for both Compton and Møller polarimeters to meet this goal

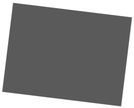




Polarimeter Schematic

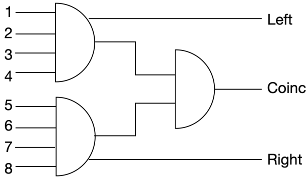


Detectors
Side View

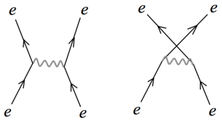


Detectors
Front View

1	5
2	6
3	7
4	8



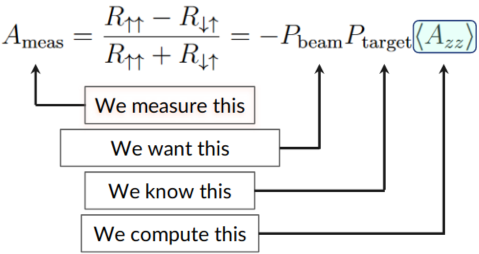
Basis for Møller Polarimetry



- We know, with some systematic error, the polarization of the target
- We compute the analyzing power of the spectrometer
- We measure a coincidence rate asymmetry
- We extract the beam polarization

$$A_{zz}(\theta) = \frac{(7+\cos^2\theta)\sin^2\theta}{(3+\cos^2\theta)^2}$$

$$\langle A_{zz}\rangle = \sum_i \frac{A(\theta)^{pol}_{zz,i}}{N^{pol}+N^{unp}}$$



$$A_{\text{meas}} = \frac{R_{\uparrow\uparrow} - R_{\downarrow\uparrow}}{R_{\uparrow\uparrow} + R_{\downarrow\uparrow}} = -P_{\text{beam}}P_{\text{target}}\boxed{\langle A_{zz}\rangle}$$

We measure this

We want this

We know this

We compute this

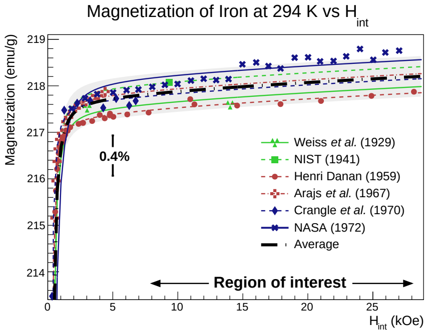
Spectrometer Description

- “Brute force” Møller polarimeter design
    - Target magnetically saturated in 4 Tesla field parallel to the beam line and perpendicular to the plane of the foil

      L.V de Bever, J Jourdan, et al (1997) NIMA S0168-9002(97)00961-3
- QQQD setup
    - Four quadrupoles steer scattered Møller electrons into dipole
    - Dipole bends moller electrons below beam line towards Møller detector
- Møller detector
    - Spaghetti fiber lead block design calorimeter
    - Connected to 8 PMTs—4 left / 4 right

Iron Foil Magnetization

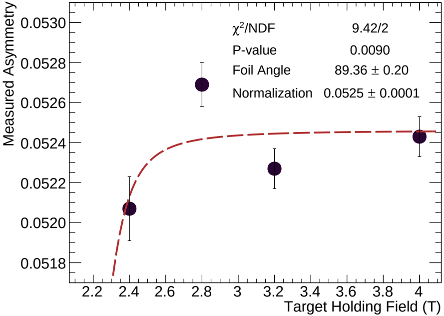
- Extensive literature review of magnetization of Fe
- Demonstrate that the saturation polarization of an Fe target can be determined to ±0.23%
- We've budgeted for 0.25% syst unc. for foil magnetization, this allows for a 0.1% uncertainty for saturation and alignment



Source: NIMA S0168-9002(22)00736-7 [2022]

Iron Foil Saturation

- Systematic error measurements taken at the end of CREX while ramping down the target holding field.
- Holding field strengths 4.0T, 3.2T, 2.8T, 2.4T, & 1T (not shown)
- Anomalous data at 2.8T will require additional systematic studies during MOLLER



Source: NIMA S0168-9002(22)00736-7 [2022]

Levchuk Effect

$$\theta^2_{Lab} = \underbrace{2m_e\left(\frac{1}{p_{\text{møller}}} - \frac{1}{p_{\text{beam}}}\right)}_{\text{Standard Møller Kinematics}}\underbrace{\left(1 - \frac{P_{\text{bound}}\cdot\hat{n}}{m_e}\right)}_{\text{Levchuk Modification}}$$

- Levchuk effect alters scattering angle of Møller scatters but not the momentum
- Can have significant effect on acceptance due to scatter from bound electrons with high atomic-momentum

Levchuk Effect:

1992 paper proposed intra-atomic motion of bound electrons is a significant source of systematic error.

https://doi.org/10.1016/0168-9002(94)90505-3

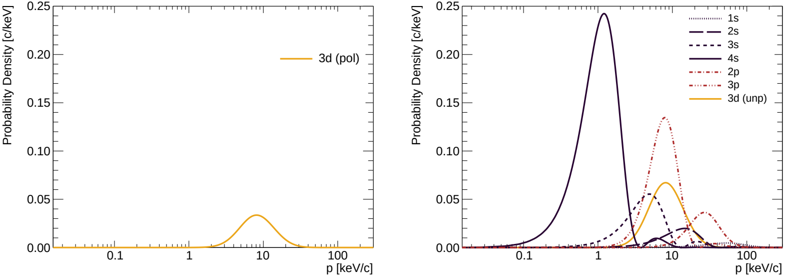
General Hydrogenic Modeling:

$$f_{unp}(p) = \sum_{j,n,l}\frac{C^j_{nl}}{P^j_n}\left(\frac{p}{P^j_n}\right)^2|\Phi_{nl}\left(\frac{p}{P^j_n}\right)|^2$$

$$f_{pol}(p) = \sum_{j}\frac{D^j_{32}}{P^j_3}\left(\frac{p}{P^j_3}\right)^2|\Phi_{32}\left(\frac{p}{P^j_3}\right)|^2$$

Improved Modeling for Levchuk Effect (cont'd)

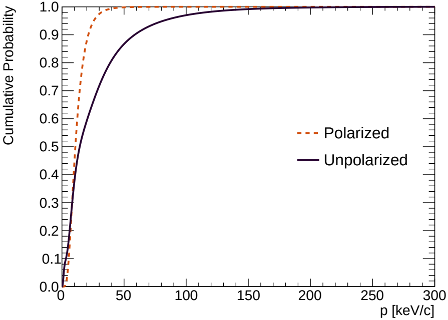
Replacement of old hydrogenic wavefunctions for bound momentum of target elections with Hartree-Fock calculated distributions.



Source: https://doi.org/10.48550/arXiv.2207.02150 [2022] :: D.E.King; D.C. Jones, et al.

Improved Modeling for Levchuk Effect (cont’d)

- Wavefunction cumulative distribution functions then used to generate events in Monte Carlo
- *Although not shown here the substantitive difference between the Hartree-Fock and Hydrogenic modeling is the 1s momentum distribution.*



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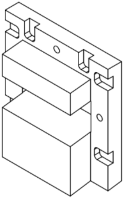
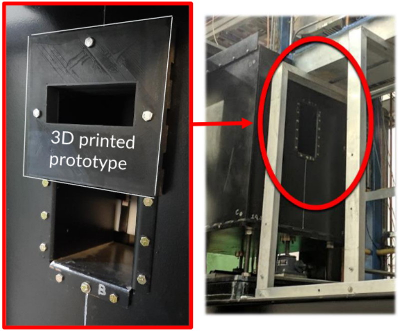
D.E.King; D.C. Jones, et al.

Detector Collimator

Collimator designed and to be added to limit detector acceptance

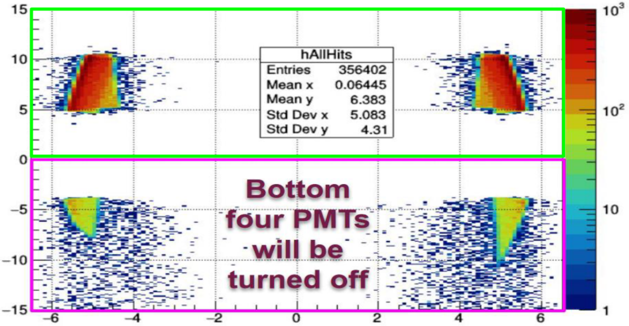
- Will be milled from tungsten (hevimet)
- 6.4 cm thick
- Designed to be inserted into the detector window
- 5.0 cm vertical acceptance window
    - ±7° Møller acceptance





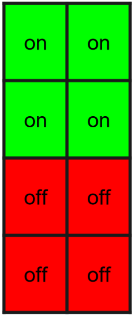
Detector Collimator (cont'd)

- Top four PMTs behind collimator window active
- Bottom four PMTs inactive
- Very clean signal cut on active PMTs



hAllHits	
Entries	356402
Mean x	0.06445
Mean y	6.383
Std Dev x	5.083
Std Dev y	4.31

Bottom four PMTs will be turned off

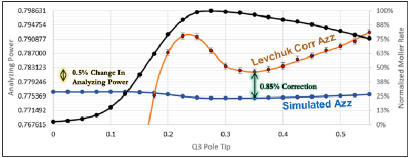


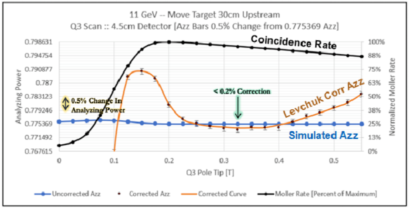
on	on
on	on
off	off
off	off

Target Move 30cm Upstream + Collimation

- Current setup restricts steering and overall acceptance at 11GeV
- Smaller than ideal $\Delta\theta_{COM}$ acceptance

- Moving target 30cm upstream allows natural separation and better steering with quads
- Larger $\Delta\theta_{COM}$ pass-through to detector = smaller Levchuk

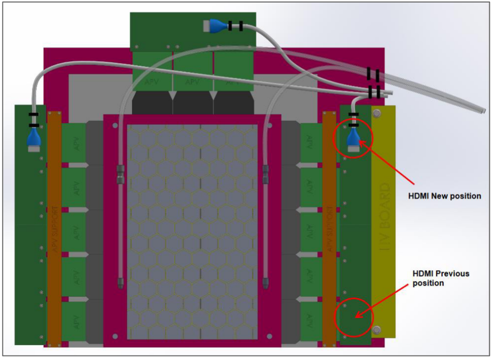




Addition of GEM Detectors

New GEMs will be used to provide quantitative insights on poorly benchmarked corrections in simulation: multiple scattering and radiative corrections and Levchuk

- GEM—Gaseous Electron Multiplier detector
- Extract coordinate data of electron tracks as they pass through
- To be installed in time for MOLLER commissioning



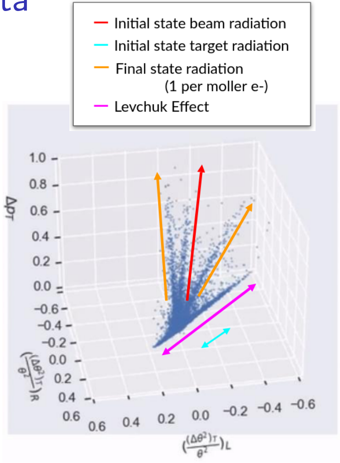
Extracted kinematics from GEM data

ρ: 1 / momentum
ϕ: Plane of scatter
$\Delta\theta$: Angular offset from Møller stripe
θ: Scattering angle

$$\begin{aligned} \rho &= f(\Delta\bar{y}, y) \\ \Phi &= f(\Delta\bar{y}, y) \\ \Delta\theta &= f(\Delta\bar{y}, y, x_1) \\ \theta &= f(\Delta\bar{y}, y) \end{aligned}$$

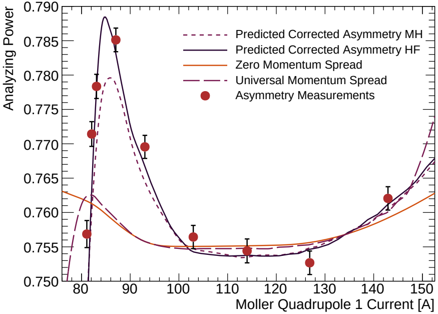
These are functions of the preferred set of values derived from chamber coordinates and various coefficients $m_1, m_2, b_1, b_2, A, B, C, D$ derived from fitting functions

$$\Delta\rho = \rho_{\text{beam}} - \rho_L - \rho_R$$
$$\theta_T^2 = \Delta\theta^2 + \theta^2$$



CREX Asymmetry Measurements

- Significantly better agreement at points of high asymmetry when using Hartree-Fock wavefunctions for Levchuk calculation in Monte Carlo.
- Reduces systematic uncertainty from 40% to 10%



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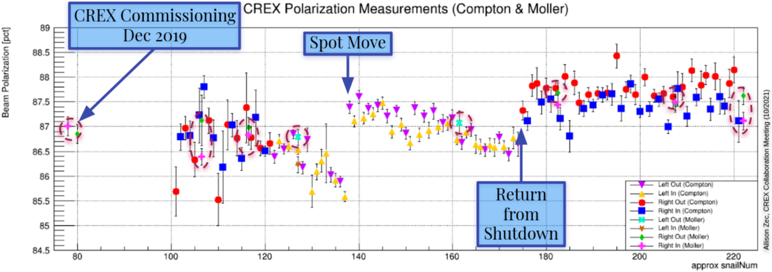
CREX Results —Møller/Compton Agreement

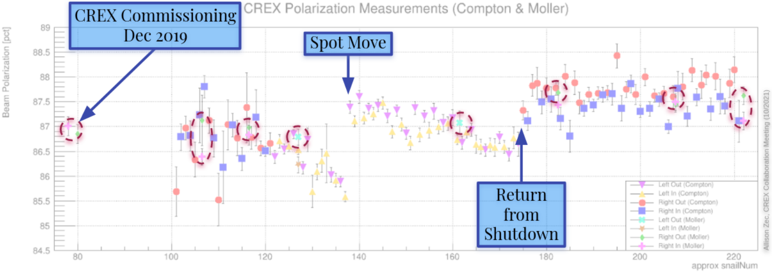

CREX Polarization Measurements (Compton & Moller)

CREX Commissioning
Dec 2019

Spot Move

Return
from
Shutdown

CREX Results —Møller/Compton Comparison



CREX Polarization Measurements (Compton & Moller)

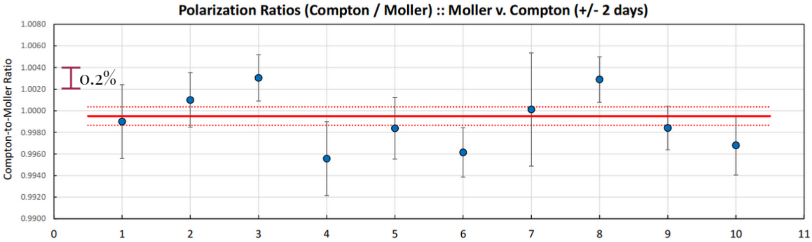
CREX Commissioning Dec 2019

Spot Move

Return from Shutdown

Allison Zec, CREX Collaboration Meeting (10/2021)

CREX Results —Møller/Compton Comparison (cont'd)



- Møller measurements compared to Compton measurements that occurred within ±48 hours [note: error bars based on stat error]
- Unprecedented level of agreement during CREX between the Compton and Møller polarimeters in Hall A.
- The mean Compton/Møller ratio was 0.9995 ± 0.0008; ratio consistent with 1 at the 0.1

Systematics from PREX2 and CREX

Polarimetry error dominated by systematic errors

- Largest error was foil polarization uncertainty, new review further constrains this
- Current dependence constrained by 2007 systematic studies

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

Systematics from PREX2 and CREX (Cont'd)

- PREX2: Beam orbit uncertainties, corrected by adding in additional position tracking
- CREX: Unexpected leakage current from high-current experiment in Hall-C

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

MOLLER Systematics Goals

Challenges:

- Ensuring target saturation
- Eliminating leakage currents during measurements
- **Current dependence systematic studies**

Uncertainty	CREX	MOLLER
$\langle A_{zz} \rangle$	0.16	0.14
Beam Trajectory	0.00	–
Foil Polarization	0.57	0.30
Dead Time	0.15	0.05
Charge Normalization	0.01	0.01
Leakage Currents	0.18	–
Laser Polarization	0.06	0.06
Accidentals	0.04	0.04
Current Dependence	0.50	0.20
Aperture Transmission	0.10	–
Null Asymmetry	0.22	0.05
Total	0.85	0.40

Thank you!

Questions

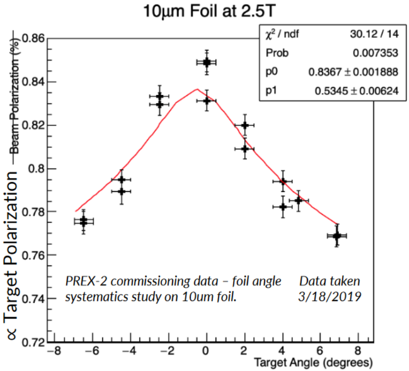
Comments

Møller Polarimetry Working Group: *Eric King, Donald Jones, Jim Napolitano, Paul Souder, Faraz Chahili, David Gaskell, William Henry and Kent Paschke.*

Target Alignment Backup Slide

Target Alignment – Plan

- Moller polarimeter target ladder has the ability to rotate.
- Foil magnetization is maximized when the foil plane plane is perpendicular to B-field.
  - ☆ Covered in Fe foil polarization publication.
- Systematic studies will be need to be run in order to determine foil alignment.
- Compare data to Stoner-Wolfarth model predictions.



PREX-2 commissioning data – foil angle systematics study on 10um foil.

Data taken 3/18/2019

Note: The y-axis label is "improperly" labeled; however, since Pbeam is constant this axis is still proportional

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