Appendix: Polarimeter

The change in the vertical polarization component of the circulating proton beam will be measured by scattering a fraction of the beam from the nuclei in a target material. The requirements [and expected characteristics] for such a system are:

- High sensitivity to (parity-allowed) proton polarization orientations. At energies near 230 MeV, this means elastic or nearly elastic (small reaction Q-value or single neutron pickup) scattering through the strong interaction at forward angles where the spin-orbit component of the force is large. [The analyzing power is expected to be 0.52-0.60.]
- High efficiency for measuring the polarization components of protons removed from the beam. This requires thick targets. [The efficiency for protons scattered into the detectors and used for a polarization measurement divided by the number of protons removed from the beam is at or above 1%.]
- Continuous operation so as to observe the change in the vertical component with time during the store. The correct time dependence is one feature of the EDM signal.
- Insensitivity to common systematic errors, including changes in the beam position and direction, intensity, or other properties over time as the beam is depleted during the store.

Rather than concentrate on the separation and detection of a single reaction channel, the polarimeter will be designed to accept a broad spectrum of events across energy, angle, and particle type so that the efficiency is high and the design and operation of the polarimeter detector remains simple. The sensitivity to polarization and systematic errors will thus be calibrated, a requirement that matches this experiment since it is likely to be limited by its sensitivity to small signals rather than its ability to measure large signals with high accuracy.

Polarimeter Design Characteristics

The best analyzer material is carbon, and there is ample information on its performance in double scattering polarimeters [Ap83, Bo90, McN85, Ra82, Wa78] using targets 5-8 cm thick. At forward angles, the cross section and analyzing power are dominated by the elastic scattering channel whose properties are shown in Fig. 1. The Figure of Merit (FOM) is given by σA^2, a quantity that varies inversely as the square of the statistical error accumulated in a given time. While the analyzing power comes very close to one near a laboratory angle of 16°, more forward angles have a higher FOM because of the larger cross section. A typical angular acceptance would range from 5° out to perhaps 20°, although only the inner limit matters. This is usually set by the point at which the multiple scattering distribution from the thick target starts to overwhelm to the single nuclear scattering distribution. Other "near elastic" reaction channels have a similarly positive analyzing power and may be included in the data sample.

For many of the double scattering polarimeters cited above, detection was made with passing scintillators. Usually there was a set of wire chambers preceding the scintillator to allow for scattering angle reconstruction. The threshold for event retention was usually a lower bound on the passing scintillator signal. This generally yielded an analyzing power near 0.52 for 230 MeV protons. A somewhat better FOM can be achieved if an absorber is used to block some of the non-elastic flux, so it may be possible to raise the analyzing power to 0.60. This will also be a help in reducing the polarimeter raw event rate. For this application, high rates will be normal, and we plan to use a gas electron multiplier (GEM) signal amplification system with about 100 pads in a readout that is segmented along the radius and azimuth. For carbon targets in the range of 7-8 cm thick, the efficiency should be close to 1%.

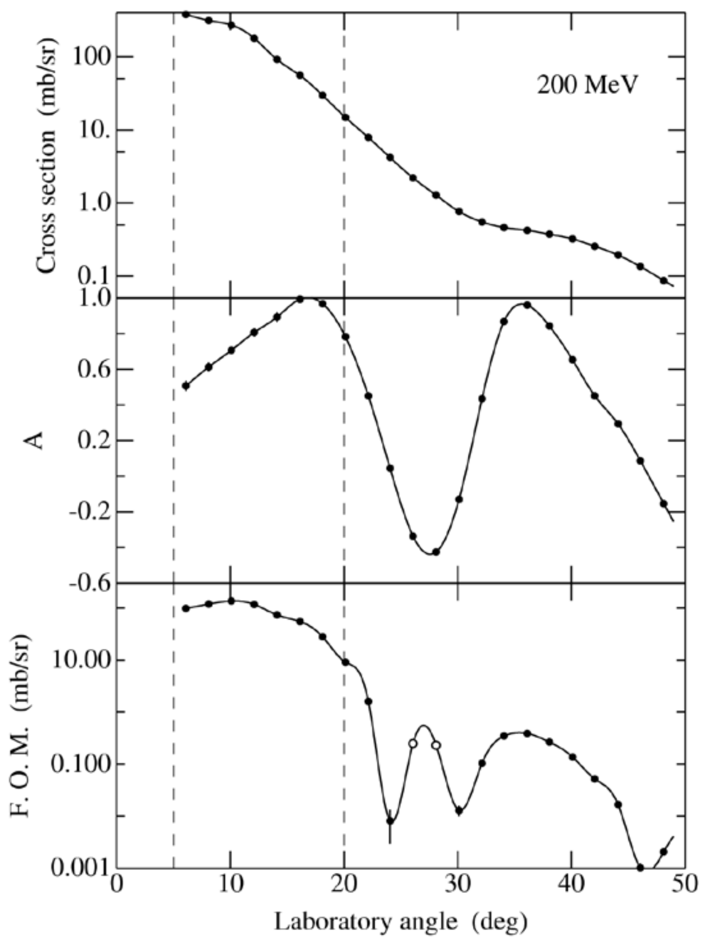


Figure 1. Measurements of the proton-carbon elastic scattering laboratory cross section and analyzing power [Me83] at 200 MeV, along with the σA^2 *figure of merit. The smooth curve is a guide to the eye. The two open points in the FOM graph correspond to negative analyzing powers and should not be included in a polarimeter operating range along with undifferentiated positive analyzing power points. The angle range useful for polarization measurements lies between the two vertical dashed lines.*

The carbon block target would be inserted close to the beam (2-3 mm) on one side (vertical or horizontal). The phase space size of the beam in that direction would be increased slowly using white noise applied to upstream electric field plates. Particles hitting the front edge of the target would be “extracted” and have the potential for scattering through a useful angle and into the polarimeter detectors. At any one time, there could be only two polarimeters operating, even if there are more available in the EDM ring. Extraction is likely to work well on only one target at a time. Since the phase space can be adjusted independently in the horizontal and vertical directions, each direction could be used as a possible polarimeter extraction. For a target mounted horizontally, however, built-in left-right asymmetries would exist and this polarimeter would be well suited to monitoring the orientation of the polarization in the horizontal plane.

Figure 2 shows a possible layout of the polarimeter with a target in the center of a split quadrupole magnet. This target would serve for both directions of the beam at the same time, but only one of the two polarimeter sections is illustrated here. The scale along the bottom is in centimeters. The vacuum chamber flares out to accommodate scattering out to 20° (outer dashed lines) and ends the flare with a thick exit wall that serves as an absorber to select nearly elastic events. This view is from above, and included is the continuation of the vertical plates that, in the straight sections, preserve the image charge characteristics for the beams. Note that the aperture of the quadrupoles near the polarimeter target is larger to accommodate proton scattering. Designs using pole tips inside the vacuum are possible will little loss in sensitivity.

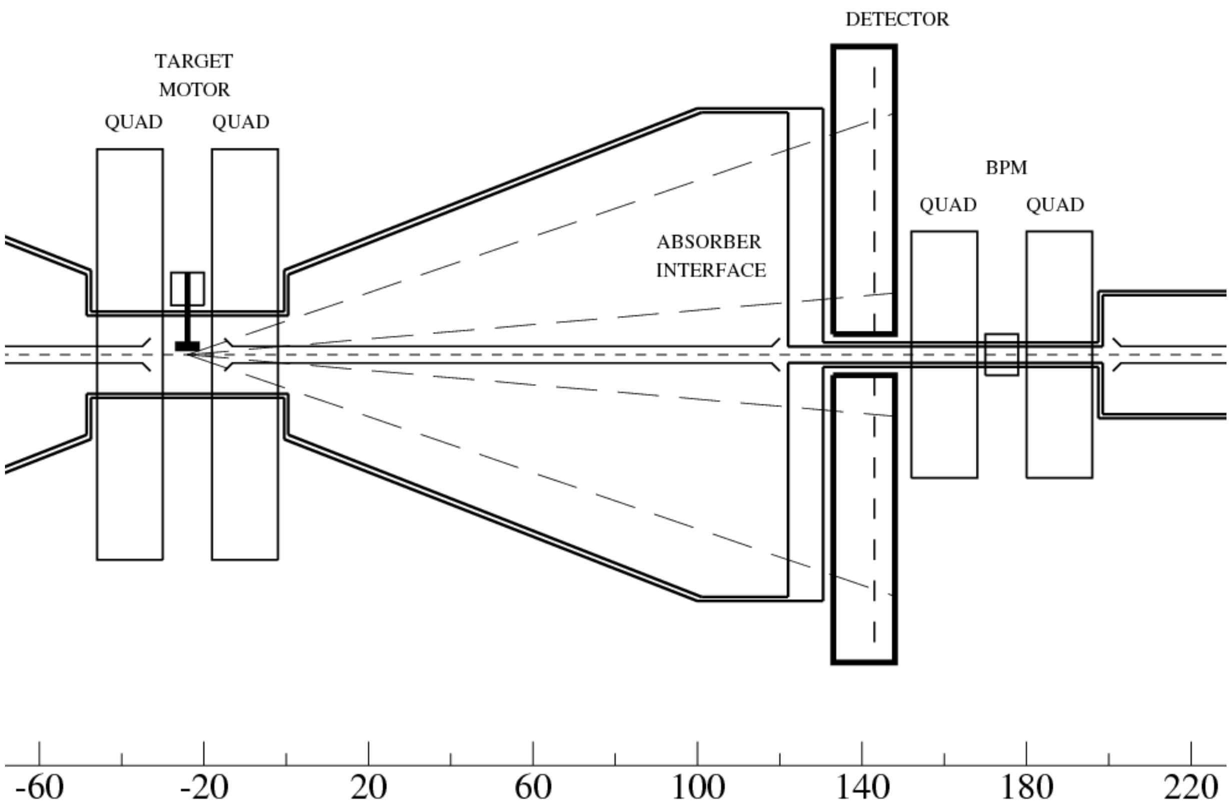


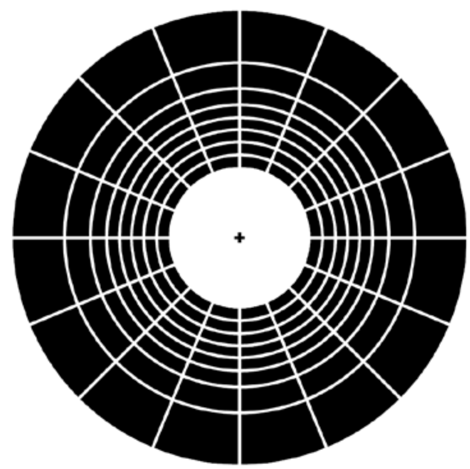
Figure 2. Layout viewed from above of one half of a polarimeter section. The carbon target is mounted on a motor drive between the halves of a split quadrupole. Guide lines show scattering at 5° and 20° into a detector at the end of a flared vacuum chamber with an absorber plate at the end. Beyond the detector, the alternating quadrupole and drift sections resume.

The detector is not completely specified, but needs to accommodate high rates and yield events across a patchwork of pads as illustrated in Fig. 3. Candidates for this detector include gas electron multiplier and/or micromegas designs that amplify the charge liberated along tracks through the detector. Data acquisition schemes must, at a minimum, be capable of counting events above threshold with essentially no dead time.

Experimental Observations

While the proton polarization's main effect is to change the scattering cross section at some angle, minimizing systematic errors has led to the routine use of various cancellation schemes that include simultaneous left- and right-side measurements and the comparison of effects for a complete reversal of the polarization direction. In addition, for an EDM search we have the comparison of clockwise and counter-clockwise (time-reversed) observations. The polarization reversal cancellation places a premium on injecting polarized beam into the ring once with the polarization direction vertical (and stable) and subsequently dividing the beam into two main parts. This can be done as well for counter-rotating beams. Then the polarization of opposite bunches can be separated and rotated into the ring plane using an RF solenoid operating at the cyclotron frequency. The size of the horizontal polarization is measured through the use of down-up asymmetries, and this must be done periodically to check the lifetime of the polarization. The greatest EDM sensitivity is achieved when this polarization lies along the beam direction, and this shift is achieved with a small perturbation to the radial electric field that lasts until the polarization makes a quarter turn.

Figure 3. An arrangement of 128 pads laid out with boundaries along the radial and azimuthal directions. The sizes of the pads were chosen to make the rate from protons scattered elastically from carbon equal for all pads.



The EDM observation requires a measurement of the slope over time of p_y during a store (500-1000s). This involves the cross ratio of events measured in the "left" and "right" counters with both polarization states. Afterward, the difference of CW and CCW observations is obtained to extract the EDM signal. With observations made with reasonable administrative efficiency over the course of a year, it should be possible to reduce the error on the slope to about 10^{-29} e·cm.

If a non-zero signal is observed at a significantly higher level, several other crucial tests become possible. The time dependence of $p_y(t)$ must be the integral of the polarization, which itself is time dependent as the polarization decreases through decoherence. If the $g-2$ rotation of the polarization in the ring plane is not completely cancelled, then the EDM signal changes from a slope to an oscillation at the rotation frequency. This oscillation must have the correct phase with respect to the $g-2$ rotation, and that phase must obey the time-reversal violating property of the EDM when the direction of the $g-2$ motion is reversed. These requirements are also useful in separating the effects of geometric phase processes from a real EDM signal.

With 10^{10} protons in each beam store, the effective number of events recorded for use in a polarization measurement can be estimated from a single asymmetry efficiency (either vertical or horizontal) of 0.55% times the average of cos φ over the acceptance (0.9) to be 5×10^4 /s when spread over a thousand-second store. Using this rate, the precision of the asymmetry measurement after one second is 4.5 parts per thousand (ppt). For 200 seconds or a whole store, these errors become 0.32 and 0.14 ppt. Any of these values could form the basis of a feedback system to regulate the electrostatic plate voltage and maintain the polarization along the direction of the velocity by setting the horizontal polarization component to zero.

Systematic Error Management

As mentioned in the previous section, the cancellation of major systematic errors in a measurement of a beam polarization involves the application of known symmetries. With symmetrically placed detectors (left, L, and right, R) and beams with forward (+) and reversed (−) polarization, one of the more robust ways to extract the polarization is to use the cross ratio method [Oh73] given by

$$p = \frac{1}{A}\frac{r-1}{r+1} \quad \text{where} \quad r^2 = \frac{L(+)R(-)}{L(-)R(+)},$$

which removes any dependence on acceptance and polarization state luminosities by construction. As discussed in the Polarimeter Systematic Error appendix, the cross ratio formula fails at second order in the errors, which are small changes due to (a) position displacement, (b) angle displacement, (c) polarization magnitude differences between (+) and (−) states, (d) gain shift or pileup changes in the detector acceptance with varying rate, etc. An experiment was completed at the Cooler Synchrotron (COSY) located at the Forschungszentrum Jülich (Germany) to use their EDDA detector system as a stand-in for an EDM polarimeter so that such errors could be studied. The main thrust of the experiment was to see if it would be possible, using information about the polarimeter and only the four count rates available in the cross ratio, to correct the asymmetry for systematic errors at a level below that needed for the EDM search, or about one part per million (ppm).

The experiment made measurements of a number of polarization parameters when positions, angles, and rates were changed. To make this correction scheme work, two other "index" parameters were defined. The first was sensitive in first order to geometric misalignments using

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

which suppresses any dependence upon the polarization. The second was the sum of the instantaneous rates as the index of rate-dependent effects

$$Rate\,(t) = L(t) + R(t)$$

for any polarization state. The experiment demonstrated that position and angle errors can be corrected with the same index parameter, and that both rate and geometry corrections can lead to polarization measurements that are independent of time, as shown in Fig. 4. In effect, the corrected (solid) points were calculated with an "advanced" form of the cross ratio formula that contains calibrated correction terms but no data other than the original four count rates used for the cross ratio. Thus it can be applied in real time and used for feedback on ring operation.

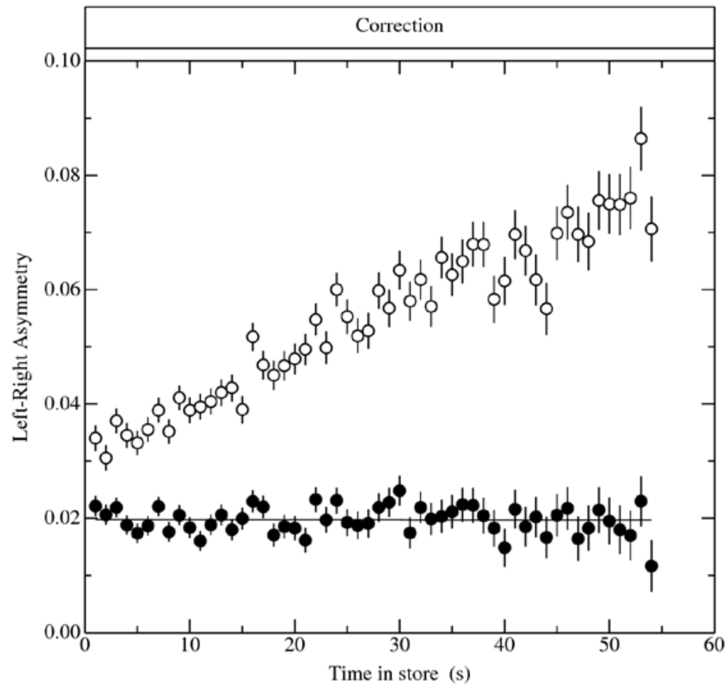


Figure 4. Measurements made of the left-right asymmetry as a function of the time in a store. The open symbols are the raw data taken while the position of the beam was ramped horizontally by 4 mm. The large change is due to a first-order systematic error and contains both rate and geometric contributions. The solid points are the corrected data based on a calibration of the error sensitivities (see the appendix on polarization systematic errors). The reduction in the size of the individual errors is a reflection of the error correlation between the original asymmetry and the correction term.

Changes as large as the 4 mm used in the COSY tests of Fig. 4 are much larger than the variations expected in the EDM ring. These should be under 10 μm, and the initial vertical asymmetry at the beginning of a beam store should be no more than 1-2%. With these constraints, the corrections calibrated in this experiment would have been less than 3×10^{-8}, well under the proposed sensitivity limit. Given the experience with thick-target proton polarimeters and the results of this test, the ability to deliver a polarimeter with systematic error contributions below the required limit has been demonstrated.

Monte Carlo calculations of the efficiency to be expected with the COSY target (1.5 cm thick) and the EDDA detector (coverage starting at 9°) were above 0.1% for the sum of all four segments (left, right, down, and up) of the detector. The efficiencies observed were between 0.08 and 0.12%, depending on which set of ring detectors were chosen and the optimization of the threshold. This confirms the basic premise that particles “extracted” from the beam using the white noise source mainly penetrate the full target thickness rather than experiencing a glancing collision with its surface.

Polarimeter Commissioning Plan

Before committing to a design for the EDM ring, it is important to build a prototype and calibrate it with a proton beam, perhaps at COSY. This would allow a number of tests to be made similar to the ones described in the Polarimeter Systematic Error appendix.

Once installed in the EDM ring, the polarimeter would be calibrated with polarized beam for its sensitivity to beam polarization. A series of measurements would be made of the sensitivity to at least position, angle, and rate errors. In addition, a series of errors could be introduced into the ring to determine whether geometric phase effects could be separated with a set of polarimeter measurements.

An additional important calibration is the location of the ring plane as projected onto the azimuthal array of pads in each polarimeter detector. This is made by allowing the polarization to precess during a store and looking for the node in the oscillating count rate pattern. The EDM signal is an asymmetry that appears along this nodal direction.

Mechanisms would need to be calibrated that make use of the systematically corrected asymmetry measurements for the purposes of feedback into the electric field regulation and the control of other ring elements.

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