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Status of the search for a muon EDM using the frozen-spin technique

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Abstract: Despite the many successes of the Standard Model of particle physics, there are still several physical observations that it cannot explain, such as the matter-antimatter asymmetry, non-zero neutrino masses, and the microscopic nature of dark matter. To address these limitations, extensions to the standard model are necessary, and searches for electric dipole moments (EDMs) of leptons are valuable test. The search for a muon EDM is the only search on a bare lepton of the second generation, complementing the searches for an EDM of the electron using polar molecules. A non-zero EDM of the muon would indicate Charge-Parity symmetry violation beyond the standard model. A dedicated experimental search for the muon EDM is being set up at PSI using the frozen-spin technique. In this technique, the anomalous spin precession of the muons in a storage ring is suppressed by applying an electric field in the radial direction. The muon EDM experiment will take place in two phases: the first phase will demonstrate the frozen-spin technique using a precursor experiment with 28 MeV/c muons, while the second phase will make use of 125 MeV/c muons, which could search for the muon EDM with a sensitivity of 6×10^{-23} e $\cdot$ cm. In this talk, we describe the precursor experiment at PSI and provide an update on the status of the experiment.

Keywords: Accelerator modelling and simulations (multi-particle dynamics, single-particle dynamics); Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Particle tracking detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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1 Introduction

The Standard Model of particle physics accurately describes most laboratory-based particle physics results. However, it is not a comprehensive theory, as indicated by several observations, such as the observed asymmetry between matter and antimatter in the Universe [1], the lack of a dark matter particle candidate [2], and the existence of the neutrino mass [3]. Various extensions to the Standard Model attempt to address these limitations. One possible hint of physics beyond the Standard Model (BSM) would be the existence of a non-zero electric dipole moment (EDM). The Hamiltonian describing the interaction of a fermion with external electric and magnetic fields is odd under both time and parity reversal. By invoking the CPT theorem [4], this implies that a non-zero EDM of a fermion will violate the combined charge-parity (CP) symmetry.

While the Standard Model allows CP violation in the weak interactions by virtue of the complex phase of the Cabibbo-Kobayashi-Maskawa matrix [5], this predicted source of CP violation is extremely small and insufficient to give rise to the observed baryon asymmetry of the Universe. In fact, contributions to the lepton EDMs only arise at the four-loop level and are significantly suppressed [6], rendering them far beyond the reach of current experimental measurements [7]. As a result, a successful experimental detection of the muon EDM would serve as compelling evidence for new physics. Moreover, the search for the muon EDM is unique, targeting a bare lepton of the second generation, and complements the ongoing searches for the electron EDM using polar molecules. The most stringent limit, $d_e < 4.1 \times 10^{-30}\,\mathrm{e \cdot cm}$ [8] for the electron EDM was obtained using paramagnetic HfF+ molecular ions. Assuming strict lepton flavor universality and minimal flavor violation in BSM, this would translate into a limit of $d_\mu < 200\,d_e$. The last experimental search for the muon EDM was done at the BNL Muon g-2 Experiment (E-821) with a sensitivity of $1 \times 10^{-19}\,\mathrm{e \cdot cm}$ [9]. A model independent EFT analysis shows that the only experimental search for a muon EDM can limit the complex part of the Wilson coefficient which would also give rise to a contribution to the anomalous magnetic moment of the muon from BSM [10]. A new dedicated experiment is being set up at the Paul Scherrer Institute with the aim of searching for the muon EDM with a sensitivity of at least 6×10^{-23} e · cm using the frozen-spin technique [11]. In case of a null result, this will improve the current direct limit on the experimental probe of the muon EDM by 3 orders of magnitude.

2 The frozen-spin technique

For a relativistic charged particle, such as a muon in the presence of external electric and magnetic fields $\vec{E}$ and $\vec{B}$, the spin precession frequency is described by Thomas precession:

$$\vec{\omega}_0 = \frac{q}{m\gamma}\left[(1+\gamma a)\,\vec{B} - \frac{a\gamma^2}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \gamma\left(a + \frac{1}{1+\gamma}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]. \tag{2.1}$$

Here, $a = (\frac{g-2}{2})$ denotes the muon's anomalous magnetic moment, q is the charge of the particle, m is its mass, γ is the Lorentz boost factor, and $\vec{\beta}$ is the velocity vector. In a storage ring with electric and magnetic fields, the muon also undergoes cyclotron motion with an angular frequency:

$$\vec{\omega}_c = \frac{q}{m\gamma}\left(\vec{B} - \frac{\gamma^2}{\gamma^2-1}\frac{\vec{\beta}\times\vec{E}}{c}\right). \tag{2.2}$$

The difference between these two frequencies, representing the rate of precession of the muon's spin with respect to the rate of change of its momentum vector, is given by:

$$\vec{\omega}_a = \vec{\omega}_0 - \vec{\omega}_c = \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{2.3}$$

where we have defined $\vec{\omega}_a = \vec{\omega}_0 - \vec{\omega}_c$ to represent the anomalous spin precession frequency. In the presence of an EDM and under the assumption that the magnetic field is transverse to the direction of the muon's velocity ($\vec{\beta}\cdot\vec{B} = 0$), the above equation becomes:

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_e = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right], \tag{2.4}$$

where the second term, denoted by $\vec{\omega}_e$, represents the precession due to the EDM. Here, η is a dimensionless constant analogous to the g-factor. In the frozen-spin technique, a radial electric field ($E \approx aBc\beta\gamma^2$) is applied in the storage region to suppress the anomalous part of the spin precession frequency. This results in a precession about the radial electric field due to the EDM, leading to a build-up of spin polarization along the magnetic field direction [11].

3 The PSI muon EDM experiment

The muon EDM experiment at PSI will be conducted in two phases. The first phase, known as the precursor experiment, will involve using 28 MeV/c surface muons injected into a solenoid with an inner diameter of 0.2 m and a length of 1 m. In contrast, phase two will use 125 MeV/c muons injected into a dedicated magnet with a larger bore. The primary objective of the precursor experiment is to demonstrate the functionality of all critical components of the experiment and, for the first time, the frozen-spin technique.

In the precursor experiment, the muons from pion decay at rest, with a longitudinal polarization of better than 95%, will be injected off-axis into the solenoid with a field strength of 3 T. This will be achieved using a collimation tube (inner diameter 15 mm and length 800 mm) inside a superconducting magnetic shield. A set of correction coils will be employed to reduce the field gradient for the injection process. At the end of the injection channel, an entrance detector with an active aperture made of scintillating tiles will be used in anti-coincidence to select muons within the acceptance phase space for maximal storage and to produce a trigger signal. This signal will generate a magnetic kick in the center of the solenoid, turning the longitudinal component of muon momentum into the transverse plane, thus enabling muon storage within the weakly-focusing field generated by a dedicated coil. To match the frozen-spin condition, a radial electric field will be applied between two cylindrical coaxial electrodes. The magnitude of the electric field will be determined by measuring the muon anomalous spin precession frequency, ω_a, as a function of the electric field and then interpolating to the value that nullifies ω_a. Once the frozen-spin condition has been established, the longitudinal asymmetry in the decay positrons will be detected to search for an EDM signal. Section 5 provides an overview of the detection scheme.

4 Optimization of the experimental setup in simulations

A baseline simulation in G4Beamline [12] has been set up to study the off-axis injection. Increasing the storage efficiency of the injected muons is a multivariate optimization problem that depends on a range of initial parameters, such as the injection angle, coordinates of the injection channel, the strength and timing of the kicker pulse, and the weakly-focusing field strength. We employ a surrogate model based on Polynomial Chaos Expansion (PCE) to speed up the computation. PCE is a spectral expansion method in which stochastically varying physical quantities, $\boldsymbol{Y}$, in response to a set of input quantities, $\vec{x}$, can be expressed in terms of orthogonal polynomials Ψ_i:

$$Y = \sum_{i=0}^{\infty} \alpha_i \Psi_i (\vec{x}) \,. \tag{4.1}$$

The orthogonal polynomials Ψ_i depend on the input variables and are determined based on their distribution. The coefficients, α_i, can be calculated using either intrusive or non-intrusive methods. Non-intrusive methods, where the simulation code is viewed as a black box, are desirable here since they do not require modification of the code at every iteration. In this case, the coefficients are estimated by regression methods, where the difference between the output predicted by the model, $\tilde{Y}$, and the true Y is minimized [13].

In practice, the expansion in eq. (4.1) is truncated at some order $P - 1$:

$$Y = \sum_{i=0}^{P-1} \alpha_i \Psi_i (\vec{x}) \,, \tag{4.2}$$

where P is given by:

$$P = \frac{(p+d)!}{p!d!}, \tag{4.3}$$

with p being the degree of the polynomial and d the dimension. For a regression-based estimation of coefficients, the number of samples (integration points) is given by $N = (d - 1)\,P$ [14]. Currently, the model, which is 8-dimensional and requires a 4th degree polynomial, is trained on 1600 samples generated using G4Beamline simulations. Subsequently, a PCE expansion generated using the Python software toolbox Chaospy [15], is fitted with the trained samples using the least squares regression method. However, this model requires a sample size of approximately 3500 and thus is currently limited due to the small number of training samples. Methods to speed up the sample generation process in the simulation are being explored.

5 Detection scheme

To precisely focus the beam onto the opening of the injection channel, a beam entrance monitor with horizontally and vertically segmented scintillating tiles coupled to SiPMs will be used. The thickness of the tile will be 2 mm to stop the surface muons and provide a strong scintillation signal. The centering of the beam can be achieved by tuning the up-down and left-right asymmetry in the number of muons to zero. Once injected, the muon trajectories will need to be characterized with $\mathcal{O}$(mrad) angular and 0.5% momentum resolution. With 28 MeV/c muons, the tracking will be heavily impacted by matter interactions, which necessitates the use of a light detector such as a gaseous timing projection chamber (TPC) [16]. The TPC would have two possibilities: measurement of longitudinal drift for momentum measurement and radial drift for angular measurement. A central positron detection tracker will be used to measure ω_a as a function of the electric field. Simulation studies suggest that the decay positrons with energy greater than $\approx$68 MeV will hit the bore of the magnet irrespective of decay direction, while those with energies between 31 MeV and 59 MeV will be within the acceptance phase space for the ω_a measurement. Cylindrical silicon strip tracking detectors at radius 35 mm and 47.5 mm will be used to measure the radial asymmetry in the decay positrons. Finally, to search for the EDM signal, an array of thin scintillating fibers (thickness 250 µm) at radius 50 mm, coupled to SiPMs, will be used to detect the longitudinal asymmetry in decay positrons.

6 Conclusion

The muon EDM experiment at PSI aims to measure the muon EDM with improved sensitivity using the frozen-spin technique. Currently, the collaboration is preparing for phase one of the experiment, building and testing prototypes of the experimental setup components. The ongoing work includes the optimization of the injection process using surrogate modeling. In Autumn 2022 beam time, initial tests were conducted on the entrance detector and the tracking TPC prototypes.

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