Møller Polarimetry on Atomic Hydrogen

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Outline

1. Motivation for precise polarimetry

2. Møller Polarimetry

3. Møller with Atomic Hydrogen Target

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PV in electron scattering: JLab and Mainz

JLab is an excellent facility for PV experiments

PV at 6 GeV

- High polarization $> 85\%$
- High beam current $< 100\mu A$
- Low noise beam

Measured: G_s
Elastic e p, e ^{4}He (HAPPEX, G0);
EW e d DIS;
Running:

- Neutron skin ^{208}Pb
  e Pb → e Pb (PREX)
- EW e p → e p (QWEAK)

PV at 11 GeV

- Same polarization
- Beam current $< 100\mu A$
- Comparable noise

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

Approved by PAC:

- PV Møller
- PV DIS (SoLID)

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11 GeV JLab: Motivation for precise polarimetry

PV Møller

Source of error	% error
Q^2 absolute value	0.5
beam polarization	0.4
beam second order	0.4
inelastic *ep*	0.4
elastic *ep*	0.3
other	0.5
total	1.0

PV DIS (with SoLID)

Source of error	% error
beam polarization	0.4
radiative corrections	0.3
Q^2 absolute value	0.2
statistics	0.3
total	0.6

Polarimetry becomes the dominant systematic errors

0.4% - can it be done?

Jefferson Lab

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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)

1% ⇒ 0.4% - a long way!

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

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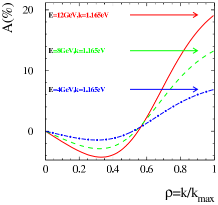
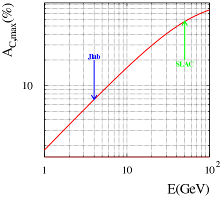
$$\frac{\sigma_{\uparrow\uparrow}-\sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow}+\sigma_{\uparrow\downarrow}} = A \cdot \mathcal{P}_b \mathcal{P}_t$$

Compton Polarimetry

$\vec{e}^{\,-} + (h\nu)_{\sigma} \rightarrow e^{-} + \gamma$ QED.



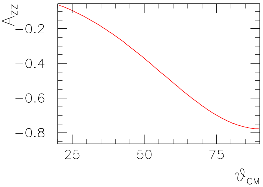


- Rad. corrections to Born $< 0.1\%$
- Detecting: γ (0°), e^{-} $E < E_{\circ}$
- Strong $\frac{dA}{dk'}$ - good $\sigma E_{\gamma}/E_{\gamma}$ needed
- $A \propto kE$ at $E < 20$ GeV
- $T \propto 1/(\sigma \cdot A^2) \propto 1/k^2 \;\times\; 1/E^2$
- $\mathcal{P}_{laser} \sim 100\%$
- Non-invasive measurement

Syst. error 3→50 GeV: $\sim 1. \rightarrow 0.5\%$

Møller Polarimetry

$\vec{e}^{\,-} + \vec{e}^{\,-} \rightarrow e^{-} + e^{-}$ QED.



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

$\sigma_{lab} \sim 180 \frac{mb}{ster}$

- 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 $\mathcal{P}_T \sim 8\%$
  - $\langle I_B \rangle < 5\ \mu A$ (heating)
  - Levchuk effect
  - Low $\mathcal{P}_T \Rightarrow$ dead time
  - Syst. error $\sigma(\mathcal{P}_T) > 0.4\%$

Important features of Electron Polarimetry

- Stat. error for a period of a possible polarization change ($\sim$ 1 h)
- Stat. error and numer 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?)

Feature	Compton	Møller with Fe target
Analyzing power variation	large	small
Special beam (much lower current)	no	yes
Continuous	yes	no
Target polarization	$\sim$100%	$\sim$8%
Target polarization measurable	yes	no

Møller Systematic Errors (talk by S.Glamazdin)

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

Variable	Hall C	Hall A		
		Fe 0.03T	Fe 4T	H 100% pol
Rad. corrections	-	0.30%	0.10%	0.10%
Target polarization	0.25%	1.50%	0.27%	0.01%
Target angle	0.00%	0.30%	0.20%	0.00%
Analyzing power	0.24%	0.30%	0.30%	0.10%
Levchuk effect	0.30%	0.20%	0.30%	0.00%
Target temperature	0.05%	0.00%	0.02%	0.00%
Dead time	-	0.30%	0.30%	0.10%
Background	-	0.30%	0.30%	0.10%
Optics	0.10%	-	-	-
Low/high beam current	0.20%	0.20%?	0.20%?	0.00%
Sum	0.51%	1.65%	0.72%	0.20%
Empirical fluctuations	-	0.50%	0.30%	0.30%?
Total	0.51%	1.70%	0.80%	0.36%

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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)

`https://userweb.jlab.org/~gen/hyd/loi_3.pdf`

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 μA: 1% in $\sim$10 min

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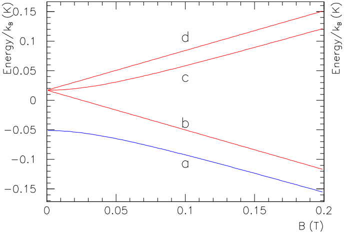
Hydrogen Atom in Magnetic Field

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

Complication from hyperfine splitting:



Low energy	High energy
$\|b\rangle = \|\downarrow\text{⇟}\rangle$	$\|d\rangle = \|\uparrow\text{⇞}\rangle$
$\|a\rangle = \|\downarrow\text{⇞}\rangle \cdot \cos\theta - \|\uparrow\text{⇟}\rangle \cdot \sin\theta$	$\|c\rangle = \|\uparrow\text{⇟}\rangle \cdot \cos\theta + \|\downarrow\text{⇞}\rangle \cdot \sin\theta$

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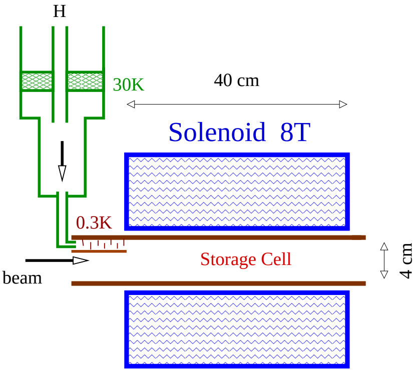
where $\tan 2\theta \approx 0.05/B(T)$, at 7 T $\sin\theta \approx 0.0035$
Mixture ∼53% of $|a>$ and ∼47% of $|b>$:
$\mathcal{P}_e \sim 1 - \delta, \qquad \delta \sim 10^{-5}$,
$\mathcal{P}_p \sim\ - 0.06$ (recombination ⇒ ∼80%)

Storage Cell



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
  - 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}He
- Density $3\cdot 10^{15} - 3\cdot 10^{17}$ cm^{-3}.
- Gas lifetime $>$ 1 h.

Dynamic Equilibrium and Proton Polarization

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

$|a\rangle = |\downarrow\Uparrow\rangle\alpha + |\uparrow\Downarrow\rangle\beta$ and

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

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

$\mathcal{P} \rightarrow 0.8$

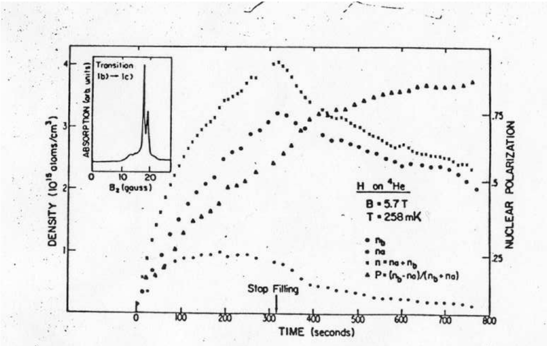


Fig. 5.11. Development of the densities of the hyperfine states and polarization as a function of time as measured by ESR. The inset shows the ESR line shape for one of the transitions (after van Yperen et al. 1983).

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

Gas Properties

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

Ref., date	conditions	H polarized		H unpolarized	
		σ, cm^2 10^{-16}	d, cm 10^{-8}	σ, cm^2 10^{-16}	d, cm 10^{-8}
Allison,71	T>1 K	87.0	5.26	68.0	4.65
Miller,77	T∼0 K	42.3	3.69	-	-
Friend,80	T∼0 K	6.5	1.44	4.9	1.25
Lhuillier,83	T=2.5 K	∼30.0	3.10	-	-

Using Miller,77:

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

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)
- $\mathcal{F} \ = 497$ MHz - bunch repetition rate
- $\gamma \geq \ \sim 10^4$ - beam γ-factor
- $\mathcal{I}_b \ = 100\ \mu$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
- $B(0,r,t) = \frac{\mathcal{I}_b}{\mathcal{F}\cdot\tau} \cdot e^{-0.5(t/\tau)^2} \cdot (1 - e^{-0.5(r/\sigma_{Bx})^2})\frac{1}{r} \cdot \frac{\mu_\circ}{(2\pi)^{3/2}}$

RF

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

$\hat{B}_n(r) = \frac{\mu_\circ \mathcal{I}_b}{2\pi r_\circ} \cdot exp(-\frac{\omega_\circ^2 k^2 \tau^2}{2}) \cdot G(r)$

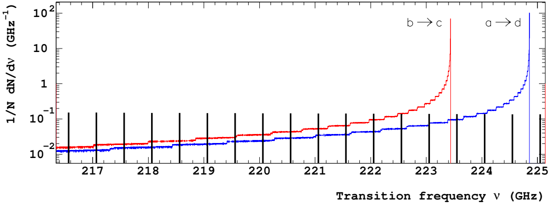
Depolarization by the Beam RF field

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

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

Non uniform magnetic field:

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



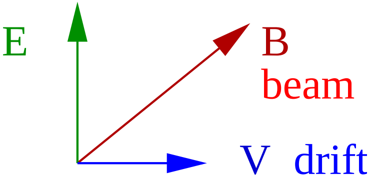
$$\frac{N_d}{N_a} \approx \frac{1}{\pi} \cdot \left(\frac{\mu_\circ \mu_e \mathcal{I}_b}{\hbar r_\circ}\right)^2 \cdot (1.205 + \ln\frac{r_\circ}{5\sigma_{Br}}) \sum_{k=-\infty}^{\infty} \frac{dP}{d\omega_{ad}}\bigg|_{\omega_\circ k} \cdot exp(-\omega_\circ^2 k^2 \tau^2) \cdot \tau_{dk}$$

- $\sim 10^{-4}$ 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 μA 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 $v = \vec{E} \times \vec{B}/B^2 \sim 12$ m/s
  - Cleaning time $\sim$ 20 μs
  - Contamination $< 10^{-5}$
  - Ions, electrons: same direction
  - Beam $\overline{E_r}(160\mu\text{m}) \approx 0.2$ 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% ($\sim 10^{-5}$ contamination).
Good understanding of the gas properties (without beam).

Gas Properties

- ○ Atom velocity $\approx$ 80 m/s
- ○ Atomic collisions* $\approx 1.4\ 10^5\ \mathrm{s}^{-1}$
- ○ 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 σ=0.5 ps
- ○ Repetition rate 497 MHz
- ○ Beam spot diameter $\sim$0.2 mm

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

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 μA Beam

- Depolarization by beam RF $< 2 \cdot 10^{-4}$
- Ion, electron contamination $< 10^{-5}$
- Excited states $< 10^{-5}$
- Ionization heating $< 10^{-10}$

Expected depolarization $< 2 \cdot 10^{-4}$

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?

Summary on Atomic Hydrogen for Møller Polarimetry (cont.)

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

Gas Heating

- $\Delta T \propto \mathcal{I}_b \cdot n\sigma/\sqrt{T}$,
- $\Delta T(0) \approx 0.03K \cdot \ln\left(\frac{R}{r_B} + 0.5\right)$,
  - $r_B = 0.2$ 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 μA, $3 \cdot 10^{15}$ 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

- Larmore $\omega_L = q_e B/m = 1.4 \cdot 10^{12}\ \mathrm{s}^{-1}$ for e$^-$, $0.8 \cdot 10^9\ \mathrm{s}^{-1}$ 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 μs : contamination $< 10^{-5}$
- Positive and negative - the same direction
- Average field of the beam $E_{max}(160\mu\mathrm{m}) \approx 0.2$ 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 $< 3 \cdot 10^{-5}$

$|a\rangle \rightarrow |d\rangle$ transitions

- 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