Measurements of Electric Dipole Moments of Charged Particles at Storage Rings

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Electric Dipole Moments (EDM) of elementary particles are considered to be one of the most powerful tools to investigate CP violation beyond the Standard Model and to find an explanation for the dominance of matter over antimatter in our universe. Up to now experiments concentrated on neutral systems (neutrons, 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 program. The JEDI (Jülich Electric Dipole moment Investigations) Collaboration has been formed to exploit the COSY facility to demonstrate the feasibility of such a measurement and to perform all the necessary investigations towards the design of a dedicated storage ring.

1 Introduction

Electric dipole moments (EDM) break parity (P), time-reversal (T) symmetry, and — via the CPT-theorem — charge-parity (CP) symmetry. The established Kobayashi-Maskawa mechanism of CP violation predicts EDMs orders of magnitude below the current experimental limits. In addition, the Standard Model Lagrangian contains a possible source of CP violation in strong interaction, which, however, does not seem to be realized in nature: the experimental bound from neutron EDM experiments (for an overview see e.g. Ref. [1]) on the strength parametrized by the vacuum angle $\theta_{\rm QCD}$ is $|\theta_{\rm QCD}| \lesssim 10^{-10}$ and, thus, unexpectedly small. Furthermore, the universal matter/antimatter asymmetry implies that there should be CP violation from physics besides the Kobayashi-Maskawa mechanism and beyond the Standard Model. EDMs are excellent probes for these new CP-violating sources [2, 3, 4].

Once an EDM has been measured, the next goal is to identify its source. Is it, for example, caused by strong CP violation or from physics beyond the Standard Model? Experimental data on the EDMs of several light nuclei could provide an answer to this question: different classes of models predict different hierarchies of EDMs and thus can be disentangled once several light-nuclear EDM experiments (protons, deuterons and possibly ^{3}He) have been performed.

2 Basic Concept

The basic concept of measuring a permanent electric dipole moment is to place the test object into a strong electric field and to monitor the spin precession caused by the electric dipole moment. For neutral systems this can be done in a quasi-static, localized setup. Charged particles, however, are accelerated by the electric field. Therefore, it has been suggested in Ref. [5] (at that time for muons) to utilize a storage ring for such a measurement. The goal of the US-based srEDM collaboration [6] and the Jülich-based JEDI collaboration [7] is to apply this concept to protons, deuterons and ^{3}He [8].

The spin motion of a particle in a storage ring due to magnetic and electric dipole moments is described by the Thomas-BMT equation [9]

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \left(\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}\right) \times \vec{S} \tag{1}$$

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m_0}\left[G\vec{B} + \left(\frac{1}{\gamma^2-1} - G\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] \tag{2}$$

$$\vec{\Omega}_{\mathrm{EDM}} = -\frac{dc}{\hbar S}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right] \tag{3}$$

with S denoting the spin of the particle, t the time in the laboratory system, q and m_0 the charge and the mass of the particle, β and γ the relativistic Lorentz factors, G the magnetic anomaly and d the electric dipole moment. Terms proportional to $\vec{\beta}\cdot\vec{E}$ and $\vec{\beta}\cdot\vec{B}$ (*i.e.*, the effect of longitudinal field components) are omitted. The general idea of the measurement is to adjust the electric and magnetic fields as well as the particle momentum such, that the term $\vec{\Omega}_{\mathrm{MDM}}$ — sensitive to the magnetic dipole moment — vanishes. For the proton with a positive anomalous magnetic moment this can be achieved with a purely electric ring by setting the momentum to $p = \frac{m_0}{\sqrt{G}}$, for deuterons and ^{3}He a suitable combination of electric and magnetic fields is necessary. Thereby, starting with the spin aligned to particle momentum, the precession caused by the transverse electric and magnetic fields (the latter creating a motional electric field $\vec{\beta}\times\vec{B}$) will lead to a vertical polarization build-up.

Assuming high intensity beams of $4 \cdot 10^{10}$ particles per fill, a polarization degree of 80%, electric fields of $E = 10\,\mathrm{MV/m}$, and spin coherence times of 1000 s (see below) a statistical error for an EDM of $10^{-29}\,e\mathrm{cm}$ is in reach for one year of measurement. The remaining challenge is to get the systematic uncertainty down to the same level.

While the effects from the magnetic dipole moment can only be canceled in a dedicated storage ring yet to be designed and built, the Cooler Synchrotron COSY at the Forschungszentrum Jülich is an ideal place for the necessary R&D work and a proof-of-principle experiment [7, 10]. COSY is a unique facility for spin physics with hadronic probes on a world-wide scale: it has a history of a highly successful operation of cooled polarized proton and deuteron beams and polarized targets. As a purely magnetic ring the spin precession caused by the magnetic dipole moment of the particles cannot be canceled. Instead, this spin motion is utilized to develop tools and equipment for the design and operation of the final ring. Furthermore, using an rf Wien filter the spin precession due to the magnetic dipole moment can be manipulated such that the motional electric field generates a net EDM effect [8, 10].

3 R&D at COSY

Currently various developments are under way at COSY: improved beam position monitors, electrostatic deflectors, polarimetry, the rf Wien filter, systematic studies of the influence of sextupoles, steerers and solenoids, etc. One major goal was to increase the spin coherence time of the particles: as an ensemble of about 10^{10} particles is under observation, the length of one experimental cycle is determined by the time the spins of all particles precess coherently with the same angular velocity. For this purpose a time marking system using the EDDA detector as polarimeter has been developed to monitor the horizontal spin precession — i.e. the in-plane polarization — of a deuteron beam at 0.97 GeV/c. Further information on the method, the data analysis and the results on the spin coherence time can be found in Refs. [11, 12]. Here a short summary: for deuterons in a pure magnetic ring with vertical bending fields the Thomas-BMT equation reduces to

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{qB}{m_0} \cdot G. \tag{4}$$

Dividing this by the cyclotron frequency $\omega_{\mathrm{cyc}} = \frac{qB}{m_0\gamma}$ one gets $\nu = \gamma G$. ν is called the spin tune and describes the number of spin revolutions per turn relative to the particle momentum. For an unbunched beam decoherence is expected within less than one second due to the spread in momentum (and, thus, in γ). To first order this spread can be compensated by a bunched beam and spin coherence times of several seconds can be achieved. Higher orders (e.g. synchrotron oscillations, dispersion effects) can be corrected by means of sextupoles. Here, spin coherence times of several hundred seconds could already be reached.

Another tool to be used for studying the effect of various ring elements like solenoids, steerer and the rf Wien filter on the spin motion is the precise measurement of the spin tune with a precision close to $\Delta\nu \approx 10^{-10}$. This has been used successfully during the last beam times and a corresponding publication is currently under preparation.

4 Summary and Outlook

At the Cooler Synchrotron COSY of the Forschungszentrum Jülich R&D work has been started towards a dedicated storage ring for measuring electric dipole moments of charged hadrons. A time marking system together with the EDDA detector has been setup to allow for high precision studies of the spin motion in COSY. As a first result large spin coherence times in the order of several hundred seconds have been achieved by tuning the standard ring sextupole magnets. There are two major milestones for the next five years: a proof-of-principle experiment at COSY with limited sensitivity and a conceptual design report for the final EDM ring.

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