Beam Polarimetry
(for Future Experiments at JLab)

E.Chudakov$^1$

$^1$JLab

PAVI-09
Outline

1. PV Program at 12 GeV - challenges
   2. Electron Polarimetry
      • Compton Polarimetry
      • Møller Polarimetry
      • Møller with Atomic Hydrogen Target

3. Conclusion
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3. Conclusion
PV opportunities at 11-GeV

CEBAF is an excellent facility for PV experiments

PV at 6 GeV
- High polarization $\sim 85\%$
- High beam current $< 100\,\mu\text{A}$
- Low noise beam

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

PV at 11 GeV
- Same polarization
- Beam current $< 100\,\mu\text{A}$
- Comparable noise

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

Proposals:
- Møller PR-09-005 - app.
- DIS PR-09-012 - cond.app.

See talks by K.Kumar and P.Souder

E.Chudakov
June 24, 2009, PAVI-09
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See talks by K.Kumar and P.Souder
Installation in Hall A
Installation in Hall A

Polarimeters
Compton  Møller

Hall A with Moller and PVDIS installations

-3000 -2000 -1000 0 1000 2000 3000
Z, cm

-4000 -3000 -2000 -1000 0 1000 2000 3000 4000
X, cm
## Error Budget of Møller and PVDIS Experiments

### Møller

<table>
<thead>
<tr>
<th>Source of error</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q^2 ) absolute value</td>
<td>0.5</td>
</tr>
<tr>
<td>beam polarization</td>
<td>0.4</td>
</tr>
<tr>
<td>beam second order</td>
<td>0.4</td>
</tr>
<tr>
<td>inelastic ( ep )</td>
<td>0.4</td>
</tr>
<tr>
<td>elastic ( ep )</td>
<td>0.3</td>
</tr>
<tr>
<td>other</td>
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</tr>
<tr>
<td>total</td>
<td>1.0</td>
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### PVDIS

<table>
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<th>Source of error</th>
<th>% error</th>
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</tr>
<tr>
<td>radiative corrections</td>
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</tr>
<tr>
<td>( Q^2 ) absolute value</td>
<td>0.2</td>
</tr>
<tr>
<td>statistics</td>
<td>0.3</td>
</tr>
<tr>
<td>total</td>
<td>0.6</td>
</tr>
</tbody>
</table>

0.4% - can it be done?
## Error Budget of Møller and PVDIS Experiments

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<td>0.5</td>
<td>beam polarization</td>
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<td>total</td>
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</tbody>
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**0.4% - can it be done?**
Electron Polarimetry for PV at JLab: Features

- Energy range $E_{\text{beam}} = 6.6 - 11$ GeV
- Current range $I_{\text{beam}} = 40 - 90$ µA

Additional features to consider:

- Time needed to achieve $\sim 0.4\%$ statistical error
- Systematic error:
  - Does polarimetry use the same beam as the experiment (energy, current, location)?
  - Continuous or intermittent (invasive?)
- Two different polarimeters/methods highly desirable
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Methods Used for Absolute Electron Polarimetry

Spin-dependent processes with a known analyzing power.

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

Atomic levels: \((3p^54p)^3D_3 \rightarrow (3p^6s)^3P_2\)
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:
\[ e^- + Z \rightarrow e^- + Z \]
\(\sigma_{syst} \sim 3\%\), \(\Rightarrow 1\%\) (?)
invasive, diff. beam

Spin-Spin Interaction
- Møller scattering:
\[ \bar{e}^- + \bar{e}^- \rightarrow e^- + e^- \text{ at } >0.1 \text{ GeV}, \]
\(\sigma_{syst} \sim 1-2\%\), \(\Rightarrow 0.5\%
intermittent, mostly invasive, diff. beam
- Compton scattering:
\[ \bar{e}^- + (h\nu)_\sigma \rightarrow e^- + \gamma \text{ at } >0.5 \text{ GeV} \sim 1-2\%, \Rightarrow 0.5\%.
non-invasive, same beam
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Spin-dependent processes with a known analyzing power.

**Atomic Absorption**

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

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**Spin-Spin Interaction**

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  non-invasive, same beam
Compton Polarimetry

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

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

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

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

Møller Polarimetry

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

- 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 \( \mathcal{P}_T \sim 8\% \)

- \( \langle I_B \rangle < 3 \mu A \) (heating 1%/100°C)
- Levchuk effect (atomic \( e^- \))
- Low \( \mathcal{P}_T \Rightarrow \) dead time
- Syst. error \( \sigma(\mathcal{P}_T) \sim 2\% \) (0.5%?)

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

\( \sigma_{lab} \sim 180 \text{mb ster} \)
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**SLAC SLD**

**Introduction**

**Electron Polarimetry**

**Conclusion**

- **Beam:** 45.6 GeV
- **Beam:** $3.5 \cdot 10^{10} \ e^{-} \times 120 \text{ Hz} \sim 0.7 \ \mu\text{A}$
- **Laser:** 532 nm, 50 mJ at 7 ns $\times$ 17 Hz
- **Crossing angle** 10 mrad
- **$e^{-}$ 17-30 GeV detector - gas Cherenkov
- **$\gamma$ detector - calorimeter
- **Statistics** 1% in 3 min

### SLAC SLD Diagram

- **532 nm Frequency Doubled YAG Laser**
- **Circular Polarizer**
- **Focusing and Steering Lens**
- **Mirror Box (preserves circular polarization)**
- **Compton Back Scattered $e^{-}$**
- **Cerenkov Detector**
- **Quartz Fiber Calorimeter**
- **Mirror Box**
- **SLD**
- **Laser Beam and Dump**
- **“Compton IP”**
- **Analyzing Bending Magnet**
- **Polarized Gamma Counter**

### Table

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

**At JLab:**

- **Low energy:** FOM: $\times 0.1$
- **Coincidence** $e^{-}, \gamma$
- **Beam current** $\times 100$

M. Woods, JLab Polarimetry workshop, 2003
Compton Polarimeter in Hall A at JLab: CW cavity

- Beam: 1.5–6 GeV
- Beam: 5 – 100 μA at 500 MHz
- Laser: 1064 nm, 0.24 W
- Fabry-Pérot cavity ×4000 ⇒ 1 kW
- Crossing at 23 mrad ε ~ 2.5%
- e− detector - Silicon μ-strip
- γ detector - calorimeter

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<tr>
<th>source</th>
<th>σ(P)/P</th>
</tr>
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<tbody>
<tr>
<td>Laser polarization</td>
<td>0.50%</td>
</tr>
<tr>
<td>Response function</td>
<td>0.40%</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.60%</td>
</tr>
<tr>
<td>Others</td>
<td>0.65%</td>
</tr>
<tr>
<td>total</td>
<td>1.15%</td>
</tr>
</tbody>
</table>

Upgrade - 1% at 1.0 GeV
- Laser: 532 nm, ~1 W
- Cavity ×2000 ⇒ 2 kW
- Detector upgrade

Stat: 1.0% 30 min, 4.5 GeV, 40 μA
Syst: 1.2% at 4.5 GeV
Compton at Hall A: Expectations for 12 GeV

- Beam: 6.6-11 GeV
- Beam: 40 – 90 $\mu$A at 500 MHz
- Laser: 532 nm, 1 W
- Fabry-Pérot cavity $\times$2000 $\Rightarrow$ 2 kW
- Crossing at 23 mrad $\varepsilon \sim 1.2\%$
- $e^-$ detector - Silicon $\mu$-strip
- $\gamma$ detector - calorimeter
- High energy:
  - $e^-$ far from the beam
  - Compton edge, $A=0$: energy calibration

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<th>$\gamma$</th>
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<td>Laser polarization</td>
<td>0.20%</td>
<td>0.40%</td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.20%</td>
<td>0.40%</td>
</tr>
<tr>
<td>Dead time</td>
<td>0.00%</td>
<td>0.00%</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><strong>Total</strong></td>
<td><strong>0.35%</strong></td>
<td><strong>0.46%</strong></td>
</tr>
</tbody>
</table>

Stat: 1.0% 1 min, 11 GeV, 90 $\mu$A
Syst: 0.4% at 6.6 GeV

Seems hard but possible
Compton at Hall A: Expectations for 12 GeV

- Beam: 6.6-11 GeV
- Beam: 40 – 90 $\mu$A at 500 MHz
- Laser: 532 nm, 1 W
- Fabry-Pérot cavity $\times 2000 \Rightarrow 2$ kW
- Crossing at 23 mrad $\varepsilon \sim 1.2\%$
- $e^-$ detector - Silicon $\mu$-strip
- $\gamma$ detector - calorimeter
- High energy:
  - $e^-$ far from the beam
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Møller Polarimetry

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

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 $\sim 0.5\%$
Møller Polarimeter with Saturated Iron foil (Hall C)

JLab, Hall C, M. Hauger et al. NIM A 462, 382 (2001), talk on PAVI09 by S.Page

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

Tests at high beam current
- Half-moon shape foil
- Kicker magnet

<table>
<thead>
<tr>
<th>source</th>
<th>$\sigma(A)/A$</th>
</tr>
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<tbody>
<tr>
<td>optics, geometry target</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>$\Rightarrow 100 \mu$A</td>
<td>?</td>
</tr>
</tbody>
</table>

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

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

- Minimal Levchuk
- $\sigma_{\text{stat}} = 1\%$ in
  $\sim 2–3$ min
- $B_Z \sim 25$ mT field
- Foil at 20° to field
- Foils 5–30 $\mu$m
- Beam $< 2\mu$A
- Systematics
  $\sim 2\%$
Hall A Møller Polarimeter: current upgrade

Upgrade, motivated by PREX requirements:

- High field magnetization (Hall C target clone)
- High instantaneous beam current: reduce heating by introducing a beam duty cycle < 5%
  - Beam repetition rate 500 MHz/4
  - “Tune beam”: 4 ms pulses at ∼60 Hz
  - Instantaneous counting rate at 50µA will be ×3 higher
  - More invasive than a kicker scheme
- Electronics upgrade to digest higher rates
Møller Systematic Errors

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hall C</th>
<th>Hall A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>Upgrade</td>
</tr>
<tr>
<td>Target polarization</td>
<td>0.25%</td>
<td>2.00%</td>
</tr>
<tr>
<td>Target angle</td>
<td>0.00%</td>
<td>0.50%</td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.24%</td>
<td>0.30%</td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>0.30%</td>
<td>0.20%</td>
</tr>
<tr>
<td>Target temperature</td>
<td>0.05%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Dead time</td>
<td>?</td>
<td>0.30%</td>
</tr>
<tr>
<td>Background</td>
<td>?</td>
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<tr>
<td>Others</td>
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<td>0.30%</td>
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<tr>
<td>Beam extrapolation</td>
<td>?</td>
<td>larger</td>
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<tr>
<td>Total</td>
<td>0.47%</td>
<td>2.10%</td>
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3 Conclusion
Possible Breakthrough in Accuracy

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

*E.Chudakov and V.Luppov IEEE Trans. on Nucl. Sc., 51, 1533 (2004)*


**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
Møller Systematic Errors

Proposed: 100%-polarized atomic hydrogen target ($\sim 3 \cdot 10^{16}$ atoms/cm$^2$).

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<tr>
<td>Levchuk effect</td>
<td>0.30%</td>
<td>0.20%</td>
<td>0.20%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Target temperature</td>
<td>0.05%</td>
<td>0.00%</td>
<td>0.02%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Dead time</td>
<td>-</td>
<td>0.30%</td>
<td>0.30%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Background</td>
<td>-</td>
<td>0.30%</td>
<td>0.30%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Others</td>
<td>0.10%</td>
<td>0.30%</td>
<td>0.30%</td>
<td>0.30%?</td>
</tr>
<tr>
<td>Beam extrapolation</td>
<td>?</td>
<td>larger</td>
<td>?</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total</td>
<td>0.47%</td>
<td>2.10%</td>
<td>$\sim 0.80%$</td>
<td>$\sim 0.35%$</td>
</tr>
</tbody>
</table>
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:
\[ \frac{n_+}{n_-} = \exp\left(-2\mu B/kT\right) \approx 10^{-14} \]

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 \( |b\rangle \):
\[ \mathcal{P}_e \sim 1 - \delta, \quad \delta \sim 10^{-5} , \]
\[ \mathcal{P}_p \sim -0.06 \) (recombination \( \Rightarrow \sim 80\% ))
First: 1980 (I. Silvera, J. Walraven) 
\( \vec{p} \) jet (Michigan) 
Never put in high power beam

- \(-\vec{\nabla}(\vec{\mu}_H \vec{B})\) force in the field gradient
  - pull \( |a\rangle, |b\rangle \) into the strong field
  - repel \( |c\rangle, |d\rangle \) 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 \( ^4\)He
- Density \( 3 \cdot 10^{15} - 3 \cdot 10^{17} \) cm\(^{-3}\).
- Gas lifetime \( > 1 \) h.
Contaminations 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).

**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

**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 $< 10^{-10}$

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

Potential for Polarimetry

- Systematic accuracy of $< 0.3\%$
- Continuous measurements
- Tools for systematic studies:
  - changing the electrical field (ionization)
  - changing the magnetic field (RF depolarization)

Problems and Questions

- Electrodes in the cell: R&D is needed
- Residual gas 0.1% accurate subtraction
- Coordinate detectors: the interaction point?
- Atomic cross section (mean free path...) needs verification
- Cost and complexity
New PV experiments require a $\sim 0.4\%$ polarimetry.

**Possible strategy**

- Continuous polarimetry
- $\sim 0.4\%$ Compton - seems feasible
- Second polarimetry method (Møller) of similar accuracy would help dramatically.
- Møller with iron targets - rather 1\% than 0.4\% 
- Møller with atomic hydrogen target potentially can provide $< 0.30\%$ accuracy, very complex, needs R&D
Mott Polarimetry

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

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

E. Chudakov June 24, 2009, PAVI-09

Beam Polarimetry
Dynamic Equilibrium and Proton Polarization

Proton polarization builds up, because of recombination of states with opposite electron spins:

$$|a\rangle = |↓↑\rangle_\alpha + |↑↓\rangle_\beta$$

and

$$|b\rangle = |↓↓\rangle$$

As a result, $|a\rangle$ dies out and only $|b\rangle = ↓↓$ is left!

$$p \rightarrow 0.8$$