Beam Polarimetry (for Future Experiments at JLab)

E.Chudakov[1]

[1]JLab

PAVI-09

Outline

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

PV opportunities at 11-GeV

CEBAF is a excellent facility for PV experiments

PV at 6 GeV

- 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 $\rightarrow$ e Pb (PREX)
- EW e p $\rightarrow$ 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.

See talks by K.Kumar and P.Souder

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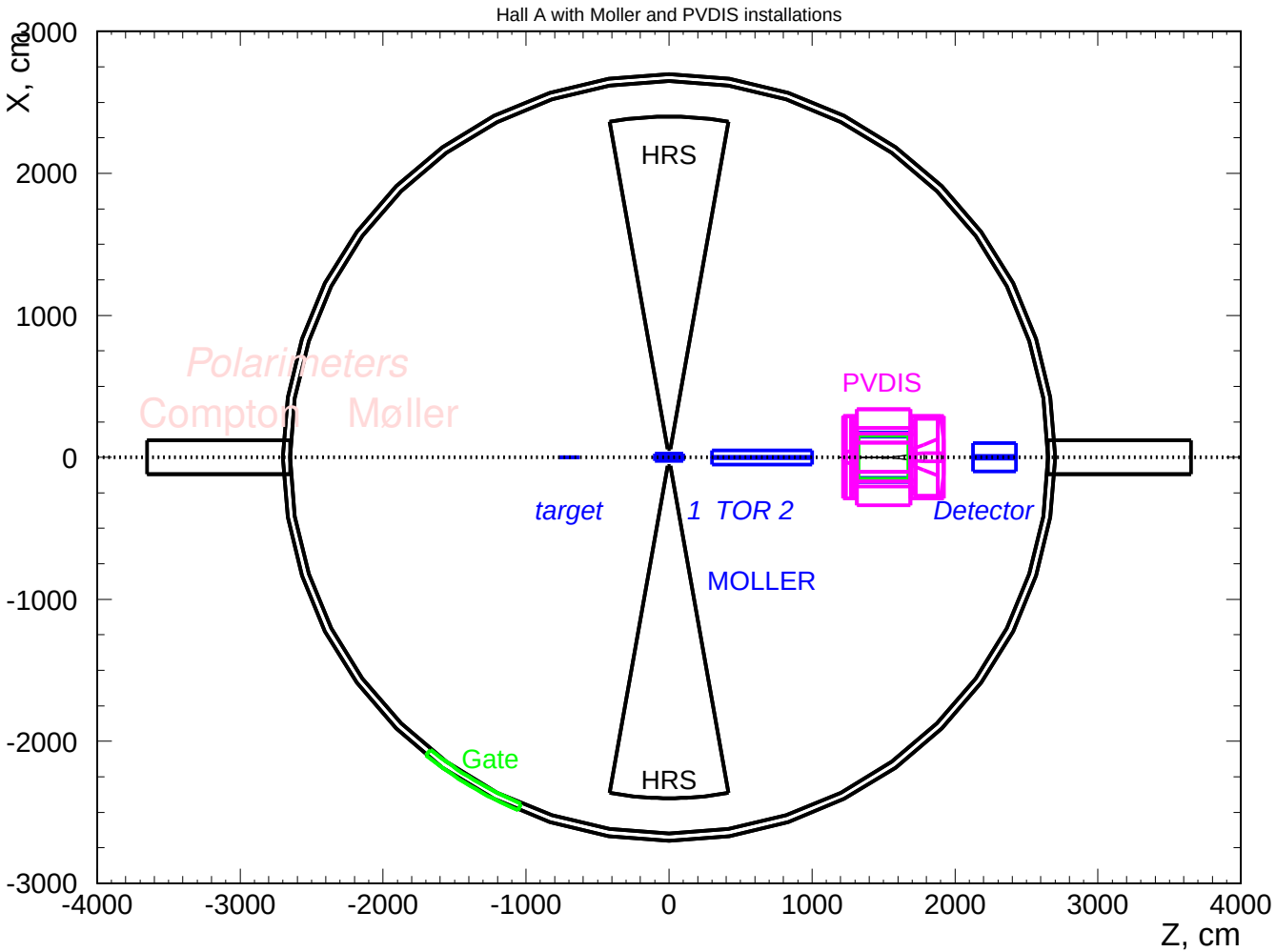
Installation in Hall A



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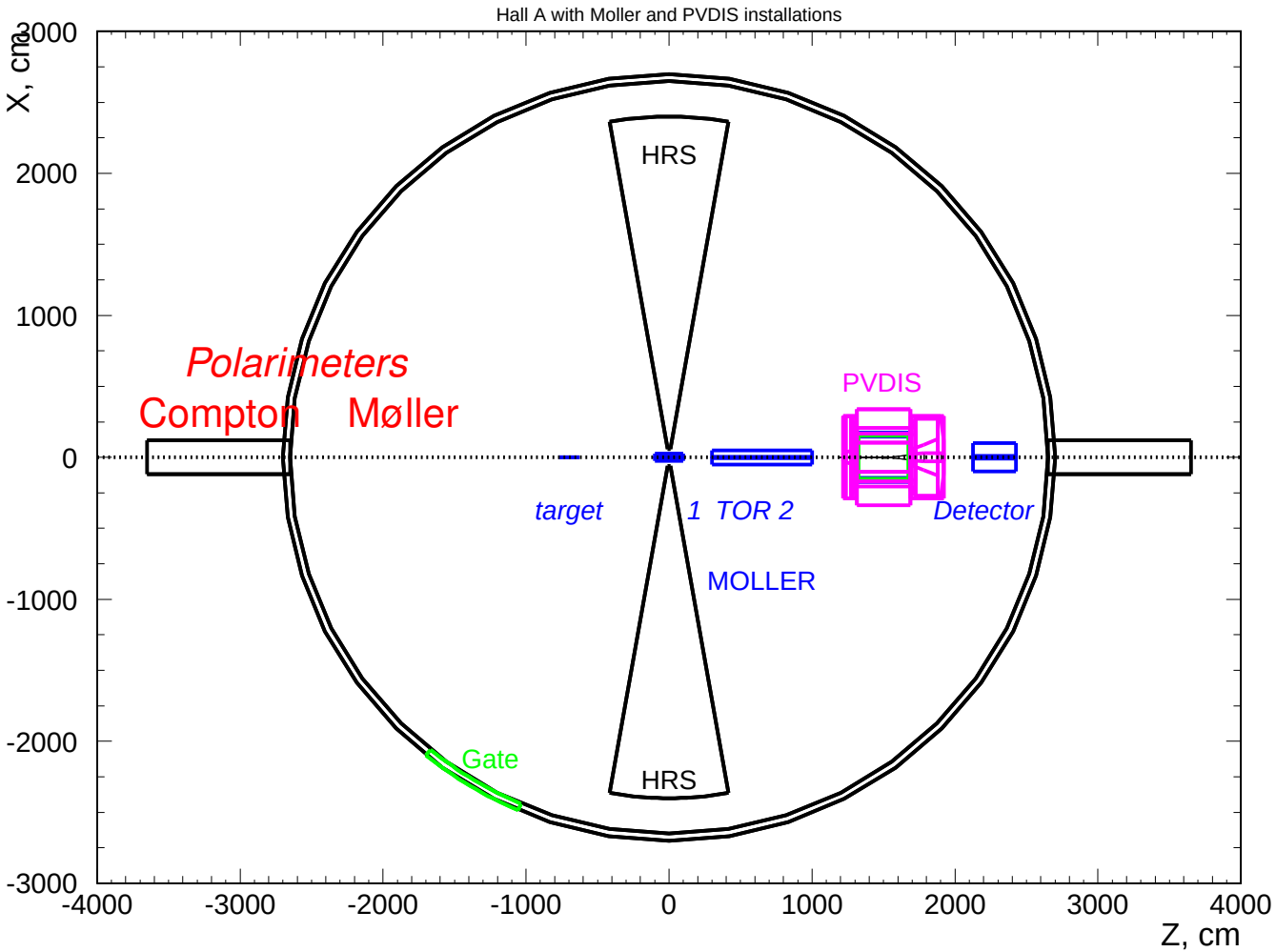

Error Budget of Møller and PVDIS Experiments

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

0.4% - can it be done?

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Electron Polarimetry for PV at JLab: Features

- Energy range $E_{beam} = 6.6 - 11\ GeV$
- Current range $\mathcal{I}_{beam} = 40 - 90\ \mu A$

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

$\vec{e}^{\,-}$ ~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

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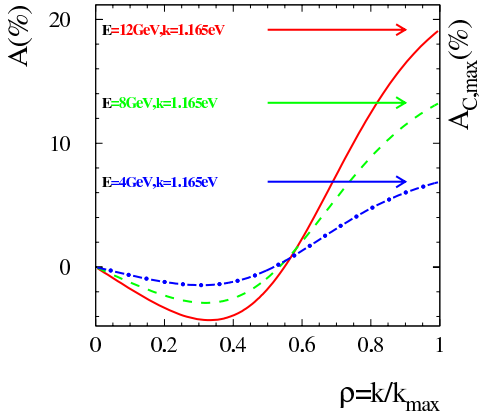
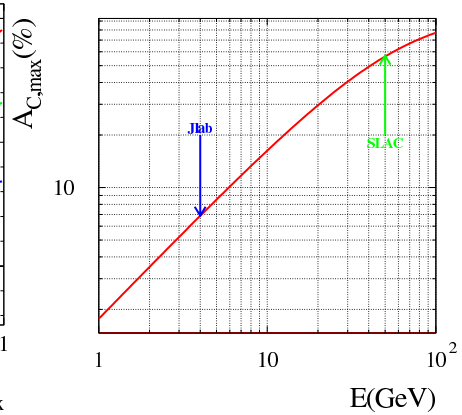
Compton Polarimetry

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

Møller Polarimetry

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

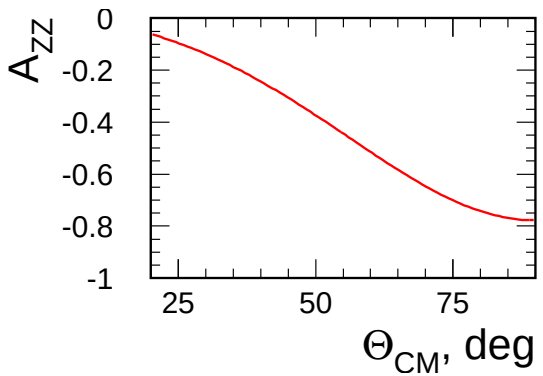




- Rad. corrections to Born $< 0.1\%$
- Detecting: γ (0°), e^- $E < E_\circ$
- Strong $\frac{dA}{dk'}$ - good $\sigma E_\gamma / E_\gamma$ needed
- $A \propto kE$ at $E < 20$ GeV
- $T \propto 1/(\sigma \cdot A^2) \propto 1/k^2 \times 1/E^2$
- $\mathcal{P}_{laser} \sim 100\%$
- Non-invasive measurement

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

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



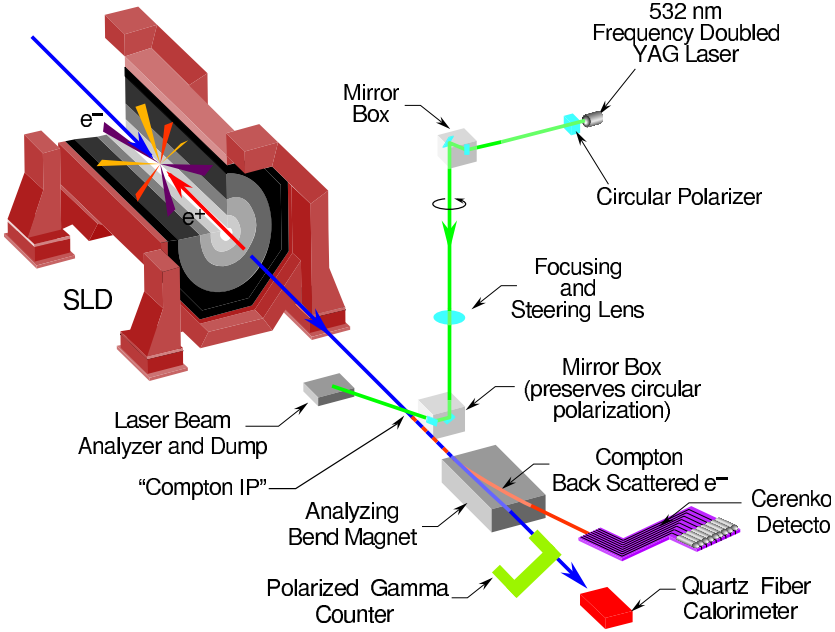
$A(E) = -\frac{7}{9}$

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

- Rad. corrections to Born $< 0.3\%$
- Detecting the e^- at $\theta_{CM} \sim 90°$
- $\frac{dA}{d\theta_{CM}}|_{90°} \sim 0$ - good systematics
- Beam energy independent
- Coincidence - no background
- Ferromagnetic target $\mathcal{P}_T \sim 8\%$
  - $\langle I_B \rangle < 3\ \mu A$ (heating 1%/100°C)
  - Levchuk effect (atomic e^-)
  - Low $\mathcal{P}_T \Rightarrow$ dead time
  - Syst. error $\sigma(\mathcal{P}_T) \sim 2\%$ (0.5%?)

Outline

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%

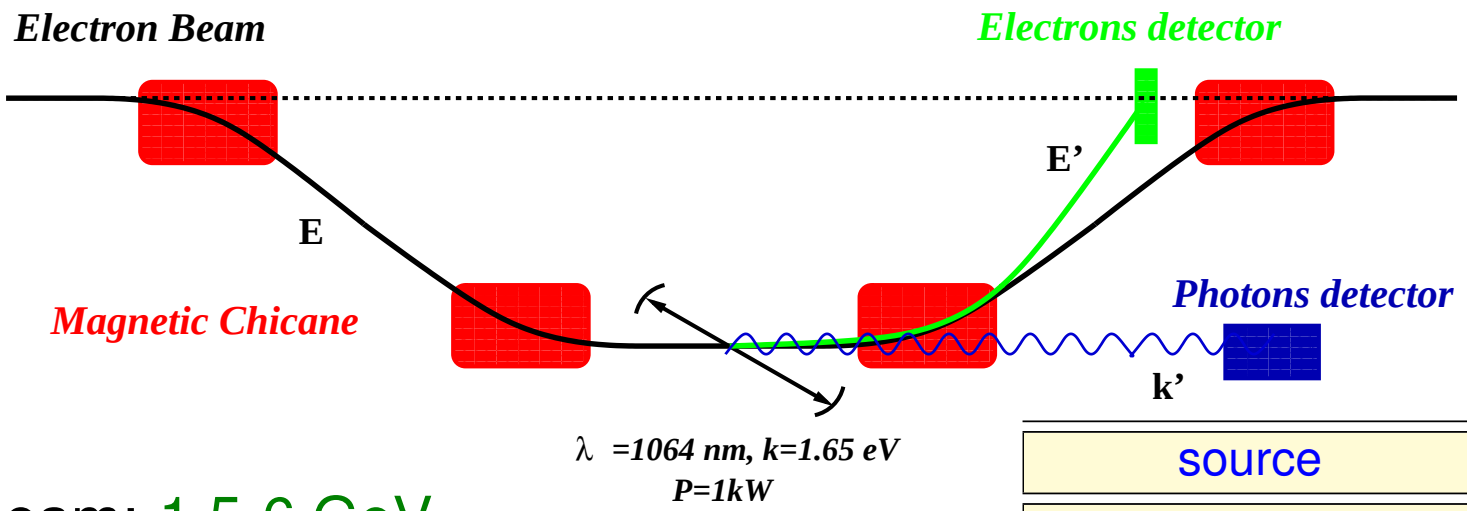
M.Woods, JLab Polarimetry workshop, 2003

- 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 $\times$ 17 Hz
- Crossing angle 10 mrad
- e^- 17-30 GeV detector - gas Cherenkov
- γ detector - calorimeter
- Statistics 1% in 3 min

At JLab:

- Low energy: FOM: $\times 0.1$
- Coincidence e^-, γ
- Beam current $\times 100$

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 $\varepsilon \sim 2.5\%$
- 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

source	$\sigma(\mathcal{P})/\mathcal{P}$
Laser polarization	0.50%
Response function	0.40%
Calibration	0.60%
Others	0.65%
total	1.15%

Upgrade - 1% at 1.0 GeV

- Laser: 532 nm, $\sim$1 W
- Cavity $\times 2000 \Rightarrow$ 2 kW
- Detector upgrade

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 μ-strip
- γ detector - calorimeter
- High energy:
  - e^- far from the beam
  - Compton edge, A=0: energy calibration

Stat: 1.0% 1 min, 11 GeV, 90 μA

Syst: 0.4% at 6.6 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%

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 μ-strip
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- High energy:
  - e^- far from the beam
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Stat: 1.0% 1 min, 11 GeV, 90 μA

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Total	0.35%	0.46%

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Møller Polarimetery

Polarazed 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

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 $\sim 2-3\%$

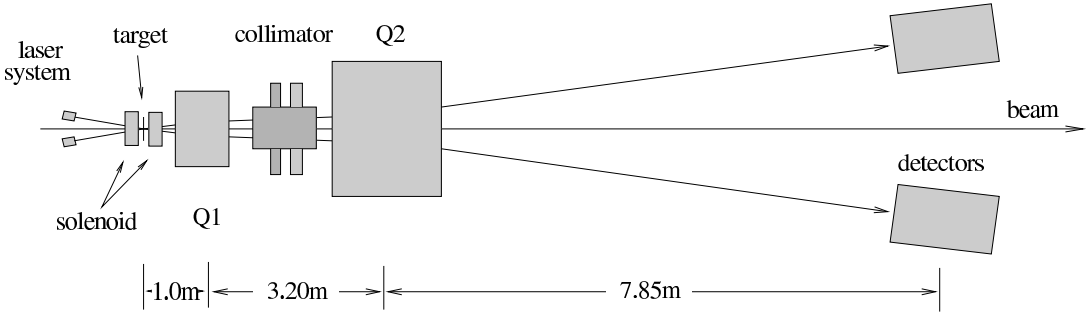
Field 3 T, foil at $\sim 90^\circ$

- 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

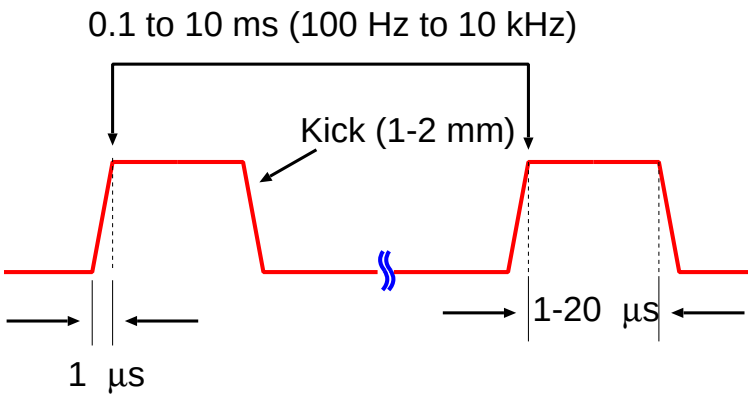
- External $B_Z \sim 3 - 4\ T$
- Target foils 1-10 μm, perp. to beam
- $\mathcal{P}_t$ not measured
- Levchuk: 3% correction



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

Tests at high beam current

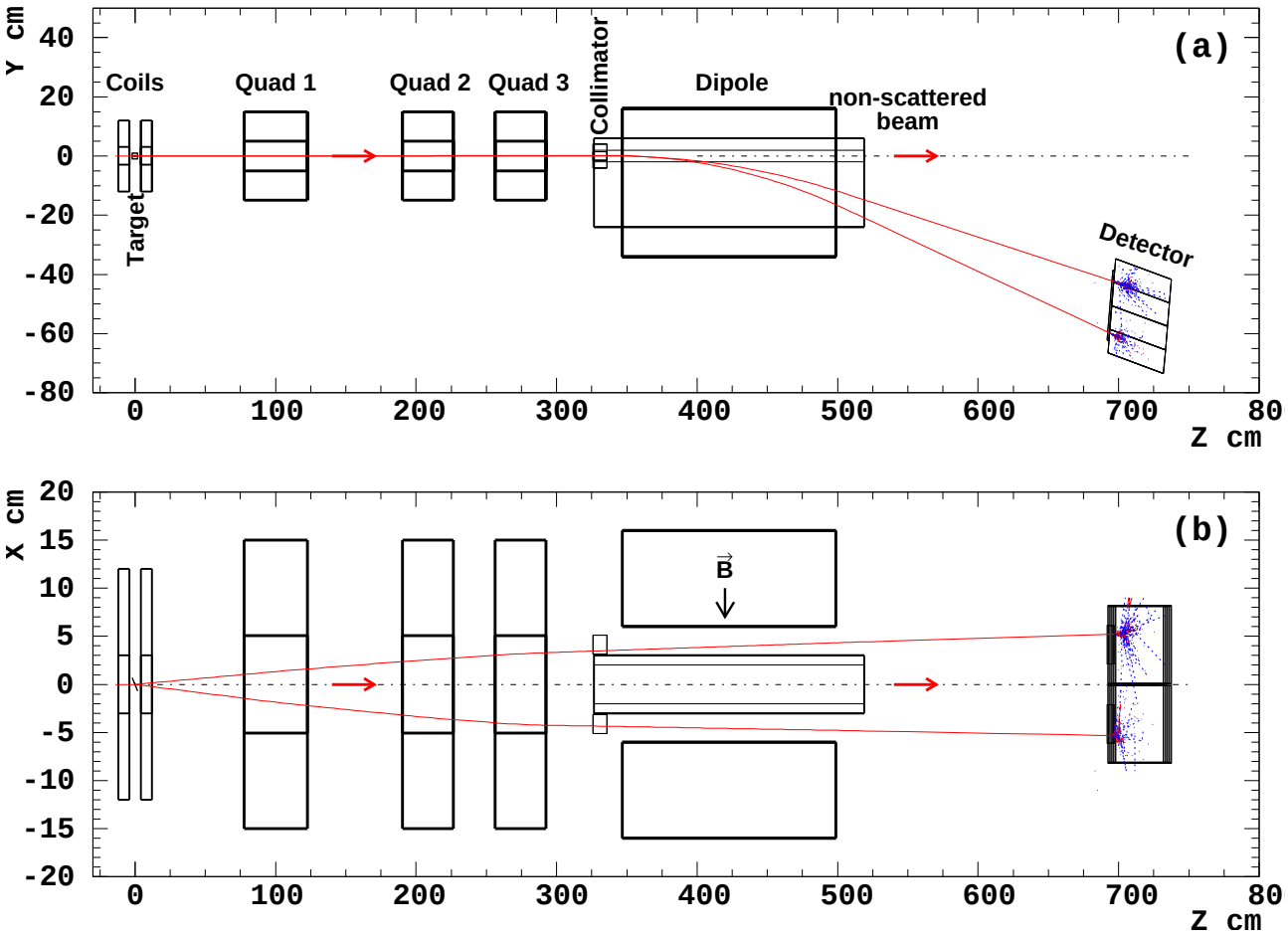
- Half-moon shape foil
- Kicker magnet



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

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

Hall A Møller Polarimeter



- Minimal Levchuk
- $\sigma_{stat} = 1\%$ in ~2–3 min
- $B_Z \sim 25$ mT field
- Foil at 20° to field
- Foils 5–30μm
- Beam <2μA
- 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 $\sim$60 Hz
  - Instantaneous counting rate at 50μA will be $\times$3 higher
  - More invasive than a kicker scheme
- Electronics upgrade to digest higher rates

Møller Systematic Errors

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

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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)

`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).

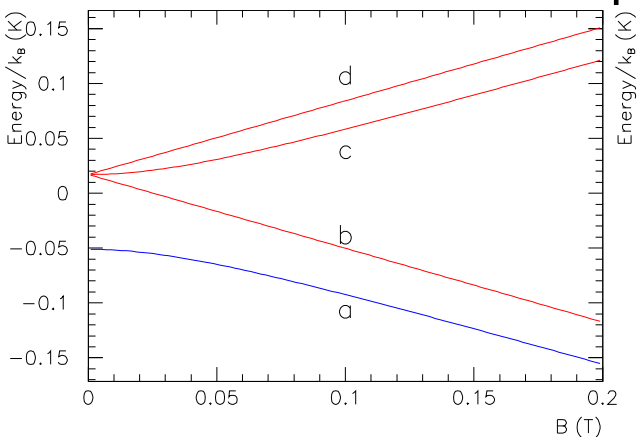
Variable	Hall C	Hall A		
		Present	Upgrade	Proposed
Target polarization	0.25%	2.00%	0.50%	0.01%
Target angle	0.00%	0.50%	0.00%	0.00%
Analyzing power	0.24%	0.30%	0.30%	0.10%
Levchuk effect	0.30%	0.20%	0.20%	0.00%
Target temperature	0.05%	0.00%	0.02%	0.00%
Dead time	-	0.30%	0.30%	0.10%
Background	-	0.30%	0.30%	0.10%
Others	0.10%	0.30%	0.30%	0.30%?
Beam extapolation	?	larger	?	0.00%
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:
$n_+/n_- = exp(-2\mu B/kT) \approx 10^{-14}$

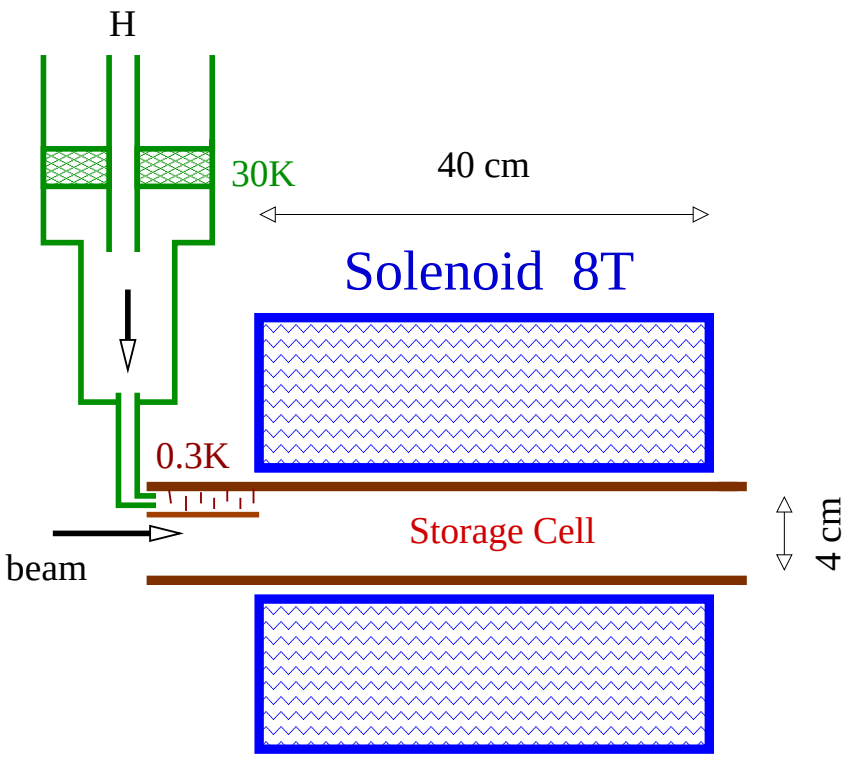
Complication from hyperfine splitting:



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

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

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

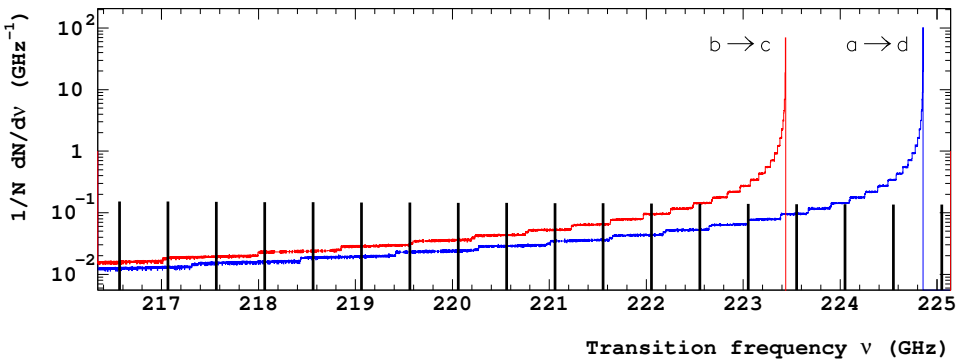
Expected depolarization $< 2 \cdot 10^{-4}$

Contaminations and Depolarization of the Target Gas

100 μA CEBAF beam:

Beam RF influence

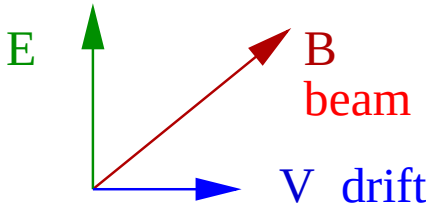
- $|a\rangle \rightarrow |d\rangle$ and $|b\rangle \rightarrow |c\rangle$ ~200 GHz
- RF spectrum: flat at <300 GHz



- $\sim 10^{-4}$ 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 ~ 20 μs
  - 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.

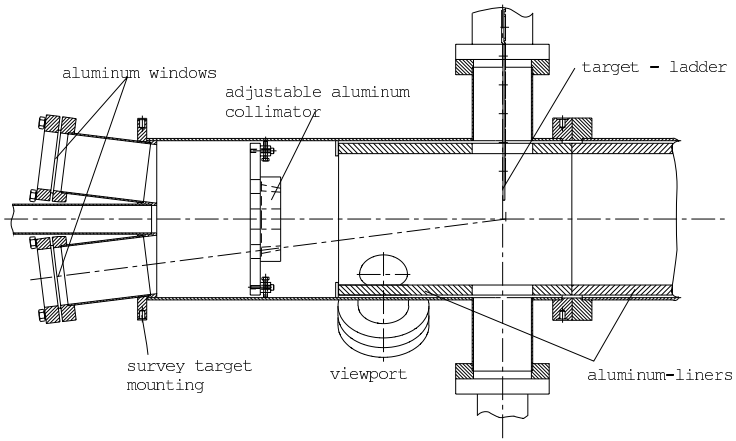
Possible strategy

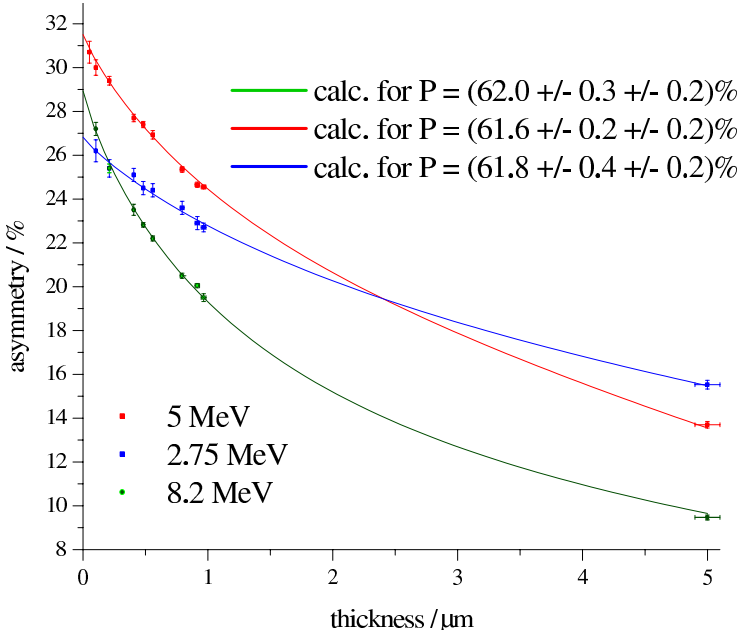
- Continuous polarimetry
- $\sim$0.4% Compton - seems feasible
- Second polarimetry method (Møller) of similar accuracy would help dramatically.
- Møller with iron targets - rather 1% than 0.4%
- Møller with atomic hydrogen target potentially can provide $< 0.30\%$ accuracy, very complex, needs R&D

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





- 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) $\oplus\sigma(extrapol)$

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!

$\mathcal{P} \rightarrow 0.8$

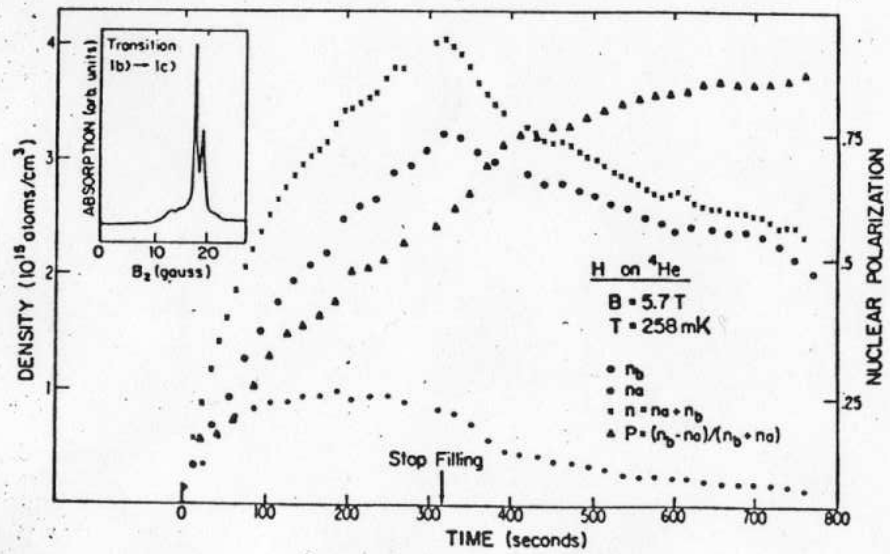


Fig. 5.11. Development of the densities of the hyperfine states and polarization as a function of time as measured by ESR. The inset shows the ESR line shape for one of the transitions (after van Yperen et al. 1983).