High Precision Electron Polarimetry

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Outline

- Motivations for Precision e-Polarimetry
- Desired Properties
- Polarimetry Techniques
  1. Mott
  2. Transmission
  3. Møller
  4. Compton
- Recent Developments & Results
- Future Possibilities
- Summary
Motivations

Spin polarized electrons have allowed us to:
- study the internal structure of nucleons
  - form factors
  - spin structure of nucleons
  - 3-D mapping of nucleons
- fundamental tests of QCD
  - Bjorken sum rule
  - GDH sum rule
- test of the SM in search of “New Physics”
  - Parity violating electron scattering (PVeS)

knowledge of the electron beam polarization is one of the major sources of uncertainty for this entire program.
PVeS: a Case Study

PVeS Experiment Summary

Precision PVeS made possible by decades of technical progress in:
- polarized sources,
- electron polarimetry
- nanometer beam stability,
- high power targets,
- low noise electronics & radiation hard detectors.

Future program requires sub-1% electron polarimetry

Figure: Courtesy of K. Paschke
Electron Polarimetry Desirables

- Large rates → rapid measurement cycle, shorter than the typical time over which polarization changes
- Uses the same beam (energy, current, location) as the experiment
- Large, well known and slowly varying analyzing power
- Continuous measurement, non-invasive to experiment
- Stable, highly polarized targets
- Target polarization easily measurable
- High efficiency detectors with well understood and stable acceptances
Techniques: Mott Polarimeters


Analyzing power based on the spin-orbit coupling between the electron’s spin and its motion in the nuclear Coulomb field.

eA cross section is given by

\[ \sigma(\theta) = I(\theta) [1 + S(\theta) \mathbf{P} \cdot \mathbf{n}] \]

\[ I(\theta) = \text{spin averaged cross section} \]

\[ S(\theta) = \text{Sherman function} \]

scattering of unpolarized electrons produces a net polarization

\[ P(\theta) = \frac{\sigma_{\uparrow}(\theta) - \sigma_{\downarrow}(\theta)}{\sigma_{\uparrow}(\theta) + \sigma_{\downarrow}(\theta)} = S(\theta) \mathbf{n} \]

polarized electrons produce a left-right asymmetry

Can be used to measure polarization transverse to the scattering plane
cross sections at lower beam energies, are very large, requiring very low-average beam currents and exceptionally thin targets.

Above ~10 MeV, the cross section is too small, and the scattering angle for maximum analyzing power is too close to 180°.
Mott Polarimeters

Mott polarimeters are routinely used with beam energies no greater than 100 to 120 keV but there are only two MeV-Mott polarimeters.

MeV Motts have advantages:
- smaller x-sections
- less plural scattering
- higher beam currents
- smaller analyzing power uncertainties
- better beam monitoring

JLab MeV-Mott

cross-ratio method

LR cross ratio defined as:
\[ r = \sqrt{\frac{N_1}{N_2}} \]

and asymmetry
\[ A_{LR} = \frac{1 - r}{1 + r}. \]

The polarization is
\[ P = \frac{1}{|S_{eff}(\theta)|} \left[ A_{LR} \hat{y} - A_{UD} \hat{x} \right] \]

Cross-ratio method cancels false asymmetries from detector efficiency, beam current, target thickness and solid angle.
Effort underway to improve uncertainty of MeV Mott to < 1%

strategy: more accurate modeling of the Sherman function extrapolation to zero thickness using GEANT4

published absolute uncertainty 1.1%

ΔP dominated by ΔS

Uncertainty in extrapolation to single atom (d=0) dominates ΔS
Transmission Polarimeters

- Polarized electrons transfer polarization to photons

- Measure the asymmetry in transmission of photons through iron magnet for opposite polarity.

- small (0.1% - 5%) analyzing power
- rapid polarization measurement at low energies
- requires cross calibration with other polarimeters

Used at MIT-Bates and Mainz for rapid, precise relative polarization measurements.
Møller Polarimeters

Møller scattering: $e^- + e^- \rightarrow e^- + e^-$ target: Fe (or Fe-alloy) foils, polarized by external B field

Analyzing power: exactly calculable in QED independent of Energy very large at 90° CM angle for longitudinally pol. electrons

Target polarization: low field along the plane on Fe/Fe-alloy (large uncertainty) very strong perpendicular field on pure Fe foils, saturates (smaller uncertainties)

“work horse” for fixed target experiments, used from 100 MeV - 50 GeV

Rapid measurements, but, operates only at low currents and is invasive

B. Wagner NIM A294, 541 (1990)
L.G. Levchuk (1992) - intrinsic momenta of the target electrons could have a significant affect on asymmetries measured in Møller polarimeters. Effect is largest in devices with very small acceptance or very high angular resolution.

“Levchuk effect” makes some of the old results unreliable. Newer polarimeters designed to minimize the uncertainty due to Levchuk effect.

For example: The JLab Hall-C Møller polarimeter

- moderate acceptance minimizes Levchuk effect (still a non-trivial contribution)
- pure Fe foil with 3-4 T superconducting magnet
- 0.25% target polarization uncertainty ([NIM A462, (2001) 382])

Figure: Courtesy of D. Gaskell (JLab)
• 2 quadrupole design maintains constant tune at detector plane (energy independent acceptance)

• collimation and coincidence detection provides clean signal
Precision Møller Polarimetry

Hall-C Møller systematic uncertainties (for QWeak run-2)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
<th>dA/A (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam position x</td>
<td>0.5 mm</td>
<td>0.17</td>
</tr>
<tr>
<td>Beam position y</td>
<td>0.5 mm</td>
<td>0.28</td>
</tr>
<tr>
<td>Beam direction x</td>
<td>0.5 mr</td>
<td>0.10</td>
</tr>
<tr>
<td>Beam direction y</td>
<td>0.5 mr</td>
<td>0.10</td>
</tr>
<tr>
<td>Q1 current</td>
<td>2% (1.9 A)</td>
<td>0.07</td>
</tr>
<tr>
<td>Q3 current</td>
<td>2.5% (3.25 A)</td>
<td>0.05</td>
</tr>
<tr>
<td>Q3 position</td>
<td>1 mm</td>
<td>0.10</td>
</tr>
<tr>
<td>Multiple scattering</td>
<td>10%</td>
<td>0.01</td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>10%</td>
<td>0.33</td>
</tr>
<tr>
<td>Collimator positions</td>
<td>0.5 mm</td>
<td>0.03</td>
</tr>
<tr>
<td>Target temperature</td>
<td>100%</td>
<td>0.14</td>
</tr>
<tr>
<td>B-field direction</td>
<td>2°</td>
<td>0.14</td>
</tr>
<tr>
<td>B-field strength</td>
<td>5%</td>
<td>0.03</td>
</tr>
<tr>
<td>Spin polarization in Fe</td>
<td>100%</td>
<td>0.25</td>
</tr>
<tr>
<td>Electronic D.T.</td>
<td>100%</td>
<td>0.04</td>
</tr>
<tr>
<td>Solenoid focusing</td>
<td>100%</td>
<td>0.21</td>
</tr>
<tr>
<td>Solenoid position (x,y)</td>
<td>0.5 mm</td>
<td>0.23</td>
</tr>
<tr>
<td>Additional point-to-point</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>High current extrapolation</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.85</td>
</tr>
</tbody>
</table>

Some uncertainties larger because of the low energy (1 GeV) operation during QWeak

total uncertainty < 1% for the recent QWeak experiment.

At higher energies the total uncertainty is expected to be ~0.45%

Only issues:
works only at low currents, invasive to the experiment

Table courtesy of D. Gaskell (JLab)
Compton Polarimeters

\[ \vec{e} + \gamma \rightarrow e + \gamma \]

Exploits the spin-dependence of the polarized electron-photon scattering cross section.

Longitudinal asymmetry increases with photon and electron energy.

Transverse polarization can be measured from the azimuthal angle dependence of the asymmetry (as an up-down asymmetry).

QED \sim 100\%
Exploits the spin-dependence of the polarized electron-photon scattering cross section.

- Analyzing power strongly energy dependent: detector thresholds and non-linearities can be an issue for photon detector
- Small asymmetry at low energies (expect lower precision at low energies)
- Negligible theoretical error: higher order corrections < 0.1% at 1 GeV increases slowly with energy (NPB 540 (1999) 58)
- Rapid: \( T \propto \frac{1}{(k^2E^2)} \), non-invasive polarimeter
- 2-in-1 polarimeter: electron and photon provide independent measurements
  - scattered electrons very close to beam at low energies
  - photon detection requires knowledge of resolution function

Compton polarimeters - used over a wide range of energies (800 MeV - 50 GeV) and a variety of accelerators - SLAC, HERA, LEP, NIKHEF, MIT-Bates & JLab
Integrating electron and photon detectors

$\delta P/P = 0.5\%$, best reported precision of all Compton polarimeters (Ann. Rev. Nuc. Part. Sci. 51, (2001) 345)

Conventional wisdom: high precision Compton polarimetry limited to very high energies.
**JLab Compton Polarimeters**

Halls A and C have similar Compton Polarimeters

- **4-dipole chicane:** deflect beam vertically
- **Laser system:** Fabry-Perot cavity pumped by CW laser (green 532 nm), few kW of stored laser power
- **Photon detector:** PbWO4 or GSO - operated in integrating mode
- **Electron detector:** micro-strip detector

Bucking conventional wisdom, in recent years, JLab Compton polarimeters have demonstrated sub-1% uncertainty at low energies
Some Recent Results

Hall A Compton Photon Calorimeter results

New GSO detector and Energy weighted asymmetry (led by Carnegie Mellon)

\[ E^\gamma = LT \int_0^{E_{\text{max}}} \varepsilon(E) E \frac{d\sigma}{dE} (E) \left( 1 \pm P_\gamma P_\gamma A_\gamma(E) \right) dE \]

\[ A_{\text{Exp}} = \frac{E^+ - E^-}{E^+ + E^-} \]

Energy weighted asymmetry \( \Rightarrow \) **no threshold** (analyzing power well understood)

**less sensitive** to knowledge of resolution function

**Challenge:** understanding detector non-linearities

(used an LED pulser system to study non-linearities)

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D. Gaskell (PaVi14) and G. Franklin (EIC14)
Some Recent Results

Hall A Compton Photon Calorimeter results

New GSO detector and Energy weighted asymmetry (led by Carnegie Mellon)

Photon detector systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic Errors</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Polarization</td>
<td>0.80%</td>
</tr>
<tr>
<td>Signal Analyzing Power:</td>
<td></td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>0.30%</td>
</tr>
<tr>
<td>Energy Uncertainty</td>
<td>0.10%</td>
</tr>
<tr>
<td>Collimator Position</td>
<td>0.05%</td>
</tr>
<tr>
<td>Analyzing Power Total Uncertainty</td>
<td>0.33%</td>
</tr>
<tr>
<td>Gain Shift:</td>
<td></td>
</tr>
<tr>
<td>Background Uncertainty</td>
<td>0.31%</td>
</tr>
<tr>
<td>Pedestal on Gain Shift</td>
<td>0.20%</td>
</tr>
<tr>
<td>Gain Shift Total Uncertainty</td>
<td>0.37%</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>0.94%</td>
</tr>
</tbody>
</table>

Systematic uncertainty < 1%, even with large contribution from laser polarization

Excluding laser polarization, total uncertainty < 0.5%

D. Gaskell (PaVi14) and G. Franklin (EIC14)

Some Recent Results

Hall C Compton results (Determining laser polarization)

Polarization inside cavity monitored using transmitted or reflected light

Transfer function translates polarization of transmitted light to polarization in the cavity.

Optical isolation through use of beam polarization, this isolation fails to the degree that light is not perfectly circular at the reflecting surface.

Possible complications:
- vacuum stress
- heating
- alignment variations

Overall systematic error on laser polarization in cavity ~ 0.1%

D. Gaskell (PaVi14) & K. Paschke (PSTP 13)
Some Recent Results

Hall C Compton Electron Detector

First use of diamond micro-strip detector as a tracking detector
desirable for its radiation hardness
**bonus:** insensitive to synchrotron radiation

Other key elements

- Low capacitance, 6 layer, flexible cable (KADFLX Inc)
- QWAD QWeak Amplifier Discriminator
  low noise pre-amplifier, shaper and discriminator chain, built by TRIUMF
- FPGA based pipeline DAQ

Sunday, October 19, 14
2 parameter fit (polarization and Compton edge) to the asymmetry spectrum. Results show that:
★ Strip width (resolution) is important
★ Zero-crossing must be in acceptance to constrain the fit well
Electron detector was used all throughout the QWeak experiment for continuous, non-invasive monitoring of polarization at full beam current.
**Preliminary Systematic Uncertainties**

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Uncertainty</th>
<th>ΔP/P (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Polarization</td>
<td>0.2%</td>
<td>0.2</td>
</tr>
<tr>
<td>Dipole field strength (0.0011 T)</td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Beam energy 1 MeV</td>
<td></td>
<td>0.09</td>
</tr>
<tr>
<td>Detector Longitudinal Position 1 mm</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Detector Rotation (pitch) 1 degree</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Asymmetry time averaging 0.15%</td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td>Secondaries (trigger) -</td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>DAQ – dead time, eff. -</td>
<td></td>
<td>0.5*</td>
</tr>
<tr>
<td>Other</td>
<td>?</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>0.60*</td>
</tr>
</tbody>
</table>

“Other” systematic uncertainties still under investigation, but final precision expected to be **better than 1%**

★ DAQ-related systematics come from combination of complicated trigger, and variation of strip efficiency: can be reduced if simpler trigger can be used
During QWeak experiment: **Møller** measurement @ 1 µA  
**Compton** measurement @ 180 µA

**Cross calibration @ 4.5 µA**

**Compton:** smaller signal to noise ⇒ larger sensitivity to noise  
**Møller:** extra corrections for beam heating and dead time corrections

**Excellent agreement**
Møller - Compton Cross Calibration

Looking for beam current dependence of polarization

Compare low current Compton & Møller with high current Compton immediately before and after the cross calibration.

No beam current dependence found
Atomic Hydrogen Möller Polarimeter


- 100% target polarization
- negligible error on target polarization
- no Levchuk effect
- thin target ⇒ no dead time
  but sufficient rates for 1% stat. in 10 min @ 100 µA
- non-invasive, continuous high current measurement

Brute force polarization of atomic H with 8T field and 300 mK temperature density $\sim 6 \times 10^{16}$ H/cc

R&D underway at Mainz and W&M
Spin-light Polarimeter


Exploit the spatial asymmetry of synchrotron radiation emitted by longitudinally polarized electrons in a magnetic field.

Relative longitudinal polarimetry may be feasible
Transverse polarimetry much less challenging

verified at the VEPP-4 storage ring; Belomestnykh et al., NIM 227, 173 (1984)

• continuous, non-invasive, rapid polarimetry
• small energy dependent asymmetry
• needs position sensitive x-ray detector
• differential detector to mitigate beam motion related false asymmetry
• large SR load on beamline
• several technical challenges

R&D and simulations underway
Summary

• Precision electron polarimetry has been at the forefront of a large physics program that ranges from nucleon structure to searches for new physics.

• A complementary set of polarimetry techniques have been developed such as Mott, Møller and Compton.

• All of these methods are being pushed to ever higher precision.

• The only way to achieve the desired higher precision in the upcoming physics program is to use multiple methods simultaneously.

• A few new alternative methods have also been proposed and R&D is ongoing to demonstrate their feasibility.