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Deuteron polarimeter developments for a storage ring electric dipole moment search

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This talk will summarize progress made at the Forschungszentrum Jülich COSY ring on deuteron beam polarimetry for a storage ring search for an electric dipole moment (EDM). Tests have demonstrated the feasibility of using thick carbon targets for highly efficient and continuous observation of the stored beam polarization. After calibration of the sensitivity to geometric misalignments and pileup contributions to the trigger rates, it is possible to correct cross-ratio polarization measurements in real time to levels below one part in 10^5. By marking each event with the clock time, the horizontal plane precession of the polarization in the ring magnets may be unfolded, yielding access to the magnitude of the horizontal polarization as a function of time. Accurate values require attention to biases from searches for the correct precession rate and false enhancements to the magnitude at low polarizations. This technique facilitates studies of various means to extend the unstable horizontal plane polarization lifetime using bunching, electron cooling, sextupole correction fields, and beam current management with the result that polarization lifetimes now exceed hundreds of seconds. Future plans include feedback to control the polarization precession rate and phase (in preparation for maintaining the polarization parallel to the velocity in a future EDM ring), database measurements to enable better polarimeter engineering, and the extension of these studies to protons.

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1. Introduction

An intrinsic electric dipole moment (EDM) aligned with the spin of a particle (or nucleus or atom) would violate parity and time-reversal conservation. When interpreted as *CP*-violation, a measurement of its size would enable an investigation of its role in creating the matter-antimatter asymmetry of the universe. Present searches involve neutral particles trapped in electric fields to measure their spin precession rate [1]. Charged particles may be trapped in a storage ring where the needed electric field is naturally present in the particle-frame radial direction to maintain the particle orbit. If the beam is polarized along the particle momentum, this electric field will precess the spin, creating a vertical polarization component that rises with time. Since particle magnetic moments always have an anomalous part, special combinations of bending electromagnetic fields are used to synchronize the orbital and spin precession rates [2].

The beam polarization (p) would be measured continuously by sampling particles in the beam, scattering them at forward angles from a thick (few cm) carbon target [3]. Besides high efficiency and analyzing power (A), an important feasibility requirement for the EDM experiment is that systematic errors in the polarization measurement be correctable to levels as low as 10^{-6}. In addition, the spread of spin precession rates caused by particle velocity variations must be reduced so that the in-plane polarization parallel to the velocity lasts for times up to 1000 s. Here we summarize the fulfillment of these requirements.

2. Correcting systematic errors in polarization measurements

At the Cooler Synchrotron (COSY) at the Forschungszentrum Jülich, the test polarimeter was the scintillator bar/ring array from EDDA [4]. The important parts are shown in Fig. 1.

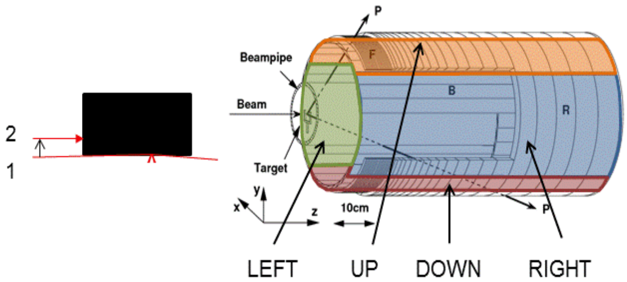


Fig. 1: A drawing of the thick carbon target showing an initial impact point (1) and a secondary impact (2) that leads to scattering. The diagram cutaway shows the ring and bar parts of EDDA and the assignment of bars to the four trigger areas.

First-order systematic errors are usually reduced by comparing scattering rates to the left (L) and right (R) and data for (+) and (–) polarization states. The cross ratio asymmetry, or pA product, is $\varepsilon = pA = (r - 1) / (r + 1)$ where $r^2 = [L(+)R(-)] / [L(-)R(+)]$. This asymmetry is insensitive to many first-order errors. In order to make further corrections for systematic errors, a second quantity is needed that is sensitive in first order to the main error driving terms. Such a quantity is $\phi = (s - 1) / (s + 1)$ where $s^2 = [L(+)L(-)] / [R(+)R(-)]$. By taking the same measurements and emphasizing the ratio of left to right, φ is sensitive in first-order to geometric misalignments in both position and angle. With the overall detector rate, W, these two additional measurements may be used, along with model sensitivities obtained from a calibration, to produce corrections to any polarization observable (such as the cross ratio shown above), as shown in the following equation.

$$\varepsilon_{CR,corr} = \frac{r-1}{r+1} - \left(\frac{\partial \varepsilon_{CR}}{\partial \phi}(\phi)\right)_{MODEL} \Delta\phi - \left(\frac{\partial \varepsilon_{CR}}{\partial W}(W)\right)_{MODEL} \Delta W$$

When applied to data with both rate and geometric systematic errors, the result is in Fig. 2.

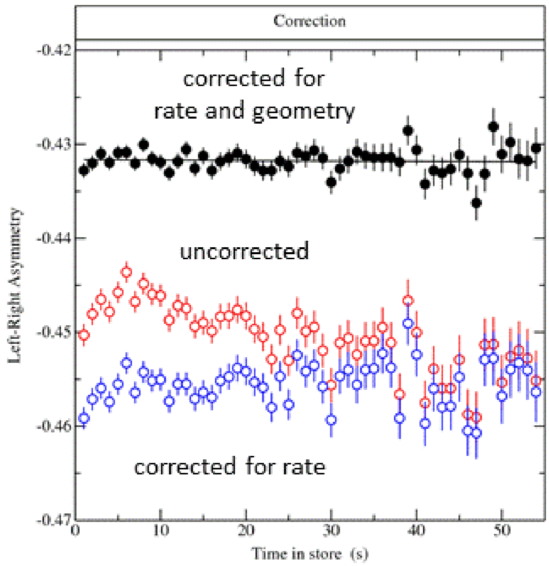


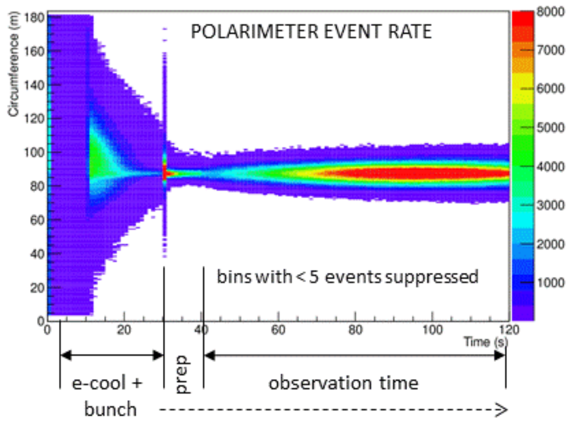
Fig. 2: Measurements of the left-right asymmetry (chosen for illustration since the effects are large) as a function of time (red points). When rate effects are removed, the blue points are the result. Application of the geometry correction yields the black points. A calculation of the slope of the black data produces $[-4 \pm 11] \times 10^{-6}\ \mathrm{s}^{-1}$ whose error is statistical only. The beam polarization is assumed to be constant with time.

The calibration against known errors may use large position, angle, and rate changes in order to increase the precision. No problem is anticipated that limits the corrections being made at the part per million level. The model of Ref. [3] contains 8 polarizations (4 states with a vector and tensor terms), 18 geometry parameters, and 11 rate parameters. These were obtained from a fit to 200 separate measurements of 7 different polarization effects. All of the tests were made with a constant polarization that was assumed to be unchanging. The model of the systematic effects also permits the construction of a transformation from the uncorrected to the corrected space, and thus allows for corrections to be applied to situations (such as the EDM search) where the polarization may be changing.

3. Measuring in-plane polarization

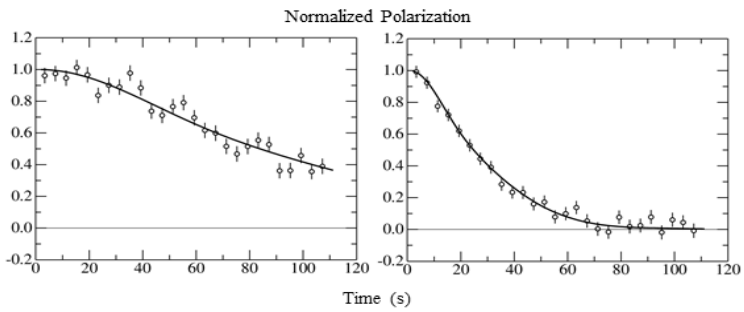
COSY is not equipped to produce a beam with the polarization always aligned parallel to the velocity. Instead, at p = 0.97 GeV/c, the in-plane polarization (produced through the action of an rf solenoid operating on the $1 - G\gamma$ spin resonance) rotates at about 120 kHz. By marking each event with the clock time when it occurred, it is possible to unfold this precession and look for a down-up asymmetry in the polarimeter whenever the polarization axis points along the radial (sideways) direction in the ring [5]. The clock operated with a time step of 92.59 ps. Using a cross calibration with the COSY rf, the event times were converted into turn numbers. The fractional part of the turn number may be separately binned. It yields the distribution of particles around the ring. The time evolution of this distribution is shown in Fig. 3. The integer part of the turn number is multiplied by the spin tune, $G\gamma$, and summed over all the time since the polarization was rotated into the horizontal plane to produce a total polarization rotation angle. The fractional part of this angle (expressed in revolutions) represents the direction of the polarization in the horizontal plane.

Fig. 3: Distribution of events as a function of the distance along the ring circumference and the time in the store. Once at full energy, electron cooling begins. The rf cavity is on at 11 s, and from there the progress of cooling is evident. At 30 s, the beam is moved next to the target, making a flash. At 41 s the rotation of the polarization is made into the horizontal plane, and observation of the polarization begins.



Using the information on the detector quadrant (Fig. 1), down-up asymmetries may be calculated for all of the direction bins. The asymmetries exhibit a sinusoidal pattern whose magnitude is the horizontal polarization. Examples of its time evolution are shown in Fig. 4.

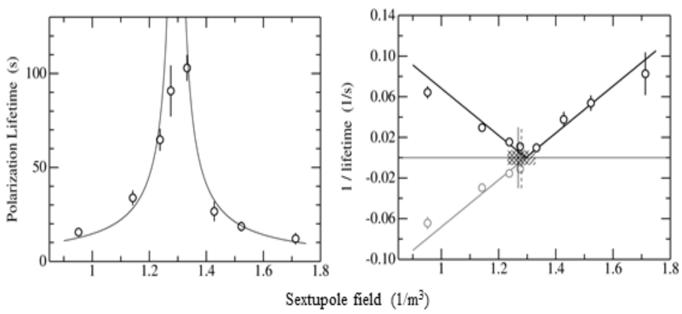
Fig. 4: Horizontal polarization measurements versus time in the store for two settings of the ring sextupoles. The lifetimes are 64.7±5.4 s and 18.6±2.6 s. The curves show the expected depolarization shape.



4. Lengthening the horizontal polarization lifetime

Depolarization arises because particles with different momenta have different rates of precession, so the spin distribution in the plane spreads out. Beam bunching helps as it forces all particles to be isochronous on average, and electron cooling reduces the size of the beam bunch in phase space. The leading second-order effects arise from betatron path lengthening. This may be compensated by adding sextupole fields to the ring, as seen in Fig. 5.

Fig. 5: (left) Polarization lifetime versus sextupole field with a curve that is a fit to the reciprocal lifetime. (right) Reciprocal lifetime versus sextupole field that is fit to a straight line (see text).



Using the MXG sextupole family in COSY (which is located where the dispersion is largest) in conjunction with the MXS family (large β_X) a scan of the strength (scale is MXG field) shows a clear maximum near 1.3 /m^3. Spin tracking programs that contain the full COSY lattice indicate that the reciprocal of the lifetime should vary linearly with the sextupole field. Such a comparison is shown in the right-side panel of Fig. 5. Points to the left of 1.3 /m^3 as well as the line, have been inverted in sign to demonstrate that the same straight line applies equally well to all parts of the data. The vertical solid and dashed lines shows where the X and Y chromaticities are zero along with hashed regions indicating the chromaticity errors.

It has been noted that the longest horizontal polarization lifetimes for electrons occur when the chromaticity of the storage ring is adjusted to be zero [6], which also requires the use of sextupole magnets. Fig. 6 shows how this result looks for the present case.

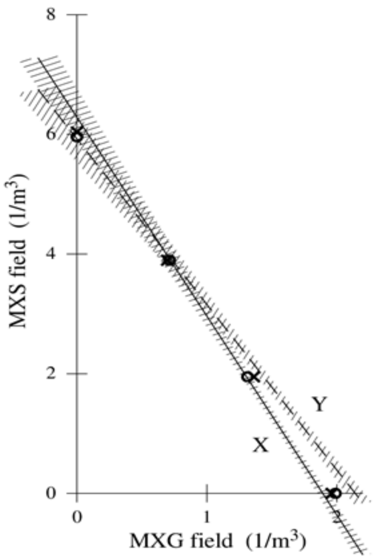


Fig. 6: The lines of zero X and Y chromaticity are shown along with errors based on the tune change measurements. In MXS by MXG space with (large β_Y) MXL = –0.14 /m^3, these lines are nearly overlapping. Scans (like Fig. 5) were made with the beam horizontally (circles) and longitudinally (crosses) stretched to explore different spin effects. The points of best polarization lifetime are plotted. The uncertainties are smaller than the points.

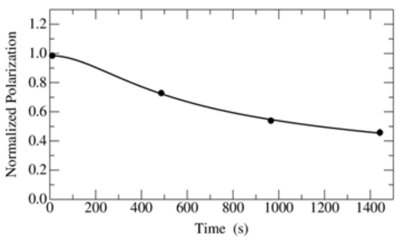


Fig. 7: Lifetime curve (like Fig. 4) where new conditions produced the longest lifetime.

Figure 7 shows the results of a search in which all arc sextupole families in COSY were optimized and the beam current was reduced to eliminate collective effects. In order to preserve beam, extraction onto the polarimeter target was made only at four times. The average polarization at each time is shown. The errors are smaller than the symbols. The lifetime, defined as the time for the polarization to fall to 60.6% of its initial value (Gaussian width) is 782 ± 117 s (1/e lifetime is 2280 ± 336 s), sufficient to support an EDM experiment. This measurement was taken near the MXS = 2 /m^3 points in Fig. 6.

References

[1] C.A. Baker et al., *Improved Experimental Limit on the Electric Dipole Moment of the Neutron*, PRL **97**, 131801 (2006).

[2] P. Benati et al., *Synchrotron oscillation effects on an rf-solenoind spin resonance*, PR-STAB **15**, 124202 (2012); ibid, **16**, 049901 (2013).

[3] N.P,M, Brantjes et al., *Correcting systematic errors in high-sensitivity deuteron polarization measurements*, NIM A **664**, 49 (2012).

[4] J. Bisplinghoff et al., *Position sensitivity by light splitting in scintillator arrays,* NIM A **329**, 151 (1993).

[5] Z. Bagdasarian et al., *Measuring the polarization of a rapidly precessing deuteron beam*, PR-STAB **17**, 052803 (2014).

[6] I.B. Vasserman et al., *Comparison of the electron and positron anomalous magnetic moments: Experiment 1987*, PL B **198**, 302 (1987).