Electron Beam Polarimetry for Future PV Experiments at JLab

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Seminar at UVA

Outline

1. PV opportunities at 12-GeV
2. Electron Polarimetry
3. Møller with Atomic Hydrogen Target
4. Appendix

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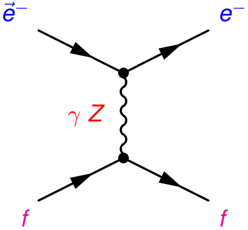
Parity Violation in Electron Scattering at $Q^2 \ll M_Z^2$

Polarized beam on Unpolarized target



$$\sigma \propto |A_\gamma + A_{weak}|^2 \sim |A_\gamma|^2 + 2A_\gamma A^*_{weak} + \dots$$

$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{A_{weak}}{A_\gamma} \propto \frac{G_F Q^2}{4\pi\alpha}\mathbf{g}$$

$\mathbf{g} = g_A^e G_V^T \pm g_V^e G_A^T$, depend on $\sin^2\theta_W$, kinem.

for $f \equiv l^\pm$ $\mathbf{g} \propto (1 - 4\sin^2\theta_W) < 0.05$

Observable $A \sim 10^{-7} - 10^{-3}$, sensitive to:

- Electroweak coupling: ⇒ CM tests
  Magnification: $\sin^2\theta_W \sim 0.23 \Rightarrow \delta(\sin^2\theta_W) \sim 0.02\frac{\delta(A)}{A}$
- Target structure ⇒ unusual FF, PDF combinations

PV opportunities at 11-GeV

PV at 6 GeV

CEBAF is a perfect facility for PV

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

Measured: G_s
Elastic e p, e ^{4}He (HAPPEX, G0)
Coming:

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

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

Proposals:

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

Physics Goals

1. Precision measurement of $\sin^2\theta_W$ at $Q^2 \ll M_Z^2$: CM test (Møller)
2. Measurement of quark axial couplings C_{2q}: CM test (PV-DIS)
3. Electroweak probe of the strong interactions (PV-DIS)

Couplings in electroweak theory

Constants

- $\alpha(Q^2) \overset{Q^2\to 0}{\sim} 1/137$ (μ_e)
- $G_F \sim 1.16 \cdot 10^{-5}$ GeV^{-2} (τ_μ)
- $M_Z \sim 91.2$ GeV (LEP-I)
- Fermions/Higgs masses, CKM

Derivatives

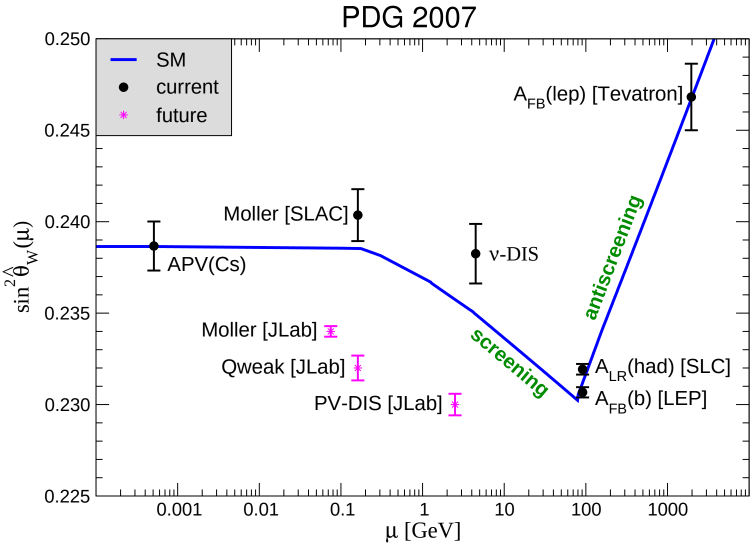
Several renormalization schemes
Popular one: $\overline{MS}$

- Renormalization scale: M_Z
- Defined $\hat{s}_Z^2 = \sin^2\theta_W(M_Z)$
- Couplings absorb loops etc.
- Running $\sin^2\theta_W(Q^2)$
- Weak dependence of $\hat{s}_Z^2$ on m_t

Experimental goal: measure $\hat{s}_Z^2(Q^2)$

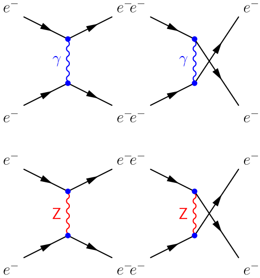
$\hat{s}_Z^2(Q^2) \xrightarrow{\overline{MS}}$ observables

Running of $\sin^2\theta_W$ in $\overline{MS}$

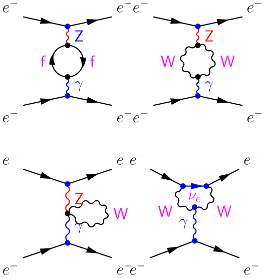


Diagrams contributing to the $\sin^2\theta_W$ running

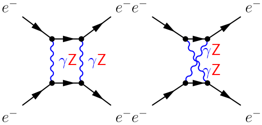
Tree diagrams



Loop diagrams



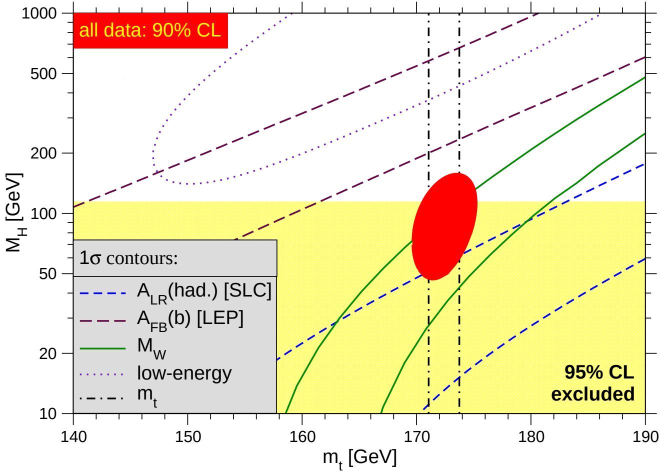
Box diagrams



Main contribution:
f-loop

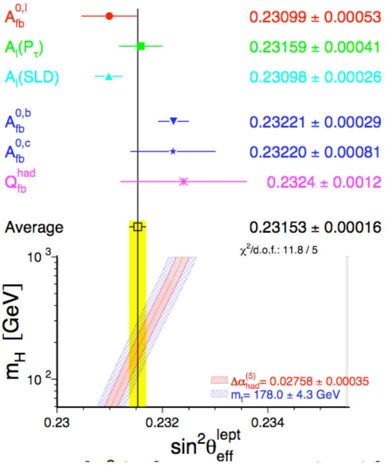
“New physics”: SUSY, Z’, leptoquarks etc. may also contribute

Constraints on M_H



Experiments: $\sin^2\theta_W$ at Z pole

Most accurate measurements so far are at Z-pole. BUT:



Pointed out by Marciano:

3σ deviation

A_L(SLD)	A_{FB}(LEP)
$\frac{\sigma_L-\sigma_R}{\sigma_L-\sigma_R}$	$\frac{\sigma_F-\sigma_B}{\sigma_F-\sigma_B}$
$\vec{e}^- e^+ \to Z$	$e^- e^+ \to Z \to b\bar{b}$
0.23098(26)	0.23221(29)
Higgs mass (GeV)	
35^{+26}_{-17}	480^{+350}_{-230}
ruled out experimentally	higher than expected
also APV	also E158
favors SUSY	rules out SUSY favors Technicolor

M_H, SUSY may be found by the LHC

Special sensitivity of PV-Møller

Assume $\sigma(\sin^2\theta^{eff}) = 0.00025$

Physics Constrains

- Model independent: contact interaction (compositeness)

  $$\mathcal{L} = \frac{4\pi}{2\Lambda_{ee}^2}\left[\eta_{LL}(\overline{\psi}_L\gamma_\mu\psi_L)^2 + \eta_{RR}(\overline{\psi}_R\gamma_\mu\psi_R)^2 + \eta_{LR}(\overline{\psi}_L\gamma_\mu\psi_L)(\overline{\psi}_R\gamma_\mu\psi_R)^2\right]$$

  $$\sin^2\theta_W^{meas} - \sin^2\theta_W^{SM} = \pm\frac{\pi}{G_F\sqrt{2}}\frac{\eta_{LL}+\eta_{RR}+\eta_{LR}}{\Lambda_{ee}^2}$$

  $\Lambda_{LL}^+ >$ 8 TeV ⇒ 15 TeV at 95% CL

  $\Lambda_{LL}^- >$ 16 TeV ⇒ 38 TeV

- Model dependent: extra Z (1 in $SO(10)$ or 2 in E_6)

  $$\frac{1-4s_W^{2(obs)}}{1-4s_W^{2(SM)}} = 1 + \frac{M_Z^2}{M_{Z1}^2}$$

  $M_{Z1} >$ 0.7 TeV ⇒ 1.8 TeV

- Other: SUSY, doubly-charged Higgs etc., but no leptoquarks.

PV DIS Asymmetry

$$\mathcal{L}^{eHadron} = \frac{G_F}{\sqrt{2}} \sum_i (C_{1i} \cdot j^e_A \cdot j^i_V + C_{2i} \cdot j^e_V \cdot j^i_A)$$

where i are partons (quarks)

$$C_{1q} = 2g^e_A g^i_V = -C_{1\overline{q}} \approx -t_{3iL} + 2Q_{ei}s^2_W$$
$$C_{2q} = 2g^e_V g^i_A = +C_{2\overline{q}} \approx -t_{3iL}(1 - 4s^2_W)$$

Cahn,Gilman 1978

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}[a(x) + Y(y) \cdot b(x)]$$

$$Y(y) = \frac{1-(1-y)^2}{1+(1-y)^2}, \quad y = \frac{\nu}{E}, \quad x = x_{Bj}$$

$$a(x) = \sum_i f_i(x) C_{1i} Q_{ei} / \sum_i f_i(x) Q^2_{ei}$$
$$b(x) = \sum_i f_i(x) C_{2i} Q_{ei} / \sum_i f_i(x) Q^2_{ei}$$

$f_i(x)$ - quark distribution functions

Isoscaler target

Deuterium: $f(x)$ largely cancel

$q^\pm \equiv q \pm \overline{q}$ in proton

$$a(x) = \frac{3}{10}(2C_{1u} - C_{1d})(1 + R_s(x))$$
$$b(x) = \frac{3}{10}(2C_{2u} - C_{2d})(1 - R_a(x))$$

$$\left.\begin{aligned} R_s(x) &= \frac{2s^+}{u^+ + d^+} \\ R_a(x) &= \frac{\overline{u} + \overline{d}}{u^+ + d^+} \end{aligned}\right\} \xrightarrow{large\ x} 0$$

$$A_{PV}(x, Q^2)/Q^2 \xrightarrow{large\ x} \mathcal{A}(y)$$

Corrections from:

- s-quarks, sea-quarks
- target mass
- higher twists

Prescott 1979 $s^2_W = 0.22 \pm 0.02$ using SM

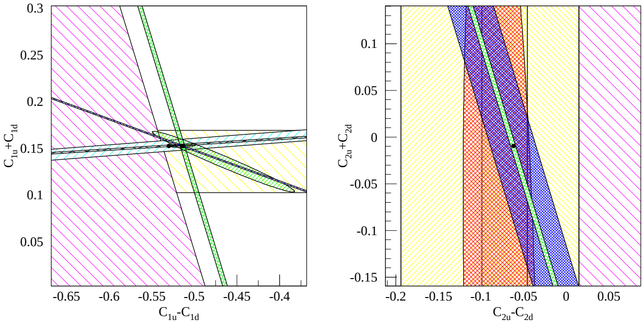
Measurements of the weak charges C_{1q}, C_{2q}

Existing measurements:

- PV-elastic in $e^- p, d, Be, C$ at Bates, Mainz, JLab
- PV-DIS in $e^- d$, $\mu^\pm C$ at SLAC, CERN
- Atomic PV experiments

Planned measurements:

- PV-DIS in $e^- d$ at Jlab 6 GeV (Hall A) $x \sim 0.3$
- PV-DIS in $e^- d$ at Jlab 12 GeV (Hall C) $x \sim 0.3$



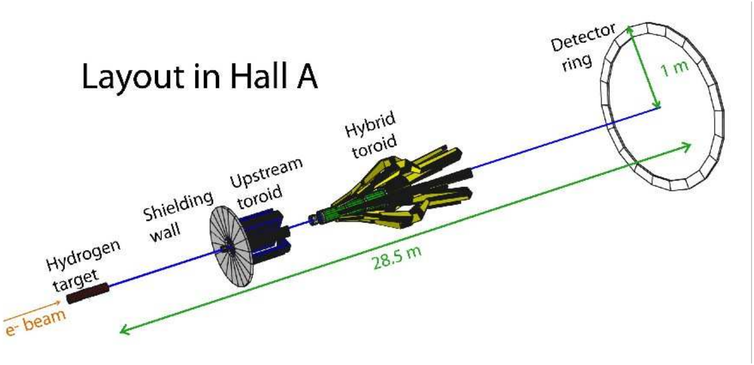
Hadronic Physics at $x_{Bj} > 0.5$

Corrections to EW results

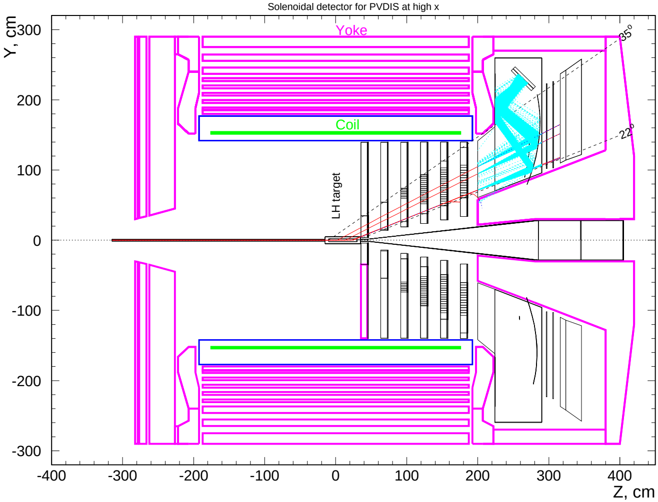
- CSV $\beta_{CSV} x^2$
- Higher twists $\beta_{HT} \frac{1}{(1-x)^3 Q^2}$

Mesurements at various x, Q^2 to extract the corrections.

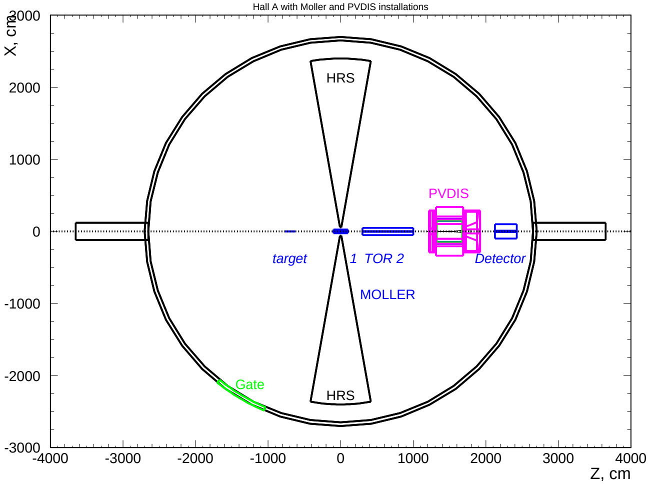
Spectrometer for the Møller PV Experiment



Spectrometer for PVDIS



Installation in Hall A



Error Budget of Møller and PVDIS Experiments

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

PVDIS

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

Electron Polarimetry for PV at JLab: Features

- Energy range $E_{beam} = 6.6 - 11\ GeV$
- Current range $E_{beam} = 50 - 100\ \mu\text{A}$

- Statistical error for a period of a possible polarization change ($\sim$ 1 h)
- Systematic error
  - Does polarimetry use the same beam (energy, current, location) as the experiment?
  - Continuous or intermittent (invasive?)

Methods Used for Absolute Electron Polarimetry

Spin-dependent processes with a known analyzing power.

Atomic Absorption

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

Atomic levels: $(3p^5 4p)^3 D_3 \rightarrow (3p^6 4s)^3 P_2$ 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: $e^{-}\uparrow + Z \rightarrow e^{-} + Z$ σ_{syst} ~3%, ⇒1% (?)

invasive, diff. beam

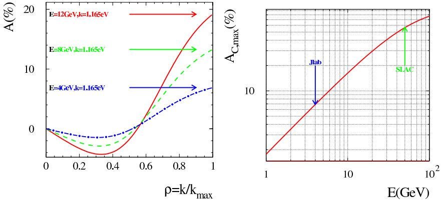
Spin-Spin Interaction

- Møller scattering: $\vec{e}^{\,-} + \vec{e}^{\,-} \rightarrow e^{-} + e^{-}$ at >0.1 GeV,
  $\sigma_{syst} \sim$ 1-2% , ⇒ 0.5%
  intermittent, mostly invasive, diff. beam
- Compton scattering: $\vec{e}^{\,-} + (h\nu)_{\sigma} \rightarrow e^{-} + \gamma$ at >0.5 GeV ~ 1-2%, ⇒0.5%.
  non-invasive, same beam

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

Compton Polarimetry

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

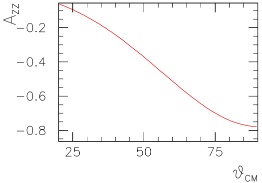


- Rad. corrections to Born $< 0.1\%$
- Detecting: γ (0°), e^- $E < E_\circ$
- Strong $\frac{dA}{dk'}$ - good $\sigma E_\gamma / E_\gamma$ needed
- $A \propto kE$ at $E < 20$ GeV
- $T \propto 1/(\sigma \cdot A^2) \propto 1/k^2 \times 1/E^2$
- $\mathcal{P}_{laser} \sim 100\%$
- Non-invasive measurement

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

Møller Polarimetry

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

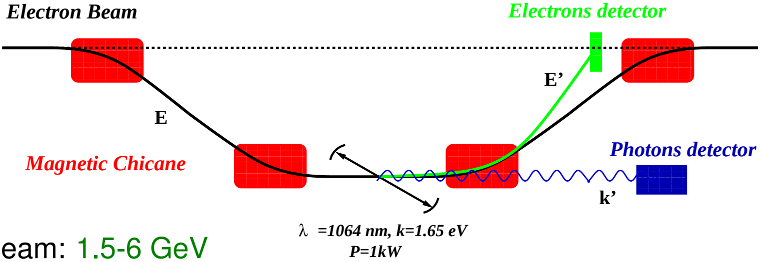


$A(E) = -\frac{7}{9}$

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

- Rad. corrections to Born $< 0.3\%$
- Detecting the e^- at $\theta_{CM} \sim 90°$
- $\frac{dA}{d\theta_{CM}}\big|_{90°} \sim 0$ - good systematics
- Beam energy independent
- Coincidence - no background
- Ferromagnetic target $\mathcal{P}_T \sim 8\%$
  - $\langle I_B \rangle < 3\ \mu A$ (heating)
  - Levchuk effect
  - Low $\mathcal{P}_T \Rightarrow$ dead time
  - Syst. error $\sigma(\mathcal{P}_T) \sim 2\%$ (0.5%?)

Compton Polarimeter at low enegy: CW cavity



- Beam: 1.5-6 GeV
- Beam: 5 – 100 μA at 500 MHz
- Laser: 1064 nm, 0.24 W
- Fabry-Pérot cavity $\times$4000 $\Rightarrow$ 1 kW
- Crossing angle 23 mrad
- e^- detector - Silicon μ-strip
- γ detector - calorimeter

Stat: 1.0% 30 min, 4.5 GeV, 40 μA

Syst: 1.2% at 4.5 GeV

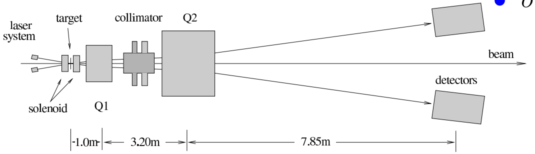
Upgrade Plans - 1% at 0.85 GeV

- Laser: 532 nm, 0.1 W
- Cavity $\times$15000 $\Rightarrow$ 1.5 kW
- Detector upgrade

Møller Polarimeter with Saturated Iron foil

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

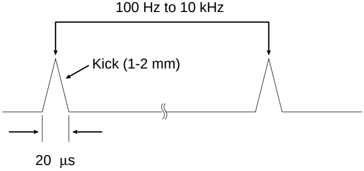
- External $B_Z \sim 4\ T$
- Target foils 4-10 μm, perp. to beam
- $\mathcal{P}_t$ not measured
- Important: annealing, etc.



source	$\sigma(A)/A$
optics, geometry	0.20%
target	0.28%
Levchuk effect	0.30%
total	0.46%
$\Rightarrow$ 100 μA	?

Tests for high current

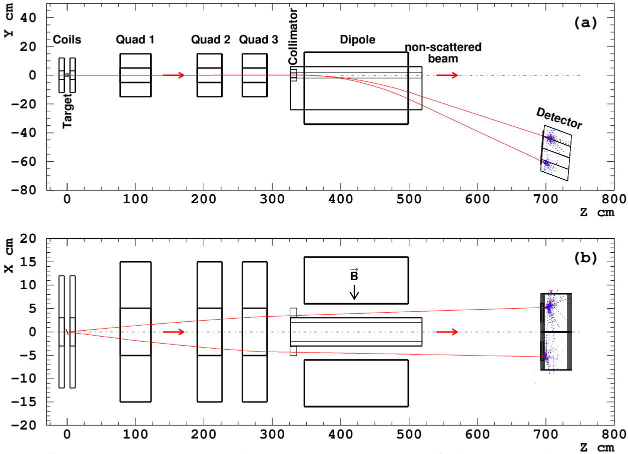
- Beam $\sigma_X \approx 50\mu$m $> r = 12\mu$m
- At 20μA - accidentals/real≈0.4
- $\sigma_{stat} \sim 1\%$ in 2h



Current Studies

- A 1μm thick half-foil
- Higher duty factor

Hall A Møller Polarimeter



- Minimal Levchuk
- $\sigma_{stat} = 1\%$ in $\sim$2–3 min
- $B_Z \sim 25$ mT field
- Foil at 20° to field
- Foils 5–30μm
- Beam <2μA

Planned upgrade to saturated foils (as in Hall C).

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)

`http://www.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 50 μA: 1% in $\sim$10 min

Møller Systematic Errors

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

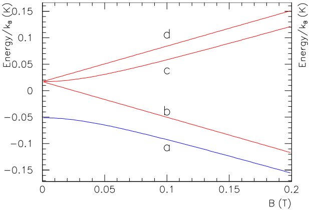
Variable	Hall C	Hall A		
		Present	Upgrade	Proposed
Target polarization	0.25%	2.00%	0.50%	0.01%
Target angle	0.00%	0.50%	0.00%	0.00%
Analyzing power	0.24%	0.30%	0.30%	0.10%
Levchuk effect	0.30%	0.20%	0.20%	0.00%
Target temperature	0.05%	0.00%	0.02%	0.00%
Dead time	-	0.30%	0.30%	0.10%
Background	-	0.30%	0.30%	0.10%
Others	0.10%	0.30%	0.30%	0.30%?
Total	0.47%	2.10%	∼0.80%	∼0.35%

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

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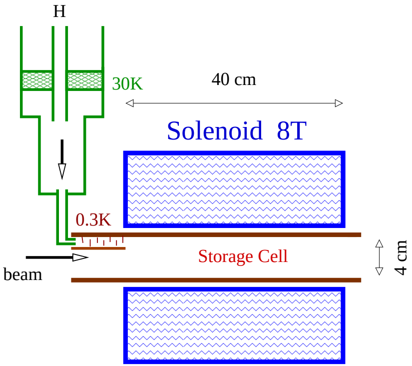
where $\tan 2\theta \approx 0.05/B(T)$, at 7 T $\sin\theta \approx 0.0035$
Mixture ~53% of $|a>$ and ~47% of $|b>$:
$\mathcal{P}_e \sim 1-\delta, \qquad \delta \sim 10^{-5}$,
$\mathcal{P}_p \sim\ -0.06$ (recombination ⇒ ~80%)

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→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!

$\mathcal{P} \rightarrow 0.8$

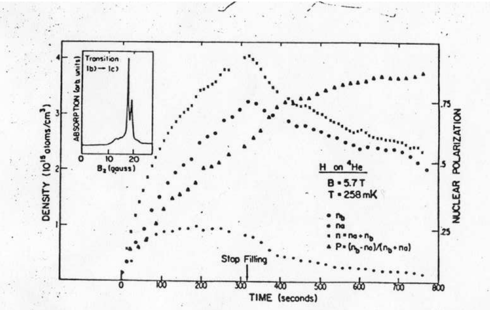


Fig. 5.11. Development of the densities of the hyperfine states and polarization as a function of time as measured by ESR. The inset shows the ESR line shape for one of the transitions (after van Yperen et al. 1983).

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 $\approx 1.4\ 10^5\ \mathrm{s}^{-1}$
- ○ 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

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 $< 10^{-10}$

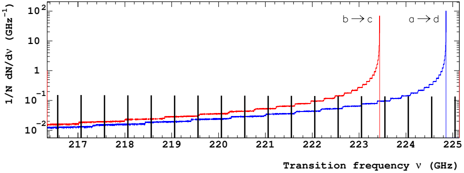
Expected depolarization $< 2 \cdot 10^{-4}$

Contaminations and Depolarization of the Target Gas

100 μA CEBAF beam:

Beam RF influence

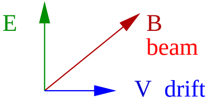
- $|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle$ $\sim$200 GHz
- RF spectrum: flat at $<$300 GHz



- $\sim 10^{-4}$ 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

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 $\overline{E}_r(160\mu\text{m}) \approx 0.2$ 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

Conclusion

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.

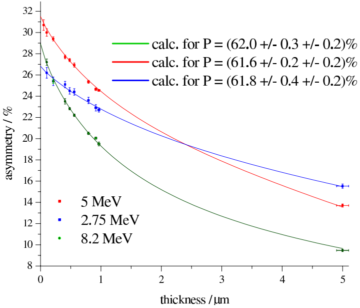
Steps to develop atomic hydrogen target

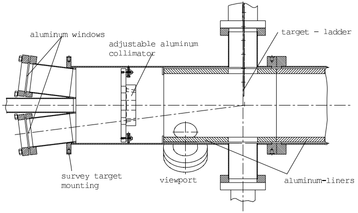
- Find a way to insert electrodes into the storage cell
- Find a way to measure/subtract the residual gas contribution
- Obtain funding to build a storage cell ...

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





- Extrapolation to zero target thickness
- $e^- \uparrow < 5\ \mu A$ - extrapolation needed

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