Electron Polarimetry Overview

E.Chudakov$^1$

$^1$JLab

Workshop: *Intense Electron Beams (IEB)*  
*June 17 - 20, Cornell, NY*
Motivation for precise electron polarimetry: PV experiments. New challenges:
- JLab experiments at 11 GeV
- New projects/proposals for lower energy (<0.5 GeV), high intensity (> 1 mA) machines: Mainz(MESA), MIT, Cornell

State of the art polarimetry
- Experience at low energies (< 6 GeV)
- Recent push for high accuracy at JLab
  - Experiment QWeak at 1.16 GeV is close to completion
- Possible improvements
- Extrapolation to the Cornell’s ERL project: 0.5 GeV, 10 mA

Acknowledgment: Thanks the QWeak team (D.Gaskell, M.Dalton, A.Narayan) for information and useful discussions
Motivation for Precise Electron Beam Polarimetry

New Generation of Parity Violation (PV) experiments

- JLab at 12 GeV: starting in ~ 1 year - 2-11 GeV available
- New machines at 100-500 MeV: the main topic at this workshop

### PV at JLab 11 GeV

JLab at 6 GeV - good for PV

11 GeV expected to be similar:

- High polarization ~ 87%
- Beam current < 80 $\mu$A
- Low noise beam

- EW Møller
- EW DIS
- Neutron skin at ~2 GeV

Polarimetry with exiting techniques: 0.5%: challenging

### PV at 100-500 MeV

- High polarization ~ 87%
- Very high beam current ~ 1 – 10 mA
- Beam quality: very stringent (small $A \propto Q^2$)

- EW $e \, p \rightarrow e \, p$ (as QWeak)

Polarimetry with exiting techniques:

- 0.5% at 500 MeV: very challenging
- 0.5% at <300 MeV: ? may need a new technique
Motivation for Precise Electron Beam Polarimetry

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E.Chudakov IEB 2015, Cornell Electron Polarimetry Overview
Important Features of Electron Polarimetry

**Electron polarization measurements: humbling experience**

*There is a history of large errors of $\sim 10\%$*

*(SLAC - Levchuk effect; DESY - Compton calorimeter ...)*

- Experiments are long, various things may change on the way
- Precise polarimetry: an experiment in its own right requiring considerable resources

- Stat. error for a period of a possible polarization change ($\sim 1 \text{ h}$)
- Stat. error & 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)? Non-invasive:
    - Better averaging?
    - More opportunities for systematic studies!
- Two different polarimeters/methods highly desirable
Methods Used for Absolute Electron Polarimetry

Spin-dependent processes with a known analyzing power.

Atomic Absorption

\[ \vec{e}^- \sim 50 \text{ keV decelerated to } \sim 13 \text{ eV} \quad \vec{e}^- + \text{Ar} \rightarrow \text{Ar}^* + e^- , \quad \text{Ar}^* \rightarrow \text{Ar} + (h\nu)_\sigma \]

Atomic levels: \((3p^54p)^3D_3 \rightarrow (3p^64s)^3P_2\) 811.5nm fluorescence

Potential \(\sigma_{syst} \sim 1\%\). Under development (Mainz) - only relative so far.
Currently - invasive, diff. beam

Spin-Orbital Interaction

Mott scattering, 0.1-10 MeV: \(e^- \uparrow + Z \rightarrow e^- + Z\)

\(\sigma_{syst} \sim 3\%\), \(\Rightarrow 1\%\) (?)

Mainz group: double Mott - absolute measurement \(\sigma_{syst} \sim 0.3\%\) seems feasible. invasive, diff. beam

Spin-Spin Interaction

- Møller scattering: \(\vec{e}^- + \vec{e}^- \rightarrow e^- + e^-\) at \(>0.1\) GeV, \(\sigma_{syst} \sim 1-2\%\), \(\Rightarrow 0.5\%\)
  intermittent, mostly invasive, diff. beam

- Compton scattering: \(\vec{e}^- + (h\nu)_\sigma \rightarrow e^- + \gamma\) at \(>0.5\) GeV \(\sim 1-2\%\), \(\Rightarrow 0.5\%\).
  non-invasive, same beam
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Compton Polarimetry

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

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

\[ \mathcal{P}_laser \sim 100\% \]

\[ \sigma_{\text{lab}} \sim 180 \text{ mb/ster} \]

Møller Polarimetry

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

\[ A(E) = \frac{7}{9} \]

\[ \frac{d\sigma}{d\Omega_{CM}} \propto \frac{1}{s} \]

- Rad. corrections to Born \(< 0.3\%\)
- Detecting \(e^-\), \(\gamma\)
- 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 \(3 \rightarrow 50\ \text{GeV}: \sim 1. \rightarrow 0.5\%\)

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Syst. error \(3 \rightarrow 50\ \text{GeV}: \sim 1. \rightarrow 0.5\%\)
Compton Polarimeters: Best Accuracy at High Energy

**SLAC SLD**

- Beam: 45.6 GeV
- Beam: $3.5 \cdot 10^{10} e^- \times 120 \text{ Hz} \sim 0.7 \mu A$
- Laser: 532 nm, 50 mJ at 7 ns $\times$ 17 Hz
- Crossing angle 10 mrad

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma(P)/P$</th>
<th>SLD 1998</th>
<th>ILC Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser polarization</td>
<td>0.10%</td>
<td>0.10%</td>
<td></td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.40%</td>
<td>0.20%</td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td>0.20%</td>
<td>0.10%</td>
<td></td>
</tr>
<tr>
<td>Electronic noise</td>
<td>0.20%</td>
<td>0.05%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.50%</td>
<td>0.25%</td>
<td></td>
</tr>
</tbody>
</table>

M.Woods, JLab Polarimetry workshop, 2003

- $e^- 17$-$30$ GeV detector - gas Cherenkov
- $\gamma$ detector - calorimeter
- Statistics 1% in 3 min
Compton Polarimeter in Hall A at JLab: CW cavity

- Beam: 1.5-6 GeV
- Beam: $5 - 100 \, \mu\text{A}$ at 500 MHz
- Laser: 1064 nm, 0.24 W
- Fabry-Pérot cavity $\times 4000 \Rightarrow 1 \, \text{kW}$
- Crossing at 23 mrad $\varepsilon \sim 1\%$
- $e^{-}$ detector - Silicon $\mu$-strip
- $\gamma$ detector - calorimeter

Stat: 1.0% 30 min, 4.5 GeV, 40 $\mu\text{A}$

Syst: 1.2% at 4.5 GeV

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<th>$e^{-}$</th>
<th>$\gamma$</th>
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<td>Laser polarization</td>
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<td>0.40%</td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.20%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Dead time</td>
<td>0.20%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.00%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Background</td>
<td>0.05%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Others</td>
<td>0.03%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Total</td>
<td>0.35%</td>
<td>0.46%</td>
</tr>
</tbody>
</table>

Prospects for 11 GeV

- Laser: 532 nm, $\sim 1 \, \text{W}$
- Cavity $\times 2000 \Rightarrow >2 \, \text{kW}$
- GSO crystal ECAL

Upgraded - 1% at 1.0 GeV
**Photon Detector**

- Counting rate ($\omega$), sensitive to
  - thresholds
  - calibration

- Integrating mode, sensitive to
  - linearity
  - background
  + no dead time
  + high rates OK
  + no threshold issues

**Electron Detector**

- Counting rate ($E_e$), sensitive to
  - alignment
  - detector efficiency
  + calibration using:
    - Compton edge, 0-crossing
    - Calibration using: Compton edge, 0-crossing

- Integrating mode, sensitive to
  - linearity
  - background
  + no dead time
  + high rates OK

---


Hall C QWeak (from D.Gaskell)
**Compton Polarimeter in Hall C for experiment QWeak**

- Beam: 1.16 GeV, < 180 μA
- Laser: 532 nm, 10 W
- Fabry-Pérot cavity ×100 ⇒ 1 kW
- Crossing at 23.5 mrad
- γ detector PbWO₄ (integration).
- New! e⁻ detector - Diamond μ-strips
  ~10 MRad - no noticeable damage
- New! New method to measure the light polarization in the cavity:
  \[ \sigma P / P \sim 0.1\% \]
- Laser cycle: 60 s ON, 30 s OFF
- BG measurement: ~25% at \( \omega_{\text{max}}/2 \)
- Electron data analysis:
  - 17 mm separation at \( \omega_{\text{max}} \)
  - Diamond: 3 planes operational
  - Diamond efficiency \( \sim 70\%/\text{plane} \)
  - “Tracks” reconstructed in FPGA
- Largest Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Current, %</th>
<th>Outlook, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser polarization</td>
<td>0.18</td>
<td>0.10</td>
</tr>
<tr>
<td>DAQ</td>
<td>0.42</td>
<td>0.15</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.19</td>
<td>0.10</td>
</tr>
<tr>
<td>Beam vert. angle</td>
<td>0.20</td>
<td>0.10</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.59</strong></td>
<td><strong>0.38</strong></td>
</tr>
</tbody>
</table>
Compton at 500 MeV?

- 532 nm: $\omega_{max} = 9$ MeV, $A_{ZZ}=1.8%$
- FOM(500 MeV) $\approx$ FOM(1 GeV)/4.
- Electron detection to 0.5$\omega_{max}$: a large chicane: $\Delta h = 100$ cm $\Rightarrow$ 0.9 cm from the beam (similar to QWeak)
- High current $I_e \sim 1 - 10$ mA $\times$ 5-50 more than QWeak

Can one reduce the light intensity?
- Can not afford to increase the background $\sim I_e$
- The origin of the background is not clear: Bremsstahlung on gas, halo interaction in the mirrors of the cavity
- Consider no-cavity: 10 W laser compensate no cavity gain by $0^\circ$ crossing ($\times 100$) Much easier!
- 10 MHz rate $\Rightarrow$ Integrating mode. Ability to count?
- Radiation hardness $\sim 500$ MRad

0.5% seems possible with existing technology
0.3% would probably need a breakthrough
Møller Spectrometers

- Select Møller scattering $\theta_{CM} \sim 90^\circ$
- Suppress Mott & photons: narrow slits
- $Q$ Bates, Mainz / $D$ SLAC
- QQ JLab C / QQQD JLab A
- Typical acceptance $\theta_{CM} \sim 80 - 110^\circ$, $\Delta \phi \sim \pm 10^\circ$
- Small acceptance $\Rightarrow$ large Levchuk effect
Polarized electron targets: magnetized ferromagnetic foils

- Iron: polarized $d$-shell (6 positions occupied out of 10)
- $P_e$ not calculable: derived from measured magnetization
- Spin-orbital corrections ($\sim 5\%$) - measured in bulk material
- Magnetizing field is along the beam
- Levchuk effect: scattering on unpolarized inner shells:
  - distorted kinematics $\Rightarrow$ smaller coincidence acceptance
  - Change in the effective target polarization 1-10%
  - Correction requires a good understanding of the acceptance

Field 20 mT, foil at $\sim 20^\circ$
- Magnetization along the foil
- Magnetization can be measured
- A few $\%$ from saturation
- Sensitive to annealing, history
- Polarization accuracy $\sim 2 - 3\%$

Field 3 T, foil at $\sim 90^\circ$
- Magnetization perp. to the foil
- Magnetization - from world data
- Foil saturated
- Polarization is robust.
- Polarization accuracy $\sim 0.5\%$

Pioneered in 1990-s by a Basel group for Hall C, JLab
Møller Polarimeter with Saturated Iron foil (Hall C)

JLab, Hall C, M. Hauger et al. NIM A 462, 382 (2001)

- External $B_Z \sim 3 - 4 \, T$
- Target foils 1-10 $\mu$m, perp. to beam
- $P_t$ not measured
- Levchuk: 3% correction

**Important factors**

- Small target angle ⇒ higher field for saturation
- Solenoidal field affects the acceptance

**Target cloned in Hall A**

<table>
<thead>
<tr>
<th>source</th>
<th>$\sigma(A)/A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>optics, geometry</td>
<td>0.20%</td>
</tr>
<tr>
<td>target</td>
<td>0.28%</td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>0.30%</td>
</tr>
<tr>
<td>total at 3 $\mu$A</td>
<td>0.46%</td>
</tr>
<tr>
<td>⇒ 100 $\mu$A</td>
<td>?</td>
</tr>
</tbody>
</table>

**PREX Target Saturation Test**

```
89.5(3.8T)−88.5(3.0T)=1.0%
```
High beam currents at saturated foils

Attempts to run at high currents $1-3\mu A \rightarrow 50\mu A$

**Hall C**
- Half-moon shape foil
- Kicker magnet

**Hall A**
- Beam duty cycle $< 5\%$
- Beam bunches $500 \text{ MHz}/n$, $n=16$
- “Tune beam”: $4 \text{ ms}$ pulses $\sim 60 \text{ Hz}$
- Instantaneous counting rate at $50\mu A$ will be $\times 3$ higher
- More invasive than a kicker scheme

Happened to be too invasive for the accelerator running

A $1\mu m$ thick half-foil: mech. problems:
- Foil unstable: holder design
- Thicker foil - high rate
- At $20\mu A$ - accidental/real $\approx 0.4$

May eventually work but so far it did not.
Needs beforehand planning on the machine side
Provided by D.Gaskell (QWeak, JLab)

Preliminary systematics $\sigma P/P$

- Compton: 0.6%
- Møller: 0.6%
**Møller Systematic Errors**

Proposed: 100%-polarized atomic hydrogen target (∼ $3 \cdot 10^{16}$ atoms/cm²).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hall C Instrument</th>
<th>Hall C QWeak</th>
<th>Hall A Fe 4T</th>
<th>Hall A H 100% pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rad. corrections</td>
<td>-</td>
<td>0.10%</td>
<td>0.10%</td>
<td></td>
</tr>
<tr>
<td>Target polarization</td>
<td>0.25%*</td>
<td>0.27%</td>
<td>0.01%</td>
<td></td>
</tr>
<tr>
<td>Target angle</td>
<td>0.00%</td>
<td>0.20%</td>
<td>0.00%</td>
<td></td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.24%</td>
<td>0.30%</td>
<td>0.10%</td>
<td></td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>0.30%*</td>
<td>0.30%</td>
<td>0.00%</td>
<td></td>
</tr>
<tr>
<td>Target temperature</td>
<td>0.05%</td>
<td>0.02%</td>
<td>0.00%</td>
<td></td>
</tr>
<tr>
<td>Dead time</td>
<td>-</td>
<td>0.30%</td>
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<td>Background</td>
<td>-</td>
<td>0.30%</td>
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<td>Optics</td>
<td>0.10%</td>
<td>-</td>
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<tr>
<td>Low/high beam current</td>
<td>0.20%?</td>
<td>0.20%</td>
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<tr>
<td>Sum</td>
<td>0.47%</td>
<td>0.72%</td>
<td>0.20%</td>
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<td>Empirical fluctuations</td>
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<td>Total</td>
<td>0.47%</td>
<td>0.60%</td>
<td>0.80%</td>
<td>0.36%</td>
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* Reduction is unlikely
Møller polarimetry with 100% polarized atomic hydrogen gas, stored in a 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 50 $\mu$A: 1% in $\sim 10$ min
Proposed: 100%-polarized atomic hydrogen target ($\sim 3 \cdot 10^{16}$ atoms/cm$^2$).

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| Empirical fluctuations          |                   |              | 0.30%        | 0.30%?            |
| Total                           | 0.47%             | 0.60%        | 0.80%        | 0.36%             |

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<tr>
<td>Analyzing power</td>
<td>0.24%</td>
<td></td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>0.30%*</td>
<td></td>
</tr>
<tr>
<td>Target temperature</td>
<td>0.05%</td>
<td></td>
</tr>
<tr>
<td>Dead time</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Optics</td>
<td>0.10%</td>
<td></td>
</tr>
<tr>
<td>Low/high beam current</td>
<td>0.47%</td>
<td>0.60%</td>
</tr>
<tr>
<td>Sum</td>
<td>0.47%</td>
<td>0.72%</td>
</tr>
</tbody>
</table>

Empirical fluctuations       | -      | 0.30%      | 0.30%?|

Total                       | 0.47%  | 0.60%      | 0.80% | 0.36%     |

* Reduction is unlikely
First: 1980 (I. Silvera, J. Walraven)
\( \vec{p} \) jet (Michigan)
Never put in high power beam

- \(-\vec{\nabla}(\mu_H \vec{B})\) force in the field gradient
  - pulls \(|a\rangle, |b\rangle\) into the strong field
  - repels \(|c\rangle, |d\rangle\) out of the field
- \(\text{H+H}\rightarrow\text{H}_2\) 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.
Proof of principle

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
Contamination and Depolarization of the Target Gas

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

**Contamination and Depolarization**

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

**CEBAF Beam**
- Bunch length $\sigma=0.5$ ps
- Repetition rate 497 MHz
- Beam spot diameter $\sim 0.2$ mm

**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**
- If certain tricks do work:
  - Depolarization by beam RF $< 2 \cdot 10^{-4}$
  - Ion, electron contamination $< 10^{-5}$
  - Excited states $< 10^{-5}$
  - Ionization heating $< 10^{-10}$

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

Potential for Polarimetry

- Systematic accuracy of < 0.3%
- Continuous measurements

Beam current limitations

- RF depolarization \( \propto Q_{bunch}^2 \cdot N_{repet} \): at 1300 MHz \( I_{beam} < 0.5 \text{ mA} \)
- Ionization \( \propto I_{beam} \): \( I_{beam} < 2 \text{ mA} \)
- Some other effects may matter

What has to be done to validate the idea?

- R&D to verify the technical tricks invented (on paper) to reduce the contamination effects
- Build a prototype and test it in a beam
- Optimize the spectrometer to have the background under control

Pursued by the U.Mainz group for MESA
Møller at 500 MeV, 10 mA

- There is no issue with the analyzing power, event rate or spectrometer optics. Fe targets may provide $\sigma P/P \sim 0.5\%$
- Hydro-Møller is limited by $I_{\text{beam}} < 0.5 \text{ mA}$
- The accurate method requires a strong longitudinal field: $\sim 0.7 \text{T} \cdot \text{m}$ for high-field iron or, even $\sim 2 \text{T} \cdot \text{m}$ for the hypothetical hydro-Møller
  - **Strong beam steering!** It is bad enough at $\sim 1 \text{ GeV}$. At 500 MeV the magnet for high-field iron, tilted by 1 mrad, will tilt the beam by 0.3 mrad
  - It requires independent locking on the beam position in the polarimeter area and the experiment area - difficult at the existing machines (not planned in advance)
- The target system should be equipped with a remotely controlled motion system, as a goniometer, perhaps with a coarser resolution.
Conclusion

Precision polarimetry at 500 MeV, 10 mA machines:

- Low energy measurements (Mott etc.)
- Compton: $\sim 0.5\%$ likely possible using the existing techniques
- Møller with iron targets $\sim 0.5\%$:
  - Invasive
  - Limited to $I_{\text{beam}} < 3 \, \mu\text{A}$ Running at high currents - not yet solved. Reducing the repetition rate may work if planned beforehand
- hydro-Møller $< 0.30\%$ accuracy, very complex, needs R&D limited to $\sim 0.5 \, \text{mA}$
- The machine and the experimental area should be designed to provide the polarimetry needs
Hydrogen Atom in Magnetic Field

$H_1$: $\vec{\mu} \approx \vec{\mu}_e$;
$H_2$: opposite electron spins

Consider $H_1$ in $B = 7 \, T$ at $T = 300 \, mK$

At thermodynamical equilibrium:

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

Complication from hyperfine splitting:

Low energy

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

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

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 $\Rightarrow \sim 80\%$)
Contamination and Depolarization of the Target Gas

100 $\mu$A CEBAF beam:

**Beam RF influence**
- $|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle \sim 200$ GHz
- RF spectrum: flat at $< 300$ GHz

**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 $v = \vec{E} \times \vec{B}/B^2 \sim 12$ m/s
- Cleaning time $\sim 20 \mu$s
- Contamination $< 10^{-5}$
- Ions, electrons: same direction
- Beam $E_r(160\mu m) \approx 0.2$ V/cm

- $\sim 10^{-4}$ 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
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!

\[ \mathcal{P} \rightarrow 0.8 \]
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 cm

<table>
<thead>
<tr>
<th>Ref., date</th>
<th>conditions</th>
<th>H polarized</th>
<th>H unpolarized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\sigma$, cm$^2$</td>
<td>$d$, cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10^{-16}$</td>
<td>$10^{-8}$</td>
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<tr>
<td>Allison,71</td>
<td>T&gt;1 K</td>
<td>87.0</td>
<td>5.26</td>
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<tr>
<td>Miller,77</td>
<td>T~0 K</td>
<td>42.3</td>
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<tr>
<td>Friend,80</td>
<td>T~0 K</td>
<td>6.5</td>
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<tr>
<td>Lhuillier,83</td>
<td>T=2.5 K</td>
<td>30.0</td>
<td>3.10</td>
</tr>
</tbody>
</table>
CEBAF Beam Parameters

General

- $\tau = 0.5$ ps - bunch time width (RMS) in LAB frame
- $\sigma_{Bx/y} = 100$ $\mu$m - bunch transverse width (RMS)
- $F = 497$ MHz - bunch repetition rate
- $\gamma \geq \sim 10^4$ - beam $\gamma$-factor
- $I_b = 100$ $\mu$A - average beam current
- $r_\circ$ - cell radius

Electromagnetic Field of the Bunch

In CM of the bunch: $\sigma_Z > 15$ cm $\gg R_{pipe} \Rightarrow E_B \propto r^{-1}$. Boost to Lab.

- The field is located in a thin disk around the bunch
- $\vec{B}(z, r, t)$ - azimuthal
- $B(0, r, t) = \frac{I_b}{F \cdot \tau} \cdot e^{-0.5(t/\tau)^2} \cdot (1 - e^{-0.5(r/\sigma_{Bx})^2}) \frac{1}{r} \cdot \frac{\mu_0}{(2\pi)^{3/2}}$

$B(t) = \sum_{n=-\infty}^{\infty} \hat{B}_n \cdot e^{i\omega_0 nt}$, where $\omega_0 = 2\pi F$.

$\hat{B}_n(r) = \frac{\mu_0 I_b}{2\pi r_\circ} \cdot \exp(-\frac{\omega_0^2 k^2 r^2}{2}) \cdot G(r)$
Depolarization by the Beam RF field

$|a⟩→|d⟩$ and $|b⟩→|c⟩$ 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 $\omega(a \rightarrow d)$

Graph showing transition frequency $\nu$ (GHz)

$$\frac{N_d}{N_a} \approx \frac{1}{\pi} \cdot \left( \frac{\mu_0 \mu_e I_b}{\hbar r_0} \right)^2 \cdot (1.205 + \ln \frac{r_0}{5\sigma_{Br}}) \sum_{k=-\infty}^{\infty} \frac{dP}{d\omega_{ad}} \bigg|_{\omega_0 k} \cdot \exp(-\omega_0^2 k^2 \tau^2) \cdot \tau dk$$

- $\sim 10^{-4}$ 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
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  - Contamination $< 10^{-5}$
  - Ions, electrons: same direction
  - Beam $E_r(160\mu$m) $\approx 0.2$ V/cm

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

- ~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.
Mott Polarimetry

0.1-10 MeV: $e^- \uparrow + Au \rightarrow e^- + Au$ analyzing power (Sherman func.) $\sim 1\text{-}3\%$

- Nucleus thickness: phase shifts of scat. amplitudes
- Spin rotation functions
- Electron screening, rad. corr.
- Multiple and plural scattering
- No energy loss should be allowed
- Single arm - background

JLab: $\sigma(P)/P = 1\% (\text{Sherman}) \oplus 0.5\% (\text{other})$ (unpublished) $\oplus \sigma(\text{extrapol})$

E.Chudakov IEB 2015, Cornell