Appendix: Polarimeter Systematic Errors,

Polarimeter R & D at COSY

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 deteriorate 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 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. Furthermore, a polarized ion source for protons and deuterons, good equipment and an experienced team of machine physicists to help with challenging projects exist. Above all we find at COSY polarimeters for the right energy range, one of them is placed behind the cyclotron to measure the polarization at low energies before injection into the storage ring.

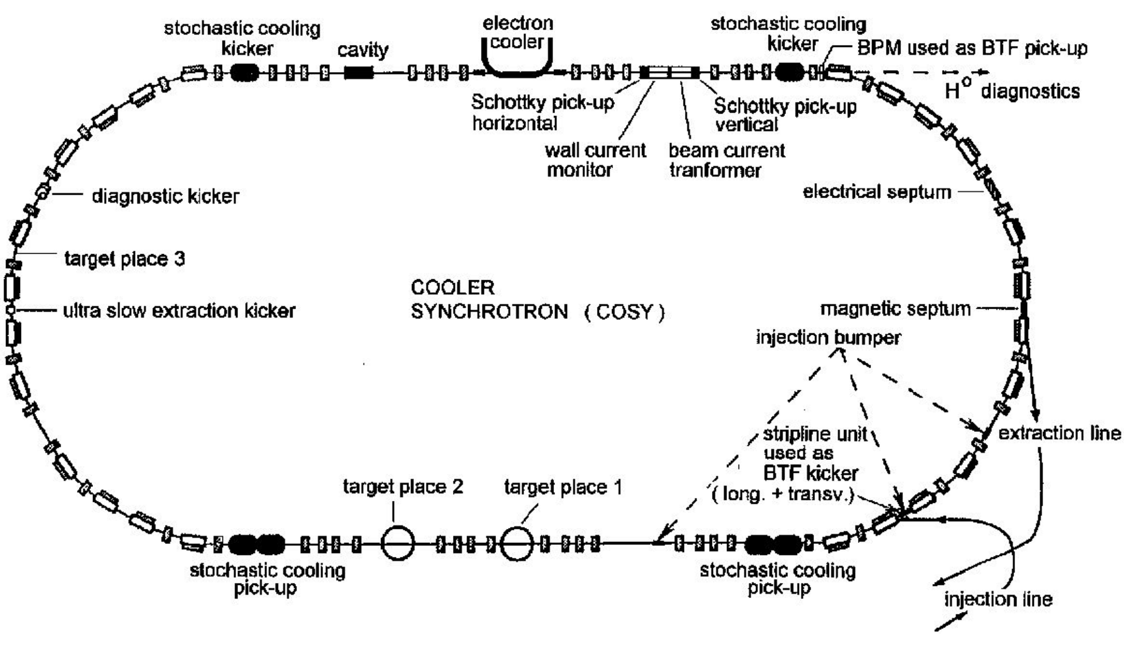


Figure 1: Sketch of the beam line of the COSY storage ring.

Another important feature of the COSY accelerator is a detector system from the former experiment EDDA at target place 2 (see Fig. 1) 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 θ and φ) 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 that group which is nearly elastic. 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 the proposed deuteron EDM experiment.

Following the original plans of measuring the EDM of a deuteron, we went three times for runs to Jülich in 2008 and 2009, using four weeks of beam time (of a total of approved eight weeks) to study these effects with polarized deuterons.

The deuteron has the advantage that it is easily polarizable and measurable. We can simply measure its polarization by an elastic scattering on carbon. To be highly sensitive, we have to build a very efficient polarimeter. The key to efficient polarimetry is to use a very thick target. An optimal thickness for deuteron-carbon elastic scattering is a length of 5 cm.

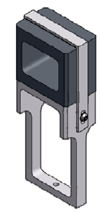


Figure 2: Tube target

We decided to use a tube target that was machined at COSY (see Fig. 2) 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 was accomplished during the first run at COSY 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 to 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.

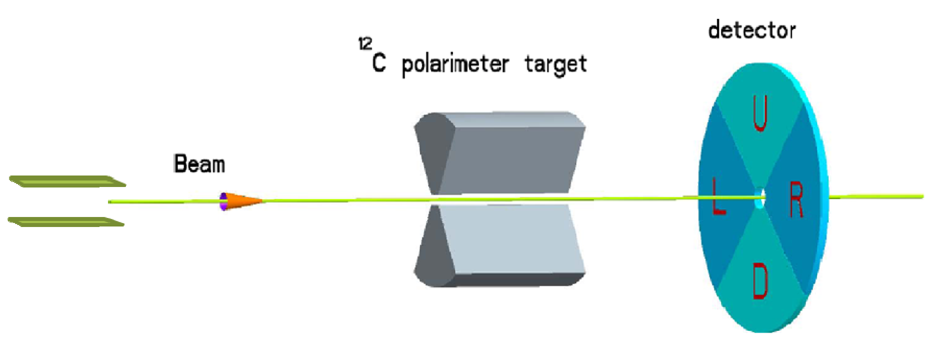


Figure 3: Polarimeter concept.

Figure 3 shows the concept of the polarimeter. It includes a detector which needs to be segmented. This segmentation gives us the possibility to measure different asymmetries.

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 down (D) and up (U) detectors actually give us the possibility of feedback, measuring the g-2 precession in the ring. They track the horizontal polarization in a) magnitude and b) orientation in plane, via the down-up asymmetry:

$$\varepsilon_{g-2} = \frac{D-U}{D+U}$$

The tensor polarization can be used for verification via

$$\varepsilon_{tensor} = \frac{D+U-L-R}{D+U+L+R}$$

The efficiency and 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 down by about an order of magnitude because the target is thinner and the minimum angle of the detectors is larger.

Figure 4 shows cross section and analyzing power versus the laboratory scattering angle at $E_d = 270$ MeV, which is close to an energy of 250 MeV for the deuterons, equivalent to a planned momentum of 1 GeV/c in the storage ring for the EDM experiment.

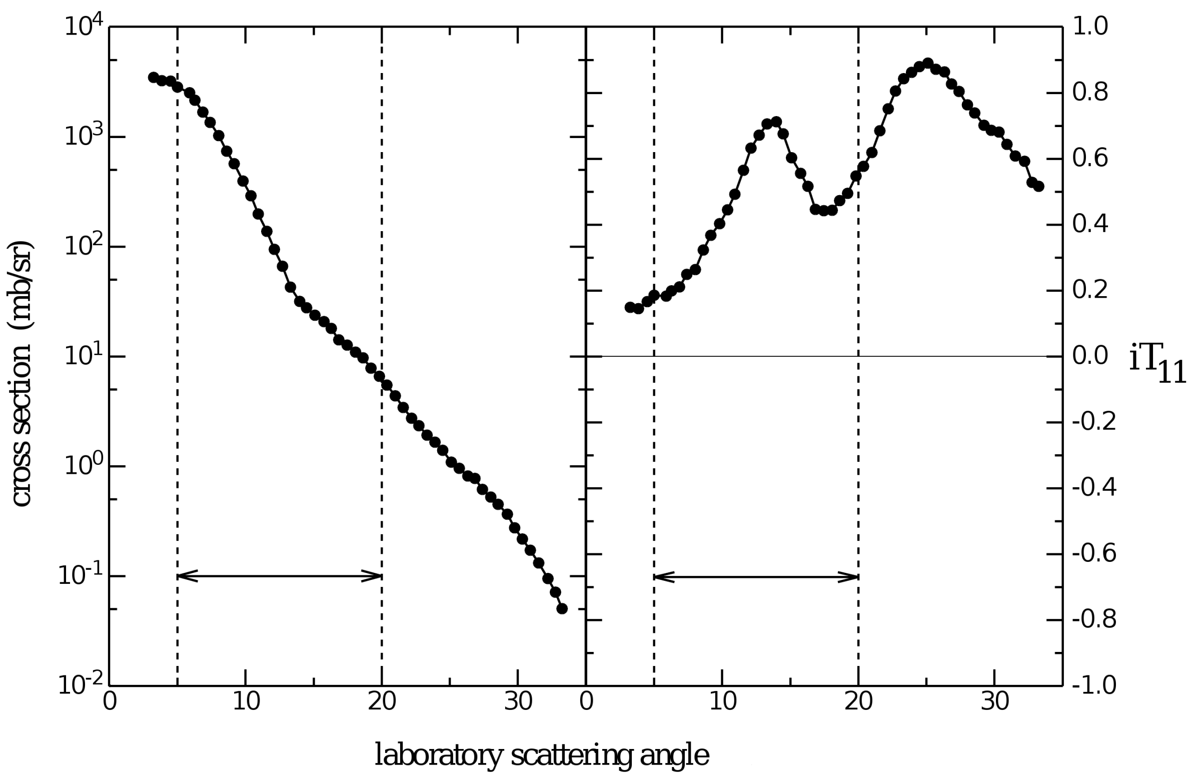


Figure 4: Cross section and analyzing power at E_d = 270 MeV [Taken from: Y. Satou et al., Phys. Lett. B 549, 307 (2002)].

The maximum of the figure of merit, i.e. cross section times analyzing power squared, gives us the region of scattering angles which is most sensitive. For the EDM experiment, we want to measure at angles from 5º to 20º. Using the detector system from EDDA, we were limited to an operating range starting at 9º.

The EDDA detector is θ and ϕ segmented, made out of scintillator bars (ϕ) and rings (θ). The bars were gain-matched to each other. To stop deuterons in the rings we chose a beam energy of E_d = 235 MeV. A separate, new set of electronics for the EDDA detector was installed while leaving the original electronics in place for routine use by the COSY staff and other experiments.

Despite limitations and variations in target thickness, angle range and energy, we found the optimal place for testing the concepts of a sensitive EDM polarimeter at COSY. Running the EDDA detector like an EDM polarimeter resulted in an efficiency between 0.08% and 0.12% and an analyzing power of around 0.35, what actually was expected from the given operating parameters.

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 geometry effects. If we exaggerate possible errors as we test, 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:

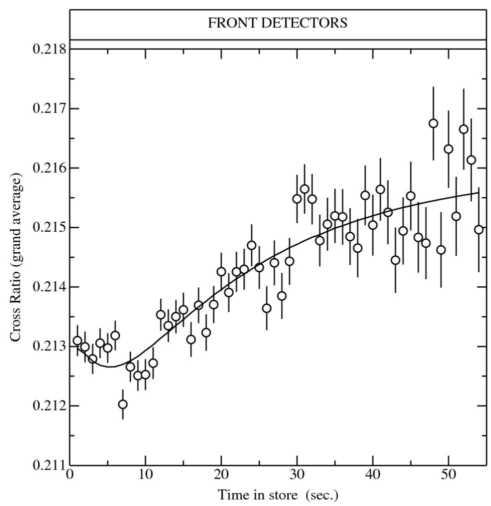
$$\varepsilon = \frac{3}{2} p_y A_y = \frac{r-1}{r+1} \qquad r = \sqrt{\frac{L_+ \cdot R_-}{L_- \cdot R_+}}$$

where p_y denotes the polarization, A_y the vector analyzing power, and +/– the two different spin states.

This observable cancels out common errors you get in the asymmetry at 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 begin of each injection the beam was raised by 3 mm to be sure to extract only on one target 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 $\Delta x = -2, -1, 0, 1$, and 2 mm and scanned angles were $\Delta\theta_x = -5, -2.5, 0, 2.5$, and 5 mrad, where mm and mrad 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. Second-order effects must be canceled or corrected.



Beyond the geometry effects we found that rate effects play a big role. The cross ratio changed during the time of a store, which had a length of one minute during the runs at COSY (see an example measured with the Front detector in Fig. 5).

Figure 5: The cross ratio changes from early to late in the store. Data taken with the front detector, during higher-rate initial running.

This is orders of magnitude larger than the change we want to detect to find an EDM signal, and therefore not acceptable. Plotting the cross ratio versus the instantaneous rate demonstrates that this is a linear rate effect (Fig. 6). As will be discussed in connection with the model analysis, these changes occur due to event pileup such that a greater fraction of the events cross threshold and are counted when the detector rate is higher.

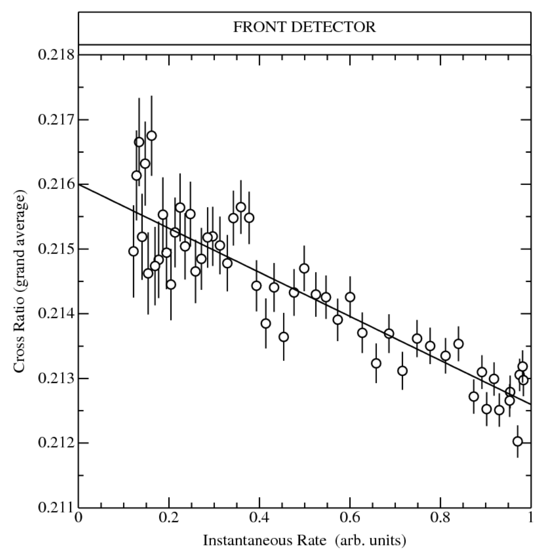


Figure 6: Linearity in the plot of cross ratio versus the instantaneous rate demonstrates that the curve has the same shape as the count rate distribution.

The EDM rate effects will be lessened through longer stores than used at COSY, uniform extraction rates, and a greater detector segmentation. Second-order failures can arise from rate-dependent effects. These are, for example, pileup, gain/threshold shifts, and others.

To cancel second-order errors one needs to know the dependence on the error. The choice is to use an index parameter φ, a parameter with first-order error dependence, as a measure of the position or angle displacement. $\varphi = \frac{s-1}{s+1}$, where $s^2 = \frac{L_+ L_-}{R_+ R_-}$.

The φ term depends mostly on the error at the target with spin sensitivities suppressed.

The linear correlation between rate and cross ratio (Fig. 6) indicates that this error is correctable using the instantaneous rate as an index.

Each polarimeter, the EDDA detector or a newly built 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. The data has to be corrected based on an index parameter.

In the simplest case, one can use data such as that shown in Fig. 6 to create an empirical correction for each effect. Given a measured rate, the value at zero rate (or no rate effect) can be extracted by applying the slope to obtain a correction to the measured value. The purpose of creating a model of geometry and rate effects was to identify such changes with specific physical causes whose size could be estimated by a Monte Carlo simulation of the polarimeter or another form of analysis. This would also permit estimates to be made of the likelihood that any model parameter might change with beam or running conditions, and to determine whether there were any effects without straight-forward explanations since these might be subject to change. The scheme outlined above permits only two index parameters, φ and the instantaneous rate. If these two parameters are not adequate to unambiguously determine a correction, then more information is needed and a scheme must be devised to provide the extra information. One of the more prominent issues of this sort is the question of whether the φ index is sufficient for both X and θ systematic error contributions.

The first step was to separate rate and geometry effects. In Fig. 6 the zero rate point was assumed to be independent of rate and useful for the analysis of geometry effects. The slope will be used for the study of rate effects.

Starting with a model for the geometry, there are several parameters that need to be included in the model of geometric systematic errors. These are:

- The EDDA analyzing powers A_y (vector) and $A_T = \dfrac{\sqrt{6}T_{22}}{\sqrt{8} - p_T T_{20}}$ (tensor).
- Four vector and four tensor polarizations p_V and p_T for the four polarized states V^+, V^-, T^+ and T^-. Having information available from the low-energy polarimeter allows us to choose these values.
- Six logarithmic derivatives: $\dfrac{\sigma'}{\sigma}$, $\dfrac{\sigma''}{\sigma}$, $\dfrac{A_y'}{A_y}$, $\dfrac{A_y''}{A_y}$, $\dfrac{A_T'}{A_T}$, $\dfrac{A_T''}{A_T}$
- Three solid angle ratios: L/R, D/U, and (D+U)/(L+R)

These are already 19 parameters. In order to adequately describe the measurements, it turned out that 7 more parameters were needed.

- A rotation of the down/up detector, caused by a broken symmetry of the ring detectors, which is sensitive to the vertical polarization: θ_{rot}
- There was a coupling of X – Y and $\theta_X - \theta_Y$ beam parameters, making vertical asymmetry measurements sensitive to horizontal errors through coupling coefficients: C_X, C_θ
- The ratio of position and angle effects, which is in principle the effective distance to the detector: X/θ = R

- There appeared to be additional small-angle scattering from the target that led to particles that continued to circle the storage ring, eventually stopping in the right detector since it was located on the low momentum side of the detector. The amount of such scattering was measured with a "tail fraction" parameter that was spin independent. Two additional parameters for a tail fraction, F_X, and F_θ, are sensitive to position and angle shifts of the low-momentum tail.

The total number of parameters is now 26.

Non-linear regression fitting revealed a continuous ambiguity involving L/R and (D+U)/(L+R) solid angle ratios, the tail fraction, effective detector distance, and all polarizations. Our choice was to freeze L/R solid angle ratio for front rings at one, thereby determining all other parameters.

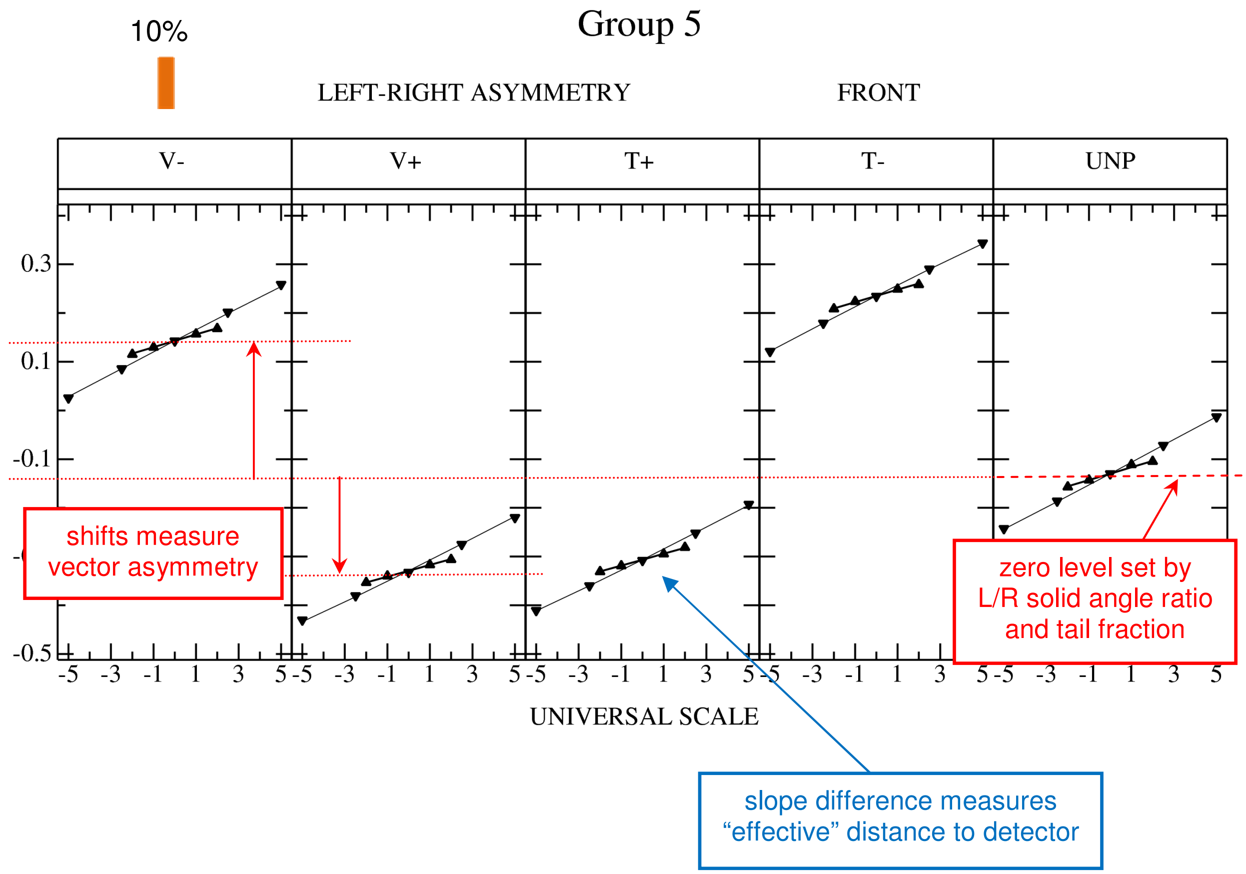
Results for the best fit for one group of data are shown in the next table:

Table 1: Parameter set for group 5

Observable		Parameter #	Value	Error
Vector Polarization	(V-)	1	0.537	3.78E-04
	(V+)	2	-0.39544	3.60E-04
	(T+)	3	-0.33989	3.83E-04
	(T-)	4	0.73112	4.05E-04
Tensor Polarization	(V-)	5	-0.15797	2.96E-04
	(V+)	6	0.084117	2.80E-04
	(T+)	7	-0.44481	3.30E-04
	(T-)	8	0.76407	3.30E-04
X/θ		9	0.52393	0.006527
L/R Ω		10	1	
σ'/σ		11	-0.02561	6.73E-05
σ"/σ		12	2.93E-04	1.21E-05
Vector analyzing power A_y		13	0.349	6.38E-04
A_y'/A_y		14	0.005502	2.14E-04
A_y''/A_y		15	7.78E-05	6.21E-05
Tensor analyzing power A_T		16	-0.0721	1.53E-04
A_T'/ A_T		17	-0.00791	0.00459
A_T''/ A_T		18	0.001292	9.08E-04
D/U Ω		19	1.0438	2.88E-04
Angle Mix		20	0.035622	0.002146
Position Mix		21	-0.03191	0.005289
Rotation		22	0.026014	5.16E-04
DU/LR Ω		23	1.3046	1.79E-04
Tail X'		24	-0.01225	6.76E-04
Tail Fraction		25	0.29848	2.14E-04
Tail θ'		26	-0.00859	2.77E-04

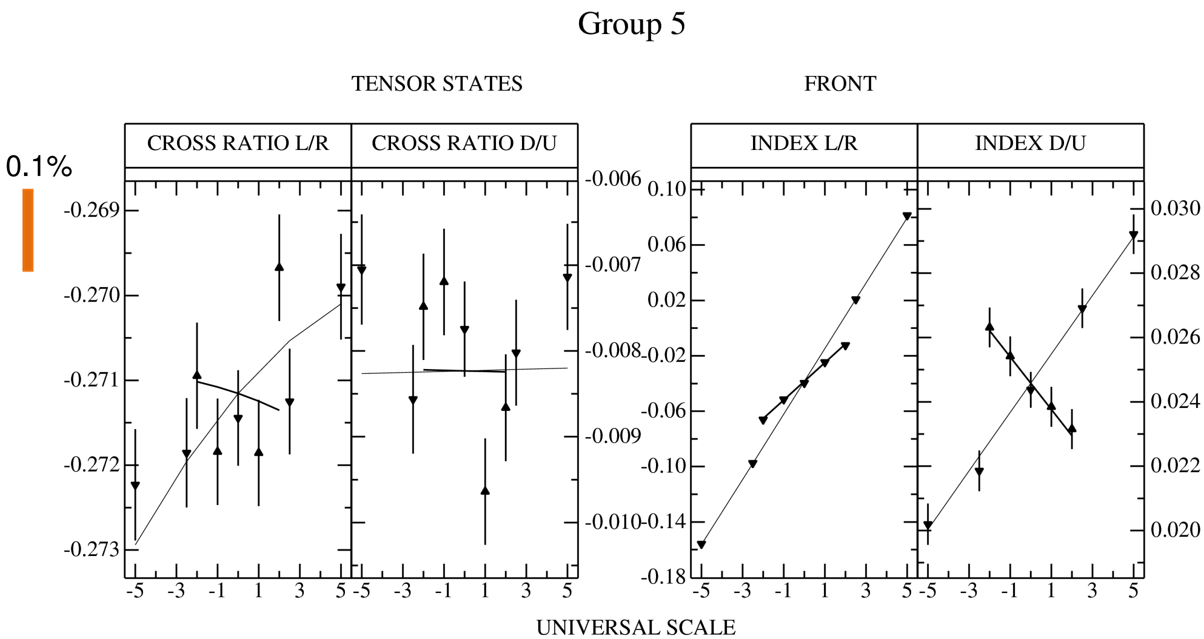
The quality of the fit is shown in Fig. 7 as an example of the left-right asymmetry and Fig. 8 as an example of the cross ratio and index parameter φ. Results from both angle and horizontal displacements are plotted versus the displacement using a "universal scale" that can be either variable in the appropriate units. A bar next to the figures illustrates the size of an effect of the noted percentage. A decrease by two orders of magnitude in the size of error effects happens when going to observables such as the cross ratio that are sensitive to systematic effects only at second order.

Figure 7: Horizontal Asymmetry in group 5 (a subset of the June, 2009 data); results for all polarization states are plotted versus the displacement.



The zero level is determined in the case of the unpolarized state, set by the left-right solid angle ratio and the tail fraction. The distance to the center of the fits in the vector polarization states measures the vector asymmetry.

Figure 8: Cross ratio and index parameter φ in group 5; results for all polarization states are plotted versus the displacement.

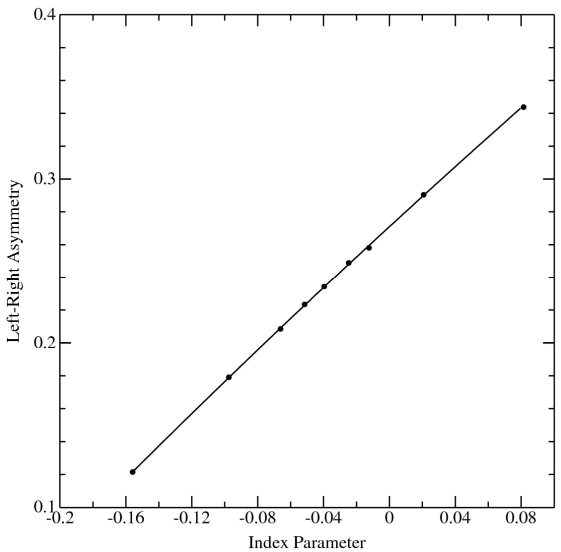


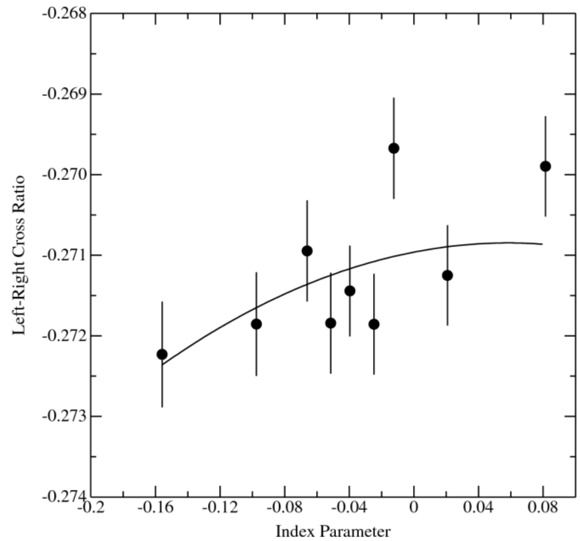
The rate model is simpler than the geometry model and requires fewer parameters in order to achieve a satisfactory representation of the measurements.

Rate effects require a non-linear response to the input rate. These effects can be parametrized by a positive or negative coefficient for an additional term that is the square of the scattered flux. In our case it is positive, meaning that at high rates there are excess events. This conclusion suggests that the rate effect is caused by pileup such that more events cross the detector threshold and were counted as a fraction of all of the flux from the target. If it had been negative and there were lost events, this might be caused by a rate-dependent PMT gain sag, for example.

Tests were made with the beam shifting steadily by 4 mm from the beginning to the end of the store. Changes in the left-right asymmetry over time could be corrected by applying geometry and rate corrections, leading to the time-independent result shown in Fig. 4 of the polarimeter appendix. These shifts were much larger than those to be expected in the EDM experiment.

Figure 9 shows the correlation between the left-right asymmetry and the index parameter φ. 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 listed above. 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 φ 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 10 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 at 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.)



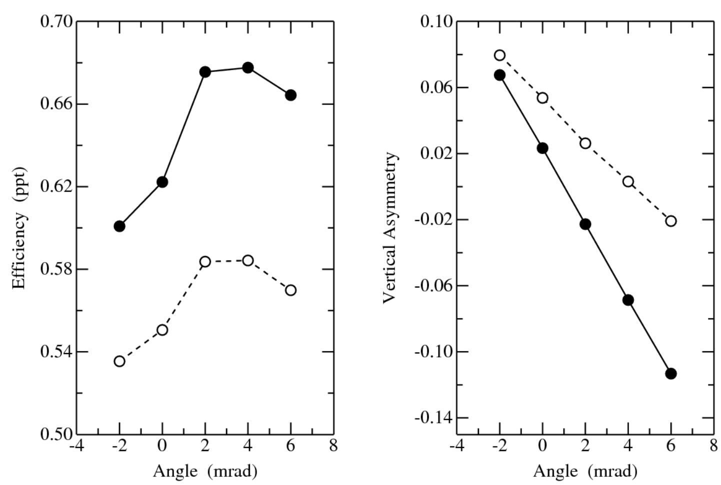


Figures 9 and 10. Measurements and model calculations for the left-right asymmetry and the cross ratio as a function of the index parameter φ.

This result makes it possible to consider the measurement of the cross ratio and its correction terms as a single formula from which we may deduce the polarization of the stored beam based solely on the four count rates for left, right, down, and up detector sections. The calibration of each correction term, like the analyzing power, are properties of the polarimeter determined in advance of the experiment through the measurement of effects much larger than those expected during the search for an EDM.

The model appears to be as complete as can be determined. The reduced chi square for the fits to all data is usually less than two per degree of freedom. The fact that it is not smaller is attributed to occasional stores in which there was an erratic injection or something happened during the time that the beam was circulating in COSY. A number of such runs were seen, but no effort was made to remove them from the data set.

Figure 11. Measurements of the efficiency for the front (solid) and back (open) rings as well as the vertical asymmetry as a function of the vertical angle of the beam on the thick COSY target. The lines are a guide to the eye connecting adjacent data points. These measurements were made with unpolarized beam.



Another issue is how well the beam must be parallel to the surface where it is being extracted. To address this, data were taken with a series of vertical angle changes. The results are shown for two observables in Fig. 11. As would be expected, the vertical asymmetry is sensitive in first order to this angle change as demonstrated by the large effect and the nearly linear dependence of the measurements. The slope of these two curves agrees well with the slopes determined for the horizontal effect with angle in Fig. 7. At the same time, there are small changes to the efficiency that would suggest a peak. This peak is interpreted as the angle at which the beam is most in line with the beam-side face of the thick target. Small changes of this angle do not produce marked changes in the efficiency, which would suggest that particles are hitting the front target face some distance from the beam-side edge. Using the rate of fall-off on the high end of the angle scale would suggest that a typical distance for a deuteron to hit away from the edge is roughly 0.5 mm. The efficiency on the other side of the peak falls more quickly, which suggests, since this is the case in which the deuterons would strike the beam-side face of the target directly, that some of the particles are reflected in a grazing collision with the beam-side face. This would produce an asymmetric efficiency peak. In either case, the changes to the efficiency with changes in the angle of the beam are not large. Some changes were also noted in the left-right asymmetry as these tests were being conducted; these changes are consistent with the level of $\theta_X - \theta_Y$ coupling needed to reproduce the effects of horizontal steering on the vertical asymmetry.

To determine typical effects during the search for an EDM, the corrections already 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.