Polarimetry for Storage Ring EDM experiments

Paul Maanen
Physics Institute III B, RWTH Aachen University
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Motivation

Polarimeter concept

Simulation studies

R&D Beam time @ COSY: First results

Summary & Outlook
Motivation
Motivation

Where is the Antimatter in our Universe?

• Sakharov (1967): Three conditions for baryogenesis
  – At least one Baryon-number violating process.
  – $\mathcal{C}$ and $\mathcal{CP}$
  – Interactions outside of thermal equilibrium.

• Baryon number asymmetry: $\frac{n_B - n_{\overline{B}}}{n_\gamma} \approx \begin{cases} 10^{-18} & (SM) \\ 10^{-10} & (Exp. ) \end{cases}$

$\Rightarrow$ Not enough $\mathcal{CP}$ in Standard Modell
Electric Dipole Moments

- Electric Dipole Moment:
  - Classical: Charge separation
  - Quantum Mechanical: $$| \vec{d} \rangle = q | \vec{r} \rangle$$

- Interaction of electric and magnetic dipole moments with $$\vec{E}, \vec{B}$$:

  $$\mathcal{H} = -\mu \mathcal{S} \cdot \vec{B} - d \mathcal{S} \cdot \vec{E}$$

  $$\mathcal{P}: \mathcal{H} = -\mu \mathcal{S} \cdot \vec{B} + d \mathcal{S} \cdot \vec{E}$$

  $$\mathcal{T}: \mathcal{H} = -\mu \mathcal{S} \cdot \vec{B} + d \mathcal{S} \cdot \vec{E}$$

  \[
  \begin{align*}
  \vec{d} &= \text{EDM} \\
  \vec{\mu} &= \text{MDM} \\
  \vec{\mu}, \vec{d} &\parallel \mathcal{S} \\
  \mathcal{T} &\Leftrightarrow \mathcal{CP}
  \end{align*}
  \]

⇒ Electric Dipole Moments violate $$\mathcal{CP}$$ (assuming $$\mathcal{CPT}$$)

⇒ Probe into the Physics of the early universe
Charged particle EDMs: Current Limits and Challenges

- Most EDM searches measure EDM of neutral particles.
  - Current Limits: $10^{-17}$ ecm – $10^{-28}$ ecm

- No direct limits for charged hadrons exist
  - Technical challenge: No trap for charged particles
    ⇒ Storage Ring needed!

- EDM search @ FZJ: p, d, $^3$He
EDM searches in storage rings

- All EDM experiments measure interaction between $\vec{d}$ and $\vec{E}$:
  \[ \frac{d\vec{S}}{dt} \propto d\vec{E} \times \vec{S} \]

- “Frozen Spin” method: Align spin with momentum vector, wait for vertical polarization change:
  \[ \frac{\Delta S_y}{\Delta t} \propto d \]

- Current candidate method for EDM search implicates a buildup of polarization with time at $\Delta P = \mathcal{O}(10^{-6}/1000\text{s})$
Nuclear scattering polarimetry

- Nuclear scattering cross section for scattering of polarized particles:
  \[ \sigma_{L,R} = \sigma_0 \cdot \left( 1 \pm P_y A_y \right) \]

- Measure left-right asymmetries in count rate:
  \[ P_y = \frac{1}{A_y} \frac{N_L - N_R}{N_L + N_R} \]

- Up and Down counting rates may be used to control systematics
Design goals for an EDM polarimeter

- Design goals for polarimeter:
  - Large statistical Figure-of-Merit: \( \text{FOM} \sim N \cdot (P_y A_y)^2 \)
  - Minimal influence on beam
  - Good handle on systematic effects
  - Good long term stability and reproducibility: 1 ppm per 1000 s
Polarimeter concept
Reaction choice

- Carbon is the current material of choice
- $\mathcal{FOM}$ concentrated in forward region
  $\Rightarrow$ Polarimeter needs to cover forward region
- Proton-Carbon elastic scattering also concentrated in forward region.
  $\Rightarrow$ Possibility for multi-purpose polarimeter
Detector concept

Detector schematic:

- Vacuum pipe
- Target chamber
- COSY beam
- Fast HCAL
- PMT/SiPM
- PL Sci

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Readout concept

Crystal → PMT → SADC → FPGA → FIFO

Pile-Up

Jesus Christ University Physik Institute III B
Simulation studies
# HCal Candidate Materials: LYSO/Plastic Scintillator

<table>
<thead>
<tr>
<th></th>
<th>LYSO</th>
<th>Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping power</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Speed</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Cost</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>
First step: Detector element dimensions

- Open Questions:
  - Optimal calorimeter element size?
  - Absorber Thickness?
  - Monolithic or Sandwich?
  - Plastic or LYSO?
- To get lateral and longitudinal range of deuteron in detector element:
  - Shoot particle gun into front face, determine $x_f, y_f, z_f$ of endpoint of primary track
  - Longitudinal range: Gaussian fit
  - Lateral width: $\int_{-x_0}^{x_0} dN/dx = 90\% \cdot N_{tot}$

- Chosen detector size of $3 \times 3 \times 10\, \text{cm}^3$ as starting point for further studies
Breakup in detector element causes distortion of energy spectrum
• Use absorber to suppress proton background and reduce length of plastic detector

• Arbitrarily chosen 100 MeV entry energy @ 270 MeV beam energy as working point for plastic scintillator
  – Iron thickness ca. 50 mm
  – Pl. scintillator thickness ca. 50 mm
$E_{\text{dep}}$ in plastic

- red: other
- blue: neutron (breakup) escapes
- green: neutron (other) escapes
- purple: $\gamma$ escapes
- yellow: deuteron escapes
- black: no particle escape

rel. freq. [%]
Next step(s): Monolithic or sandwich detector?

- Generated 100k events each at $T_d = 270$ MeV, $5^\circ < \Theta < 20^\circ$, $0^\circ < \phi < 360^\circ$
  - Signal: $^{12}\!\!\!\!\!\text{C} (\vec{d}, d) ^{12}\!\!\!\!\!\text{C}, \sigma \approx 84$ mb, $\langle A_y \rangle \approx 0.32$
  - Background: $^{12}\!\!\!\!\!\text{C} (\vec{d}, pn) ^{12}\!\!\!\!\!\text{C}, \sigma \approx 121$ mb, $\langle A_y \rangle \approx -0.09$

- $\mathcal{FOM} \propto \sigma_{\text{eff}} \times \langle A_{y,\text{eff}} \rangle^2$
• Using data-driven model for signal and background

• Elastically scattered deuterons retain almost complete beam energy

• Contribution of recoil carbons negligible
• Break-up has almost no analyzing power, so discard it

• Protons and neutrons from break-up are energetically well separated from signal
  \[ \text{But: Break-up in target is not distinguishable from break-up in detector!} \]

• No reliable model for inelastic reactions available
  – Qualitative experiments show: Inelastic reactions carry some analysing power, so maybe keep these
Detection efficiencies (lyso)

**dceelastic detection efficiency in lyso**

- 0%
- 5%
- 10%
- 20%

**dcbreakup detection efficiency in lyso**

- 0%
- 5%
- 10%
- 20%

**relative fom in lyso**

- 0%
- 20%

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Detection efficiencies (plastic)

- dcelastic detection efficiency in plastic
- dcbreakup detection efficiency in plastic
- relative fom in plastic

$E_{cut}$ [MeV]

$\psi$

$\in\{0\%, 5\%, 10\%, 20\%\}$

rel. fom [au]

$E_{cut}$ [MeV]
Simulation Results

• Main cause of efficiency loss is breakup in detector

• Maximum relative FOM:

<table>
<thead>
<tr>
<th></th>
<th>0%</th>
<th>20%</th>
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<tbody>
<tr>
<td>Plastic</td>
<td>15.5</td>
<td>14.5</td>
</tr>
<tr>
<td>LYSO</td>
<td>17</td>
<td>12</td>
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</table>

• LYSO and plastic scintillators provide comparable performance

• Plastic scintillator performance exhibits no strong dependence on energy resolution
R&D Beam time @ COSY: First results
Beam time spring 2016

- External beam at COSY in Jülich
- LYSO crystals from two different manufacturers
- PMT and Silicon Photomultiplier (SiPM)
- Unpolarized Deuteron beam @ 100MeV, 200MeV, 235MeV and 270MeV
- Struck 14 bit, 250 MS/s Flash ADC
Measurement setup

Start Counters / Trigger

Beam

Beam Exit Window

Forward Veto

Positioning Table

Side Vetos

LYSO Modules

Picture courtesy of Fabian Müller
Measurement setup (cont’d)

Module 3: SiPM, Saint-Gobain

Module 4: PMT, splitted, Saint-Gobain

Module 1: PMT, Epic Crystal

Module 2: PMT, Saint-Gobain

Picture courtesy of Fabian Müller
Energy resolution

R = \frac{A}{E} \oplus \frac{B}{\sqrt{E}} \oplus C

<table>
<thead>
<tr>
<th>Module</th>
<th>A [% × MeV]</th>
<th>B [% × MeV]</th>
<th>C [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LYSO Module 1</td>
<td>57.9532</td>
<td>14.7454</td>
<td>-0.0000</td>
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<tr>
<td>LYSO Module 2</td>
<td>75.9614</td>
<td>8.6201</td>
<td>0.8336</td>
</tr>
<tr>
<td>LYSO Module 4.1</td>
<td>140.1629</td>
<td>0.0003</td>
<td>0.6828</td>
</tr>
<tr>
<td>LYSO Module 4.2</td>
<td>92.3399</td>
<td>5.9990</td>
<td>0.7675</td>
</tr>
</tbody>
</table>

Picture courtesy of Fabian Müller
Deuteron Reconstruction Efficiency of LYSO Modules

\[ \varepsilon = A_{\varepsilon} e^{\lambda_{\varepsilon} E} \]

<table>
<thead>
<tr>
<th>Module</th>
<th>( A_{\varepsilon} ) [%]</th>
<th>( \lambda_{\varepsilon} ) [1/MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LYSO Module 1</td>
<td>4.6597</td>
<td>-0.0014</td>
</tr>
<tr>
<td>LYSO Module 2</td>
<td>4.6612</td>
<td>-0.0015</td>
</tr>
<tr>
<td>LYSO Module 4.1</td>
<td>4.6910</td>
<td>-0.0016</td>
</tr>
<tr>
<td>LYSO Module 4.2</td>
<td>4.7072</td>
<td>-0.0019</td>
</tr>
</tbody>
</table>

Picture courtesy of Fabian Müller

Energy [MeV]

Deuteron Reconstruction Efficiency [%]

80 100 120 140 160 180 200 220 240 260 280
Measurement Results

- 5 LYSO modules succesfully commissioned, PMT and SiPM readout tested
- Calibration curve exhibits considerable nonlinearity
- Energy resolution between 1% and 4%
- Deuteron reconstruction efficiency above 70%
Summary & Outlook
Summary

- We have a candidate layout for JEDI polarimeter
- Simulations suggest promising performance
- A deuteron beam with five different energies up to 270MeV was used to examine the prototype LYSO modules
- The resolution of the LYSO modules was better than 3%
- A deuteron reconstruction efficiency over 65% has been achieved in the whole energy spectrum
Outlook

- Theoretical calculations for signal and background cross sections and analyzing powers are under progress and will be included in simulation.

- Next beamtime will include a greater number of crystals and test sandwich detector and polarization response.

- Measurement of cross sections and analyzing powers with WASA @ COSY in preparation.