Dipole moments of heavy particles at LHC

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References and credits


- V. G. Baryshevsky, *On the search for the electric dipole moment of strange and charm baryons at LHC and parity violating ($P$) and time reversal ($T$) invariance violating spin rotation and dichroism in crystal*, arXiv:1708.09799 (2017).


Outline

- Introduction
- Proposed MDM/EDM experiment
- Major results achieved
- Challenges
- Summary
Introduction

- Electromagnetic dipole moments are among the most prominent **static properties** of elementary particles.
- Have never been measured for short-lived (heavy) particles, i.e. charm, beauty baryons, $\tau$ lepton.

$$\mu = g \mu_p \frac{s}{2} \quad \text{magnetic dipole moment (MDM)}$$

$$\delta = d \mu_p \frac{s}{2} \quad \text{electric dipole moment (EDM)}$$

- Evidence of an **EDM** would be a clear signature of **new physics**.
- **MDM** measurement for **QCD models** and baryon internal structure, and **SM test** for $\tau$. 
Interesting sensitivities

- **Uncharted territory**
  
  Any direct measurement of MDM/EDM of short-lived charm, beauty, $\tau$ particles would be the first of its kind

- **MDM desirable precision:**
  
  ✓ charm, beauty baryons $\leq$ few %
  
  ✓ $\tau$ lepton $\leq$ 0.1% level for testing SM prediction

- **EDM indirect limits:**
  
  ✓ charm $\leq 4.4 \times 10^{-17}$ ecm (Sala)  
  
  ✓ beauty $\leq 7 \times 10^{-15}$ ecm (Grozin et al.)  
  
  ✓ $\tau$ lepton $\leq 4.5 \times 10^{-17}$ ecm (Inami et al.)
# Experimental proposal

<table>
<thead>
<tr>
<th>Baryon</th>
<th>Solution</th>
<th>MDM</th>
<th>EDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charm</td>
<td>Fixed target setup</td>
<td>First measurement for QCD &amp; baryon internal structure test</td>
<td>First search sensitivity $\sim 10^{-17}$ ecm</td>
</tr>
<tr>
<td>$\Lambda_c^+, \Xi_c^+$</td>
<td>LHCb detector</td>
<td>$\sim 10^{-3}$ precision</td>
<td></td>
</tr>
<tr>
<td>lifetime</td>
<td>Dedicated experiment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sim 10^{-13}$ s</td>
<td></td>
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<td></td>
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Long bent crystals

![Diagram of proposed target setup](image)

- New silicon Upstream Tracker (UT)
- New pixel VELO detector
- Proposed target setup
- New RICH optics and photodetectors
- New electronics for calorimeter and muon system

F. Martinez Vidal, 25/01/2019
### Experimental proposal

<table>
<thead>
<tr>
<th>Baryon Requirements</th>
<th>MDM</th>
<th>EDM</th>
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</thead>
<tbody>
<tr>
<td>Polarized baryons</td>
<td>First measurement for QCD &amp; baryon internal structure test</td>
<td>First search sensitivity $\sim 10^{-17} \text{ ecm}$</td>
</tr>
<tr>
<td>Reconstruct TeV baryons uniquely produced at LHC</td>
<td>$\approx 10^{-3} \text{ precision}$</td>
<td></td>
</tr>
<tr>
<td>Lifetime $\sim 10^{-13} \text{ s}$</td>
<td>Crystal channeling, effective $B$ field $\approx 10^3 \text{ T}$</td>
<td></td>
</tr>
</tbody>
</table>

### Experimental solution

- **Strong production of baryons in fixed target**
- **Use LHCb forward detector** *(dedicated small experiment at higher intensity in a 2nd phase)*
- **Crystal with large bending angle** to deflect particles in detector acceptance and induce large spin precession
The high electric field between the crystallographic planes makes the heavy baryon spin precess, giving access to dipole moments (MDM/EDM) of heavy particles.
Baryon initial polarization

- Parity conserving production, polarization transverse to the proton-baryon production plane
- Unknown for p-N at $\sqrt{s} \approx 115$ GeV/c
- $s_0 = -0.65 \pm 0.20$ from 230 GeV/c $\pi^-$ on copper target, $p_T > 1.1$ GeV/c
- Between $\approx 0.2$ and $-0.7$ vs $p_T$ from 500 GeV/c $\pi^-$ on platinum and diamond thin target foils (E791)

Channeled $\Lambda_c^+$
$\approx -0.4$ average polarization
### Sensitivity on MDM

- **S1 configuration**: LHCb using $10^{15}$ PoT, 5 mm W target
- **S2 configuration**: dedicated experiment using $10^{17}$ PoT, 0.5 cm W target

- **PoT**: protons on target
- **Silicon**
- **Germanium**

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**Graphical representation**

- Test QCD models
- Control

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Dipole moments of heavy particles at LHC
Sensitivity on EDM

- S1 configuration: \textbf{LHCb} using $10^{15}$ PoT, 5 mm W target
- S2 configuration: \textit{dedicated experiment} using $10^{17}$ PoT, 0.5 cm W target

PoT: protons on target

\textbf{Silicon} \textbf{Germanium}

\textbf{indirect limits}
τ lepton

- More challenging
- Exploit production of $D_s^+ (\rightarrow \tau^+ \nu_\tau)$
- Use $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$ decay to reconstruct decay vertex
- **Crystal separated** $\approx 12$ cm from target:
  - Channeling $\tau^+$ produced by $D_s^+$
  - $\tau^+$ spin precession
**τ lepton: spin polarization**

- \( \tau^+ \) has negative helicity in \( D_s^+ \) rest frame

- Selection of **high momentum** \( \tau^+ \) induces negative \( z \) (longitudinal) **polarization**, due to the large Lorentz boost and the \( D_s^+ \) production spectrum, i.e. more FW than BW \( \tau^+ \)
  - Kinematic selection based upon \( p_{3\pi} > 0.8 \) TeV requirement
  - \( z \) polarization for MDM and enhanced EDM sensitivity

- \( \tau^+ \) emitted at relatively **large angles** wrt \( D_s^+ \) flight direction in bending plane have \( y \) (transverse) **polarization**
  - \( \theta_y \) tagging (e.g. global event info, tracker, 2 crystals)
  - \( y \) polarization for enhanced MDM sensitivity
τ lepton: sensitivity

- Use **multivariate classifier** based on reconstructed $\tau^+$ variables to determine the polarization
  - Optimal sensitivity and $\tau$ hadronic model independence

**Graph 1**: Classifier output for polarization along $\eta$ axis

**Graph 2**: Test $g$-2 SM prediction with $\sim 10^{18}$-$10^{19}$ PoT, 1cm W target

EDM sensitivity $\sim 10^{-18}$ ecm
Major results achieved

- Successful test in SPS of two-crystal scheme [UA9 Collab., IPAC2018]
- Successful test of LHC beam extraction [UA9 Collab., PLB758 (2016) 129]

- Program of preparatory measurements in LHCb started: c-baryon polarization and cross-section in p-gas fixed-target configuration and pp

- Experimental proposal in LHCb and physics program being positively reviewed by dedicated LHCb panel

- Vacuum valve to be installed upstream of LHCb to allow crystal installation during EYETS (LHCb)

- Long bent crystal prototypes produced and tested on beam
**LHCb detector setup & running scheme**

- **W target** positioned at $\approx (0, 0.4, -116)$ cm attached to long bent crystal
- Target **thickness** 0.5-2 cm, to optimize depending on proton flux (pW int. prob. 5% for 0.5 cm, 18% for 2 cm)
- Need **long crystal** ($\approx 6$ cm) with **large bending** ($\geq 15$ mrad) for optimal sensitivity and detector acceptance

- $\approx (10^{15}) 2 \times 10^{14}$ protons on (0.5) 2.0 cm thick W target could be reached with

  **Parallel detector running**
  - Flux $10^7$ p/s
  - Pileup $\nu \approx 0.13$ (W+Ge)
  - 10% occupancy
  - 3 years
  - $\approx 3 \times 10^4$ reco’d $\Lambda_c^+ \rightarrow pK^-\pi^+$

  **Dedicated detector running**
  - Flux $10^8$ p/s
  - Pileup $\nu \approx 1.3$
  - 2 weeks/year
  - 3 years
  - $\approx 3 \times 10^4$ reco’d $\Lambda_c^+ \rightarrow pK^-\pi^+$

  [\(\nu \approx 7.6\) in pp collisions]
Additional vacuum valve

- To allow installation/maintenance of required instrumentation without breaking the VELO beam vacuum, a new vacuum valve will be installed in LS2

![Diagram of vacuum valve installation](image)
Long bent crystals

- **R&D ongoing** at INFN-Ferrara (& PNPI/IHEP?)
- Need special bending techniques with very precisely machined (~100 nm) holder to maintain uniform deformation
- Some **prototypes** produced

<table>
<thead>
<tr>
<th>Crystal material</th>
<th>Silicon or germanium, preferably germanium.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal length along the beam</td>
<td>~9 cm in case of silicon</td>
</tr>
<tr>
<td></td>
<td>~6 cm in case of germanium</td>
</tr>
<tr>
<td>Crystal + support height</td>
<td>≤ 55 mm</td>
</tr>
<tr>
<td>Crystal + support weight</td>
<td>To be determined</td>
</tr>
<tr>
<td>Channeling plane</td>
<td>(110) or (111)</td>
</tr>
<tr>
<td>Channeling axis</td>
<td>&lt;111&gt;, &lt;110&gt; or &lt;100&gt;</td>
</tr>
<tr>
<td>Miscut for planar channeling</td>
<td>To be determined</td>
</tr>
<tr>
<td>Torsion</td>
<td>&lt; 1 urad/mm</td>
</tr>
<tr>
<td>Bending angle</td>
<td>~16 mrad</td>
</tr>
<tr>
<td>Dislocation density</td>
<td>&lt; 1 cm²</td>
</tr>
<tr>
<td>Acceptable holder materials</td>
<td>Titanium grade 5, steel 316 LN</td>
</tr>
</tbody>
</table>

Courtesy of A. Mazzolari, INFN-Ferrara

Silicon: 8 cm long @ 16.0 mrad
Silicon: 5 cm long @ 14.5 mrad
Long bent crystals: test beam

- October 2018 test beam at CERN SPS H8 beam line (pion beam 120 GeV)

A formidable and enthusiastic team

LHCb Spokesperson
G. Passaleva amused taking pictures of the setup
Long bent crystals: test beam

- Predicted channeling efficiency in **agreement** with experimental results
- Measured **channeling efficiency** lower due to beam divergence and telescope tracker angular resolution

<table>
<thead>
<tr>
<th>Angular resolution</th>
<th>Beam divergence</th>
<th>Channeling efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infinite</td>
<td>0 urad</td>
<td>~32% (theoretical)</td>
</tr>
<tr>
<td>~5 urad</td>
<td>~16 urad</td>
<td>~14% (theoretical)</td>
</tr>
<tr>
<td>~5 urad</td>
<td>~16 urad</td>
<td>~12% (experimental)</td>
</tr>
</tbody>
</table>
Challenges

- Optimal **machine layout**, simulations for IP8 and for dedicated experiment scenario, absorber of the “split” beam and secondary products

- Long **bent crystal** construction: uniform bending, crystal torsion, mechanical imperfections of holder and crystal (SELDOM & CRYSBWAM ERCs)

- Fixed-target **experiment**: design, operation, event reconstruction. LHCb 1st phase, dedicated experiment 2nd phase e.g. beauty, τ
Possible layout at IP8

Splitting proton halo with crystal 1

- Implementation seems **feasible** but limited to proton flux \( \sim 10^6 \) proton/s (ongoing)
Possible layout at IP8

- Considering also other locations in the LHC ring, e.g. IP7, could reach \( \sim 10^8 - 10^9 \) protons/s (ongoing)
Summary

- **Vibrant and intense activity** ongoing during the last 2 years for MDM/EDM proposal for heavy particles with bent crystals at LHC

- **Milestones** achieved: feasibility detector studies, long bent crystal prototypes, preparatory physics studies in LHCb under way, vacuum valve, two-crystal scheme at SPS, LHC beam extraction, physics program extended

- **Challenges** ahead: machine layout (LHCb, dedicated experiment), absorber of the “split” beam and secondary products, long bent crystal construction, compact engineering design, detector operation

- **2019** will be a critical & exciting year: aiming for LHCb and LHCC approvals
Backup
**Basics of coherent interaction in crystals**

Potential well between crystallographic planes

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**Crystal effective atomic potential**

(a) Unchanneled particle

(b) Volume-reflected particle

(c) Volume-captured particle

(d) Channeled particle

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Critical (Lindhard’s)

\[ \theta_c = \sqrt{\frac{2U_0}{E}} \]

Potential well depth

Particle energy

2.3 μrad at 7 TeV

*Particles are emerging from crystal with this divergence!*

Incident **positively-charged particles** can be **trapped** if their **transverse energy** is **small** (incidence angle < \( \theta_c \))