Electron Polarimetry Overview

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[1] JLab

Workshop: *Intense Electron Beams (IEB)*
June 17 - 20, Cornell, NY

Outline

1. 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
2. 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 $\sim$ 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 $\sim$ 87%
- Beam current $< 80\mu$A
- Low noise beam

- ○ EW Møller
- ○ EW DIS
- ○ Neutron skin at $\sim$2 GeV

Polarimetry with exiting techniques:
0.5%: challenging

PV at 100-500 MeV

- High polarization $\sim$ 87%
- Very high beam current $\sim 1-10$ 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

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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

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- Stat. error for a period of a possible polarization change ($\sim$ 1 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

$\vec{e}^{\,-}$ ∼50 keV decelerated to ∼13 eV $\vec{e}^{\,-} + Ar \to \vec{Ar}^{*} + e^{-}$, $\vec{Ar}^{*} \to Ar + (h\nu)_{\sigma}$
Atomic levels: $(3p^{5}4p)^{3}D_{3} \to (3p^{6}4s)^{3}P_{2}$ 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: $e^{-}\uparrow + Z \to e^{-} + Z$
σ_{syst} ∼3%, ⇒1% (?)
Mainz group: double Mott - absolute measurement σ_{syst} ∼0.3% seems feasible. invasive, diff. beam

Spin-Spin Interaction

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

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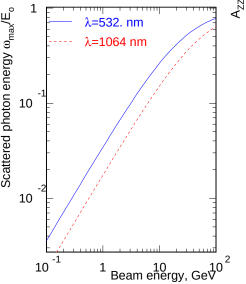
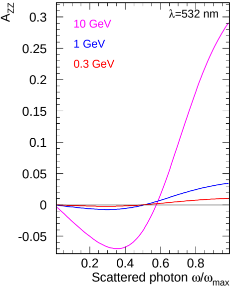
$$\frac{\sigma_{\uparrow\uparrow}-\sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow}+\sigma_{\uparrow\downarrow}} = A\cdot\mathcal{P}_b\mathcal{P}_t$$

Compton Polarimetry

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



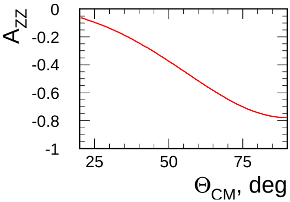


- Rad. corrections to Born $< 0.1\%$
- Detecting e^-, γ
- Strong $\frac{dA}{dk'}$ - good $\sigma E_\gamma / E_\gamma$ needed
- $A \propto kE$ at $E < 20$ GeV
- $T \propto 1/(\sigma\cdot A^2) \propto 1/k^2 \;\times\; 1/E^2$
- $\mathcal{P}_{laser} \sim 100\%$
- Non-invasive measurement

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

Møller Polarimetry

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



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

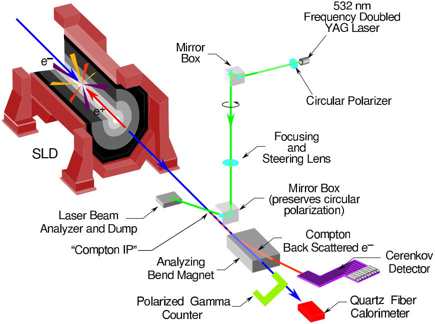
$\frac{d\sigma}{d\Omega_{CM}} \propto \frac{1}{s}$

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

- Rad. corrections to Born $< 0.3\%$
- Detecting the e^- at $\theta_{CM} \sim 90^\circ$
- $\frac{dA}{d\theta_{CM}}\big|_{90^\circ} \sim 0$ - 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 $\sigma(\mathcal{P}_T) > 0.4\%$
    - Invasive measurement
    - Best syst. errors reported 0.5-1%

Compton Polarimeters: Best Accuracy at High Energy

SLAC SLD



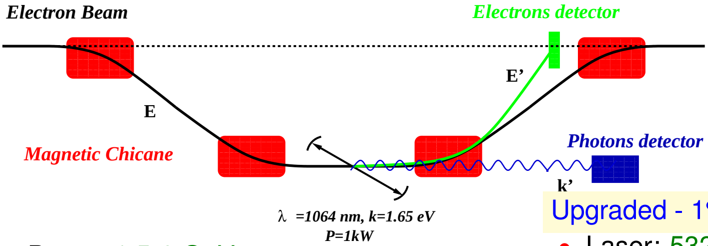
source	$\sigma(\mathcal{P})/\mathcal{P}$ SLD 1998	ILC Goal
Laser polarization	0.10%	0.10%
Analyzing power	0.40%	0.20%
Linearity	0.20%	0.10%
Electronic noise	0.20%	0.05%
total	0.50%	0.25%

M.Woods, JLab Polarimetry workshop, 2003

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

- e^- 17-30 GeV detector - gas Cherenkov
- γ detector - calorimeter
- Statistics 1% in 3 min

Compton Polarimeter in Hall A at JLab: CW cavity



- Beam: 1.5-6 GeV
- Beam: $5-100\ \mu$A at 500 MHz
- Laser: 1064 nm, 0.24 W
- Fabry-Pérot cavity $\times$4000 $\Rightarrow$ 1 kW
- Crossing at 23 mrad $\varepsilon \sim$ 1%
- 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

Upgraded - 1% at 1.0 GeV

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

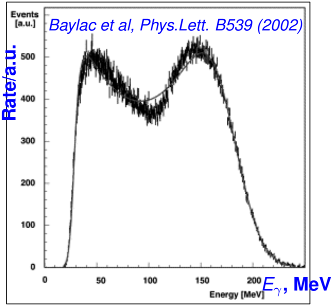
Prospects for 11 GeV

source	e$^-$	γ
Laser polarization	0.20%	
Analyzing power	0.20%	0.40%
Dead time	0.20%	0.00%
Pileup	0.00%	0.10%
Background	0.05%	0.05%
Others	0.03%	0.03%
Total	0.35%	0.46%

Compton Polarimeters - What is Measured?

Photon Detector

- Counting rate (ω), sensitive to
  - – thresholds
  - – calibration

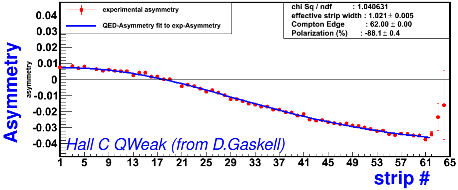


Baylac et al, Phys.Lett. B539 (2002)

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

Electron Detector

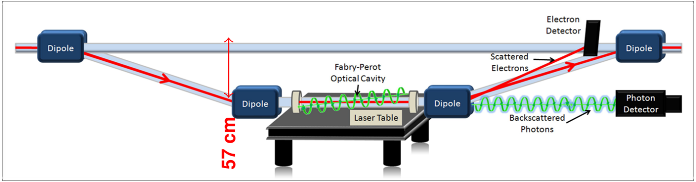
- Counting rate (E_e), sensitive to
  - – alignment
  - – detector efficiency
  - + calibration using: Compton edge, 0-crossing



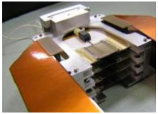
Hall C QWeak (from D.Gaskell)

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

Compton Polarimeter in Hall C for experiment QWeak



e^-: Diamond
μ-strips



- Beam: 1.16 GeV, $< 180\ \mu$A
- Laser: 532 nm, 10 W
- Fabry-Pérot cavity $\times$100 $\Rightarrow$ 1 kW
- Crossing at 23.5 mrad
- γ detector PbWO$_4$ (integration).
- New! e^- detector - Diamond μ-strip
  $\sim$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: $\sim$25% at $\omega_{max}/2$

- Electron data analysis:
  - 17 mm separation at ω_{max}
  - Diamond: 3 planes operational
  - Diamond efficiency $\sim$70%/plane
  - "Tracks" reconstructed in FPGA
    dead time: can be improved

Largest Uncertainties

source	Current, %	Outlook, %
Laser polarization	0.18	0.10
DAQ	0.42	0.15
Trigger	0.19	0.10
Beam vert. angle	0.20	0.10
Others		
Total	0.59	0.38

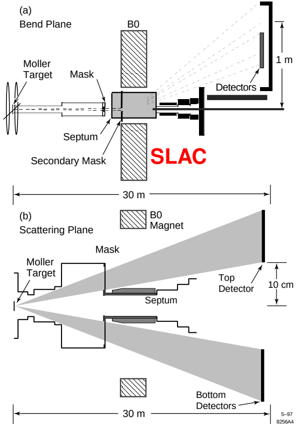
Compton at 500 MeV?

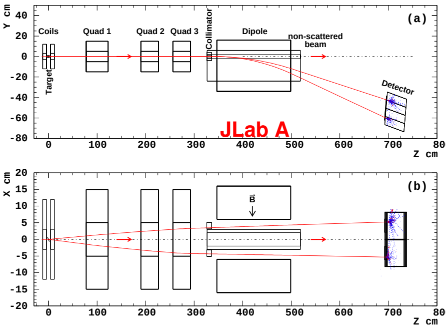
- 532 nm: $\omega_{max} = 9$ MeV, A_{ZZ}=1.8%
- FOM(500 MeV)≈FOM(1.GeV)/4.
- Electron detection to $0.5\omega_{max}$: a large chicane: $\Delta h = 100$ cm ⇒ 0.9 cm from the beam (similar to QWeak)
- High current $I_e \sim 1 - 10$ mA ×5-50 more than QWeak
  Can one reduce the light intensity?
  - Can 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° crossing (×100)
    Much easier!
  - 10 MHz rate⇒Integrating mode. Ability to count?
  - Radiation hardness $\sim$ 500 MRad

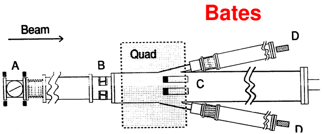
0.5% seems possible with existing technology
0.3% would probably need a breakthrough

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 ⇒ large Levchuk effect







Ferromagnetic targets for Møller Polarimetry

Polarized electron targets: magnetized ferromagnetic foils

- Iron: polarized *d*-shell (6 positions occupied out of 10)
- $\mathcal{P}_e$ 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 $\sim 90^\circ$

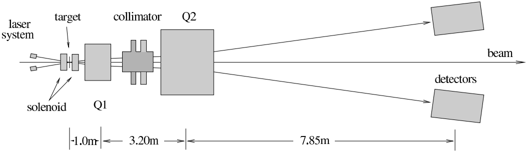
- Magnetization perp. to the foil
- Magnetization - from world data
- Foil saturated
- Polarization is robust.
- Polarization accuracy $\sim 0.5\%$

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 μm, perp. to beam
- $\mathcal{P}_t$ not measured
- Levchuk: 3% correction

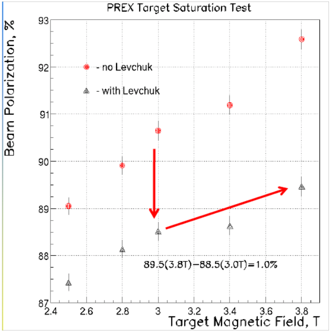


source	$\sigma(A)/A$
optics, geometry	0.20%
target	0.28%
Levchuk effect	0.30%
total at 3 μA	0.46%
$\Rightarrow$ 100 μA	?

Important factors

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

Target cloned in Hall A

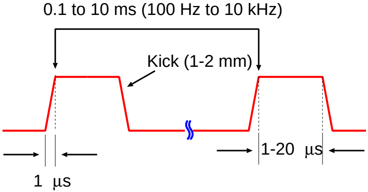


High beam currents at saturated foils

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

Hall C

- Half-moon shape foil
- Kicker magnet



A 1μm thick half-foil: mech. problems:

- Foil unstable: holder design
- Thicker foil - high rate
- At 20μA - accidentals/real$\approx$0.4

Hall A

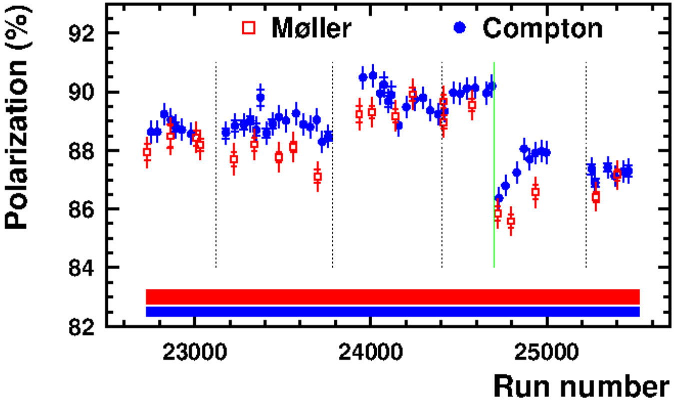
- Beam duty cycle $< 5\%$
  - Beam bunches 500 MHz/n, n=16
  - “Tune beam”: 4 ms pulses $\sim$60 Hz
  - Instantaneous counting rate at 50μA will be $\times$3 higher
  - More invasive than a kicker scheme

Happened to be too invasive for the accelerator running

May eventually work but so far it did not.
Needs beforehand planning on the machine side

QWeak: Compton/Møller comparison (preliminary)

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 ($\sim 3 \cdot 10^{16}$ atoms/cm^2).

Variable	Hall C		Hall A	
	Instrument	QWeak	Fe 4T	H 100% pol
Rad. corrections	-		0.10%	0.10%
Target polarization	0.25%*		0.27%	0.01%
Target angle	0.00%		0.20%	0.00%
Analyzing power	0.24%		0.30%	0.10%
Levchuk effect	0.30%*		0.30%	0.00%
Target temperature	0.05%		0.02%	0.00%
Dead time	-		0.30%	0.10%
Background	-		0.30%	0.10%
Optics	0.10%		-	-
Low/high beam current			0.20%?	0.00%
Sum	0.47%		0.72%	0.20%
Empirical fluctuations	-		0.30%	0.30%?
Total	0.47%	0.60%	0.80%	0.36%

* Reduction is unlikely

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, continuation

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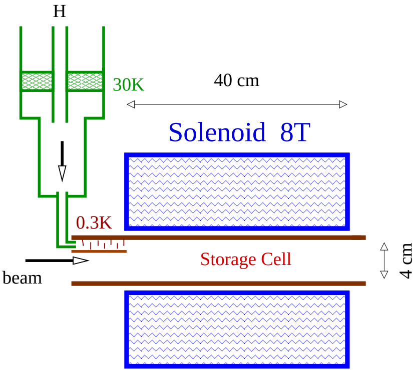
Storage Cell



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.

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).

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

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 $\propto Q^2_{bunch} \cdot N_{repet}$: at 1300 MHz $I_{beam} < 0.5$ mA
- Ionization $\propto I_{beam}$: $I_{beam} < 2$ 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 $\sigma P/P$ ∼0.5%
- Hydro-Møller is limited by $I_{beam} < 0.5$ mA
- The accurate method requires a strong longitudinal field: ∼0.7 T·m for high-field iron or, even ∼2 T·m for the hypothetical hydro-Møller
  - Strong beam steering! It is bad enough at ∼1 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 $I_{beam} < 3\ \mu A$ 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 mA
- The machine and the experimental area should be designed to provide the polarimetry needs

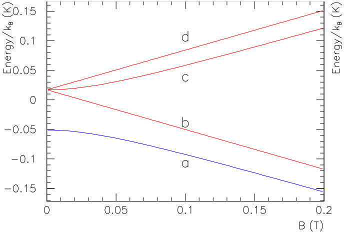
Backup

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

$|b\rangle = |\downarrow\text{⇟}\rangle$

$|a\rangle = |\downarrow\text{⇞}\rangle \cdot \cos\theta - |\uparrow\text{⇟}\rangle \cdot \sin\theta$

High energy

$|d\rangle = |\uparrow\text{⇞}\rangle$

$|c\rangle = |\uparrow\text{⇟}\rangle \cdot \cos\theta + |\downarrow\text{⇞}\rangle \cdot \sin\theta$

---

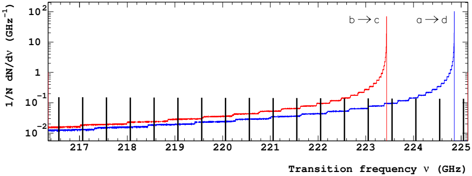
where $\tan 2\theta \approx 0.05/B(T)$, at 7 T $\sin\theta \approx 0.0035$
Mixture ∼53% of $|a>$ and ∼47% of $|b>$:
$\mathcal{P}_e \sim 1 - \delta, \qquad \delta \sim 10^{-5}$,
$\mathcal{P}_p \sim\ -0.06$ (recombination ⇒ ∼80%)

Contamination and Depolarization of the Target Gas

100 μA CEBAF beam:

Beam RF influence

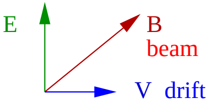
- $|a\rangle \to |d\rangle$ and $|b\rangle \to |c\rangle$ ~200 GHz
- RF spectrum: flat at $<$300 GHz



- $\sim 10^{-4}$ 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 ~40% in beam
- Solution: electric field ~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



Dynamic Equilibrium and Proton Polarization

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

$|a\rangle = |\downarrow\text{⇡}\rangle\alpha + |\uparrow\text{⇣}\rangle\beta$ and

$|b\rangle = |\downarrow\text{⇣}\rangle$

As a result, $|a\rangle$ dies out and only $|b\rangle = \downarrow\text{⇣}$ is left!

$\mathcal{P} \rightarrow 0.8$

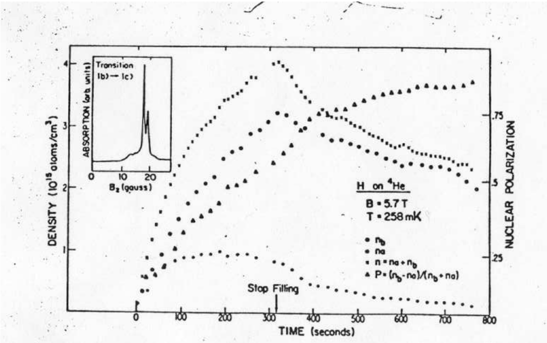


Fig. 5.11. Development of the densities of the hyperfine states and polarization as a function of time as measured by ESR. The inset shows the ESR line shape for one of the transitions (after van Yperen et al. 1983).

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 σ

Ref., date	conditions	H polarized σ, cm^2 10^{-16}	H polarized d, cm 10^{-8}	H unpolarized σ, cm^2 10^{-16}	H unpolarized 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
- $\frac{dn_{col}}{dt} = \sigma \cdot 4n\sqrt{\frac{kT}{\pi m}} \approx 1.4 \cdot 10^5\ \text{s}^{-1}$ - 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 $|Z| = 10$ cm
- $\tau_R \approx 2\ \text{ms}$ - mean drift time R=0 $\rightarrow$ 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 $\omega_\circ = 2\pi\mathcal{F}$.

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

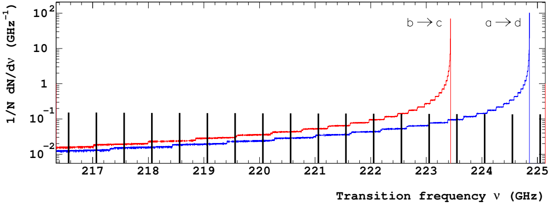
Depolarization by the Beam RF field

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

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

Non uniform magnetic field:

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



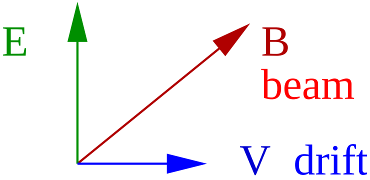
$$\frac{N_d}{N_a} \approx \frac{1}{\pi} \cdot \left(\frac{\mu_\circ \mu_e \mathcal{I}_b}{\hbar r_\circ}\right)^2 \cdot \left(1.205 + \ln \frac{r_\circ}{5\sigma_{Br}}\right) \sum_{k=-\infty}^{\infty} \left.\frac{dP}{d\omega_{ad}}\right|_{\omega_\circ k} \cdot exp(-\omega_\circ^2 k^2 \tau^2) \cdot \tau_{dk}$$

- $\sim 10^{-4}$ 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 ~ 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?

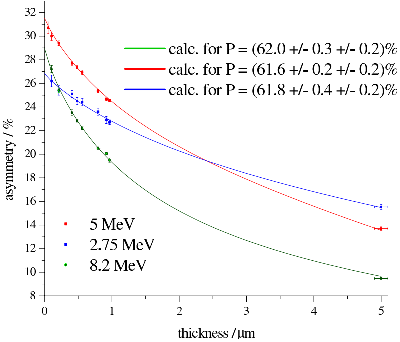
Residual Helium Gas in the Storage Cell

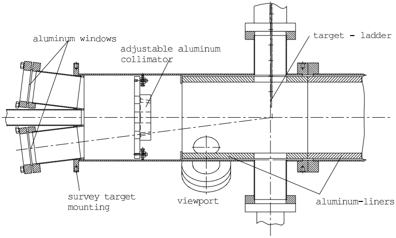
- $\sim$0.1% - from Michigan measurements
- Strategy:
  - Measure with a probe (technique used at Michigan)
  - Measure with the beam changing the hydrogen concentration
  - Reconstruct the trajectories of the Møller electrons using special detectors (Si strips) and the position of the vertex (inside the solenoid and at the edges). May be difficult for very low and very high beam energies.

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 thicknes
- $e^- \uparrow < 5\ \mu$A - extrapolation needed

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