Møller Polarimetry on Atomic Hydrogen

E.Chudakov$^1$

$^1$JLab

PAVI11, Roma, 2011 Sept 5-9
Outline

1. Motivation for precise polarimetry

2. Møller Polarimetry

3. Møller with Atomic Hydrogen Target
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3 Møller with Atomic Hydrogen Target
JLab is an excellent facility for PV experiments

**PV at 6 GeV**
- High polarization > 85%
- High beam current < 100µA
- Low noise beam

Measured: $G_s$
Elastic $e\, p, e\, ^4He$ (HAPPEX, G0);
EW $e\, d$ DIS;
Running:
- Neutron skin $^{208}\text{Pb}$
  $e\, \text{Pb} \rightarrow e\, \text{Pb}$ (PREX)
- EW $e\, p \rightarrow e\, p$ (QWEAK)

**PV at 11 GeV**
- Same polarization
- Beam current < 100µA
- Comparable noise

Higher energies: $A \propto Q^2$ larger, but $\sigma_{elastic}$ suppressed by FF

Approved by PAC:
- PV Møller
- PV DIS (SoLID)
PV in electron scattering: JLab and Mainz

JLab is an excellent facility for PV experiments

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## 11 GeV JLab: Motivation for precise polarimetry

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Polarimetry becomes the dominant systematic errors

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0.4% - can it be done?

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Polarimetry becomes the dominant systematic errors

**0.4% - can it be done?**
Polarimetry Methods

1. **Compton Scattering**: State of the art 0.5% (45 GeV, SLAC), \( \sim 1\% \) (6 GeV, JLab)

2. **Møller Scattering**: \( \sim 1.0\% \) (6 GeV, Hall A JLab)

Electron polarization measurements: humbling experience history full of notorious errors of \( \sim 10\% \)

(SLAC - Levchuk effect; DESY - Compton calorimeter ... )
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Electron polarization measurements: humbling experience history full of notorious errors of \(\sim 10\%\)

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1% \(\Rightarrow\) 0.4% - a long way!
Compton Polarimetry

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

\[ \frac{\sigma_{\upsilon\upsilon} - \sigma_{\sigma\upsilon}}{\sigma_{\sigma\upsilon} + \sigma_{\upsilon\upsilon}} = A \cdot \mathcal{P}_b \mathcal{P}_t \]

\[ \tilde{e}^{-} + \tilde{e}^{-} \rightarrow e^{-} + e^{-} \text{ QED.} \]

Møller Polarimetry

- Rad. corrections to Born < 0.1%
- Detecting: \( \gamma \) (0\(^\circ\)), \( e^{-} E < E_{\circ} \)
- Strong \( \frac{dA}{dk} \) - good \( \sigma E_{\gamma} / E_{\gamma} \) needed
- \( A \propto kE \) at \( E < 20 \text{ GeV} \)
- \( T \propto 1/(\sigma \cdot A^2) \propto 1/k^2 \times 1/E^2 \)
- \( \mathcal{P}_{\text{laser}} \sim 100\% \)
- Non-invasive measurement

Syst. error 3\( \rightarrow \)50 GeV: \( \sim 1. \rightarrow 0.5\% \)

- Rad. corrections to Born < 0.3%
- Detecting the \( e^{-} \) at \( \theta_{CM} \sim 90^\circ \)
- \( \frac{dA}{d\theta_{CM}} |_{90^\circ} \sim 0 \) - good systematics
- Beam energy independent
- Coincidence - no background
- Ferromagnetic target \( \mathcal{P}_T \sim 8\% \)
  - \( \langle I_B \rangle < 5 \mu A \text{ (heating)} \)
  - Levchuk effect
  - Low \( \mathcal{P}_T \Rightarrow \text{dead time} \)
  - Syst. error \( \sigma(\mathcal{P}_T) > 0.4\% \)

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Important features of Electron Polarimetry

- Stat. error for a period of a possible polarization change ($\sim 1$ h)
- Stat. error and number of measurements $\Rightarrow$ handle on the systematics
- Systematic error
  - Does polarimetry use the same beam (energy, current, location) as the experiment?
  - Continuous or intermittent (invasive?)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Compton</th>
<th>Møller with Fe target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyzing power variation</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>Special beam (much lower current)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Continuous</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Target polarization</td>
<td>$\sim 100%$</td>
<td>$\sim 8%$</td>
</tr>
<tr>
<td>Target polarization measurable</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>
Proposed: 100%-polarized atomic hydrogen target ($\sim 3 \cdot 10^{16}$ atoms/cm$^2$).

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<tr>
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<tr>
<td></td>
<td></td>
<td>0.02%</td>
</tr>
<tr>
<td>Dead time</td>
<td>-</td>
<td>0.30%</td>
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<tr>
<td>Background</td>
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<tr>
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<tr>
<td>Low/high beam current</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Sum</td>
<td>0.51%</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>0.72%</td>
</tr>
<tr>
<td>Empirical fluctuations</td>
<td>-</td>
<td>0.50%</td>
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<tr>
<td></td>
<td></td>
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<td>Total</td>
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<td>0.80%</td>
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E.Chudakov                  |         |                  |
PAVI11 Roma                 |         |                  |
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Possible Breakthrough in Accuracy

Møller polarimetry with 100% polarized atomic hydrogen gas, stored in an ultra-cold magnetic trap.


Advantages:
- 100% electron polarization
  - very small error on polarization
  - sufficient rates $\sim \times 0.005$ - no dead time
  - false asymmetries reduced $\sim \times 0.1$
- Hydrogen gas target
  - no Levchuk effect
  - low single arm BG from rad. Mott ($\times 0.1$ of the BG from Fe)
  - high beam currents allowed: continuous measurement

Operation:
- density: $\sim 6 \cdot 10^{16}$ atoms/cm$^2$
- Stat. error at 100 $\mu$A: 1% in $\sim 10$ min
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Consider $H_1$ in $B = 7 \, T$ at $T = 300 \, mK$

At thermodynamic equilibrium:

$$n_+ / n_- = \exp(-2\mu B / kT) \approx 10^{-14}$$

Complication from hyperfine splitting:

Low energy

$$|b\rangle = |\downarrow \uparrow\rangle$$

$$|a\rangle = |\downarrow \uparrow\rangle \cdot \cos \theta - |\uparrow \downarrow\rangle \cdot \sin \theta$$

High energy

$$|d\rangle = |\uparrow \uparrow\rangle$$

$$|c\rangle = |\uparrow \downarrow\rangle \cdot \cos \theta + |\downarrow \uparrow\rangle \cdot \sin \theta$$

where $\tan 2\theta \approx 0.05 / B(T)$, at 7 T $\sin \theta \approx 0.0035$

Mixture $\sim 53\%$ of $|a\rangle$ and $\sim 47\%$ of $|b\rangle$:

$P_e \sim 1 - \delta, \quad \delta \sim 10^{-5}$

$P_p \sim -0.06$ (recombination $\Rightarrow \sim 80\%$)

$\mu \approx \mu_e$; $H_2$: opposite electron spins
First: 1980 (I. Silvera, J. Walraven) 
\( \vec{p} \) jet (Michigan) 
Never put in high power beam

- \(-\nabla (\mu_H \vec{B})\) force in the field gradient
  - pulls \(|a\rangle, |b\rangle\) into the strong field
  - repels \(|c\rangle, |d\rangle\) out of the field
- \(H+H \rightarrow H_2\) recombination (+4.5 eV) 
  high rate at low \(T\)
  - parallel electron spins: suppressed
  - gas: 2-body kinematic suppression
  - gas: 3-body density suppression
  - surface: strong unless coated
  \(\sim 50\) nm of superfluid \(^4\text{He}\)
- Density \(3 \cdot 10^{15} - 3 \cdot 10^{17}\) cm\(^{-3}\).
- Gas lifetime \(> 1\) h.
Proton polarization builds up, because of recombination of states with opposite electron spins:

\[ |a⟩ = |↓↑⟩_α + |↑↓⟩_β \] and

\[ |b⟩ = |↓↓⟩ \]

As a result, \( |a⟩ \) dies out and only \( |b⟩ = |↓↓⟩ \) is left!

\[ P \rightarrow 0.8 \]
Would it work for polarimetry?

What is the effective polarization of the gas in the beam area? The most important factors found:

- **Cleaning time** - time needed for atoms of the opposite polarization and unpolarized molecules to leave the beam area and the cell
- **Spin flips caused by the RF field of the beam** - depolarization in the beam area
- **Ionization by the beam** - contamination in the beam area
- **Residual He gas in the cell** - contamination in the beam area
Gas Properties

- $n = 2 \cdot 10^{15} \text{ cm}^{-3}$ - density
- $T = 0.3 \text{ K}$ - temperature
- Diffusion speed $\Rightarrow$ cleaning time
- Heat conductance
- Depend on the atomic cross-section $\sigma$

Using Miller,77:

- $\bar{v} = \sqrt{8kT/\pi m} = 80 \text{ m/s}$ - atom speed
- $\frac{dn_{col}}{dt} = \sigma \cdot 4n\sqrt{\frac{kT}{\pi m}} \approx 1.4 \cdot 10^5 \text{ s}^{-1}$ - atomic collisions
- $\ell = (\sigma n\sqrt{2})^{-1} \approx 0.57 \text{ mm}$ - mean free path
- $\tau_{es} \approx 1.4 \text{ s}$ - mean drift time to $|Z| = 10 \text{ cm}$
- $\tau_R \approx 2 \text{ ms}$ - mean drift time $R=0 \rightarrow R=2 \text{ cm}$

<table>
<thead>
<tr>
<th>Ref., date</th>
<th>conditions</th>
<th>$\sigma$, cm$^2$</th>
<th>$d$, cm</th>
<th>$\sigma$, cm$^2$</th>
<th>$d$, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allison,71</td>
<td>$T &gt; 1 \text{ K}$</td>
<td>87.0</td>
<td>5.26</td>
<td>68.0</td>
<td>4.65</td>
</tr>
<tr>
<td>Miller,77</td>
<td>$T \sim 0 \text{ K}$</td>
<td>42.3</td>
<td>3.69</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Friend,80</td>
<td>$T \sim 0 \text{ K}$</td>
<td>6.5</td>
<td>1.44</td>
<td>4.9</td>
<td>1.25</td>
</tr>
<tr>
<td>Lhuillier,83</td>
<td>$T = 2.5 \text{ K}$</td>
<td>$\sim 30.0$</td>
<td>3.10</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
CEBAF Beam Parameters

General

- τ = 0.5 ps - bunch time width (RMS) in LAB frame
- σ_{Bx/y} = 100 µm - bunch transverse width (RMS)
- \mathcal{F} = 497 MHz - bunch repetition rate
- γ ≥ \sim 10^4 - beam γ-factor
- I_b = 100 µA - average beam current
- r_0 - cell radius

Electromagnetic Field of the Bunch

In CM of the bunch: σ_Z > 15 cm ≫ R_{pipe} ⇒ E_B \propto r^{-1}. Boost to Lab.

- The field is located in a thin disk around the bunch
- \vec{B}(z, r, t) - azimuthal
- B(0, r, t) = \frac{I_b}{\mathcal{F} \cdot \tau} \cdot e^{-0.5(t/\tau)^2} \cdot (1 - e^{-0.5(r/σ_{Bx})^2})^{1/2} \cdot \frac{\mu_o}{(2\pi)^{3/2}}

RF

B(t) = \sum_{n=-\infty}^{\infty} \hat{B}_n \cdot e^{i\omega_o n t}, where \omega_o = 2\pi \mathcal{F}.

\hat{B}_n(r) = \frac{\mu_o I_b}{2\pi r_0} \cdot \exp(-\frac{\omega_o^2 k^2 \tau^2}{2}) \cdot G(r)
Depolarization by the Beam RF field

$|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle$ transitions $\sim 200$ GHz.

$B_r$: harmonic perturbation $\mu e \cdot B \cdot e^{i\omega t} \Rightarrow \frac{dV_{a \rightarrow d}}{dt} = \frac{2\pi}{\hbar^2} |\mu e \cdot B|^2 \delta(\omega - \omega_{ad})$

Non uniform magnetic field:

$\frac{dP}{d\omega_{ad}}$ - spectral density of atoms for $\omega(a \rightarrow d)$

$\frac{N_d}{N_a} \approx \frac{1}{\pi} \left( \frac{\mu_0 \mu e I_b}{\hbar r_o} \right)^2 \cdot (1.205 + \ln \frac{r_o}{5\sigma_{Br}}) \sum_{k=-\infty}^{\infty} \frac{dP}{d\omega_{ad}} \bigg|_{\omega_0 k} \cdot \exp(-\omega_0^2 k^2 \tau^2) \cdot \tau dk$

- $\sim 10^{-4}$ s$^{-1}$ conversions (all atoms)
- $\sim 6\%$ s$^{-1}$ conversions (beam area)
- Diffusion: contamination
  - $\sim 1.5 \cdot 10^{-4}$ in the beam area
- Solenoid tune to avoid resonances - tune to a resonance to study the effect
Ionization by the beam

100 $\mu$A CEBAF beam:
Gas Ionization

- $10^{-5}$ s$^{-1}$ of all atoms
- 20% s$^{-1}$ in the beam area
- Problems:
  - No transverse diffusion
  - Recombination suppressed
  - Contamination $\sim 40\%$ in beam
- Solution: electric field $\sim 1$ V/cm
  - Drift $\nu = \vec{E} \times \vec{B}/B^2 \sim 12$ m/s
  - Cleaning time $\sim 20$ $\mu$s
  - Contamination $< 10^{-5}$
  - Ions, electrons: same direction
  - Beam $\vec{E}_r(160\mu$m$) \approx 0.2$ V/cm

Technical issue: how to build electrodes in the copper storage cell?
Residual Helium Gas in the Storage Cell

- $\sim 0.1\%$ - from Michigan measurements

Strategy:

- Measure with a probe (technique used at Michigan)
- Measure with the beam changing the hydrogen concentration
- Reconstruct the trajectories of the Møller electrons using special detectors (Si strips) and the position of the vertex (inside the solenoid and at the edges). May be difficult for very low and very high beam energies.
Summary on Polarization of the Target Gas

Ideally, the trapped gas polarization is nearly 100% (≈ $10^{-5}$ contamination). Good understanding of the gas properties (without beam).

Gas Properties
- Atom velocity ≈ 80 m/s
- Atomic collisions* ≈ 1.4 $10^5$ s$^{-1}$
- Mean free path $\lambda$ ≈ 0.6 mm
- Wall collision time $t_R$ ≈ 2 ms
- Escape (10cm drift) $t_{es}$ ≈ 1.4 s

CEBAF Beam
- Bunch length $\sigma=0.5$ ps
- Repetition rate 497 MHz
- Beam spot diameter $\sim0.2$ mm

- Contamination and Depolarization
  - No Beam
    - Hydrogen molecules $\sim 10^{-5}$
    - Upper states $|c\rangle$ and $|d\rangle$ < $10^{-5}$
    - Excited states < $10^{-5}$
    - Helium and residual gas <0.1% - measurable with the beam
  - 100 $\mu$A Beam
    - Depolarization by beam RF < $2 \cdot 10^{-4}$
    - Ion, electron contamination < $10^{-5}$
    - Excited states < $10^{-5}$
    - Ionization heating < $10^{-10}$

* Based on $\sigma_{HH} = 42 \cdot 10^{-16}$ cm$^2$ needs verification

Expected depolarization < $2 \cdot 10^{-4}$
Summary on Atomic Hydrogen for Møller Polarimetry

### Potential for Polarimetry

- Systematic accuracy of $< 0.3\%$
- Continuous measurements
- Statistical accuracy $\sim 1\%$ in 10 min at $100 \mu A$
- Tools for systematic studies:
  - changing the electrical field (ionization)
  - changing the magnetic field (RF depolarization)

### Next step: Problems and Questions to Solve

- Atomic cross section (mean free path...) needs verification
- Electrodes in the cell: R&D is needed
- Residual gas $0.1\%$ accurate subtraction
  - Coordinate detectors: the interaction point?
Other Technical challenges

- Thermal shielding of the 0.3 K cell from the beam pipe
- Alignment of the 8 T solenoid to avoid beam steering
- Møller optics with 8 T solenoid
- Combined beam optics with the main taget, Compton and Møller polarimeters
Appendix: Beam Ionization

Energy Loss

- 6.3 MeV/g\cdot cm^2 full loss per beam particle
- 1.8 MeV/g\cdot cm^2 carried out of the cell by $\delta$-electrons
- 4.5 MeV/g\cdot cm^2 absorbed in the cell
- 100 $\mu$A, $3 \cdot 10^{15}$ cm$^{-3}$:
  $1.4 \cdot 10^{13}$ eV/s/cm loss $\Rightarrow$ 0.04 mW in the cell

Gas Heating

- $\Delta T \propto I_b \cdot n \sigma / \sqrt{T}$,
- $\Delta T(0) \approx 0.03 K \cdot \ln \left( \frac{R}{r_B} + 0.5 \right)$,
  - $r_B = 0.2$ mm (no raster) $\Delta T(0) \approx 0.140$ K
  - $r_B = 2.0$ mm (raster) $\Delta T(0) \approx 0.075$ K
- Density $n \cdot \sqrt{T} =$const : 10% drop at the center
- Depolarization: $10^{-16} \rightarrow 10^{-11}$ - OK
- Is raster needed?
Appendix: Beam Ionization

Ions and Free Electrons

Primary and secondary ionization in hydrogen: 40 eV/pair
100 \( \mu \)A, \( 3 \cdot 10^{15} \) cm\(^{-3} \): \( 3.5 \cdot 10^{11} \) pairs/s/cm : \( 10^{-5} \) s\(^{-1} \) - all atoms, \( \sim 20\% \) s\(^{-1} \) - beam area

Problems:

- No transverse diffusion of charged particles
- Recombination kinematically suppressed
- For \( \tau_{ch} = 1.4 \) s contamination \( \sim 40\% \) in the beam

Solution: electric field \( \sim 1 \) V/cm normal to the axis

- Larmor \( \omega_L = q_e B/m = 1.4 \cdot 10^{12} \) s\(^{-1} \) for e\(^-\), \( 0.8 \cdot 10^9 \) s\(^{-1} \) for p \( \Rightarrow \omega_L \tau_{coll} \gg 1 \)
- Drift with \( v = \vec{E} \times \vec{B}/B^2 \sim 12 \) m/s
- Cleaning time \( \sim 20 \) \( \mu \)s : contamination \( < 10^{-5} \)
- Positive and negative - the same direction
- Average field of the beam \( E_{max}(160\mu m) \approx 0.2 \) V/cm - not important
- Design for electrodes?
Appendix: Excitations by the Beam Particles

- Neutral atoms $n > 1$
  - Total energy release: $1.4 \cdot 10^{13}$ eV/s/cm
  - Excitation energy $> 10$ eV
  - Excited atoms $< 1.4 \cdot 10^{12}$ eV/s/cm - $< 4 \cdot 10^{-5}$ s$^{-1}$ of all, 50% - wrong polarization
  - For $\tau_{es} = 1.4$ s contamination $< 3 \cdot 10^{-5}$

- Single beam particle - similar to the beam RF calculation
- Integrating for $r > 10^{-8}$ cm $V^B_{a\rightarrow d} \sim 10^{-12}$ s$^{-1}$: negligible