Managing Systematic Errors in a Polarimeter for the Storage Ring EDM Experiment

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Managing Systematic Errors in a Polarimeter for the Storage Ring EDM Experiment

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Abstract. The EDDA plastic scintillator detector system at the Cooler Synchrotron (COSY) has been used to demonstrate that it is possible using a thick target at the edge of the circulating beam to meet the requirements for a polarimeter to be used in the search for an electric dipole moment on the proton or deuteron. Emphasizing elastic and low Q-value reactions leads to large analyzing powers and, along with thick targets, to efficiencies near 1%. Using only information obtained comparing count rates for oppositely vector-polarized beam states and a calibration of the sensitivity of the polarimeter to rate and geometric changes, the contribution of systematic errors can be suppressed below the level of one part per million.

1. Introduction

Access to *charged* particles in the search for an intrinsic electric dipole moment (EDM) is available using polarized beams such as protons or deuterons circulating in a storage ring [1]. By using an entirely electric field ring and the right momentum (p = 0.701 GeV/c) for protons or a combination of magnetic dipoles in conjunction with outwardly directed electric fields for deuterons, it becomes possible to maintain the beam polarization pointing along the beam velocity for long periods (providing decoherence is also controlled). If an EDM is present, the electric field in the particle frame pointing toward the center of the ring will precess the longitudinal polarization slowly into the vertical (stable) direction where this component's growth over time is the signal of the EDM.

Such an experiment requires a means of sampling the vertical component of the beam polarization during the beam storage time with enough sensitivity to measure changes as small as 10^{-6} in 1000 s (needed to reach a limit of 10^{-29} e·cm within a year of data collection). Thus the goal for polarimeter efficiency is to detect and use for the measurement 1% of the particles extracted from the beam. This must be accompanied by a large analyzing power. And even with the changes that accompany slow extraction, systematic errors must be kept below the level of the 10^{-6} signal.

The scintillators of the EDDA system [2] located on the Cooler Synchrotron (COSY) at Jülich were chosen to be the detectors for studies leading to a demonstration of these polarimeter properties. The assembly, which can select solid angle patches using rings for scattering angle (θ) and bars for azimuthal angle (φ), was located downstream of its normal position so that scattering events at θ_{LAB} > 9° could be recorded. The deuteron beam momentum was set for 0.97 GeV/c so that forward angle elastic scattering events would stop in the ring scintillators. At forward scattering angles, elastic scattering exhibits a large vector analyzing power as needed [3]. Lastly, a carbon tube target 15 mm thick with an opening 15 mm high by 20 mm wide was installed at the EDDA target position. The beam was slowly extracted over a minute onto the upper inner edge of the tube opening using white noise applied to a pair of vertical electric field plates ahead of the target. Events in the scintillators that were above a threshold chosen to maximize the figure of merit were recorded with no dead time in arrays of scalers. The number of beam particles was determined from a current transformer that encircled the beam. For the study of systematic errors, horizontal beam position (≤ 2 mm) and angle (≤ 5 mrad) were changed in steps in both directions as the data were taken.

2. Polarimeter efficiency and analyzing power

The essential requirement for high polarimeter efficiency is a thick target material that allows many opportunities for a nuclear interaction since every particle that touches the target will be lost from the circulating beam. The optimal thickness at 235 MeV (the energy used here and also planned for the EDM polarimeter) is 5-7 cm, about 4 times what space constraints allowed at EDDA. In a similar fashion, efficiency and the figure of merit improve as the minimum detected scattering angle decreases until just before the Coulomb amplitude becomes significant near $\theta_{LAB} = 5°$. The mock polarimeter used the forward-most 3 scintillator rings of EDDA, yielding an efficiency of 6.8×10^{-4}. A Monte Carlo estimate of this efficiency gave 5.7×10^{-4}, a value in good enough agreement to support the basis for the estimate. The same calculation reaches an efficiency of 0.01 when a thicker target and smaller scattering angles are included.

Tests in which the vertical angle of the beam was adjusted to alter alignment with the tube surface are consistent with scattered deuterons striking the front target face about 0.2 mm from the corner. This is far enough to significantly remove multiple scattering out of the target tube surface as a mechanism for lost efficiency.

The analyzing power for the mock polarimeter was $A_y = 0.4316 \pm 0.0005$ (stat.) with a calibration scale error of 0.028 from the COSY Low Energy Polarimeter [4].

3. Systematic error management plan

Many first-order (in a small error parameter) errors can be removed by using symmetric (left and right) detectors and comparing rates for positive and negative polarization states. These rates (L and R for detector, + and – for state) can be combined to yield the cross-ratio asymmetry [5]

$$\epsilon = \frac{3}{2} p_y A_y = \frac{r-1}{r+1} \quad \text{where} \quad r^2 = \frac{L(+)R(-)}{L(-)R(+)}.$$

But this scheme fails to cancel errors at second-order, as illustrated in figure 1 that shows the cross-ratio asymmetry as a function of beam displacement for the In-Beam Polarimeter [6] at the KVI in Groningen. The curve is a prediction based on elastic deuteron scattering from carbon at 130 MeV and the modifications due to a quadratic dependence on the displacement Δx^2 and a quadratic interference term ux where the polarization difference is $u = p(+) + p(–)$ with $p(–) < 0$ between the spin up and down states.

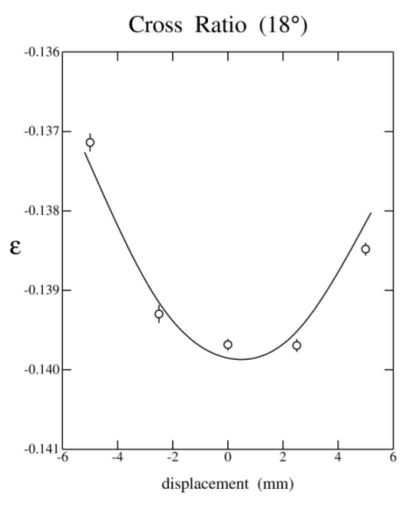

Figure 1. Cross-ratio asymmetry as a function of beam displacement x along with a prediction based on elastic scattering and the known spin up and down polarization difference.

Independent information is available in first order on the size of the error arising from position or angle displacement through a second cross-ratio error parameter

$$\varphi = \frac{s-1}{s+1} \quad \text{where} \quad s^2 = \frac{L(+)R(+)}{L(-)R(-)}$$

which is insensitive in first order to beam polarization effects. In addition, it is possible to see changes to various polarization observables from high detector rates as pulses add to cross threshold or change the gain of the photomultiplier system. This leads to a second rate error parameter that is the sum of the individual detector rates, $W = L(+) + R(+) + L(-) + R(-)$. Combining these two parameters, it is possible to obtain corrections to the cross-ratio asymmetry in the form

$$\varepsilon = \frac{r-1}{r+1} - \left(\frac{\partial \epsilon}{\partial \varphi}(\varphi)\right)_M \Delta\varphi - \left(\frac{\partial \epsilon}{\partial W}(W)\right)_M \Delta W$$

where the subscript M refers to a model based on the calibration of the sensitivity to errors. Since φ and W are known from the original data, correction of asymmetries can take place in real time as the data are acquired.

4. Model of polarimeter errors

A model was constructed that incorporated all polarization sensitivities and systematic errors through their effects on the count rate. These included the vector analyzing power and the effect of tensor polarization on the difference between the vertical and horizontal count rates, as well as the vector (p_y) and tensor (p_{yy}) polarization for each of the 4 polarized beam states. Changes in the cross section and analyzing power were parameterized by expanding the cross-section weighted average of these quantities over the detector acceptance in a Taylor series about the unchanged scattering angle. Last, the solid angle acceptance ratios were included for left/right, down/up, and (down+up)/(left+right) and a parameter, the effective detector distance, was included that connected position and angle changes.

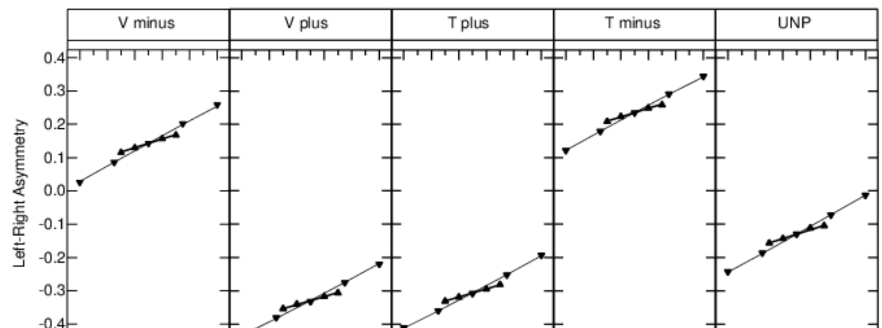

Figure 2. Measurements of position (▲) and angle (▼) effects on the left-right asymmetry as a function of either position (mm) or angle (mrad) on a "universal scale". The lines are the model fits. The slopes measure the first logarithmic derivative of the cross section with scattering angle; differences between position and angle determine the effective detector distance. The downward shift of the unpolarized asymmetry from zero is mainly due to the tail fraction (30%). Shifts up or down with respect to this are effects of the vector beam polarization (present in all states).

This list proved inadequate. Also required were an effective rotation of the ring detectors caused by the geometry of the photomultiplier tube coupling, vertical-horizontal beam motion coupling for both position and angle, and a spin-independent, but position and angle dependent, tail that added rate to the right detector system (low-momentum side of the beam). Each of the polarization observables also depended linearly on total detector rate W. These slopes were measured, and the zero-rate point taken as the measurement of the purely geometric change. With these added degrees of freedom, it was possible to reproduce all systematic error data with a reduced chi square of 1.7, a value considered reasonable considering that anomalous stores were not systematically removed from the data set.

A sample reproduction of the simple left-right asymmetry is shown in figure 2. Figure 3 illustrates the tensor asymmetry.

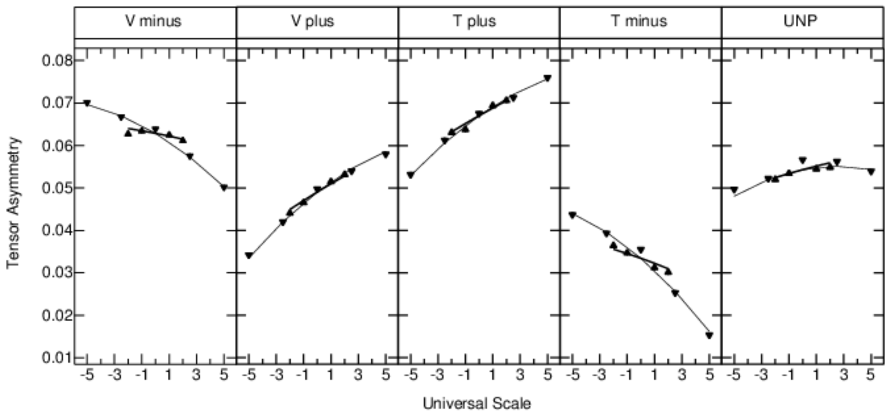

Figure 3. Measurements similar to Fig. 2 but for the tensor asymmetry (D+U–L–R)/(D+U+L+R). The slopes are the product of the vector asymmetry and the first logarithmic derivative of the cross section. The curvature determines the second logarithmic cross section derivative. The upward shift of the unpolarized asymmetry depends on solid angle ratios and the tail fraction. Shifts from this reference give the tensor asymmetries for each of the polarized beam states.

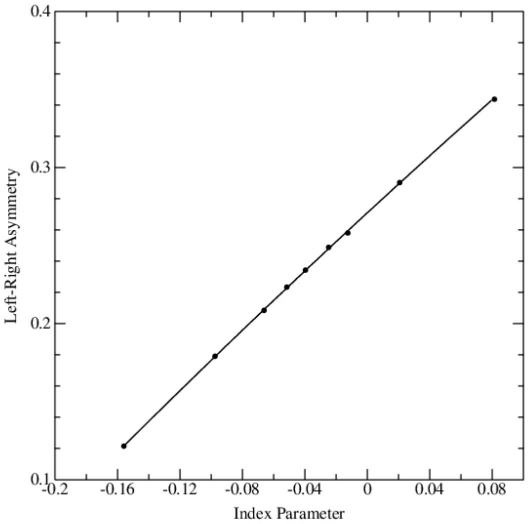

Figure 4. Left-right asymmetry correction versus φ.

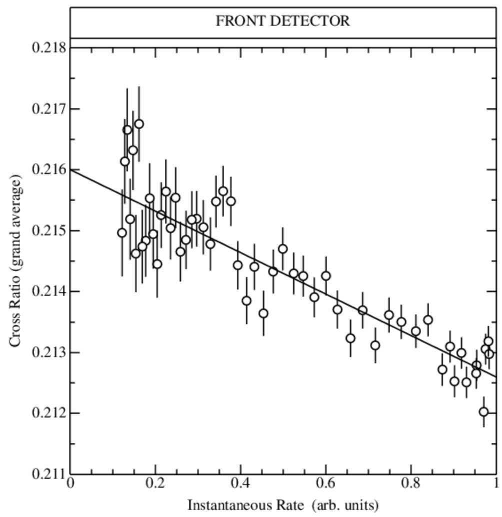

Figure 5. Cross ratio versus instantaneous rate.

The most important test of the simple correction scheme above is whether position and angle errors can both be treated successfully with a single geometry error parameter φ. To within the statistical errors (smaller than the points in figure 4) the correction curve for position (tightly bunched 5 points) is the same as for angle (broadly spaced 5 points). Figure 5 illustrates the linear relationship of the rate-dependent correction of the cross ratio to the instantaneous rate W. During a store the rate initially rises as the beam phase space expands due to white noise, then falls during extraction on the polarimeter target. In these two examples, the correction derivatives are nearly constant over the calibrated range of the error parameter. Figure 6 illustrates the geometric correction for the cross ratio;

it has curvature for the EDDA polarimeter detectors, but not as much as was observed at lower energy for the KVI In-Beam Polarimeter.

Several runs were made with position or angle changing with time to determine how well the calibrated error corrections were working. Figure 7 shows one series of points as a function of time in the store (red = original, blue = corrected for rate only, black = corrected for rate and geometry). The end result is flat with time (the inclusion of additional data with the geometry correction reduces statistical errors in this case).

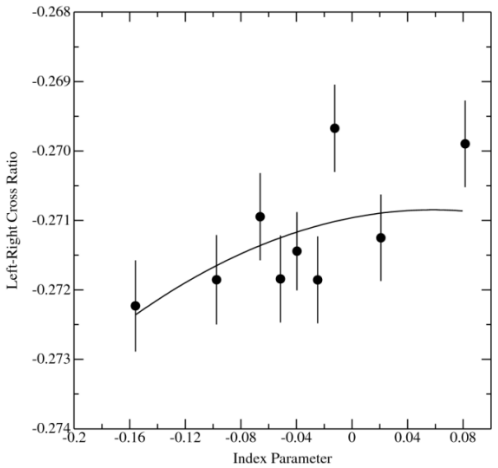

Figure 6. Cross ratio versus error parameter φ.

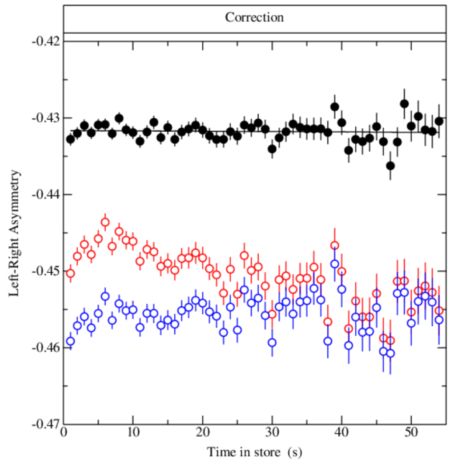

Figure 7. Left-right asymmetries as a function of time during a beam store (s). The original data is red. Blue corrects for rate; black also includes geometry.

The slope and curvature of the model line in figure 6 depend on the first and second logarithmic derivatives of the analyzing power. For an EDM polarimeter where the cross ratio is used, the first derivative is most important. Here $\partial A_y/A_y\partial x = 0.0055(2)$. If for the EDM, $\varepsilon < 0.01$, $u < 0.05$, and $\Delta x <$ 0.03 mm, then the largest correction to the cross ratio would be less than 0.1 part per million.

5. Conclusions

Tests with the EDDA detector and a polarized deuteron beam at COSY have demonstrated that it is possible to construct a polarimeter suitable for an EDM search using a 6-cm thick carbon target at the edge of the beam and scintillators that intercept all elastic and nearly elastic events with a laboratory angle range of 5°-20°. Efficiencies of 1% can be reached with an effective analyzing power of $3A_y/2 >$ 0.6.

By using two error parameters (one for rate and another for geometry) that are derived from real time data, corrections based on a prior calibration can be made in real time to any polarization observable derived from the data. By applying this calibration to the tolerances expected for an EDM search, the corrections to the cross ratio asymmetry are already much less than one part per million; thus the errors in the final result will be even smaller.

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