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Recent Progress of the JEDI Collaboration

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Abstract This article describes two different methods to measure the electric dipole moment (EDM) of charged particles in storage rings. The frozen spin concept relies on a large fraction (possibly 100%) of the bending field to be electric while an rf Wien filter method can also be used in purely magnetic rings albeit at lower sensitivity. In recent years the JEDI collaboration has developed several important techniques that are applicable for both methods and major milestones are presented here.

1 Introduction

Electric dipole moments (EDMs) of elementary particles violate both time reversal and parity symmetry. Via the CPT theorem this entails also CP violation which, according to Sacharov, is a requirement to explain the observed matter - antimatter asymmetry in the universe and hence our very existence. It looks therefore prudent to search for EDMs as one possible source of additional CP violation, especially since many theories beyond the Standard Model predict much higher values for EDMs than the Standard Model. But finding an EDM in one particle species will not solve all problems. Various theories provide different sources for e.g. hadron EDMs like a nonzero theta-term in QCD or quark EDMs. In order to distinguish between different sources it will be necessary to measure the EDMs of different particles. Simple systems like light nuclei are of special importance in this respect since they are the easiest to understand from a theoretical point of view. From an experimental point of view however they have a big disadvantage: they are charged particles and get strongly accelerated in the strong electric fields necessary to couple to the EDM. The idea to overcome this issue is to use the electric fields as bending

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fields in a storage ring in order to trap the particles. Such a ring does not exist at present and therefore the Jülich Electric Dipole Moments Investigation (JEDI) collaboration is currently designing one within the larger CPEDM collaboration including groups from CERN and Korea. Over the last several years the JEDI collaboration also developed techniques for polarization measurement and control in a storage ring at the COoler SYnchrotron (COSY) in Jülich. Many of these techniques are directly applicable to a designated EDM ring and we will report here about the recent achievements.

2 Spin Evolution in Accelerators and Measurement Principles

The spin evolution of an ensemble of particles can be described by the classical Thomas-BMT equation. Describing the spin direction $\mathbf{S}$ relative to the momentum vector $\mathbf{p} = m\gamma\boldsymbol{\beta}c$ of a particle with charge q it reads

$$\frac{d\mathbf{S}}{dt} = \mathbf{S} \times (\boldsymbol{\Omega}_{MDM} + \boldsymbol{\Omega}_{EDM}) \tag{1}$$

$$\boldsymbol{\Omega}_{MDM} = \frac{q}{m}\left(G\mathbf{B} - \frac{\gamma G}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\mathbf{B}) - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\boldsymbol{\beta}\times\mathbf{E}}{c}\right) \tag{2}$$

$$\boldsymbol{\Omega}_{EDM} = \frac{\eta q}{2mc}\left(\mathbf{E} - \frac{\gamma}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\mathbf{E}) + c\boldsymbol{\beta}\times\mathbf{B}\right) \tag{3}$$

where $G = (g-2)/2$ is the anomalous magnetic moment and η is the corresponding proportionality constant for the EDM. For the proton it is $G \approx 1.79$ while an EDM of $10^{-29}\,\mathrm{e\,cm}$ would correspond to $\eta \approx 10^{-15}$, i.e. the spin precession due to the magnetic dipole moment $\boldsymbol{\Omega}_{MDM}$ will in general be much larger than the precession caused by the EDM. Fortunately it is possible to choose operating conditions such that $\boldsymbol{\Omega}_{MDM}$ vanishes. The easiest way is to have no B-field and choose the momentum such that the last term in eq. 2, describing the motional magnetic field, vanishes. This happens for the so-called magic momentum $p = m/\sqrt{G}$ which is $p \approx 0.7\,\mathrm{GeV/c}$ for protons. In this case the spin precession due to the EDM is directly proportional to the electric field strength. If a particle has a negative anomalous magnetic moment like the deuteron ($G \approx -0.14$) it is not possible to get rid of the motional magnetic field in this way, but it is always possible to choose a suitable combination of E- and B-fields to make $\boldsymbol{\Omega}_{MDM} = 0$. The advantage of this second method is, that it allows one to choose the momentum freely but it precludes running with clockwise and counterclockwise beams at the same time, something that is very desirable for controlling systematic errors. In both cases the experiment would look as follows: A longitudinally polarized beam is injected into the ring which is operated such that the spin stays frozen in the longitudinal direction. Neglecting systematic errors, the only cause for spin precession is due to the EDM which causes a precession out of the accelerator plane at a slow rate on the order of nrad/s for an EDM of $10^{-29}\,\mathrm{e\,cm}$ and E-fields of $10\,\mathrm{MV/m}$.

Obviously long runs of at least 1000 s are desirable and very stable running conditions are required.

As stated before, such a ring currently doesn't exist but is under development. Instead a third option with lower sensitivity can be used in a conventional magnetic ring like COSY. In a magnetic ring the spin precesses rapidly around the vertical B-field at a spin tune (spin revolutions per turn) of $\nu = G\gamma$. If the spin points along the momentum direction, the EDM causes a slight precession of the spin out of the accelerator plane while this reverses exactly when the spin is antiparallel to the momentum. The idea is now to introduce an rf Wien filter running exactly on the spin precession frequency. The effect on the orbit is zero because E- and B-fields are matched exactly such that there is no Lorentz force and also the effect on the spin precession due to the EDM is zero. However the effect of the vertical B-field together with the motional B-field ($\propto \boldsymbol{\beta} \times \mathbf{E}$) from the Wien filter is to rotate the spin faster or slower in the horizontal plane. This can be used to keep the spin longer in the forward direction in the main dipoles where the up-down wiggling of the spin due to the EDM will then not cancel anymore. In this way a vertical spin component can be built up resonantly. This method is currently pursued at COSY and first commissioning results of the Wien filter can be found in the proceedings of J. Slim.

3 Recent Achievements of the JEDI Collaboration

Both methods, frozen spin as well as Wien filter method, require a feedback system. In case of the frozen spin method it is needed to keep the spin in the longitudinal direction while in the Wien filter method it helps to keep the Wien filter in resonance with the horizontal spin precession. The feedback systems for both methods are very similar and the development for the Wien filter method can therefore be directly applied to the frozen spin method as well. In order to make a feedback (and the complete EDM measurement) possible, a long spin coherence time (SCT) is required. That is, the precession rates of the individual spins have to be sufficiently similar to keep the in plane polarization for a long time. This can be achieved by bunching the beam to keep all particles at the same revolution frequency, using a precooled beam to keep the momentum spread and beam size low and additionally use specific sextupole settings (zero chromaticity setting) to correct for second order effects. In this way a spin coherence time of about a thousand seconds has been reached for a deuterium beam, see [1]. However, it is not enough to keep the polarization, one also has to measure it, all while the spin may be rapidly precessing. The polarization is determined by measuring the asymmetry of particles scattered from a carbon block. If the spin is precessing, the asymmetry will oscillate and the count rate in the detector will be too low to resolve this oscillation. A careful time stamping algorithm has been developed to map many subsequent events into one oscillation period from which the asymmetry can be determined, compare [2]. The time stamping requires knowledge of the spin precession frequency which can be extracted from the data at high precession. Using data from a 1.3 s interval it was possible to measure the spin tune with an absolute precision on the order of 10^{-8}. Fitting the data from such intervals over a complete cycle allows for even higher precision on the order of 10^{-10}, see [3]! Such accurate data can now be used as input for a feedback system which regulates some control parameter to keep the measurement conditions optimal. For the Wien filter method this would be the Wien filter frequency. Initial tests have been performed at COSY before the Wien filter was in place by changing the frequency of the bunching cavity in order to control the phase of the spin at an rf solenoid. The effect of the solenoid is to rotate the spin into the vertical direction when the spin initially points into the radial direction. Changing the spin direction relative to the solenoid phase allows to influence the build up rate of the vertical spin component. This has been shown experimentally and confirmed the expectations, see [4]. A very similar thing can be done with the Wien filter. If the Wien filter is rotated around the longitudinal axis, the B-field has a radial component which causes the spin to precess out of the accelerator plane and hence is a systematic error for an EDM measurement. During a Wien filter commissioning beam time this buildup rate was determined for three different rotation angles of the Wien filter where zero corresponds to the ideal vertical direction and again the feedback system was used to set the phase of the spin relative to the Wien filter. The behavior of the buildup rate versus this phase is shown in fig. 1 for three different angles of the Wien filter. It is made from a preliminary data analysis and should be taken with care. The fact that there is a buildup for the case with vertical B-field (green curve) points to a non-vertical stable spin axis, possibly caused by misalignments in the ring. It roughly corresponds to an EDM at the 10^{-18} e cm level.

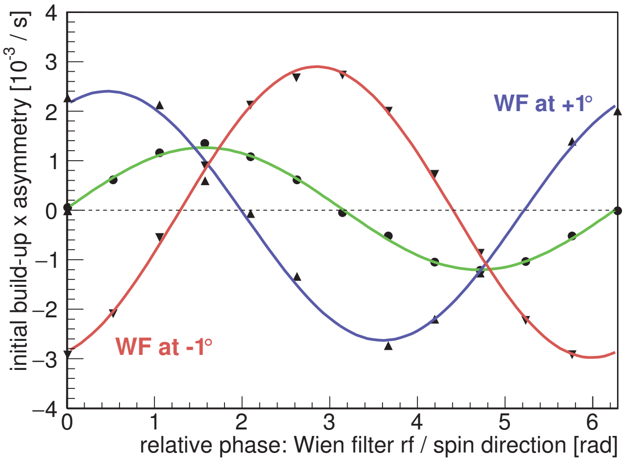

Fig. 1 Initial buildup rate from preliminary analysis of the vertical spin component for three different Wien filter orientations. The green curve shows the vertical case while the other two curves are for a rotation of ±1°. The curves are individual fits to guide the eye.

4 Summary/Outlook

It was shown that all necessary techniques for a successful EDM run are in place. Together with the successful commissioning of the rf Wien filter it puts the JEDI collaboration in place to determine an upper bound of the deuteron EDM at COSY some time in 2019. At the same time hardware development for and design of a future dedicated EDM ring are well underway (see these proceedings) and will continue. Because of known and unknown uncertainties and the extremely high precision needed for a successful EDM measurement it looks prudent to start with a smaller prototype ring in order to investigate various issues. This approach is currently pursued as well.

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