Direct measurement of charm baryons dipole moments at LHC

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Summary. — The magnetic and electric dipole moments of fundamental particles serve as valuable tools for studying physics within and beyond the Standard Model. However, experimental access to these short-lived particles has been challenging due to their brief lifetimes. A new experimental technique has been developed to directly measure the electromagnetic dipole moments of charm baryons, and potentially the tau lepton, at the Large Hadron Collider (LHC). The experimental test is planned for 2025 in the IR3 region of the LHC and aims to demonstrate the feasibility of a fixed-target experiment using bent crystals. This test will validate the proposed methodology and lay the groundwork for a future experiment on the dipole moments of charm baryons. Prospects for the future experiment and the expected sensitivity in various luminosity scenarios will be discussed.

1. – Charm baryons dipole moments

The electric dipole moment (EDM) and magnetic dipole moment (MDM) are critical properties of particles that provide valuable insights into fundamental physics. The EDM measures the separation of positive and negative charges within a particle, while the MDM determines the force experienced by a particle in a magnetic field. For spin 1/2 particles, the intrinsic electric and magnetic dipole moments are defined as $\delta = \frac{1}{2} d\mu_B P$ and $\mu = \frac{1}{2} g\mu_B P$, respectively. Here, d and g are the gyroelectric and gyromagnetic factors, μ_B is the Bohr magneton, and P is the spin polarization unit vector given by $P = \frac{2\langle S \rangle}{\hbar}$, with S being the spin operator [1]. EDMs and MDMs are stringent tests of the Standard Model. Measurements of MDMs provide crucial data for modeling strong interactions and performing QCD calculations. Conversely, detecting a non-zero EDM would indicate new physics beyond the Standard Model. In the system's Hamiltonian, $H = -\mu \cdot B - \delta \cdot E$, the term involving the EDM violates T and P symmetries, thereby violating CP symmetry through the CPT theorem. Despite their importance, there are currently no measurements of the electromagnetic dipole moments of charm baryons due to their extremely short lifetimes, $\leq 2 \times 10^{-13}$ seconds [2][3]. To overcome this challenge, a novel experimental method has been proposed that leverages particle spin precession within bent crystals [4]. When particles strike the crystal surface at a sufficiently small angle, they are not only channelled but also experience spin vector precession due to the intense electric and magnetic fields within the bent crystal [5][6]. The MDM of the particle can be determined from the precession angle $\phi = \omega\left(1 + \gamma\frac{g-2}{2}\right)$, while the EDM is related to the spin-polarization component perpendicular to the production plane $s_x = s_0\frac{d}{g-2}(1 - \cos\phi)$ [7][8].

2. – Fixed target experiment at LHC

The proposed experimental technique is based on a fixed-target experiment at the LHC, where 7 TeV protons impinge on a tungsten (W) target, at a center-of-mass energy $\sqrt{s} \approx 110\,\text{GeV}$. This fixed-target experiment at LHC is based on a double-crystal setup [9]. The first crystal, the target collimator crystal for splitting (TCCS), has a bending angle of 50 μrad and is used to deflect protons from the beam halo towards a tungsten W target positioned about 100 m downstream of the TCCS. A second crystal, the target collimator crystal for precession (TCCP), with a bending angle of 0.7 mrad is positioned right after the W target. It induces spin precession to channelled charm baryons and deflects their trajectory within the acceptance of a forward detector to perform the reconstruction of signal decays. For experiment at LHC there are two alternative scenarios: i) a dedicated experiment at the insertion region 3 (IR3), the baseline scenario; ii) the use of the LHCb detector at the interaction point 8 (IP8), kept as a fallback option. Different studies have been conducted to understand the feasibility of the measurement and which scenario might be better suited for the future experiment. The first considerations to be done are on the kinematics of the produced charm baryons. The single event topology has two peculiar features: i) the average momentum of the channelled charm baryons is very high, i.e. about 1.8 TeV/c for Λ_c^+ baryons for a bending angle $\theta_c = 7$mrad; ii) the direction in the bending plane of the channelled baryons is determined by the crystal bending angle. As a consequence, the momentum distribution of the decay products reaches 1.0 TeV/c and the angular distance between the charm baryon and the daughter particle momenta is $1/\gamma$ rad. The nominal solution at IR3, offers the advantage of an optimal detector design and particle identification information (PID) in the range of momenta up to 1 TeV/c. The detector layout for the dedicated experiment at IR3, Fig. 1, consists of a spectrometer and a Ring Imaging Cherenkov (RICH) detector. The spectrometer features pixel detectors positioned inside four Roman Pot (RP) stations, while the RICH detector is based on Helium as radiator gas with a SiPM photosensor array. The length of the whole detector along the beam line is approximately 10 m, about 4.4 m is the spectrometer length, and 5.0 m for the RICH. The transverse dimension of the detector is confined within 1.0 m to fit within the available space along the LHC tunnel. The spectrometer features a warm dipole magnet, MCBWV.4L3.B2, with a magnetic field of 1.1 T and an effective magnetic length of 1.7 m. Nevertheless, the construction of a new detector in the LHC tunnel will require significant resources and time for the design, construction, installation, and commissioning. On the other hand, the LHCb based solution has the advantage of using an existing tracking detector and infrastructure, located in a equipped experimental area, but the LHCb detector does not provide PID information for momenta greater than 100 GeV/c and the project could have potential interference with the LHCb core program and data taking. The tentative timeline of the experiment is the following: i) proof-of-principle test during Run 3; ii) construction and installation during the LHC Long Shutdown 3 (LS3); iii) commissioning and data taking during Run 4. The region for the TWOCRYST PoP at IR3 has been identified and being instrumented for operations in 2025. The same region is considered also suitable for the proposed experiment.

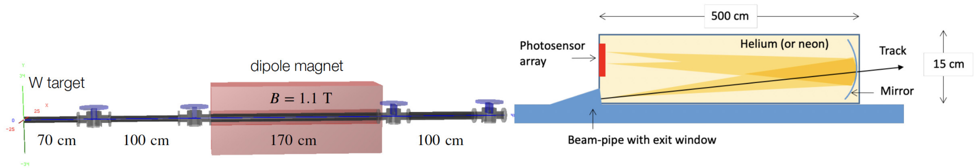

Fig. 1.: Experimental setup for proposed fixed target experiment at IR3.

3. – Proof-of-principle test at LHC

A proof-of-principle (PoP) test in LHC, the TWOCRYST project, has been approved and is starting in 2025 with the following objectives: i) demonstrate the feasibility of the machine operations; ii) confirm the achievable proton rate on target; iii) measure the channelling efficiency at TeV energy using LHC protons; iv) perform the necessary background studies to validate the simulations and the detector optimisation. This test will deliver tangible input on critical aspects that are only accessible in simulation so far. The experimental apparatus for the PoP is a reduced version of the one of the proposed experiment, as shown in Fig. 2. The first crystal is used to channel the secondary halo of the proton beam while the second one is used for the spin precession and to channel the baryons. For this first test, downstream to the second crystal there will be only one tracking station placed inside a roman pot. The detector package consists in three layers of silicon pixel sensors. The chosen sensors are the VeloPix Silicon pixel sensor, state of the art technology already used by the Vertex Locator detector of LHCb. The pixel dimension is 55× 55 μm^2 with a resolution of 12 μm and a maximum readout rate of 600 MHz/cm^2 [10]. The sensors will be placed few mm far from the main circulating beam and will measure the channelled particles with respect to the non-channelled ones, to make the efficiency measurement. The detector modules are almost ready to be assembled and qualified, while the crystal have already been tested at the SPS. The installation works at the LHC will start at the end of 2024.

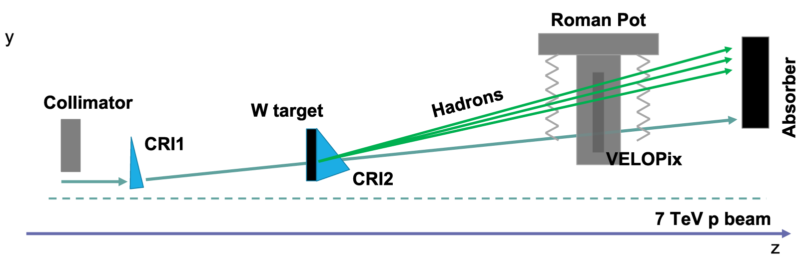

Fig. 2.: Experimental setup for the proof-of-principle test at IR3.

4. – Detector developments

The TCCS and TCCP bent crystals were produced at INFN Ferrara according to the specifications required for installation at the LHC. They were characterized on beam at the CERN H8 SPS in August 2023 using a 180 GeV/c positive hadron beam. The INFN tracking telescope utilizes silicon strip sensors with a 50 μm pitch to measure the incoming angle of hadrons striking the crystal with an accuracy of 3.5 μrad. Downstream of the crystal, silicon strip sensors with pitches of 50 μm and 242 μm are used to achieve an angular resolution of about 7 μrad for the outgoing track angles. A goniometer with 1 μrad accuracy is employed for precise crystal alignment to ensure optimal channelling conditions. Preliminary results indicate a channelling efficiency of approximately 60% for the TCCS crystal and about 16% for the TCCP crystal. The offline analysis considers a potential mechanical torsion of the bent crystal, measured to be about 20 μrad/mm. A detailed report on the test beam results is currently being prepared.

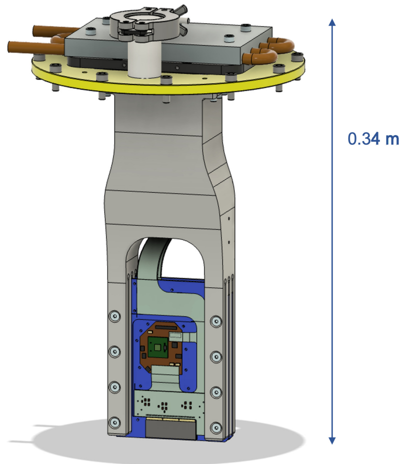

Fig. 3.: Experimental setup for the proof-of -principle test at IR3.

The pixel detector of the proof-of-principle is based on the LHCb VELO pixel sensors and VeloPix ASIC. The Si sensor is 200 μm thick and it is built in n-in-p technology. The pixel size is 55 μm and the sensor is organised in tiles with an area of 15 x 43 mm^2. Each sensor tile is read out by three VeloPix ASICs, connected to the sensor via bump-bonding. The VeloPix ASIC consists in a matrix of 256 $\times$ 256 pixels and is built in TSMC 130 nm CMOS technology, with radiation hardness greater than 4 MGy and tolerance to single-event upset. The maximum peak rate per pixel is 50 kHz, and the data rate per ASIC is 20.48 Gb/s, with an associated power consumption of about 1.2 W. Quality assurance test of the sensors and ASICs have been performed at CERN. The ASICs were tested using a semi-automatic probe station and involved two types of scans. The first scan, a digital scan, included power-up, chip ID burning, register and digital signal routing, ECS interface, matrix counter, and DAC scan. The second scan focused on the analog aspects, including the eye diagram of GWT links, equalization, noise scan, and the functionality of the analog test pulse. The sensors were visually inspected to control the quality of the bump and then tested for IV measurements up to -800V. Almost all the tiles have proven suitable for use during operations. The design of the pixel sensor module is illustrated in Fig. 3. It includes the sensor tile, the data flex, and the GBTx chip, which provides a bidirectional 4.8 Gb/s link between the radiation-hard on-detector custom electronics and the off-detector systems. The aluminum base plate, known for its good thermal conductivity, is connected to a cooling system utilizing a Peltier device placed inside the RP to dissipate the power from the front-end electronics. The Peltier device is further connected to an external water circuit to transfer heat away from the RP box. During the test, the three pixel modules will be installed within an RP station. The cooling system is designed to handle 45 W of power dissipation and maintain a temperature of 20°C for the sensor areas. A vacuum feedthrough board and a rigid-flex data cable have been developed to manage control and data lines inside the RP station and to interface with the optical and power board (OPB). The OPB's primary function is to convert high-speed data and control signals between optical and electrical forms for communication with the detector module. An ATLAS-ALFA RP station, previously removed from the LHC tunnel, has been repurposed to house the TWOCRYST pixel detector. The RP slot has a rectangular cross-section measuring 128×60 mm^2 and features a 2 mm thick aluminum layer inside the RP box to facilitate heat dissipation.

5. – Conclusions

In summary, the proposed experimental method aims to measure the EDMs and MDMs of charm baryons using a fixed-target experiment at the LHC. Two scenarios are under evaluation, with significant focus on constructing a dedicated experiment at IR3. An initial test with a reduced setup is planned for 2025 at IR3. R&D is ongoing for the tracking stations, while the crystals have already been tested at the SPS. Installation work at the LHC is scheduled to begin at the end of 2024.

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