Electron Beam Polarimetry at JLab

- Experiments using polarized electrons at JLab
- JLab polarized beam
- Polarimetry at JLab:
  - Mott polarimetry
  - Møller polarimetry
  - Compton polarimetry
- Special challenges of new experiments
- Possible improvements in polarimetry (outlook)
**SIMULTANEOUS COMPLEMENTARY EXPERIMENTS**

**HALL A**
Pair of identical High Resolution Spectrometers (HRS$^2$)

**HALL B**
CEBAF's Large Acceptance Spectrometer (CLAS) and Bremsstrahlung Photon Tagger

**HALL C**
High Momentum Spectrometer (HMS) and Short Orbit Spectrometer (SOS)
More than half of all experiments in Halls A/B/C are using the longitudinal beam polarization:

**Single Spin: Parity Violation Experiments**

- Parity violation
- \( e^- p, A \rightarrow e^- p, A \) elastic: formfactors HAPPEX, G0, SM QWEAK
- \( e^- A \rightarrow e^- A \) elastic: nuclear physics \(^{208}\)Pb
- \( e^- p \rightarrow e^- X \) inelastic: SM

\[ A_{obs} \propto P_{beam} \times A_{reaction} \]

**Double Spin Experiments**

- \( e^- p \rightarrow e^- \vec{p} \) elastic: formfactors \( G_E^p \)
- \( e^- \vec{N} \rightarrow e^- N \) elastic: formfactors \( G_E^n \)
- \( e^- \vec{N} \rightarrow e^- X \) inelastic: structure functions, GDH

\[ A_{obs} \propto P_{beam} \times P_{target} \times A_{reaction} \]
\[ A_{obs} \propto P_{beam} \times A_{recoil} \times A_{reaction} \]

Typically, \( \sigma P_{beam}/P_{beam} < \sigma P_{target}/P_{target} \)
Features of CEBAF Operations

- Beam energy 0.8 - 6.0 GeV, current 0.01 - 100 μA
- 3 Halls are running simultaneously with different beam energies and currents
  - The beam may interfere with beams to other halls
  - Spin precession in different halls is different
- Operations, invasive for other halls are better avoided
Electron Beam Polarimetry at JLab

Continuous Electron Beam Accelerator Facility

Gain switched diode lasers
499 MHz, $\Delta \phi = 120^\circ$

Pockels cell

Gun

0.4 GeV linac
(20 cryomodules)
1497 MHz

45 MeV injector
(2 1/4 cryomodules)
1497 MHz

RF separators
499 MHz

Double sided septum
Features of CEBAF Injector

- Strained GaAs provides $\mathcal{P} \sim 80\%, I < 80 \, \mu A$
- 30Hz helicity flip
- 2 ways to attenuate the beam:
  - Laser light attenuation
  - Electron chopper slit
- Opposite beam polarization in some halls
- Laser dark current $\Rightarrow$ leak of a wrong laser through the slit

The beam polarization may be diluted by a leak through from another hall beam.

- Current dependent
- Depends on the other hall operation

The beam polarization may depend on the current
Electron Beam Polarimetry at JLab

CEBAF Polarization dependence on laser phase

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E. Chudakov
Electron Polarimetry at JLab

Injector

- Mott polarimeter at 5 MeV, $\sigma_{syst} \sim 3\% \Rightarrow 1\%$ (?)

Hall A

- Møller polarimeter, 2 arm 0.8-6.0 GeV, $\sigma_{syst} \sim 3\%$
- Compton polarimeter $>2$ GeV, $\sigma_{syst} \sim 1-2\%$

Hall B

- Møller polarimeter, 2 arm 0.8-6.0 GeV $\sigma_{syst} \sim ?$

Hall C

- Møller polarimeter, 2 arm 0.8-6.0 GeV $\sigma_{syst} \sim 1.5(0.5)\%$

- Description of the polarimeters
- Cross-calibration of the polarimeters
0.1-10 MeV: $e^- \uparrow + Au \rightarrow e^- + Au$

Analyzing power - Sherman functions $\sim 1-3\%$:

- Dirac equation on a pure Coulomb potential
- Nucleus thickness: phase shifts of scat. amplitudes
- Spin rotation functions
- Other: electron screening, radiative corrections etc

- Multiple and plural scattering
- No energy loss should be allowed
- Single arm - backgrounds are important

Typical target: Au foils $0.01-1.00\mu m$ thick $\Rightarrow 0$ thickness
Measurements 5 MeV and ~ 1 μA

Careful shielding
Veto detectors
Energy measured

\[ \sigma(\mathcal{P})/\mathcal{P} = 1\%(\text{Sherman}) \oplus 0.5\%(\text{other}) \] (unpublished)

- Low current measurement
- Invasive for all 3 halls at CEBAF
\[
\bar{e}^- + e^- \rightarrow e^- + e^- \quad \text{QED (unpolarized: Møller, 1932)}.
\]

\[
\frac{d\sigma}{d\Omega_{CM}} = \frac{d\sigma_0}{d\Omega_{CM}} \cdot (1 + \sum_{i=X,Y,Z} (A_{ii} \cdot \mathcal{P}_{\text{targ} i} \cdot \mathcal{P}_{\text{beam} i}))
\]

\[
\frac{d\sigma_0}{d\Omega_{CM}} \approx \frac{r_e^2}{4\gamma^2} \cdot \left(\frac{4 - \sin^2\theta_{CM}}{\sin^2\theta_{CM}}\right)^2 \quad \text{in CM, or}
\]

\[
\frac{d\sigma_0}{d\Omega} \mid_{\theta_{CM}=90^\circ} \approx 176 \text{ mbarn/ster} \quad \text{in LAB}
\]

**Asymmetry:**

\[
A_{ZZ} = -\frac{\sin^2\theta_{CM} \cdot (7 + \cos^2\theta_{CM})}{(3 + \cos^2\theta_{CM})^2}
\]

\[
A_{XX} = -\frac{\sin^4\theta_{CM}}{(3 + \cos^2\theta_{CM})^2}, \quad A_{YY} = -A_{XX}
\]

At \(\theta_{CM} = 90^\circ\) \(A_{ZZ} = 7/9, \quad A_{XX} = -A_{YY} = -1/9\)
Møller Polarimetry

Advantages:

- High analyzing power at $\theta_{CM} = 90^\circ$ $A_{ZZ} = 7/9$
- $\frac{dA_{ZZ}}{d\theta_{CM}}|_{\theta_{CM}=90^\circ} = 0$ - small systematics
- Large cross-section
- 2 particles in the final state with $E \sim E_0/2$: coincidence eliminates backgrounds

Disadvantages mainly come from the target choice of magnetized ferromagnetics:

- Relatively low polarization $\sim 8\%$
- Beam current limit ($\sim 1 \, \mu A$) due to target heating
- Systematic errors on the target polarization
- Kinematic distortion of scattering on K,L-shell electrons ("Levchuk effect")
So far, Möller polarimeters used ferromagnetic foils, magnetized in an external field, for the target.

Features of the Fe group:

- **3D shell only partially filled**: $3d^6$ - 4 electrons missing
- Overlap of the wave-functions with neighbour atoms and electron gas: "exchange force" aligning spins on $3d^6$ in the SAME direction. In Fe atom, $\; 2.22 \; e^- \; $ aligned at saturation
- "Quenching" - orbital momentum contribution cancelled, magnetization is caused by the spins
- Magnetization drops with temperature and comes to 0 at $T_c \approx 800 \; ^\circ C$

Materials used:

- Pure Fe - best understood and studied
- Alloys, like permendur: Fe(49%), Co(49%), V(2%) - more easily magnetized
Ferromagnetic Targets: Polarization

\[ P_{foil} = B_{foil} \cdot \frac{g'-1}{2\pi g'} \cdot \frac{1}{N_e \mu_B} \], where

- \( B_{foil} \) - magnetic field in the foil
- \( g' = 1.900 \pm 0.005 \) - spin/orbital correction, supermendur
- \( g' = 1.919 \pm 0.002 \) - spin/orbital correction, Fe
- \( N_e = \rho \cdot A\nu \cdot Z/A \) - electron density
- \( \mu_B \) - Bohr magneton

Magnetization in an external field

Boundary conditions on a surface:

- \( B_{perpend} = \text{const} \) and \( H_{parallel} = \text{const} \)

Two ways to magnetized the target foil are used:

- \( B_{parallel} \sim 100 - 300 \text{ Gs} \), foil at \( \sim 20^\circ \)
- \( B_{perp} \sim 3 - 4 \text{ T} \) “brute force”
Foil in “Weak” Field

- Used everywhere, except in Hall C at JLab
- External $B \sim 80 - 600$ Gs, parallel to the beam
- Target foil 10-100 $\mu$m thick at $\sim 20^\circ$ to the beam
- Important: annealing, mechanical treatment

The magnetic flux through the foil can be measured with a pickup coil wound around the foil, and:

$$\Phi = \int \varepsilon(t) dt, \quad B_{foil} = \Phi/(\text{width} \cdot \text{thick}) = \Phi \cdot \rho \cdot \text{length/weight}$$

Measuring $\Phi$: different methods.

Hall A: constant field, removing the foil from the coil

$$P_{foil} = \frac{g'-1}{2\pi g'} \cdot \frac{1}{\mu_B} \cdot \Phi_{foil} \cdot \frac{\text{length} \cdot A}{\text{weight} \cdot Av \cdot Z}$$

- Measured: an average over a large surface
- Foil's non-uniformity
- At the end, different foils compared give $\sigma(P)/P \sim 3\%$
Foils in Saturating Fields

- Used in Hall C at JLab
- External $B \sim 4 \, T$, parallel to the beam
- Target foils $4-10 \, \mu m$ thick perpendicular to the beam
- Important: annealing, mechanical treatment

The foil should be fully saturated.

Attempts to measure the magnetization with the Kerr effect: rotation of the polarization plane of the reflected light.

Problems:

- Rotation angle is a fraction of a degree only
- Field on the surface and in the bulk may be different (band theory)

Good relative measurements have been done: saturation at $2.8 \, \text{Tm}$, temperature dependence.

The magnetization value was taken from literature.

Claim: $\sigma(P)/P \sim 0.25\%$
Møller Polarimeter Optics

- Single arm used with pulsed beams (SLAC)
  BG~10-30% from radiative Mott
- Double arm - practically no background

Optic selection:

- Use Møller $\theta$-p correlation: quad focussing
- Use Møller $E \sim E_0/2$: dipole deflection
- Select an acceptance of $80^\circ < \theta_{CM} < 100^\circ$ or so
2 quadrupole magnets and many movable collimators.
2-3 quadrupole magnets and a dipole.
Levchuk Effect

Noticed in 1994. Many polarimetry measurements done before were wrong by 5-10%!

Main points:

- Scattering on K-shells distorts the $\theta$-$p$ correlation
- A strong optical focussing in exploiting the $\theta$-$p$ correlation
- Acceptance of electrons, scattered on K-shells (unpolarized) and D-shells (polarized) is different ($K<D$):
  the effective target polarization is larger!

A correction is needed, or the optics should minimize the effect (Hall A).
\[ A_{\text{obs}} = \frac{N_{+} - N_{-}}{N_{+} + N_{-}} \approx \overline{A_{ZZ}} P_{\text{targ}} P_{\text{beam}} \cdot \kappa_{\text{transv}} \kappa_{BG} \kappa_{DT} \kappa_{\text{Lev}} + \Delta_{\text{false}} \]

\[ \kappa = (1 + \Delta) \approx 1 \] - corrections

Statistical error: ±1% per ~2 min

- \( \overline{A_{ZZ}} \sim 0.758 - 0.772 \) - simulation

- \( P_{\text{targ}} = P_{\text{foil}} \cdot \cos \alpha_{\text{targ}} \) - target polarization
  - \( P_{\text{foil}} \) - magnetization measurement
  - \( \cos \alpha_{\text{targ}} \) target-beam angle \( \sim 20^\circ \& 160^\circ \)

- \( \Delta_{\text{transv}} \) influence of transverse polarization,
  Measuring at \( \alpha_{\text{targ}} \sim 25^\circ \& 155^\circ \) helps

- \( \Delta_{BG} \) non–polarized background, \( \sim 30 - 70\% \) in single arm, depending on \( E_{\text{beam}} \), low in coincidence.
  Accidental coincidences are subtracted.

- \( \Delta_{DT} \) dead time of electronics

- Levchuk effect

- Observed fluctuations, (beam current?)

Total systematic error: 3.4%
### Møller Hall C: Systematic Errors

<table>
<thead>
<tr>
<th>source</th>
<th>uncertainty</th>
<th>A error</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam position X</td>
<td>0.5 mm</td>
<td>0.15%</td>
</tr>
<tr>
<td>beam position Y</td>
<td>0.5 mm</td>
<td>0.03%</td>
</tr>
<tr>
<td>beam direction X</td>
<td>0.15 mr</td>
<td>0.04%</td>
</tr>
<tr>
<td>beam direction Y</td>
<td>0.15 mr</td>
<td>0.04%</td>
</tr>
<tr>
<td>current Q1</td>
<td>2%</td>
<td>0.10%</td>
</tr>
<tr>
<td>current Q2</td>
<td>1%</td>
<td>0.07%</td>
</tr>
<tr>
<td>position Q2</td>
<td>1 mm</td>
<td>0.02%</td>
</tr>
<tr>
<td>multiple scattering</td>
<td>10 %</td>
<td>0.12%</td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>10 %</td>
<td>0.30%</td>
</tr>
<tr>
<td>position collimator</td>
<td>0.5 mm</td>
<td>0.06%</td>
</tr>
<tr>
<td>target temperature</td>
<td>50 %</td>
<td>0.05%</td>
</tr>
<tr>
<td>direction of B-field</td>
<td>2°</td>
<td>0.06%</td>
</tr>
<tr>
<td>value of B-field</td>
<td>5%</td>
<td>0.03%</td>
</tr>
<tr>
<td>target polarization</td>
<td></td>
<td>0.25%</td>
</tr>
<tr>
<td>dead time</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>beam current</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>0.25%</td>
</tr>
</tbody>
</table>
Compton Polarimetry

\[ \bar{e}^- + (h\nu)_\sigma \rightarrow e^- + \gamma \quad \text{QED.} \]

\[ k(\text{GeV}) \]

1

10^-1

0 100 200 300
\( \theta_\gamma (\mu\text{rad}) \)

\[ k_{\text{max}} = 2.12\text{GeV} \quad E = 12\text{GeV} \quad k = 1.165\text{eV} \]

\[ k_{\text{max}} = 1.00\text{GeV} \quad E = 8\text{GeV} \quad k = 1.165\text{eV} \]

\[ k_{\text{max}} = 0.27\text{GeV} \quad E = 4\text{GeV} \quad k = 1.165\text{eV} \]

Compton edge:
\[ k_{\text{max}}' \approx 4y\gamma^2k, \]
\[ y = \frac{1}{1+4k\gamma/m} \sim 1 \]

Asymmetry:
\[ A \propto kE, \]
Max asymmetry:
\[ A_{\text{max}} \approx \frac{1-y^2}{1+y^2}, \]
Compton Polarimetry

- Detecting the $\gamma$ at 0 angle
- Detecting the $e^-$ with an energy loss
- Strong $\frac{dA}{dk'}$ - good energy resolution for photons
- Photon energy cutoff
- Time needed for a measurement:
  \[ T \propto \frac{1}{(\sigma \cdot A^2)} \propto \frac{1}{k^2} \times \frac{1}{E^2} \]
- Small crossing angle needed
- Non-invasive measurement

Very good polarimetry at high energy or/and high current (storage rings)

August 13, 2004  
E.Chudakov  
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Compton Polarimeter in Hall A

- Laser Nd:YAG 230 mW, $E_{h\nu} = 1.165$ eV, $E\lambda = 1064$ nm
- Monolithic 85 cm Fabry-Pérot cavity: $G \sim 8000$, 1500 W, $P \sim 99.3\%$
- Crossing angle 23 mrad
- Chicane of 4 dipoles for the beam
- Photon detector at $0^\circ$ $2 \times 2 \times 23$ cm$^3$ PbWO $5 \times 5$
- Electron detector Si $\mu$-strip $48 \times 600 \mu$m $\times 4$ planes
The electron detector is used for calibration. Limitations:

- $\mu$-strip pitch $\Rightarrow \sigma_E \sim 5$ MeV
- Low energy - acceptance loss

Good agreement with the observed spectrum

Gain drift correction
## Compton Errors (Hall A)

Conditions: beam 4.5 GeV, 40 μA, 40 min run

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asymmetry</td>
<td></td>
</tr>
<tr>
<td>Statistical</td>
<td>0.80%</td>
</tr>
<tr>
<td>Position and angle</td>
<td>0.30%</td>
</tr>
<tr>
<td>Background</td>
<td>0.05%</td>
</tr>
<tr>
<td>Dead time</td>
<td>0.10%</td>
</tr>
<tr>
<td>Cuts</td>
<td>0.10%</td>
</tr>
<tr>
<td>Light</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>0.50%</td>
</tr>
<tr>
<td>Analyzing power</td>
<td></td>
</tr>
<tr>
<td>Response function</td>
<td>0.45%</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.60%</td>
</tr>
<tr>
<td>Pile up</td>
<td>0.45%</td>
</tr>
<tr>
<td>Rad. correction</td>
<td>0.26%</td>
</tr>
<tr>
<td>Total systematic</td>
<td>1.15%</td>
</tr>
<tr>
<td>Total</td>
<td>1.40%</td>
</tr>
</tbody>
</table>
Comparison of Different Polarimetry Techniques

A comparison of polarimetry methods at 4.5 GeV.

<table>
<thead>
<tr>
<th>Type</th>
<th>$T_{1%}$ Stat</th>
<th>Syst. error</th>
<th>beam $\mu$A</th>
<th>Invasive?</th>
<th>Energy GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mott</td>
<td>5 min</td>
<td>3(1)%</td>
<td>1</td>
<td>yes</td>
<td>0.005</td>
</tr>
<tr>
<td>Moller A</td>
<td>2 min</td>
<td>3%</td>
<td>0.3-1.0</td>
<td>yes</td>
<td>0.8-6</td>
</tr>
<tr>
<td>Moller C</td>
<td>5 min</td>
<td>1.5(0.5)%</td>
<td>0.5-1.0</td>
<td>yes</td>
<td>0.8-6</td>
</tr>
<tr>
<td>Compton</td>
<td>40 min</td>
<td>1.1%</td>
<td>20-100</td>
<td>no</td>
<td>$&gt;2$</td>
</tr>
</tbody>
</table>

Cross-calibration of polarimeters

One laser: DC
Slits open
Spin rotation

August 13, 2004 E.Chudakov
### Future experiments at JLab

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Syst. err without pol</th>
<th>Polar. error</th>
<th>Stat. error</th>
<th>Energy GeV</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}\ \rho_s$</td>
<td>0.6%</td>
<td>2.0%</td>
<td>2.2%</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>$^{208}\text{Pb}\ \text{n-skin}$</td>
<td>0.5%</td>
<td>1.0%</td>
<td>3.0%</td>
<td>0.85</td>
<td>?</td>
</tr>
<tr>
<td>$\text{eP } sin^2\theta_W$</td>
<td>2.4%</td>
<td>&lt;1.4%</td>
<td>2.8%</td>
<td>1.16</td>
<td>?</td>
</tr>
<tr>
<td>DIS $sin^2\theta_W$</td>
<td>0.3%</td>
<td>&lt;1.0%</td>
<td>0.8%</td>
<td>10.0</td>
<td>distant</td>
</tr>
</tbody>
</table>

For 2 experiments at low energy there is no clear way to each the accuracy needed using the existing polarimeters.

- Compton: uncomfortably low energy
- Moller with Fe target: low current

### Improvements Considered

- Compton: green laser (still marginal performance)
- Moller: 100% polarized atomic hydrogen target
Møller Polarimetry with Atomic Hydrogen Targets

Advantages:

- 100% electron polarization
- hydrogen target: no Levchuk effect, low background
- high beam current

Goal:

\[ \sim 0.5\% \text{ systematic error} \]

Atomic hydrogen ground state: \( \vec{\mu}_H \sim \vec{\mu}_e \)

Stored in a trap at \( \sim 300 \text{ mK} \):

- Z: solenoid field \( B_{max} \sim 5 - 8 \text{ T} \), energy \( \sim \vec{\mu} \cdot \vec{B} \)
- R: copper cylinder \( d \sim 3 \text{ cm} \), superfluid He film
- Density \( \sim 3 \cdot 10^{15} \text{ H/cm}^3 \)
- Polarization \( \sim 1 - \mathcal{P} \sim \exp\left(\frac{-2\vec{\mu}B}{kT}\right) \sim 10^{-15} \),
  hyperfine interaction: \( \sim 1 - \mathcal{P} \sim 10^{-6} \)
- Lifetime: recombination (3-body coll., surfaces) \( > 1000 \text{ sec} \)
- Self-cleaning time \( \sim 2 \text{ msec} \)
- Filling the cell: several minutes

Statistical accuracy 1% in \( \sim 30 \text{ min} \) at 30 \( \mu \text{A} \)
Conclusion

- Various polarimetry techniques are used in JLab
- Polarimetry errors become the dominant one for the planned parity violation experiments
- An accuracy of $\sim 1.5\%$ is achieved at 2-6 GeV
- New methods are considered for improving the accuracy in the full range of CEBAF 0.8-6 GeV. Using of atomic hydrogen may provide a superb error of $\sim 0.5\%$