

Polarimeter Development for an Electric Dipole Moment Search in a Storage Ring

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Abstract. The search for a charged particle EDM in a storage ring with the goal of a statistical sensitivity of 10^{-29} e-cm/year requires a very sensitive polarimeter. Studies described here have shown that systematic error effects can be handled and corrected to a sensitivity better than the required 10^{-6} level. The required statistical precision was shown to be attainable using a thick scattering target onto which the stored beam is slowly extracted. Models for geometric and rate systematic error effects describe the results well.

1. Introduction

Electric dipole moments (EDM) violate both T (time reversal) and P (parity) symmetries and conserve C (charge) symmetry. Assuming conservation of the combined CPT symmetry, T violation also means CP violation. The weak interaction CP violation contributes a very small EDM, orders of magnitude below current experimental limits. However, most models beyond the Standard Model (SM) predict EDM values near the current experimental limits. Hence, the study of EDMs is a search for CP violation beyond the SM. If a non-zero EDM value is found within the next generation of searches, it could prove crucial in understanding the matter-antimatter asymmetry of our universe which requires new, large sources of CP violation beyond standard model expectations. That fundamental connection with the origin of our very existence coupled with the popularity of well-motivated “new physics” scenarios such as supersymmetry (SUSY) with potentially large new sources of CP violation make searches for EDMs exciting and at the forefront of high energy and nuclear physics. Indeed, it is anticipated that the next generation of EDM experiments with several orders of magnitude improved sensitivity may be on the verge of a major discovery with far-reaching implications.

2. Search for an EDM in a Storage Ring

We are planning to search for the EDM of the proton in a storage ring with a statistical sensitivity of $\sim 2.5 \times 10^{-29}$ e-cm/year. At this level it will be an order of magnitude more sensitive than the currently planned neutron EDM experiments at SNS (Oak Ridge) and ILL (Grenoble-France). The ring, after a major upgrade, can accommodate a deuteron EDM experiment with similar sensitivity.

To put the respective dipole moments d_n , d_p and d_D into perspective, we note that a priori, all are independent and could have significantly different values. Only when interpreted within the context of a specific theoretical framework do their values become related and a comparison is

meaningful. If d_n is found to differ from zero, d_p and d_D will prove crucial in unfolding the new source of CP violation responsible for it. To sort out its structure, the I=1 and 0 isospin combinations

$$\begin{aligned} d_N^{I=1} &= (d_p - d_n)/2 \\ d_N^{I=0} &= (d_p + d_n)/2 \end{aligned}$$

along with d_D (which samples various isospin effects) will be complementary.

Magnetic moment determinations of charged particles are common inasmuch as the required magnetic field can also trap the particles. EDM determinations have been limited to neutral systems, e.g. neutrons, atoms and molecules since the necessary electric field would remove charged particles from any volume under study unless constrained as in a storage ring in which the applied electric field bends the charged particle beam so as to follow a closed orbit. The method will be most sensitive when the spin vector is kept along the momentum vector for the duration of the storage, as shown in figure 1. This happens for a stored proton beam when the momentum is 0.701 GeV/c. Without an EDM, the spin remains frozen in the horizontal plane along the momentum direction whereas, if there is an EDM, it will precess vertically, out of the plane. For the deuteron case with a small, negative anomalous magnetic moment, the polarization is maintained along the velocity with a combination of ring dipole magnets and an outwardly-directed electric field along the ring radius. In this configuration, the relative \mathbf{E} and \mathbf{B} field strengths are chosen so that the spin rotates at the same rate as the velocity [1]. The remainder of this paper will discuss deuteron polarization measurements.

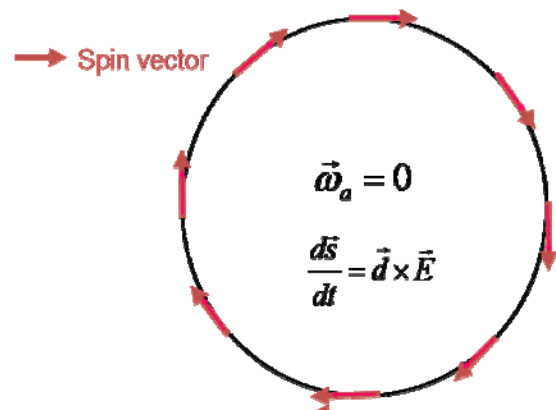


Figure 1. A top view of an ideal storage ring EDM experiment. The spin and momentum vectors are kept aligned for the duration of the storage, i.e. the in-plane $g-2$ precession $\vec{\omega}_a = 0$. If the EDM vector (\vec{d}) is not zero the particle spin will precess out of plane as a function of storage time due to the radial E-field.

3. Polarimeter Development

One important part of the search for a permanent Electric Dipole Moment (EDM) in a storage ring is to record the growing vertical polarization component with a continuously operating polarimeter. It has to be demonstrated that a very high-efficiency polarimeter is technically feasible for this purpose and in particular that systematic errors that might arise in the polarimeter can be handled at a level of sensitivity approaching one part per million. The high efficiency depends on a scheme in which the beam is slowly extracted onto the face of a thick target from which scattered particles enter the detector. To be useful, the impact onto the face has to be far enough from the beam-side edge that losses due to multiple scattering through this edge do not seriously degrade the efficiency.

Beams in storage rings are subject to considerable variations with time, most simply in average position and angle, as the beam is used up during a store. If possible, the polarimeter data stream should contain enough information that, along with a prior sensitivity calibration, corrections can be made to any asymmetry value for such systematic errors so that they do not become confused with any possible EDM effect.

The best place for doing these research and development tests happens to be at the Forschungszentrum Jülich in Germany. Jülich has an existing storage ring, a COoler SYnchrotron (COSY), which is most like a future EDM ring, and a polarized ion source for protons and deuterons. Furthermore, we find at COSY polarimeters suitable for the energy range of interest, one of which is

placed behind the cyclotron to measure the polarization at low energies before injection into the storage ring.

Figure 2 shows the cross section and analyzing power versus the laboratory scattering angle for deuteron-carbon elastic scattering at $E_d = 270$ MeV kinetic energy [2] which is close to 250 MeV, the energy planned for the EDM storage ring experiment.

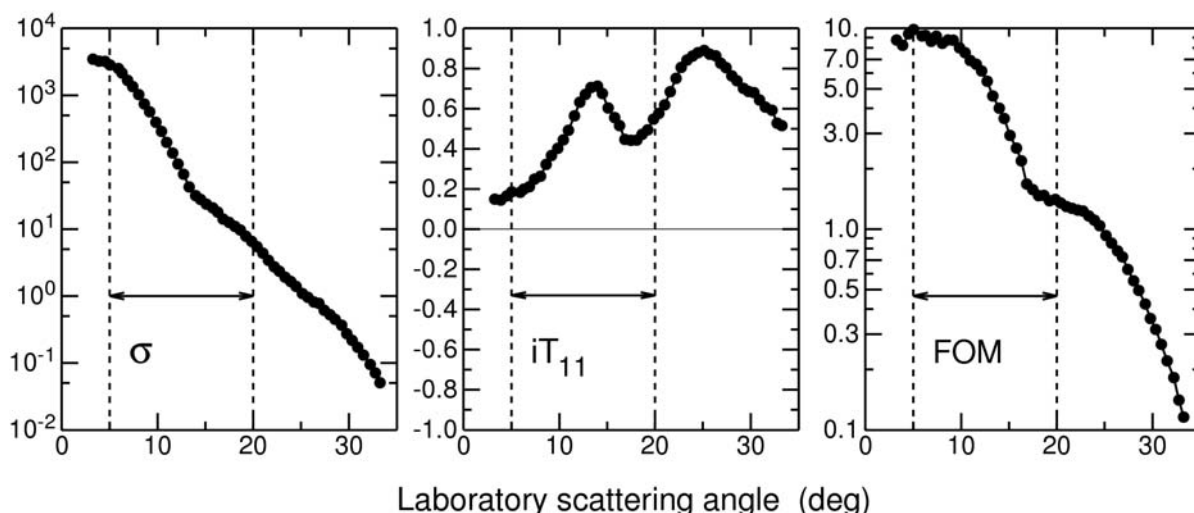


Figure 2. Cross section (mb/sr), analyzing power, and figure of merit $[= \sigma(iT_{11})^2]$ (mb/sr) for d+C elastic scattering at $E_d = 270$ MeV [2]. The angle range to be used lies between the dashed lines.

The maximum of the figure of merit, i.e. cross section times analyzing power squared, gives us the region of scattering angles which is statistically the most sensitive. For the EDM experiment, we want to measure at angles from 5° to 20° . Thus any EDM deuteron polarimeter should be based on accumulating (mostly) elastic scattering events.

To maximize the efficiency of any EDM polarimeter, each deuteron whose spin is to be analyzed should penetrate several centimeters of carbon. The efficiency and the analyzing power (A_y) for deuterons are expected to be 1% and 0.35, respectively, in an EDM polarimeter. For the tests at COSY, the efficiency will be reduced by about an order of magnitude because the target is thinner and the minimum angle of the detectors is larger.

Another important feature of the COSY accelerator is a detector system from the former experiment EDDA that is suited as a mock-up polarimeter to study systematic error effects. This detector consists of a series of ring and bar scintillators (for measurements of σ and A_y) in an arrangement that wraps completely around the beam pipe downstream of the target position. While an EDM polarimeter would be sensitive to angles as small as 5° , the smallest angle available at EDDA of 9° is nevertheless sufficient to establish the principles of efficient target extraction and systematic error correction. It is expected that the scattered events in an EDM polarimeter will be recorded in a way that emphasizes the most useful signal by stopping deuterons (or protons) that are close to beam energy since their analyzing power is similar to elastic scattering. This is possible for deuteron beams at EDDA at a momentum of 0.97 GeV/c, which is very close to the operating point of 1 GeV/c of the proposed deuteron EDM experiment.



Figure 3.
 Tube target

Following the original plan of measuring the deuteron EDM, we had three runs at COSY in Jülich in 2008 and 2009, using four weeks of beam time to study these effects with polarized deuterons.

We decided to use a tube target that was machined at COSY (see figure 3) and installed in the EDDA carousel in front of the detector system. We were limited in the thickness of the carbon tube due to the beam line opening in the carousel. Therefore the target was designed to be 15 mm thick, with an opening of 20 mm by 15 mm.

One major achievement accomplished during the first run at COSY was to show that using such a thick target is actually successful in a storage ring. This tube target serves as the defining aperture: all beam which is lost is lost on this target.

Electrostatic plates were mounted upstream of the polarimeter target. Applying white noise to these plates increases the vertical phase space until the beam extracts on either the upper or lower edge of the opening in the carbon block.

Figure 4. Polarimeter concept.

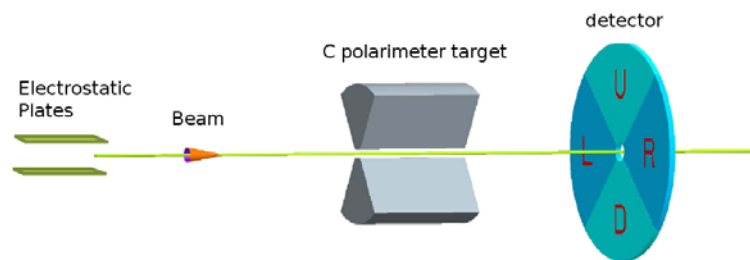


Figure 4 shows the concept of the detector. It includes a detector which needs to be segmented. This segmentation gives us the possibility of measuring the distribution of asymmetries in addition to reducing the instantaneous rate on detector elements and consequently accidentals. Using the count rates in the left (L) and the right (R) detector, we will measure the EDM signal via the left-right asymmetry: $\varepsilon_{EDM} = \frac{L-R}{L+R}$. Count rates in the down (D) and up (U) detectors actually give us the possibility of feedback by monitoring the $g-2$ precession in the ring. They track the horizontal projection of the polarization via the down-up asymmetry: $\varepsilon_{g-2} = \frac{D-U}{D+U}$. The tensor polarization can be used for additional information via $\varepsilon_{tensor} = \frac{D+U-L-R}{D+U+L+R}$.

Running the EDDA detector like an EDM polarimeter resulted in an efficiency as large as 0.07% and an analyzing power of 0.39(3), which was expected from the given operating parameters and where the uncertainty reflects the calibration of the Low Energy Polarimeter at COSY [3].

The EDM signal appears as a change between the beginning and end of a store. Considering the time of 1000 seconds for a store, a lot can happen in this interval. Systematic errors can appear from shifts of the beam in angle and position. We have to be able to correct for all of these geometric effects. If we exaggerate possible errors in COSY, we gain clarity about possible effects. So the running plan for COSY was to make changes much bigger than the errors expected in the EDM experiment by about two orders of magnitude and to demonstrate that correction of these errors is possible. The usual way to track what happens is to measure on both sides (left and right), flip the

initial spin and use the following cross ratio formula: $\varepsilon = \frac{3}{2} p_y A_y = \frac{r-1}{r+1}$, where $r = \sqrt{\frac{L_+ \cdot R_-}{L_- \cdot R_+}}$,

where p_y denotes the polarization, A_y the vector analyzing power, and $+/-$ the two different vector-polarized spin states. This observable cancels out the common errors obtained in the asymmetry to first order in the errors. Left/right efficiency differences cancel as well as luminosity differences.

During our last run in June 2009 we were able to run an automated super-cycle in which each new beam store was created with a different systematic error value. At the beginning of each

injection the beam was raised by 3 mm to be sure to extract only on one target inner edge, followed by applying white noise to the electrostatic plates, increasing the vertical phase space to extract the beam. The beam was moved to a new position or angle after each store. Possible positions were $\Delta x = \bullet 2, \bullet 1, 0, 1,$ and 2 mm and scanned angles were $\Delta_x = \bullet 5, \bullet 2.5, 0, 2.5,$ and 5 mrad, where mm and mrad changes have almost the same effect as the detector rings were about one meter away from the target. Zero was the same for both cases, so that the super-cycle went through nine different experimental settings. After each cycle of stores the polarization state at the ion source was automatically changed to the next state in order. Five states were used for this investigation, two vector and two tensor polarized states as well as an unpolarized state.

By deliberately introducing many error values, we accumulated and studied a large data set on geometric systematics. Observables sensitive to first-order errors like the left-right asymmetry show big effects if the beam moves by only a few millimeters. Observables like the cross ratio, whose error sensitivities begin at second order, show that these effects are remarkably reduced. However, this is not good enough for measuring a very small observable like the EDM at the proposed sensitivity. Second-order effects must be canceled or corrected.

Besides the geometric effects we found that rate effects can also play a big role. During the time of a store, of one-minute length at the COSY runs, the cross-ratio changed. We also made a study of the dependence of the measured asymmetries on the instantaneous event count rate. Using effects much larger than those we expect to find in an EDM experiment, we were able to demonstrate that these effects of high data rate are linear on our set of observables.

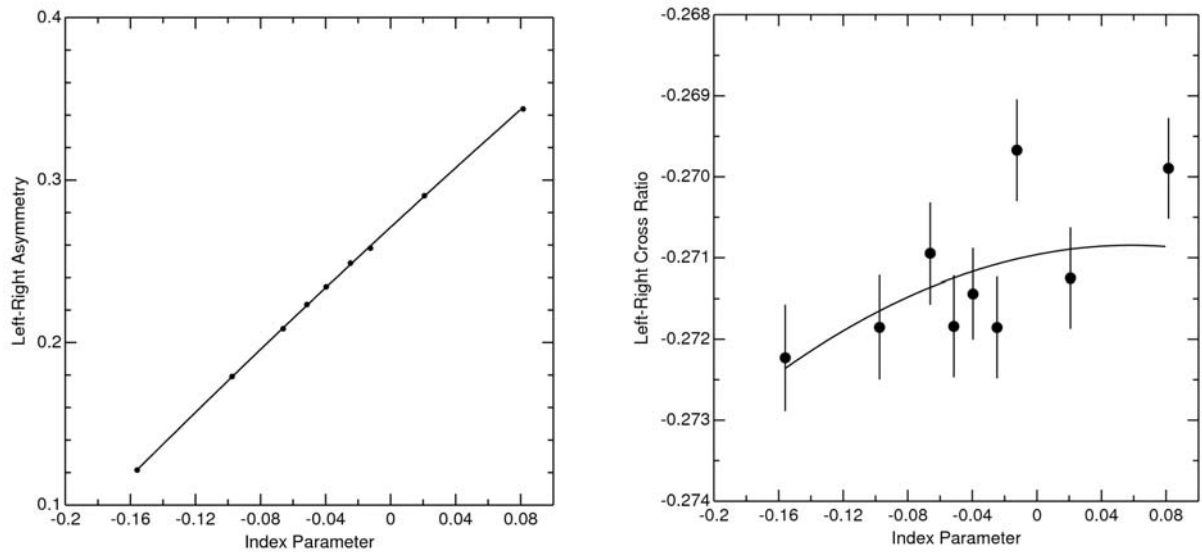
To cancel second-order geometric errors one needs to know the dependence on the error. The choice is to use a correction parameter ϕ , a parameter with first-order error dependence, as a measure of the position or angle displacement: $\phi = \frac{s-1}{s+1}$, where $s^2 = \frac{L_+L_-}{R_+R_-}$. The term depends mostly on the error at the target with spin sensitivities suppressed.

The linear correlation between rate and cross ratio indicates that this error is correctable using the instantaneous rate as an index.

Each polarimeter, the EDDA detector or a future EDM polarimeter, has to be calibrated. All these tests to measure the sensitivity to large systematic errors (X and θ) and spin dependence have to be redone for the EDM polarimeter.

We built a model framework of parametrized effects, for geometric and rate effects separately, to investigate whether any polarization observable can be corrected and whether angle and position errors can be treated using the single correction parameter ϕ . For the geometric effects 16 parameters were included. The rate model is simpler than the geometry model and required only 13 parameters in order to achieve a satisfactory representation of the measurements.

Including and adjusting all parameters we were able to confirm that using the index parameter works in all cases, including all asymmetries and cross ratios. Figure 5 shows the correlation between the left-right asymmetry and the index parameter. Both angle (widely distributed) and position (five points closest to the middle) data are included. The errors are smaller than the data points. The curve is a calculation using the model parameters. The high degree of overlap between the model and the two sets of data confirm that accurate corrections can be made with the single index parameter regardless of whether the initial error is in position or angle. Thus we do not need additional information outside the polarimeter data (and its systematic error sensitivity calibration) to determine corrections. Figure 6 shows the same comparison, with the same conclusion, for the cross ratio. In a similar fashion, the linear nature of all rate effects demonstrates the ability to use only the instantaneous rate as the parameter for this correction. In the case of the cross ratio, the curvature of the fit is a result of sensitivity to data of other observables as well as that shown on this graph. All data were used simultaneously to obtain the parameter set.



Figures 5 and 6. Measurements and model calculations for the left-right asymmetry and the cross ratio as a function of the index parameter .

To determine typical effects during the search for an EDM, the corrections shown must be scaled down to what are expected to be the typical sizes of position and angle errors in the EDM ring. For example, the beam position is expected to be stable to less than 10 μm . In some systematic error effects, there is a scaling with some power of the asymmetry, so it is also important that the initial vertical polarization component before the change due to an EDM begins be rather small. With straight-forward precautions, it should be easy to hold such an initial component to less than 1%. With these two constraints, no correction to the cross ratio as determined in the calibration of the EDDA detector exceeds 30 parts per billion, well under the limiting sensitivity needed for an EDM search. It is likely that the sensitivity to systematic polarimeter errors will increase as the inner angle of the detector is reduced to 5°. The small size of this correction, and the fact that it is a correction and not a limit on the sensitivity, means that even with some increase in error effects in the EDM polarimeter, there should be no problem with polarimeter systematic errors in the EDM search.

References

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