Møller Polarimetry with Atomic Hydrogen Targets

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Proposal for high precision electron polarimetry at medium energies

- Motivation
  - Demand for precision polarimetry
  - Møller and Compton polarimetry
- Polarimetry with Atomic Hydrogen Targets
  - Storage of ultra-cold polarized atomic hydrogen
  - Systematic errors
  - Figure of merit
  - Impact of the CEBAF beam on the stored gas

Challenges to Polarimetry

Parity violating electron scattering experiments:

- Progress in reducing the systematic errors
- Beam polarization: becomes the dominant error!

JLab planned experiments, beam current 50-100μA:

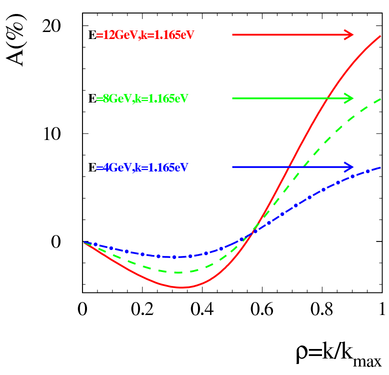
Experiment	Syst. err without pol	Polar. error	Stat. error	Energy GeV	Comments
$^4He\ \rho_s$	0.6%	2.0%	2.2%	3.2	soon
^{208}Pb n-skin	0.5%	1.0%	3.0%	0.85	soon
eP $sin^2\theta_W$	2.4%	$<$1.4%	2.8%	1.16	?
DIS $sin^2\theta_W$	0.3%	$<$1.0%	0.8%	10.0	distant

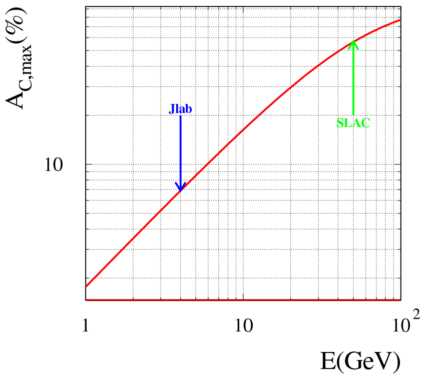
A 1%, or better, polarimetry accuracy is needed

Møller Polarimetry with Atomic Hydrogen Targets

Compton Polarimetry

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





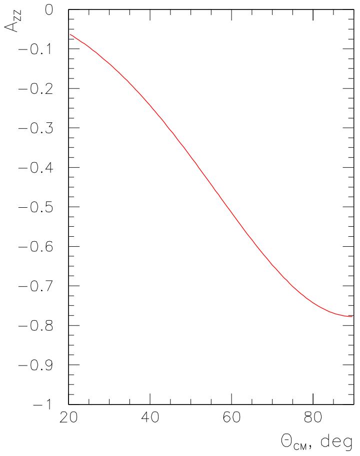
- Detecting the γ at 0 angle
- Detecting the e^- with an energy loss
- $A \propto kE$ at $E < 20$ GeV
- Strong $\frac{dA}{dk'}$ - good $\sigma E_\gamma / E_\gamma$ needed
- $T \propto 1/(\sigma \cdot A^2) \propto 1/k^2 \;\times\; 1/E^2$
- $\mathcal{P}_{laser} \sim 100\%$
- Non-invasive measurement

Syst. error 3→50 GeV: $\sim 1.5 \to 0.5\%$

Hard at <1 GeV

Møller Polarimetry

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



A(E)=const=7/9

- Detecting the e^- at $\theta_{CM} \sim 90^\circ$
- Beam energy independent
- $\frac{dA}{d\theta_{CM}}|_{90^\circ} \sim 0$ - good systematics
- Ferromagnetic target $\mathcal{P}_T \sim 8\%$
  - ○ Beam $I_B < 2 - 4\ \mu A$ (heating)
  - ○ Invasive measurement
  - ○ Syst. error $\sigma\mathcal{P}_T \sim 3\%$ (0.3%)
  - ○ Levchuk effect
  - ○ Low $\mathcal{P}_T \Rightarrow$ dead time

Syst. error $\sim 3\%$ typically

Possible Breakthrough in Accuracy

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
  - high beam currents allowed
  - low single arm BG from radiative Mott (×0.1 of the BG from Fe)

Goal:

∼0.5% systematic error

Hydrogen Atom in Magnetic Field

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

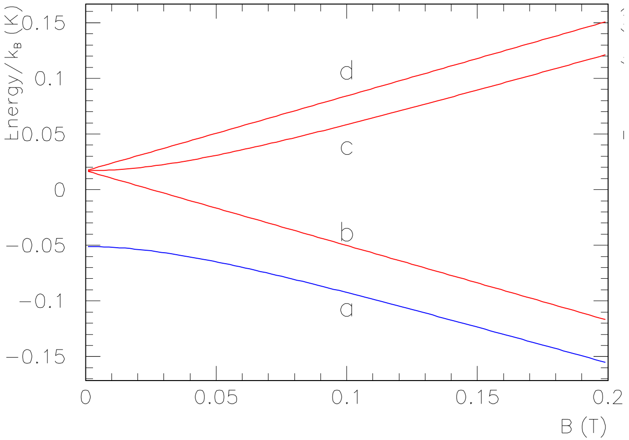
$E = -\vec{\mu}\vec{B}$, population $\propto exp(-E/kT)$

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

$|d\rangle=|\uparrow\text{⇞}\rangle$

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

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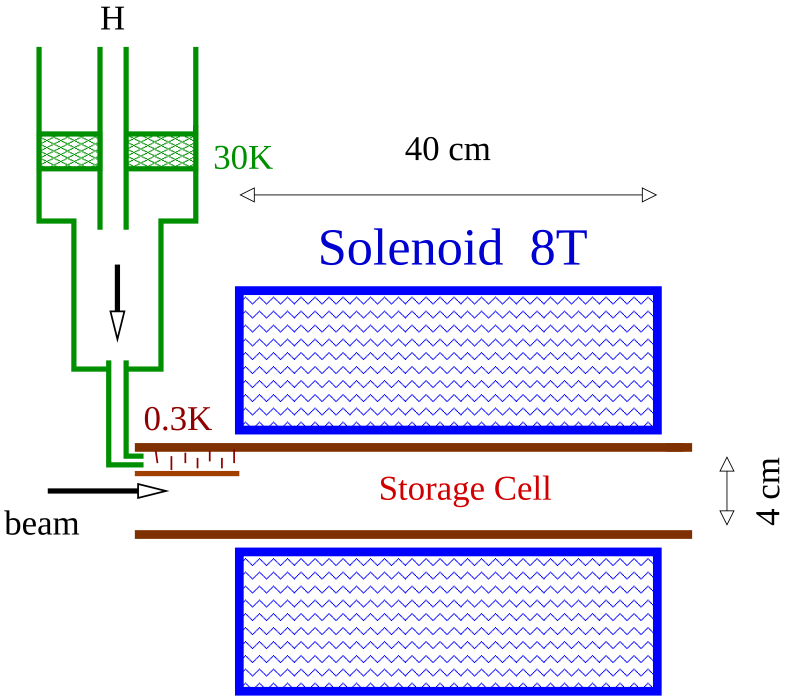
where $\tan 2\theta \approx 0.05/B(T)$, at 7 T $\sin\theta \approx 0.0035$

Mixture ∼53% of $|a>$ and ∼47% of $|b>$:

$\mathcal{P}_e \sim 1 - 10^{-5}$,

$\mathcal{P}_p \sim\ -0.06$ (recombination ⇒ ∼80%)

Storage Cell



First: 1980 (I.Silvera,J.Walraven)

$\vec{p}$ jet (Michigan)

Never put in high power beam

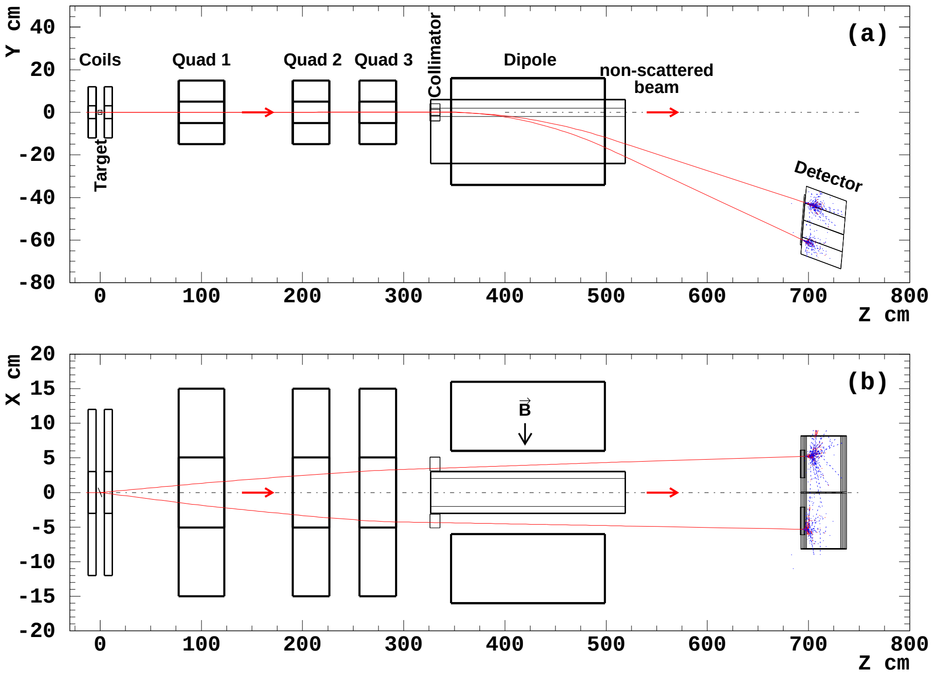
- $-\vec{\nabla}(\vec{\mu_H}\vec{B})$ force in the field gradient
  - pulls $|a\rangle$, $|b\rangle$ into the strong field
  - repels $|c\rangle$, $|d\rangle$ out of the field
- H+H→H_2 recombination (+4.5 eV) high rate at low T
  - gas: 2-body kinematic suppression
  - surface: strong unless coated ∼50 nm of superfluid ^{4}He
  - parallel electron spins: recombination suppressed
- Density $3 \cdot 10^{15} - 3 \cdot 10^{17}$ cm^{-3}.

Polarimeter with Atomic Hydrogen

Modification of Hall A Møller polarimeter - target replacement only.
Acceptance: Z $\pm 5\ cm$. Scaling the parameters of the existing polarimeter:

Hall A polarimeter, Fe target

- stat. 1% in 2 min on 30μm Fe at 0.3μA



Hall A polarimeter, H target

- Solenoid $B_{max} \sim 7\ T \sim\ 300\ mK$ cell $\sim$ 30 cm long
- Gas density $\sim 3{\cdot}10^{15}$ e$^-$/cm^3 - conservative
- Target length 10 cm (0.85 GeV), 20 cm (> 1.5 GeV)
- Target density $\geq\ 3 \cdot 10^{16}$e$^-$/cm^2
- Same acceptance as for Fe
- 30μA

Stat. accuracy 1% in $\sim$ 30 min

Syst. accuracy $< 0.5\%$

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 ≈ 80 m/s
- Atomic collisions $\approx 1.4 \cdot 10^5$ 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 0.5 ps
- Repetition rate 500 MHz
- Beam spot diameter ~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%

100 μA Beam

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

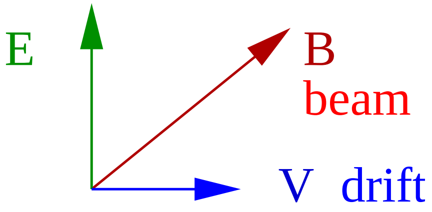
Expected depolarization $< 2 \cdot 10^{-4}$

The Most Important Beam Impacts on the Target Gas

100 μA CEBAF beam:

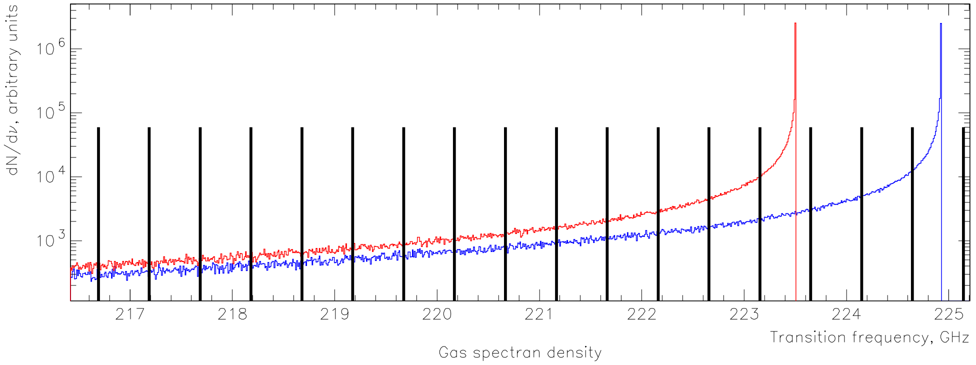
Gas Ionization

- 10^{-5} s^{-1} of all atoms
- 20% s^{-1} in the beam area
- Problems:
  - ○ No transverse diffusion (charged)
  - ○ 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 ~ 20 μs
  - ○ Contamination $< 10^{-5}$
  - ○ Ions and electrons: same direction
  - ○ Beam $\overline{E_r}(160\mu\text{m}) \approx 0.2$ V/cm



Beam RF influence

- $|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle$ ∼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

Conclusion and Outlook

Polarimetry with ultra-cold atomic hydrogen in a magnetic trap:

- Systematic error $<1.\%$, potentially $\sim0.5\%$
- Good reason to expect no serious problem with beam
- Working parallel with the experiment
- Competition/complementarity with Compton:
  - Compton: less influence on the beam
  - Moller: better systematics on the analyzing power

Proton Polarization

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

$|a\rangle = |\downarrow⤉\rangle\alpha + |\uparrow⤈\rangle\beta$ and

$|b\rangle = |\downarrow⤈\rangle$

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

$\mathcal{P} \rightarrow 0.8$

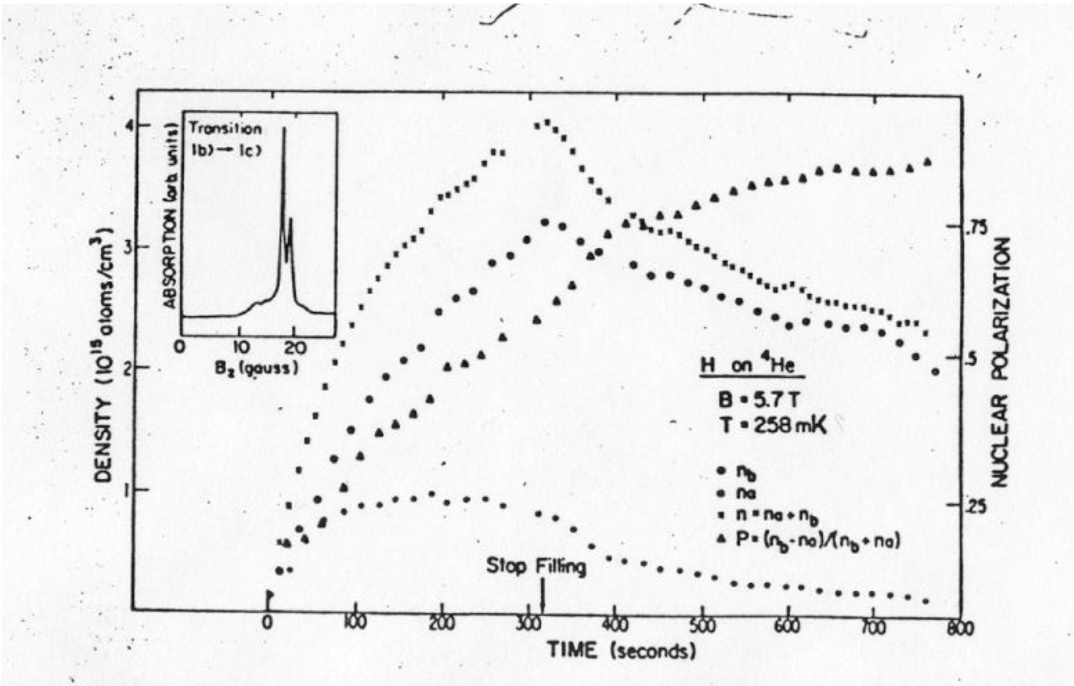


Fig. 5.11. Development of the densities of the hyperfine states and polarization as a function of time as measured by ESR. The inset shows the ESR line shape for one of the transitions (after van Yperen et al. 1983).

Beam Impact

- Beam electromagnetic field
  - Cell heating
  - Depolarization by beam generated RF field
- Beam ionization
  - gas heating
  - contamination by depolarized ions and electrons
  - contamination by excited atoms

Gas Properties

- $n = 2 \cdot 10^{15}$ cm^{-3} - density
- $T = 0.3$ K - temperature

- Diffusion speed $\Rightarrow$ 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 $\rightarrow$ 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

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
- $\vec{E}(z,r,t)$ - radial
- $\vec{B}(z,r,t)$ - azimuthal, $B(z,r,t) = E(z,r,t)/c$
- $B(0,r,t) = \frac{\mathcal{I}_b}{\mathcal{F}\cdot\tau} \cdot e^{-0.5(t/\tau)^2} \cdot (1-e^{-0.5(r/\sigma_{Bx})^2})\frac{1}{r} \cdot \frac{\mu_\circ}{(2\pi)^{3/2}}$
  $B(0,r,t)_{max} = B(0,160\mu\text{m},0) = 0.144$ mT
- $W = \mathcal{F} \cdot |B|^2 c/\mu_\circ/2 \approx 2$ mW - energy flux $\ll 20$ mW of the refrigerator.

Beam Spectral Density

One Bunch

$B(t) = B_\circ \cdot exp(-\frac{t^2}{2\tau^2}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega \cdot \hat{B}(\omega) e^{i\omega t}$, where

$\hat{B}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt \cdot f(t) e^{-i\omega t} = B_\circ \cdot \tau \cdot exp(-\frac{\omega^2\tau^2}{2})$

$\tau \cdot 200$ Ghz$\cdot 2\pi = 0.62$ - no spectral suppression!

RF

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

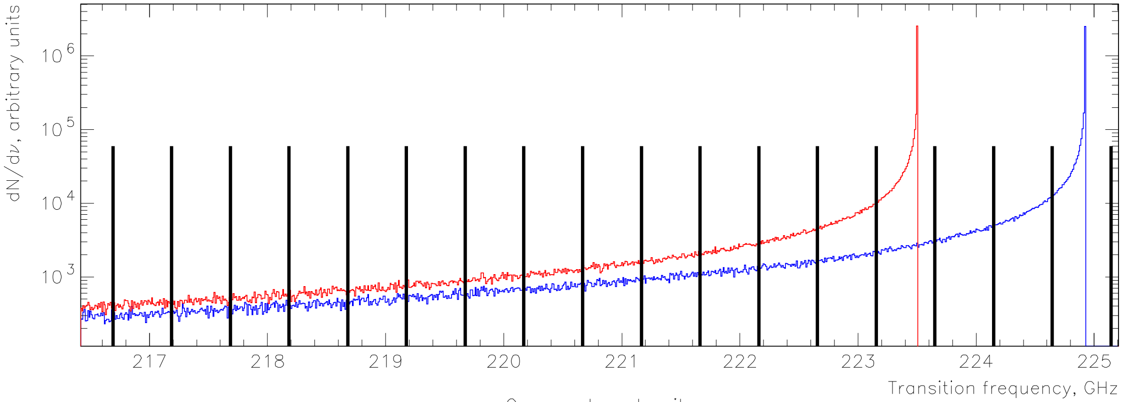
$\hat{B}_n \approx B_\circ \sqrt{2\pi} \cdot \tau\mathcal{F} \cdot exp(-\frac{\omega_\circ^2 n^2 \tau^2}{2})$,

Depolarization by Beam RF

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

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

One bunch: $V^B_{a\rightarrow d}=\left(\frac{\mathcal{I}_b}{\mathcal{F}}\right)^2\left(\frac{\mu_\circ\mu_e}{2\pi\hbar r_\circ}\right)^2\cdot exp(-\omega^2_{ad}\tau^2)G^2(r)$



Gas spectran density

100 μA inflicts:

- $\sim 10^{-4}$ s^{-1} conversions (all atoms)
- $\sim 6\%$ s^{-1} conversions (beam area)

Diffusion:

- Lifetime $\tau_d\approx 1.4$ s, lateral diffusion ~ 2 ms
- Contamination (beam area) $\sim 1.5\cdot 10^{-4}$
- Solenoid uniformity $<10^{-3}$
- Magnetic field tune to avoid resonances
- Magnetic field tune to destroy $|a\rangle$?

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?

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, ∼20% s^{-1} - beam area
- Problems:
  - No transverse diffusion of charged particles
  - Recombination kinematically suppressed
  - For $\tau_{ch} = 1.4$ s contamination ∼40% in the beam
- Solution: electric field ∼1 V/cm normal to the axis
  - Larmore $\omega_L = q_e B/m = 1.4 \cdot 10^{12}$ s^{-1} for e$^-$, $0.8 \cdot 10^9$ 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 ~ 20 μs : contamination $< 10^{-5}$
  - Positive and negative - the same direction
  - Average field of the beam $E_{max}(160\mu\text{m}) \approx 0.2$ V/cm - not important
  - Design for electrodes?

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

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- Systematic error $<$1.%, potentially $\sim$0.5%
- Good reason to expect no serious problem with beam
- Working parallel with the experiment
- Competition/complementarity with Compton:
  - Compton: less influence on the beam
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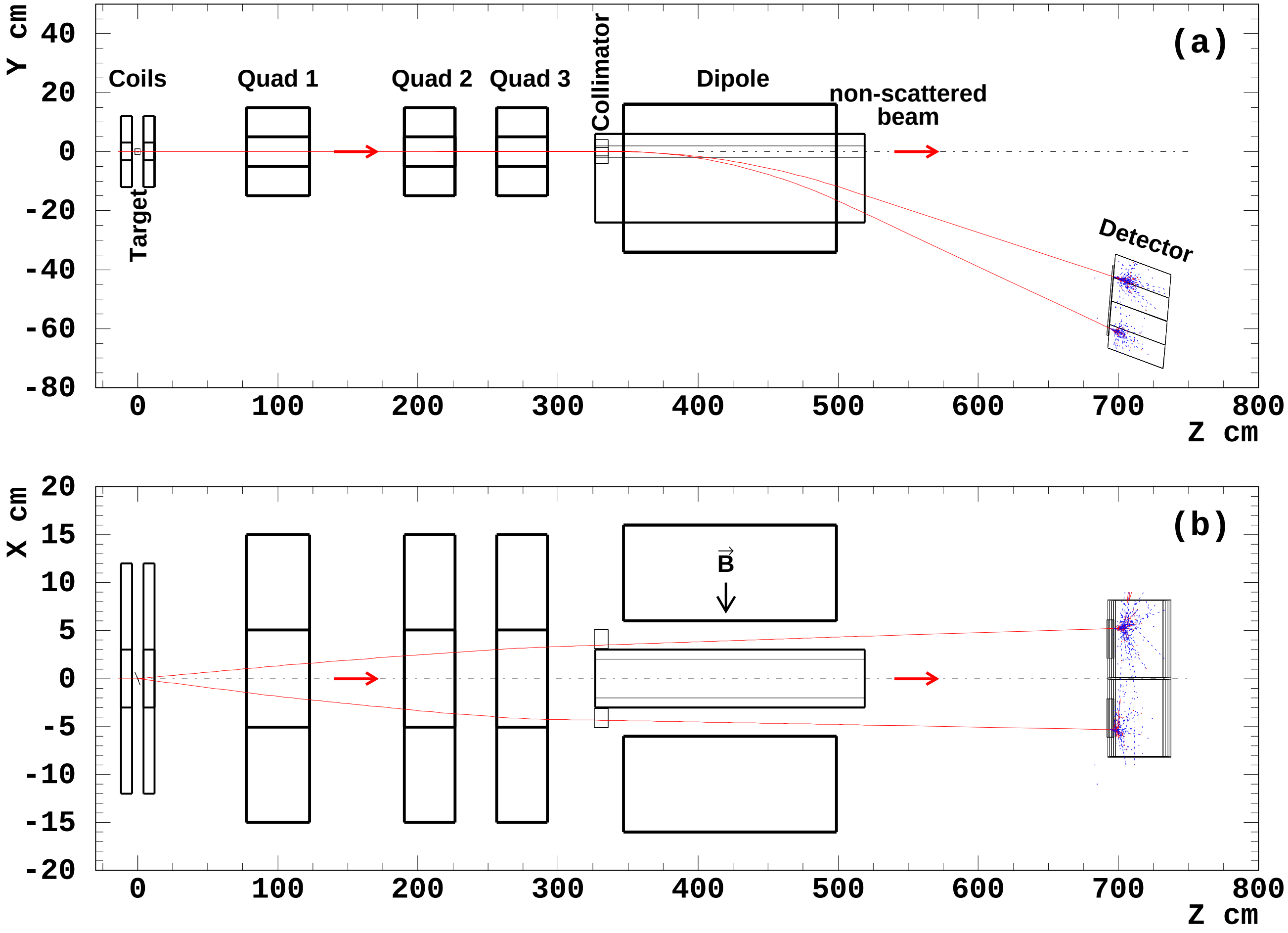
Physics application:

- Proton polarization $\sim$80%: $\theta \sim 0$ GDH
  - Counting rate $\sim$3 Hz at 100 μA in $d\omega/\omega \sim 0.1$
  - Bremsstrahlung counting rate $\sim 30\ kHz$
  - Detecting electron and a signal in a surrounding calorimeter to suppress Bremsstrahlung
  - Bremsstrahlung photon veto

Hall A Møller Polarimeter



Minimization of the Levchuk effect.

Møller Halls A,C: Systematic Errors

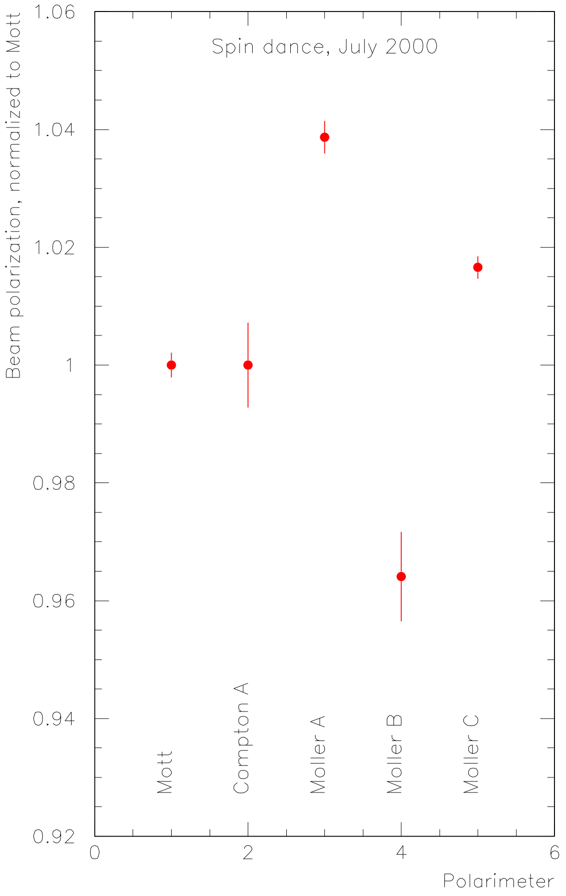
source	Hall C		Hall A		$\vec{H}$
	uncertainty	A error	uncertainty	A error	
beam position X	0.5 mm	0.15%	-	-	
beam position Y	0.5 mm	0.03%	-	-	
beam direction X	0.15 mr	0.04%	-	-	
beam direction Y	0.15 mr	0.04%	-	-	
current Q1	2%	0.10%	-	-	
current Q2	1%	0.07%	-	-	
position Q2	1 mm	0.02%	-	-	
position collimator	0.5 mm	0.06%	-	-	
analyzing power		0.21%		0.3%	↓
radiat. corrections		?		?	
multiple scattering	10 %	0.12%	-	-	×
target temperature	50 %	0.05%	50 %	0.1 %	
direction of B-field	2°	0.06%	-	-	
value of B-field	5%	0.03%	-	-	
target polarization		0.25%		3.0%	×
Levchuk effect	10 %	0.30%	30%	0.2%	×
target angle	-	-		0.5%	×
Background		?		<1%	↓
dead time		?		0.3%	×
beam current		?		1%	×
total		0.45%		3.4%	

Comparison of Different Polarimetry Techniques

A comparison of polarimetry methods at 4.5 GeV.

Type	$T_{1\%}$ Stat	Syst. error	beam μA	Inva-sive?	Energy GeV
Mott	5 min	3(1)%	1	yes	0.005
Moller A	2 min	3%	0.3-1.0	yes	0.8-6
Moller C	5 min	1.5(0.5)%	0.5-1.0	yes	0.8-6
Compton	40 min	1.1%	20-100	no	$>$2

Cross-calibration of polarimeters



One laser: DC
Slits open
Spin rotation