Electric Dipole Moment Measurements at Storage Rings

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Electric Dipole Moments (EDM) of elementary particles, including hadrons, are considered as one of the most powerful tools to discover CP violation beyond the Standard Model. Such CP violating mechanisms are required to explain the dominance of matter over anti-matter in our universe.

Up to now experiments concentrated on neutral systems (neutron, atoms, molecules). Storage rings offer the possibility to measure EDMs of charged particles by observing the influence of the EDM on the spin motion. The Cooler Synchrotron COSY at the Forschungszentrum Jülich provides polarized protons and deuterons up to a momentum of 3.7 GeV/c and is thus an ideal starting point for such an experimental programme. Plans for measurements of charged hadron EDMs and results of first test measurements will be presented.

INTRODUCTION

This paper discusses the progress of the JEDI collaboration [1] towards a measurement of electric dipole moments of charged particles in storage rings. First a physics motivation is given. In the next section the principle of EDM measurements of charged particles in storage rings will be discussed. Finally, several milestones towards a first deuteron EDM measurement at the storage ring COoler SYnchrotron COSY [7] will be presented.

MOTIVATION

The existence of electric dipole moments (EDMs) of (sub-)atomic particles (e.g. atoms, certain molecules, hadrons) is only possible if parity (P) and time reversal (T) symmetry are violated. Assuming that the CPT theorem holds, T-violation is equivalent to CP-violation. Note that in this context we talk only about *permanent* EDMs. The well known EDMs of certain molecules (e.g. H_20, NH_3) are not of this nature and don't require violation of P and T symmetries. These molecules appear to have a permanent EDM because of two almost degenerated energy levels of opposite parity. This implies that the energy levels grow linearly with an applied electric field – a sign of a permanent EDM. However, in very small electric fields E, the energy levels grow quadratically with the electric field strength (quadratic Stark effect). This is the case if the interaction energy eE is smaller than the energy difference of the two almost degenerated energy levels. A more detailed discussion can be found in Ref. [2].

The measurement of EDMs has a long history. Starting 60 years ago with the measurement of the neutron EDM by Smith, Purcell and Ramsey [3]. Fig. 1 shows an overview of experimental results. Up to now all measurements show results consistent with zero. The resulting upper limits for various particles (red triangles) together with predictions from super-symmetric models (SUSY) and the Standard Model are shown. Most of the measurement were performed on neutral systems. The proton limit was deduced from an EDM measurement of the mercury atom for example. One exception is the muon. The limit shown in Fig. 1 was obtained at a the storage ring experiment where the main purpose was to measure the anomalous magnetic moment of the muon [4].

Based on this idea experiments are proposed to measure EDMs of charged particles in storage rings [1, 5]. The principle will be discussed in the next section.

PRINCIPLE OF STORAGE RING EDM EXPERIMENTS

For an elementary particle, the spin is the only vector defining a direction. A possible EDM has to be aligned along this axis. If an EDM exists, the spin vector will experience a torque in addition to the one caused be the magnetic moment. For a polarisation direction initially aligned in the horizontal plane of the storage ring, this torque causes a polarisation component in the vertical direction. The polarisation direction can be determined by scattering the beam off a carbon target and analyzing the azimuthal distribution of the scattered particles. Although the measurement principle is simple, the smallness of the expected effect makes this a challenging experiment.

One complication is that the magnetic moment causes a precession of the spins in the horizontal plane. This prevents a continuous build-up of a vertical polarisation due to the EDM. Several methods are proposed to solve this problem. One solution is to run in a so called frozen-spin condition where the precession in the horizontal plane is suppressed by a suitable electric and magnetic field combination [5]. In a second method, which can be applied at a pure magnetic storage ring, the horizontal spin precession is influenced by a radio frequency Wien filter in such a way that a build-up due to the EDM can be observed [6].

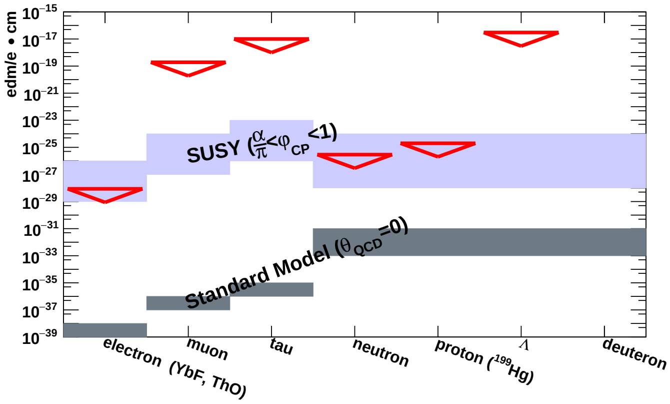

FIG. 1. Experimental limits (red triangles) of EDMs together with predictions from super symmetric models (SUSY) and the Standard model.

For the first method a dedicated storage ring has yet to be designed and built. The second option can be performed at an existing magnetic storage ring like the COoler SYnchrotron COSY at Forschungszentrum Jülich, Germany. In the following section several preparatory measurements and milestones towards a first EDM measurement at COSY will be described.

IMPORTANT MILESTONES TOWARDS AN EDM MEASUREMENT

The JEDI collaboration plans a first measurement of the deuteron EDM at the storage ring COSY. In preparation, many activities are ongoing. Mandatory for the measurement at COSY is the construction of a radio-frequency Wien filter which is described in detail in the proceedings of J. Slim [8]. To reach the desired statistical precision, the spin precession in the horizontal plane has to be kept coherent for about 1000 s. This goal as been reached for deuterons of $p = 970\text{MeV}/c$. Details can be found in Ref. [9] and in the proceedings of E. Stephenson [10]. A feedback system to manipulate the polarisation in the horizontal plane is discussed in the proceedings of N. Hempelmann [11]. Spin tracking simulations to investigate systematic effects are discussed in the proceedings of M. Rosenthal [12] and E. Valetov[13].

In this document the measurement of the spin precession in the horizontal plane, the so called spin tune, is discussed in more detail. The spin tune is defined as the number of spin precessions per particle turn. In an ideal storage ring it is given by $\nu_s = \gamma G$, where γ is the Lorentz factor and G is the magnetic anomaly. The experiment was performed with deuterons at $p = 970\text{GeV}/c$. In this case $\nu_s \approx -0.16$. This causes the polarisation vector to precess with a frequency $f_s = \nu_s f_{\text{rev}} \approx 120\,\text{kHz}$, where $f_{\text{rev}} \approx 753\text{kHz}$ is the revolution frequency of the beam. The spin tune determination is mandatory for the spin coherence time measurement and the feedback system.

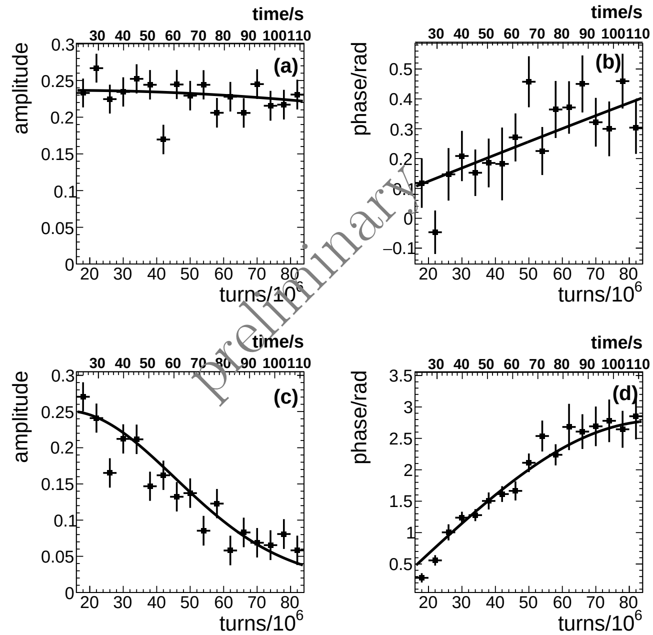

FIG. 2. Amplitude and phase vs. turns (or time in cycle) for a cycle with long spin coherence time ((a) and (b)) and a cycle with short spin coherence time ((c) and (d)). The curves show a combined fit to amplitude and phase assuming a spin tune distribution according to eq. 1.

Details of the experimental setup and a first analysis are presented in Ref. [14]. It was shown that the spin tune can be determined with a relative precision of 10^{-9} in a single cycle of 100 s. Compared to Ref. [14] a simpler algorithm for the spin tune determination was developed which reaches the same statistical accuracy.

Due to the spin precession the up and the down detector rates are modulated by the 120kHz precession frequency. In the new algorithm a Fourier analysis of the detector signals is performed in macroscopic time intervals of $4 \cdot 10^6$ turns corresponding to 5.2 s. Fig. 2 shows amplitude and phase of the Fourier analysis vs. turn number or time for a fixed frequency closed to the precession frequency.

The upper plots ((a) and (b)) show results from a run with a long spin coherence time (SCT). This can be seen in (a) from the fact that the amplitude which is proportional to the polarisation in the horizontal plane stays almost constant. The lower plots ((c) and (d)) show results from a run with a shorter SCT.

At the time of the publication of Ref. [14], a non-linear behavior of the phase vs. time was fully associated with a spin tune change over the time in the cycle. Meanwhile part of the phase variations are understood by assuming a Rayleigh distribution for the spin tune [15]. A particle on the reference orbit has a spin tune ν_s^{ref} and all other particles have a larger spin tune due to longer path lengths. The Rayleigh distribution is given by following functional form

$$P_{\nu_s}(\nu_s|\nu_s^{\mathrm{ref}}, \sigma_R) = \frac{\nu_s - \nu_s^{\mathrm{ref}}}{\sigma_R^2}\,\mathrm{e}^{-\frac{(\nu_s-\nu_s^{\mathrm{ref}})^2}{2\sigma_R^2}}\,, \quad \nu_s > \nu_s^{\mathrm{ref}}\,. \tag{1}$$

Apart from ν_s^{ref} it is described by a single parameter σ_R. Based on this distribution the change in phase can be described together with the change of the amplitude.

The curves in Fig. 2 show a combined fit to amplitude and phase assuming a spin tune distribution according to eq. (1). The curves and data show a reasonable agreement given the fact that the fit has essentially only one free parameter σ_R. Thus for the first time it was possible to describe phase changes observed during a cycle with a simple model. Note that if the fit describes the data, the average spin tune

$$\langle \nu_s \rangle = \nu_s^{\mathrm{ref}} + \sqrt{\frac{\pi}{2}}\sigma_R$$

stays constant over the cycle. Deviations indicate a time varying spin tune. Details of the analysis can be found in Ref. [16].

CONCLUSION & OUTLOOK

Measurements of the JEDI collaboration towards the first measurement of the deuteron EDM at COSY were discussed. With the essential milestones reached: precise measurement of the horizontal spin precession, construction of a radio frequency Wien filter, spin coherence times of over 1000 s and implementation of a polarisation feedback system, a first EDM measurement is planned in 2018/19.

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