Progress towards an experiment for electromagnetic dipole moments of unstable particles at the LHC

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on behalf of the SELDOM team

DyProSo 2019
Ferrara, 8-12 September 2019
Outline

‣ Physics motivations

‣ Experimental method
  - short-lived particles, e.g. charm and beauty baryons, τ lepton
  - long-lived particles, e.g. Λ baryon (not covered in this talk)

‣ EDM/MDM sensitivities

‣ R&D and preparatory studies

‣ Summary
Introduction

Electromagnetic dipole moments are static properties of particles, never measured for short-lived charm, beauty baryons, and \( \tau \) lepton

\[ \delta = \text{electric dipole moment (EDM)} \quad \delta = d\mu_N \frac{S}{2} \]

- EDM searches are sensitive to new physics. Violation of P, T and CP via CPT theorem.

\[ \mu = \text{magnetic dipole moment (MDM)} \quad \mu = g\mu_N \frac{S}{2} \]

- MDM measurements for QCD model and baryon substructure test (SM test for \( \tau \) lepton)
EDM physics motivations

- EDM of fundamental particles from the structure of quarks and gluons, and processes with photon and flavour-diagonal coupling

- A measurement of a heavy baryon EDM is **directly sensitive** to:

  \[ q_{\text{EDM}} \gamma \left( -\frac{i}{2} \delta q \sigma_{\mu\nu} \gamma_5 q F_{\mu\nu} \right) \]

  \[ q_{\text{CEDM}} \gamma g \left( i \sigma q \gamma_{\mu\nu} \gamma_5 t_a q G_{\mu\nu}^a \right) \]

Charm EDM in SM-CKM \( \sim 10^{-32} \) e cm
Khriplovich, Lamoreaux (1997)

Charm EDM with new physics \( \sim 5 \times 10^{-17} \) e cm
EPJC 77 (2017), 102

- EDM observation = clear signature of **new physics**
MDM physics motivations

- Experimental anchor points for test of low-energy QCD models, related to non-perturbative QCD dynamics
- Test of baryon substructure
- Measurement of MDM of particles and antiparticles would allow a test of CPT symmetry
Status of EDM measurements

- SM–CKM
- SM–Θ

$<d^{(expected)}$  $<d^{(meas)}$

EDM (e.cm)

PID

CERN-PBC-REPORT-2018-007
MDM theoretical predictions

Provide experimental anchor points for heavy baryon MDM model predictions. Trigger further theory activity

\[ \Lambda_c^+ \]

\[ \Xi_c^+ \]

CERN-PBC-REPORT-2018-008
Experimental method for short-lived particles:

\[ \Lambda_c^+, \Xi_c^+, \Xi_b^+, \Omega_b^+, \tau^+ \]

(\( \tau \approx 10^{-13} - 10^{-12} \text{ s} \))
Channeling in bent crystals

- Potential well between crystal planes
- Incident positive charge particle can be trapped if parallel to crystal plane (within few μrad)
- Well understood phenomenon (Lindhard 1965)
- Bent crystals used to:
  - steer high-energy particle beams, very high effective magnetic field $B\approx500$ T
  - induce spin precession
Spin precession in bent crystals

- Firstly predicted by Baryshevsky (1979)
  V.G. Baryshevsky, Pis’ma Zh. Tekh. Fiz. 5 (1979) 182.

- Determine particle gyromagnetic factor from BMT equation

\[
\theta_S = \frac{g - 2}{2} \gamma \theta_C
\]

\( \theta_S = \) spin rotation angle  
\( \theta_C = \) crystal bending angle  
\( g = \) gyromagnetic factor  
\( \gamma = \) Lorentz boost

**Fig. 1.** Spin rotation in a bent crystal.
EDM with bent crystals

Fill the experimental gap in heavy baryon electric dipole moment searches. Method proposed in EPJC (2017) 77:181

Spin precession in crystal electromagnetic field ($E^* \perp B^*$ in particle rest frame)

\[ \frac{dS}{dt} = \mu \times B^* + \delta \times E^* \]

- MDM and EDM precession in the limit $\gamma \gg 1, d \ll g - 2$

\[ \theta_s \approx \frac{g - 2}{2} \gamma \theta_c \]

\[ S_x \approx S_0 \frac{d}{g - 2} [\cos(\Phi) - 1] \]
**Novel** fixed-target experiment at LHC for charm baryons

- **EDM/MDM** from spin precession of channeled baryons in bent crystals

![Diagram of experiment setup](image)

1) Crystal kicker
2) W target
3) Bent crystal
4) Absorber

1) LHCb detector

- Beam halo
- Deflected beam
- ≈100 m
- Zoom in

1) $s^*$ = EDM signature
2) Bent crystal

$p$ extraction
Novel fixed-target experiment at LHC for charm baryons

- **EDM/MDM** from spin precession of channeled baryons in **bent crystals**

- **p** extraction $\Lambda_c^+$ polarised production

![Diagram](image-url)
**Novel** fixed-target experiment at LHC for charm baryons

- **EDM/MDM** from spin precession of channeled baryons in **bent crystals**

1. Crystal kicker
2. W target
3. Bent crystal
4. Absorber

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1) $s_0$
2) Bent crystal
3) LHCb detector
4) LHCb detector

$p$ extraction $\Lambda_c^+$ polarised production channeling spin precession

$\approx 100$ m

-not to scale

$\approx 1$ cm

Beam halo

- Deflected beam

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Attention: not in scale
**Novel** fixed-target experiment at LHC for charm baryons

- **EDM/MDM** from spin precession of channeled baryons in **bent crystals**

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$p$ extraction $\Lambda_c^+$ polarised production  channeling  spin precession  event reconstruction
LHCb Upgraded detector

All sub-detectors read out at 40 MHz for a fully software trigger

- New silicon Upstream Tracker (UT)
- New scintillating fibre tracker (SciFi)
- New pixel VELO detector
- Proposed target setup
- New RICH optics and photodetectors
- New electronics for calorimeter and muon system
Sensitivity on MDM

- **S1 configuration:** LHCb using $10^{15}$ PoT
  - PoT = proton on target
  - W target 5 mm thick

- **S2 configuration:** dedicated experiment using $10^{17}$ PoT

Measurements are statistically limited

Material of the crystal:
- Silicon
- Germanium

EPJC (2017) 77:828
Sensitivity on EDM

- S1 configuration: **LHCb** using $10^{15}$ PoT  
  PoT = proton on target  
  W target 5 mm thick

- S2 configuration: dedicated experiment using $10^{17}$ PoT

Material of the crystal:
- Silicon
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EPJC (2017) 77:828

Measurements are **statistically limited**
R&D and preparatory studies
• **Channeling** of 6.5 TeV at LHC already **demonstrated** by UA9
• **Viable layout:** $10^6$-$10^7$ proton/sec on target close to LHCb
• Improved performance for a potential dedicated experiment at the LHC
Long bent crystal results

Silicon crystal 8 cm long
Bending angle 16 mrad

Si: 8 cm long, bent @16.0 mrad
Ge: 5 cm long, bent @14.5 mrad

- Si and Ge long bent crystals developed at INFN-Ferrara.
  Channeling efficiency >10% for 180 GeV/c pions

Preliminary

Courtesy of A. Mazzolari
Preparatory studies in LHCb

- Program of preparatory measurements in LHCb started: \( \Lambda_c^+ \) polarisation and cross-section in p-gas fixed-target configuration (LHCb-PUB-2018-015)

- Good performance for signal reconstruction and background rejection studied using LHCb full simulation for the new fixed-target setup

![Graph showing the cross-section of LHCb vs. \( \sqrt{s_{NN}} \) in GeV with NLO pQCD predictions and data points.]

New proposals for $\tau$ lepton


Novel method for the direct measurement of the $\tau$ lepton dipole moments

Target:
- production of $D_{s}^{+}(\rightarrow \tau^{+} \nu_{\tau})$

Single Crystal after target:
- $\tau$ spin precession

Spin polarisation:
- kinematic selection on $p_{3\pi}>0.8$ TeV, longitudinal ($z$) polarisation for MDM and enhanced EDM sensitivity
- Tagging $\theta(D_{s},\tau)\leq 0$ (e.g. 2 crystals, other) transverse ($y$) polarisation for enhanced MDM sensitivity

Novel method for the direct measurement of the $\tau$ lepton dipole moments

Multivariate classifier based on reconstructed $\tau$ variables to determine the polarisation and average event information $S=0.42$

$$S_i^2 = \frac{1}{N_{\tau+} \sigma_i^2} = \left\langle \left( \frac{\mathcal{W}_i^+(\eta) - \mathcal{W}_i^-(\eta)}{\mathcal{W}_i^+(\eta) + \mathcal{W}_i^-(\eta)} \right)^2 \right\rangle$$

Test $g-2$ SM prediction with $\sim 10^{17}$ PoT
EDM sensitivity $\sim 10^{-17}$ e cm
Challenging: dedicated experiment needed

Summary

- The proposal for measuring MDM/EDM of unstable particles extends the LHC physics program

- **Milestones** achieved: feasibility detector studies, long bent crystal prototypes, preparatory studies in LHCb, machine layout, physics program extended

- **Next steps**: produce a technical design report and if approved proceed with installation, data taking

- **Workshop** 3-4 October 2019 in Milano

Proposed timeline

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<th>2018</th>
<th>2020</th>
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<td>R&amp;D</td>
<td>Install (YETS)</td>
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<td>LS2</td>
<td>Run3</td>
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- LHCb

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<tr>
<td>Data taking</td>
<td>Run4</td>
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Acknowledgements


References for baryons


- 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).


References for $\tau$ lepton


Backup slides
Electromagnetic dipole moments

- Classic systems
  \[ \delta = \int r \rho(r) d^3r \quad \mu = \int r \times j(r) d^3r \]

- Quantum systems
  \[ \delta = d\mu_N \frac{S}{2} \quad \mu = g\mu_N \frac{S}{2} \]

\( \delta \) = electric dipole moment (EDM)

\( \mu \) = magnetic dipole moment (MDM)

- Hamiltonian
  \[ H = -\delta \cdot E - \mu \cdot B \]

Time reversal, Parity:

\[ d\mu_N \frac{S}{2} \cdot E \xrightarrow{T,P} - d\mu_N \frac{S}{2} \cdot E \]

The EDM violates \( T \) and \( P \) and via CPT theorem, violates \( CP \)
At IR3 with optimised detector acceptance and reduced crystal bending (5 mrad), about x100 channeled particles can be achieved
Proof of principle in E761

- E761 Fermilab experiment firstly observed spin precession in bent crystals and measured MDM of $\Sigma^+$

- $350 \text{ GeV/c } \Sigma^+$ produced from interaction of 800 GeV/c proton beam on Cu target

- Used upbent and downbent silicon crystals $L=4.5\text{ cm}$, $\theta_C=1.6$ mrad for opposite spin precession, reduced systematics


FIG. 3. Measured polarizations and uncertainties (1$\sigma$ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.
MDM of short-lived baryons

- **Charm baryon MDM** with bent crystals firstly studied in:
  - V. V. Baublis et al., NIMB 90 (1994) 112-118

- Recently revisited for LHC energies:
  - O. A. Bezshyyko et al., JHEP 8, 107 (2017)
Charm baryon polarisation

- Fixed-target production: polarisation is perpendicular to production plane due to parity conservation in strong interaction

- $\Lambda_c^+$ polarisation vs transverse momentum measured by E791 experiment in 500 GeV/c $\pi^-$-N reactions
  - Increases with $\Lambda_c^+$ transverse momentum
Detector simulation studies
Simulation studies

- Tungsten (W) 5 mm fixed target + bent crystal positioned in (0, 0.4, -116) cm, before the interaction point

- Use EPOS for fixed-target minimum bias events, PYTHIA for baryons produced in pW hard collisions

- Signal reconstruction and background rejection studied using LHCb full simulation
Fixed-target simulation

- Radiography of the target in (0, 0.3, -116) cm
- Distribution of origin vertex of stable charged particles in simulated events
- Simulated processes include: hadronic interactions, pair production, Bremsstrahlung, Compton, δ rays
Identification of signal events

- About $10^{-4} \Lambda_c^+$ produced in the target are channeled in the bent crystal

- Use PV to identify $\Lambda_c^+$ produced in W target, and $\Lambda_c^+$ vertex helps to identify decays outside of the crystal (max spin precession)

- $\Lambda_c^+$ angle determined by crystal bending angle, e.g. $\theta_C=15$ mrad

- Channeled baryons have high momentum $\gtrsim 1$ TeV/c
$\Lambda_{c^+}$ momentum distribution

- At production (top)
- After channeling and $p>800$ GeV/c (bottom)

Si, $L\sim 7$ cm, $\theta_C \sim 14$ mrad

- $<p> \sim 1.320$ TeV

Ge, $L\sim 5$ cm, $\theta_C \sim 15$ mrad

- $<p> \sim 1.379$ TeV
Background rejection

- Rejection of unchanneled $\Lambda_c^+$ produced in W target

  - **Signal events**
  - **Crystal-transparent events**

  - **Channeled particles**
    - Signal region: $14.8^\text{o}<\theta<15.2$ mrad [$\sigma(\theta)\sim 25\mu\text{rad}$], $p_{\Lambda_c}> 800$ GeV/c
    - Background rejection $10^{-7}$ level and signal efficiency 80%
    - High momentum $\Lambda_c^+$ most sensitive for EDM measurements
EDM/MDM sensitivity studies
Sensitivity to EDM/MDM

Studies based on:

- $\Lambda_c^+$ from fixed-target (Pythia + EvtGen)
- Reconstruction, Decay flight efficiency (LHCb simulation)
- Channeling efficiency (parametrization)
- Fit to spin precession (pseudo experiments)

\[
\begin{align*}
N_{\Lambda_c^+}^{\text{reco}} &= N_{\Lambda_c^+} B(\Lambda_c^+ \to f) \varepsilon_{\text{CH}} \varepsilon_{\text{DF}} \varepsilon_{\text{det}} \\
\sigma(pp \to \Lambda_c^+ X) &\approx 18.2 \mu b \\
|S_0| &\approx 0.6 \\
\varepsilon_{\text{det}} &\approx 20\% \quad \varepsilon_{\text{DF}} \approx 10\% \\
\varepsilon_{\text{ch}} &\approx 10^{-4} \\
\frac{dN}{d\Omega} &\propto 1 + \alpha_f S \cdot p \\
\alpha_{\Delta^{++}K^-} &\approx -0.67 \\
\sigma_d &\approx \frac{g - 2}{\alpha_f s_0 (\cos \Phi - 1)} \frac{1}{\sqrt{N_{\Lambda_c^+}^{\text{reco}}}} \\
\sigma_g &\approx \frac{2}{\alpha_f s_0 \gamma \theta_c} \frac{1}{\sqrt{N_{\Lambda_c^+}^{\text{reco}}}}
\end{align*}
\]
Channeling efficiency

- Channeling efficiency for $\Lambda_c^+$ particles within Lindhard angle
- Total channelling efficiency: Lindhard angle, dechanneling, $\Lambda_c^+$ decay flight: $1 \cdot 10^{-5}$ (Si), $4 \cdot 10^{-5}$ (Ge)

$$w(\theta_C, R) = \left(1 - \frac{R_c}{R}\right)^2 \exp\left(-\frac{\theta_C}{\theta_D \frac{R_c}{R} (1 - \frac{R_c}{R})^2}\right).$$

Crystal optimisation

- Optimised sensitivity to EDM and MDM. Channeling and reconstruction efficiency included

Regions of minimal uncertainty of EDM (continuous line) and MDM (dotted line) defined as +20% uncertainty with respect to the minimum (point marker)
Future plans for $\tau$ lepton
Future plans

- New proposals for τ lepton MDM/EDM direct determination using bent crystals

- Large statistics needed for interesting measurements, i.e. PoT ≳ 10^{17} [2.5 cm W target]
- Many challenges: dedicated experiment needed
- Preparatory studies in LHCb
Feasibility of $\tau$ lepton electromagnetic dipole moments measurement using bent crystal at the LHC

Crystal 1:
- directing a part of LHC primary halo on Target

Target:
- production of $D_s^+(\rightarrow \tau^+\nu_\tau)$
  $\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$

Crystal 2:
- deflection and “collimation” of $D_s^+$

Crystal 3:
- selecting $\tau$ produced by $D_s^+$
- filtering $\tau$ initial polarisation
- $\tau$ spin precession

$\frac{\partial N_\tau}{\partial \varepsilon_\tau}, 10^{-12} \text{ TeV}^{-1} / p$
Polarisation

Deflected $\tau$

Feasibility of $\tau$ lepton electromagnetic dipole moments measurement using bent crystal at the LHC

MDM: $10^{16}$ PoT — to reach the present accuracy [DELPHI: J. Abdallah et al. EPJC 35:159–170, 2004]

$10^{18}$ PoT — to reach an accuracy equivalent to the Standard Model value

EDM: $10^{19}$ PoT — to reach the present accuracy [BELLE: K. Inami et al. PLB 551:16–26, 2003]
Future plans for $\tau$ MDM/EDM


Requires a future dedicated experiment

Preparatory measurements are possible in LHCb