Progress Report on the A4 Compton Backscattering Polarimeter

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The A4 experiment

physics goal: determine strange-quark contribution to the nucleon properties

method: measure the parity violating cross-section-asymmetry in elastic electron-nucleon scattering with polarized beams

Calorimeter: PbF₂
Target: ℓH₂
Transmission Polarimeter
Dump

E = 855 MeV, 570 MeV
I = 20µA
P = 80%

measured quantity:

\[ A_{\text{exp}} = P_e A_{\text{phys}} \]

exp. asymmetry
physics asymmetry
beam polarization

Need to measure the absolute beam polarization
Method: Compton backscattering polarimetry
2. Compton Polarimetry

Scattering of photons on leptons

Compton cross-section:

\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} + Q \frac{d\sigma_1}{d\Omega} - V P_{\text{long}} \frac{d\sigma_{\text{long}}}{d\Omega} - V \frac{P_{\text{trans}}}{\cos \varphi} \frac{d\sigma_{\text{trans}}}{d\Omega}
\]

Q, V : “Stokes Parameters” (initial photon polarization)
Q : linear contribution
V : circular contribution (+1 : right circular, -1 : left circular)

With circular light: asymmetry between scattering of right- and left-handed photons

average over \( \varphi \) (longitudinal polarization)

\[
A = \left( \frac{d\sigma}{d\Omega} \right)_\text{right} - \left( \frac{d\sigma}{d\Omega} \right)_\text{left} = -\left| V \right| P_{\text{long}} \frac{d\sigma_{\text{long}}}{d\Omega}
\]

Asymmetry proportional to beam polarization
Angular distribution of cross-section and asymmetry:

> backscattered photons concentrated to small cone

\[ E = 854.3 \text{ MeV} \quad \vartheta_\gamma = 0.6 \text{ mrad} \]
\[ \gamma = 1671.8 \quad k_{\text{max}} = 26.2 \text{ MeV} \]
\[ k_{\text{in}} = 2.41 \text{ eV} \]

> most calorimetric detectors will average over \( \varphi \)

**Measuring time**

counting rate asymmetry  
energy spectrum asymmetry

\[ t \propto \frac{1}{L \left\langle A \right\rangle^2} \]

**Luminosity requirements**

<table>
<thead>
<tr>
<th>( \Delta P/P ) [%]</th>
<th>( t ) [min]</th>
<th>( L ) [kHz/b]: 855 MeV</th>
<th>570 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>15</td>
<td>1.15</td>
<td>2.51</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>4.59</td>
<td>10.05</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>12.76</td>
<td>27.91</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>114.86</td>
<td>251.16</td>
</tr>
</tbody>
</table>

green light (514.5nm), 80% electron polarization

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Luminosity for colliding beams

\[ L = n_{rel} \int \rho_1(\bar{x})\rho_2(\bar{x})d^3x \]

depends on:
- beam focusing
- crossing angle

numerical results:

\[
\begin{array}{c|c|c}
\alpha [\text{mrad}] & L [\text{kHz/barn}] & \text{Laser focusing:} \\
\hline
0 & 3.5 & z_\alpha = 0.5 \text{ m} \\
5 & 3.0 & z_\alpha = 1.0 \text{ m} \\
10 & 2.5 & z_\alpha = 1.5 \text{ m} \\
15 & 2.0 & z_\alpha = 2.0 \text{ m} \\
20 & 1.5 & z_\alpha = 2.5 \text{ m} \\
25 & 1.0 & z_\alpha = 3.0 \text{ m} \\
\end{array}
\]

assumptions:
- laser light, 514.5 nm
- laser power 10W
- gaussian beams

\[
\begin{align*}
E_L &= 26\pi \ \mu \text{m mrad} \\
E_e^{\text{hor}} &= 7.8\pi \ \mu \text{m mrad} \\
E_e^{\text{vert}} &= 1.0\pi \ \mu \text{m mrad}
\end{align*}
\]

→ antiparallel geometry is desirable
→ more laser power needed
3. Layout of the A4 Polarimeter

Methods of increasing the laser power

1. Fabry–Pérot external cavity (e.g. JLab Hall A)

   - resonance buildup
   - intensity gain up to 10000

   drawback: gain–bandwidth–product
   
   \[ g \times \Delta \omega \approx \text{const} \]

   - frequency stabilization necessary

2. Internal cavity (A4 Polarimeter)

   - extend cavity
   - make all mirrors high reflective

   - no frequency stabilization necessary

   but: maximum intensity lower than with external cavity
Schematic View of the Polarimeter

magnetic chicane (Poster by Jeong Han Lee)

plasma tube

wire scanners

fibre detector

Stokes parameter measurement

M1

M45

M2

2.42 m

2.7 m

Ar-Ion laser 
\[ \lambda = 514.5 \text{nm} \]

plasma tube

quadran diode

for laser beam stabilization (Poster by J. Diefenbach)

2.7 m

total cavity length : 7.8 m
interaction zone : 2.7 m

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Optical System

- design based on commercial laser crate
- subject to boundary conditions:
  1. beam profile in laser medium unchanged
  2. optics accessible for maintenance
  3. system to fit into chicane
  4. profile matching for high luminosity despite vibrations in the optical system

Problem:
  - Sensitivity of beam axis to optics vibration depends on optics spacing.
  - Sensitivity of luminosity to beam axis fluctuations depends on beam focusing

perform MC–simulations to find compromise

Mean luminosity as function of tilt noise amplitude:

![Graph showing mean luminosity as a function of tilt noise amplitude.](image_url)

laser focusing:
- $z_{R2} = 0.5m$
- $z_{R2} = 1.0m$
- $z_{R2} = 1.5m$
- $z_{R2} = 2.0m$
- $z_{R2} = 2.5m$
- $z_{R2} = 3.0m$

with stabilization (preliminary)

without stabilization (preliminary)

compromise: $z_{R2} = 2.5m$

$L_{\text{max}} = 2.1 \text{ kHz/barn per 10W}$
Polarization

- Polarization of the laser light enters into asymmetry

\[ A \propto -|V| \]

\[ \Rightarrow \] maximize \( V \) (=circular polarization)

\[ \Rightarrow \] measure polarization state

1. Resonator analysis with Jones/Stokes–formalism
- need two waveplates (because within resonator)
- analyze resulting polarization when rotating one waveplate

\[ \theta \] [°]

\[ 0 \quad 45 \quad 90 \quad 135 \quad 180 \quad 225 \quad 270 \quad 315 \quad 360 \]

- round-trip attenuation
- Stokes parameter \( V \)

\[ \Rightarrow V=+/-1 \text{ possible} \]

2. Stokes parameter measurement
- use vacuum window as beamsplitter
- method: rotating waveplate and linear polarizer
- result: intensity modulation, amplitudes proportional to Stokes parameters

\[ I(\theta) = \frac{1}{4} \left[ (2I + Q) - 2V\sin2\theta + U\sin4\theta + Q\cos4\theta \right] \]

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Detector

Photon arm

Nal calorimeter, 3 crystals, 4PM each
- length: $12 \times X_0$
- radius: $2.2 r_M$

Electron arm

- involved electron loses energy
- dispersion in dipole magnets leads to displacement behind chicane

► detect electron with SciFi-array and measure photons in coincidence with electrons

► background reduction
4. Status and Results

- successfully installed magnetic chicane in MAMI Hall 3 (Dec 2002)
- no degradation of beam quality on A4 target

- successfully installed laser and optical system
- at first, operated without waveplates (Dec 2002)

\[ P = 70 \text{ W (max)} \]

- resolved problems with stress birefringence in the vacuum windows (Mar 2004)
- installed the waveplates (Mar 2004)

\[ P = 90 \text{ W (max)} \]

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- performed first successful overlap tests and measured backscattered photons with the NaI (Aug 2003)

- installed a SciFi array behind the chicane array is operational and has been used for background reduction in a test beamtime (May 2004)

<table>
<thead>
<tr>
<th>Without fibre detector</th>
<th>With fibre detector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compton rate:</strong></td>
<td>2.6 kHz</td>
</tr>
<tr>
<td><strong>background rate:</strong></td>
<td>18.6 kHz</td>
</tr>
<tr>
<td><strong>SNR:</strong></td>
<td>1:7.11</td>
</tr>
<tr>
<td><strong>Compton rate:</strong></td>
<td>60.5 Hz</td>
</tr>
<tr>
<td><strong>background rate:</strong></td>
<td>125 Hz</td>
</tr>
<tr>
<td><strong>SNR:</strong></td>
<td>1:2.07</td>
</tr>
</tbody>
</table>

despite non–optimal experimental conditions:
- imperfect overlap
- no laser stabilization
- installed a beam stabilization system (Nov 2003)
- system has been tested and being prepared for routine operation within the polarimeter system (cf. poster contribution by J. Diefenbach)
- installed a Stokes parameter measurement system (Aug 2003)

- system has been tested and is being prepared for routine operation within the polarimeter
5. Summary and Outlook

- planned and successfully installed a magnetic chicane for a Compton backscattering polarimeter
- planned and successfully installed an optical system, laser intensities up to 90W @ 514.5 nm
- commissioned a detector and measured first backscattered photons
- planned and successfully installed a stabilization system for the laser optics
- commissioned an electron detector and improved SNR from 1:7 to 1:2

Next steps:

- refine laser polarization measurement and measure the Compton asymmetry with circular light
- upgrade the vacuum system

➤ ready for longitudinal asymmetry program

- upgrade to transverse spin measurement: use position-sensitive detector to measure spatial Compton asymmetry

➤ ready for entire physics program