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Electromagnetic dipole moments of baryons with strangeness and charm at the LHC(*)

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Summary. — The program for measuring electric and magnetic dipole moments can be extended to baryons with strangeness and charm at the LHC. The observation of an electric dipole moment would provide a signal for physics beyond the Standard Model and the existence of a new mechanism for CP violation that could help explain the observed difference between matter and antimatter in the Universe. Measuring magnetic dipole moments is useful for validating non-perturbative quantum chromodynamics theoretical models and providing new information about the internal structure of hadrons. Additionally, measuring the magnetic dipole moment for a particle and its antiparticle would allow a test of the CPT symmetry. We present new possibilities for conducting such measurements at the LHC by exploiting the spin precession of baryons with charm in bent crystals and baryons with strangeness inside the magnet of the LHCb tracking system. Feasibility studies of the proposed techniques and the expected precision of the measurements will be outlined.

1. – Introduction

The magnetic dipole moment (MDM, $\vec{\mu}$) and the electric dipole moment (EDM, $\vec{\delta}$) are static properties and for spin 1/2 particles they are defined as

$$\vec{\mu} = g\mu_B \frac{\vec{s}}{2}, \tag{1}$$

$$\vec{\delta} = d\mu_B \frac{\vec{s}}{2}. \tag{2}$$

The spin-polarization vector $\vec{s}$ is equal to $2 < \vec{S} > /\hbar$, with $\vec{S}$ the spin operator. The particle magneton is $\mu_B = e\hbar/(2mc)$ with m the pass of the particle, and d and g are the gyroelectric and gyromagnetic factors respectively. There has been a word-wide effort in measuring these quantities in many different particles. The reason is due to the

(*) IFAE 2023 - "Intensity Frontier" session fact that, assuming the validity of the CPT theorem, the existence of the EDM would imply a new source of CP violation, since it is T-odd and P-odd. ITs existance would have implications on the mechanism of baryogenesis. The measurement of MDM of a particle and its antiparticle would provide an additional test of the CPT theorem and experimentally add insights on the QCD models proposed at low energy, being sensitive to the internal dynamics of the baryons. In this work we focus on the measurement of the EMDMs of the Λ baryons and of the charmed baryons as Λ_c^+ and Ξ_c^+. For the strange baryon the most recent measurement has been performed at Fermilab between 1970 and 1980. The result obtained for the magnetic dipole moment of the Λ baryon was [1]

$$\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N.$$

There was no possibility to measure the $\bar{\Lambda}$ MDM. An upper limit was set for the EDM at 95% C.L. of

$$|\delta_\Lambda| < 1.5 \times 10^{-16}\,\mathrm{e\,cm},$$

which is the best limit up to date. The proposed work aims at improving the precision on the Λ MDM by one order of magnitude, collecting 50 fb^{-1} data with the LHCb experiment. With the same amount of data we expect to reach a sensitivity on the EDM of the Λ baryon of the order of 10^{-18} e cm. For the charmed baryons the EMDMs have never been measured due to their short lifetime. With two years of datataking at 10^{13} protons on target we expect to perform the first measurement with a sensitivity on the EDM of the order of 10^{-16} e cm and an uncertainty on $g-2$ of 10^{-2} [2].

2. – Experimental method

The dipole moments measurements exploit the phenomenon of spin precession in an electromagnetic field and are characterised by the presence of three main components:

- a source of polarized particles, such as Λ baryons from charm or beauty weak decays or Λ_c^+ and Ξ_c^+ baryons produced by protons on a fixed target,
- a magnetic field strong enough to induce an observable precession during the short lifetime of the particles,
- a detector to reconstruct the final state particles used to build the angular distribution sensitive to the polarization.

Due to the different lifetime of the Λ and the charmed baryons, respectively of the order of 10^{-10} and 10^{-13} s, two different experimental technique have to be developed to measure their precession.

2˙1. Λ *case.* – The LHCb experiment can satisfy all the listed requirements for particles that are able to fly until the region beyond the magnetic field, such as Λ baryons.The LHCb collaboration has measured the polarisation of Λ baryons originated from $\Lambda_b^0 \to J/\Psi\Lambda$ weak decays decaying before the magnetic field to be maximal along its direction of motion, in agreement with other LHC measurements. The experimental measurement of dipole moments relies on the measurement of the precession angle of the polarization

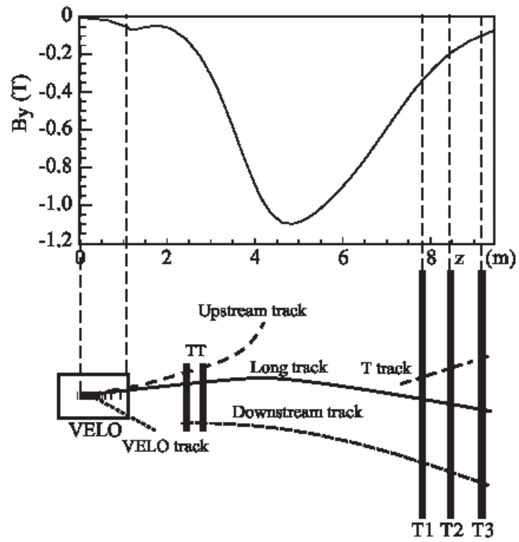

Fig. 1. – Scheme of the LHCb tracking system and different tracks type [6].

($\vec{s}$) in an external magnetic field. The spin equation of motion, is described by Thomas-Bargmann-Michel-Telegdi (T-BMT) equations [3-5]

$$\frac{d\vec{s}}{dt} = \vec{s} \times \vec{\Omega}, \tag{3}$$

with t the time in the laboratory frame, while $\vec{\Omega}$ is the precession angular velocity. In the particular case of neutral Λ baryons in LHCb, where $\vec{E} = 0$,

$$\vec{\Omega} = \frac{\mu_B}{\hbar}\left[g\left(\vec{B} - \frac{\gamma(\vec{\beta}\cdot\vec{B})\vec{\beta}}{\gamma+1}\right) + d\vec{\beta}\times\vec{B}\right], \tag{4}$$

and the precession angle $\vec{\Phi}$, linked to the dipole moments is

$$\vec{\Phi} = \frac{\mu_B}{\beta\hbar c}\left[g(\vec{D} - \frac{\gamma\beta(\vec{\beta}\cdot\vec{D})}{\gamma+1}) + d\vec{\beta}\times\vec{D}\right]. \tag{5}$$

With $\vec{D} \simeq \int_0^l \vec{B} dl' \simeq 4$ T$\cdot m$, the magnetic field integrated along the particle flight length.

This solution simplifies further considering Λ flying along the z-axis in the laboratory frame, with an initial polarization $\vec{s}_0 = (0, 0, s_0)$ and the magnetic field $\vec{B} = (0, B_y, 0)$. This approximation can describe quite well the situation in the LHCb detector. The final polarization ($\vec{s}$) becomes

$$\vec{s} = (-s_0 \sin\Phi, -s_0\frac{d\beta}{g}\sin\Phi, s_0\cos\Phi), \tag{6}$$

with $\Phi = \frac{D_y\mu_B}{\beta\hbar c}\sqrt{d^2\beta^2 + g^2} \simeq \frac{gD_y\mu_b}{\beta\hbar c}$, which is expected to be about $\pi/4$. The spin-polarization vector precesses in the plane perpendicular to the magnetic field, with an angle approximatly proportional to the gyromagnetic factor. The presence of an EDM would induce a component s_y different from zero. In addition, since the precession takes place in the plane perpendicular to the magnetic field, it is important that Λ baryons are highly polarized in the same plane to maximize the precession. For this reason we consider Λ particle produced in weak decays, otherwise the strong interaction would suppress this component to conserve the parity symmetry. It is now clear why, to obtain the dipole moments, it is important to extract the precession angle, measuring the spin polarization both before and after the magnetic field. The angular distribution of the daughter particles in $\Lambda \to p\pi^-$ decay is sensitive to the Λ polarization. Since Λ and p have spin 1/2 and π has spin 0, the angular distribution of the decay, obtained using the helicity formalism [7, 8], is the following

$$\frac{dN}{d\Omega'} \propto 1 + \alpha \vec{s} \cdot \hat{k}. \tag{7}$$

Where $\hat{k} = (\sin\theta' \cos\phi', \sin\theta' \sin\phi', \cos\theta')$ is momentum direction of the proton in the Λ rest frame, while α represents the decay asymmetry parameter (0.732 ± 0.014 [9]). Due to the CP invariance in the decay, the charge-conjugate decay should have $\bar{\alpha} = -\alpha$. The solid angle Ω' equals $(\cos\theta', \phi')$, which are respectively the polar and azimutal angle of the proton in the Λ rest frame.

The most challenging part is to measure the polarization after the precession, due to the fact that the trajectories of the pions and protons are reconstructed using information only from the tracking stations downstream of the magnet (T stations, fig. 1), with their mother particle decaying between 6 and 8 m after the interaction point. These tracks, called T tracks, have never been used in LHCb for physics measurement because of their poor resolution. In particular, T tracks have a momentum resolution between 20 and 30% [10], to be compared with 1% of particles which hit the full tracking system (Long tracks) and the resolution on the vertex is about 50 cm, to be compared with 100 μm of the Long tracks. Another factor is the "closing-track" topology which characterizes the considered decay: the trajectories of the two daughter particles intercepts in two points, the true decay vertex of the Λ and another point to which we refer as ghost vertex. This topology introduces a bias in the vertex reconstruction. All these factors play a role on the measurement of the polarization after the precession. The angular resolution is affected by the presence of ghost vertices, their removal would improve the resolution of about a factor two. Currently a Boosted Decision Tree has been trained to identify and remove these kind of events, preliminary studies on MC show good performance. Also the statistics influence the polarization measurement and the main responsible of the decrease in efficiency is the vertexing algorithm, which convergence rate is only 50%, due to an interplay between the already mentions factors. Further studies are in progress to overcome these reconstruction limitations and improve the sensitivity on the polarization.

2·2. Λ_c^+ *and* Ξ_c^+ *case.* – For the charmed baryons case, since their lifetime is three orders of magnitude smaller than the Λ, a strong magnetic filed, of the order of 10^3 T is necessary in a short length, about 5 cm. The technological solution can be found in bent crystals. Positively-charged particles are produced by protons interacting with a fixed target and channeled between the atomic planes of the crystal and move along a curved path under the action of the intense electric field between the crystal planes of the order of 1 GV/cm. Due to the parity conservation in the strong force, the polarization is produced perpendicularly to the production plane (xz) and the crystal is bent in yz

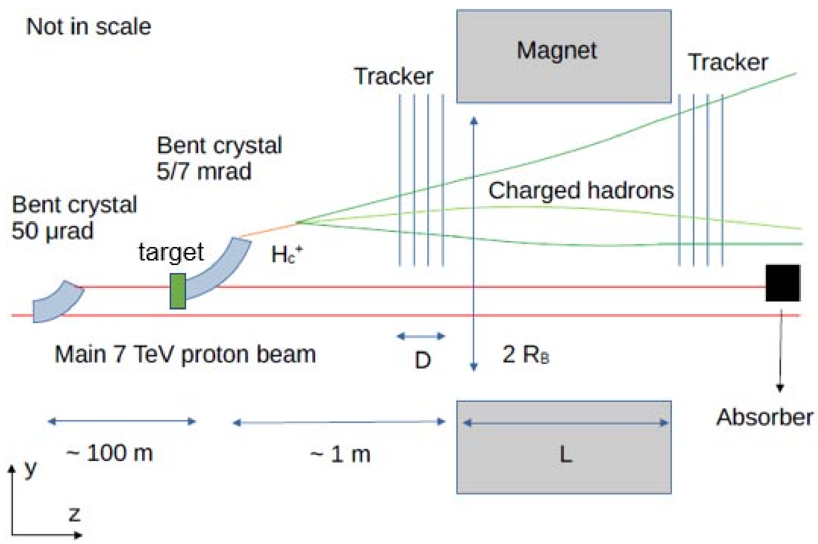

Fig. 2. – Scheme of the IR3 proof of principle setup.

to induce the spin rotation. Similarly to the Λ case, the spin precession angle (ϕ) is sensitive to the MDM

$$\phi \approx \frac{g-2}{2}\gamma\theta_C, \tag{8}$$

where γ is the Lorentz factor and θ_C is the crystal bending angle [2]. The presence of a non-zero EDM induce the spin rotation to be also in the xz plane and the polarization after the precession is

$$\vec{s} \approx \left(\frac{d}{g-2}s_0(\cos\phi - 1), s_0\cos\phi, s_0\sin\phi\right). \tag{9}$$

We propose an experiment to be performed at the LHC and to be developed in three different phases. First, a proof of principle test at the interaction point 8 of the LHC with the aim of measuring the channeling efficiency in the crystals at the LHC energy and to study the backgrounds. A second phase, for an experiment to collect the first physics data to measure the dipole moments. Finally, a third phase for the ultimate precision measurement. The proof of principle is foreseen to start in 2025 with a simplified apparatus. A first bent crystal is used to extract protons from the LHC beam halo, then a system composed by a Tungsten target and a second bent crystal are responsible for the production and spin precession of the charmed baryons. A tracking system is needed to detect the charmed baryons daughter particles and extract the polarization after the precession. The spectrometer is composed by a magnet, already available in situ, and two tracking stations for the reconstruction of the particle trrajectories. Each station is composed by silicon pixel sensors inside the secondary vacuum of a Roman Pot. The pixel dimension is $55 \times 55\ \mu m^2$ with a pitch of $12\ \mu m$ and a maximum readout rate of 600 MHz/cm^2.

3. – Conclusions

The electromagnetic dipole moments measurement of the Λ baryon can be performed at LHCb by studying the spin precession inside the magnetic field of the tracking system. The analysis of $\Lambda_b^0 \to J/\Psi\Lambda$ decays is ongoing and sensitivity studies are quite encouraging, showing the possibility to improve by one order of magnitude the current best measurement of the MDM and improve the sensitivity on the EDM by two orders of magnitude. The first measurement of electromagnetic dipole moments measurement of the charmed Λ_c^+ and Ξ_c^+ baryons can be performed at the in 2025 at LHC-IR3. R&D and simulation studies for a future experiment are ongoing.

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REFERENCES

[1] Pondrom L. *et al.*, *Phys. Rev. D*, **23** (1981) 814(R).
[2] Botella F. J., Garcia Martin L. M., Marangotto D., Martinez Vidal F., Merli A., Neri N., Oyanguren A. and Ruiz Vidal J., *Eur. Phys. J. C*, **77** (3) 181.
[3] Thomas L. H., *Nature*, **117** (1926) 514.
[4] Thomas L. H., *Philos. Mag.*, **3** (127) 1.
[5] Bargmann V., Michel L. and Telegdi V. L., *Phys. Rev. Lett.*, **2** (1959) 435.
[6] LHCb Collaboration, *Int. J. Mod. Phys. A*, **30** (2015) 1530022.
[7] Jacob M. and Wick G. C., *Ann. Phys.*, **7** (1959) 4.
[8] Richman J. D., *An experimenter's guide to the helicity formalism*, Tech. Rep. (1984).
[9] Particle Data Group (Zyla P. A. *et al.*), *Prog. Theor. Exp. Phys.*, **2020** (2020) 083C01.
[10] LHCb Collaboration, *Long-lived particle reconstruction downstream of the LHCb magnet*, arXiv:2211.10920 (2022).