CALIBRATION OF THE K600 FOCAL PLANE POLARIMETER

E. J. Stephenson, A. K. Opper, S. W. Wissink,
A. D. Bacher, C. Olmer, and R. Sawafta
Indiana University Cyclotron Facility, Bloomington, IN 47408

During November of 1988, we successfully operated and calibrated the focal plane polarimeter that had been installed on the K600 magnetic spectrometer. This was carried out for protons of 170, 185, and 200 MeV elastically scattered from a carbon target. This running time was used to check the operation of the fast clear and reject circuit for unscattered protons (see technical description in another section of this Annual Report[1]), measure the efficiency and analyzing power A_{FPP} for protons of different energies, and gather information on the presence of instrumental asymmetries. Such asymmetries would give rise to systematic errors, predominantly in the measurement of induced polarization. The calibration information obtained during this running time was used for the analysis of measurements made in experiment 306, which was completed in January, 1989.[2]

Since there are no chambers for the measurement of y-axis (or vertical) position at the K600 focal plane, y-axis scattering angles were not considered in the analysis scheme. This permitted us an accurate measurement of only the x-axis scattering angle, and limited the experimental information available to only the normal spin components. Thus in addition to measurements of cross section and analyzing power, the polarimeter at this stage in its development could provide information only on the induced polarization and the spin transfer coefficient $D_{NN'}$. In a simple picture, the x-axis angle cuts then select two vertical strips through the detector which represent the potentially active regions for seeing scattered particles from each ray through the focal plane. Chambers to measure the y-axis information are under development, and are expected to undergo first testing in July 1989. Once this is completed, a second calibration run will be required in order to study the effects of utilizing the full azimuthal dependence of proton scattering from the carbon analyzer.

The analyzing power of the polarimeter is obtained by computing the asymmetry observed in the two active vertical strips when protons with a known polarization are incident upon the carbon analyzer. Information from all four x-axis wire chambers (two at the K600 focal plane and two in the polarimeter following the carbon analyzer) is used to compute the x-axis scattering angle θ_x. Symmetric boundaries for "left" and "right" scattering are made using values of θ_x. The efficiency is defined to be the sum of all events that scatter into either of these active strips divided by the number of all vslid focal plane events.

While estimates of the effective polarimeter analyzing power may be calculated from the known values of the analyzing power for protons scattering elastically and inelastically from carbon, any polarimeter optimized for high efficiency will average these analyzing powers within complicated constraints set by the software limits chosen for acceptable events. Thus, the analyzing power, or sensitivity to spin, must be calibrated using beams of known polarization, and the sensitivity of the polarimeter properties to the constraints measured. In this polarimeter, the two most important limits are those on the x-axis scattering angle and the energy deposition in the focal plane and polarimeter scintillators.

The angle limits were chosen to maximize the figure of merit (efficiency $\times A^2_{FPP}$) for the polarimeter, and were set to encompass a range from 4.9° to 23.2°. The cross section falls substantially with angle, so the larger limit matters little to the performance of the polarimeter. The lower limit is set to eliminate contributions from multiple scattering in the carbon analyzer, which manifests no spin dependence.

The x-axis scattering angle is the sum of terms from the polarimeter chambers and the focal plane chambers, and the determination of 0° is critical to the elimination of systematic errors. Using the known horizontal offsets in the polarimeter chambers, pairs of wires were selected and used to define a line approximately perpendicular to the polarimeter wire chambers. Illuminating the chambers with protons travelling along a range of angles permitted us to trace these selected rays back through the focal plane chambers, and to determine their average angle there. This was then defined to be 0°. Since the definition depends on actual rays and not on geometry, it is self-correcting should the original choice of wire pairs not represent a line perfectly perpendicular to the wire chambers. The choice may be checked by calculating asymmetries for angles within the multiple scattering distribution from the carbon analyzer. Some small aymmetries were observed that were barely statistically different from zero. Knowing the slope of the multiple scattering distribution at each point, we found that these asymmetries corresponded to an angle misalignment of typically 0.05 mr, confirming the self-calibrating aspects of the procedure.

Polarimeters for higher energy protons at TRIUMF[3] and LAMPF[4] operate in an energy range where elastic and quasielastic scattering have similar analyzing powers, hence it is advantageous to cover both of these regimes with the acceptance of the polarimeter. As the energy is lowered to the range near 200 MeV, the elastic analyzing power goes through a large maximum at relatively small scattering angles while the quasielastic analyzing power is dropping (some analyzing power data in this energy region is available on elastic scattering from Meyer[5] and on inclusive scattering including continuum contributions from Ransome[6]). Hence it is an advantage to utilize only elastic events. For this reason, the second scintillator on the polarimeter was made thick enough (7.6 cm) to provide a precision energy loss measurement. The light guides for these detectors were designed to provide a response across the detector uniform to beter than 2%. Since the protons do not stop in this scintillator, the total energy of the proton is not directly available. Instead, the energy the proton had as it exited the carbon analyzer is calculated, then corrected for kinematic energy losses so that all scattering angles can be compared. The energy reconstruction makes use of the pulse heights in both polarimeter scintillators (the first being 0.6 cm thick), knowing the angle of incidence, and the kinematics for scattering from carbon. The resulting effective exit energy distribution is shown in Fig. 1. The resolution is about 7 MeV. The final selection of events used all energies in excess of the point where the Gaussian tail of the elastic group intersects the carbon continuum.

Other requirements are also imposed, though they have little effect on the spin sensitivity of the polarimeter. A single hit is required for all four of the polarimeter wire chambers. The multiple hit events appear to arise from events randomly in coincidence with a background particle from the room, and from delta rays generated by the protons passing through the polarimeter. Altogether the loss rate is about 15% for operation with

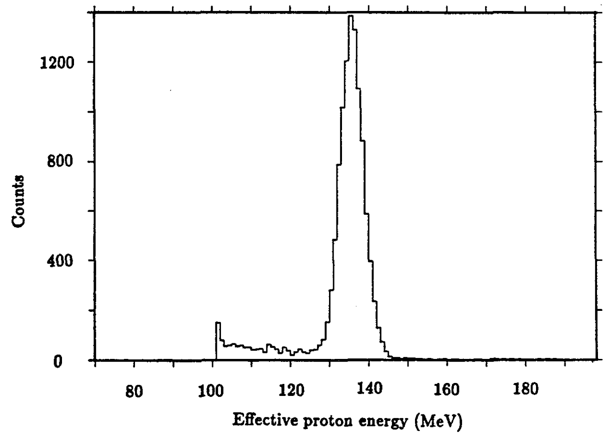

Figure 1. Reconstructed energy spectrum for scattered protons in the focal plane polarimeter representing the energy they had upon exit from the carbon analyzer, corrected for the kinematics of elastic scattering. Thus all elastic events should fall into a single peak. The algorithm has a numerical threshold at 101 MeV.

the external beam dump. No attempt has yet been made to recover the correct pairs from multiple hit events since it was felt that there was a substantial risk of introducing systematic errors if the limits for a successful choice were not perfectly symmetric in θ_x.

A selection was made on events that scattered at the carbon analyzer. This selection was facilitated by moving the horizontal focus of the protons in software to the first x-axis polarimeter chamber. This chamber is immediately behind the carbon analyzer, and gives a good account of the position of the event in that analyzer. A similar limit was set on y-axis information, but without upstream information it was impossible to make any significant selection with this limit.

An important feature of the readout electronics is the ability to rapidly encode the first hit position in each chamber, and to compare these positions to determine crudely the angle of scatter. The hardware limits on polarimeter angle are loaded into a memory lookup unit (LeCroy 2372), and used to discard unscattered protons and clear the electronics within 2 μs. For this calibration experiment, the hardware limits were set at very small angles so that any useful events would not be lost. A larger limit could always be imposed later in the replay program to investigate the influence of this choice on the polarimeter performance. A selection was made in both the x and y directions. These limits removed about 85% of the focal plane events. It appears in replay that selections as large as 93% would be practical without changing the response of the polarimeter. In order to sharpen the definition of the scattering angle on the basis of just the information in the polarimeter chambers, the angle aperture at the K600 entrance was set to 0.5°. The question of a larger angle opening will be discussed at the end of this report.

The outgoing polarization p' for protons elastically scattered from a 0^+ target is given by

$$p' = \frac{p + A}{1 + pA} \tag{1}$$

where p is the polarization of the incoming cyclotron beam and A is the analyzing power for the target in the scattering chamber. Two schemes were used to generate known values of p' for use in the calibration.

The first scheme involved setting the scattering angle to a value where the analyzing power (from the target in the scattering chamber) vanishes. In this case, Eq. (1) reduces to $p' = p$. The value of p is measured upstream in either the beam line 2 polarimeter or the high energy polarimeter, and then p' is known. Since the sign of p can be changed at the ion source, a comparison of the asymmetries in the focal plane polarimeter for these two cases can also yield information on the instrumental asymmetries present there.

The second scheme involved setting the scattering angle to a value where the analyzing power was as large (and positive) as possible. For all of these three bombarding energies, angles exist that offer values of A within a few percent of unity. In this case p' becomes almost identically equal to one. Suppose that $A = 1 - \delta$ where δ is a small quantity. Then to first order in δ

$$p' = 1 - \frac{1-p}{1+p}\delta \quad (2)$$

In the case where the incident beam polarization is positive, the coefficient in front of δ becomes small. For typical values of $p = 0.75$, $p' = 1 - \delta/7$. Not only does p' become substantially closer to unity by a factor of 7, but the error in p' from inaccurate knowledge of either A or p is also reduced. The same coefficient that renders the errors small when p is positive also makes them large when p is negative, and checks of systematic errors in the polarimeter are not easily made for this case. The importance of this aspect of the calibration is that it affords a second standard apart from either the beam line 2 or the high energy polarimeters by which the analyzing power of the focal plane polarimeter can be calibrated.

Figure 2 shows two pairs of scattering angle (θ_x) plots for the two calibration schemes. The solid lines correspond to measurements made with positive beam polarization. For the $A = 0$ case a clear asymmetry exists that reverses with the direction of the beam polarization. In the $A = 1$ case this asymmetry is larger. The difference in the normalization of the two curves for the $A = 1$ case is due to the influence of the target analyzing power on the count rate into the polarimeter. In both cases the number of events near $\theta_x = 0°$ is reduced because of the preselection made in the hardware window.

Calculations of the polarimeter analyzing power A_{FPP} from this set of measurements are shown in the bottom of Fig. 3. Values taken when $A = 0$ are shown as open points which are averaged over positions along the face of the polarimeter, and values taken when $A = 1$ are solid points. Calculations of the efficiency are based on distributions of θ_x made for events triggered by the focal plane only (without any hardware restrictions) to preserve a measure of the scattering near 0°. These estimates of the efficiency do not consider losses due to wire chamber efficiency, including the restriction to single-hit events in the polarimeter. At all but 170 MeV, the analyzing power measurements exhibit near equality for the two methods. This confirms the calibration of the analyzing power determined for the high energy polarimeter. At 170 MeV, scattered protons have a range comparable to the total thickness of plastic scintillator available, and the reproducibility of the energy window is less reliable. (This problem may be removed with additional absorber material before the detectors.)

Figure 4 shows the calibration of the analyzing power for different positions along the face of the polarimeter. These points agree with each other within errors, indicating a similar response at all places. Figure 5 shows the instrumental asymmetry deduced from the $A = 0$ calibration measurements. Besides instrumental asymmetries, there may be

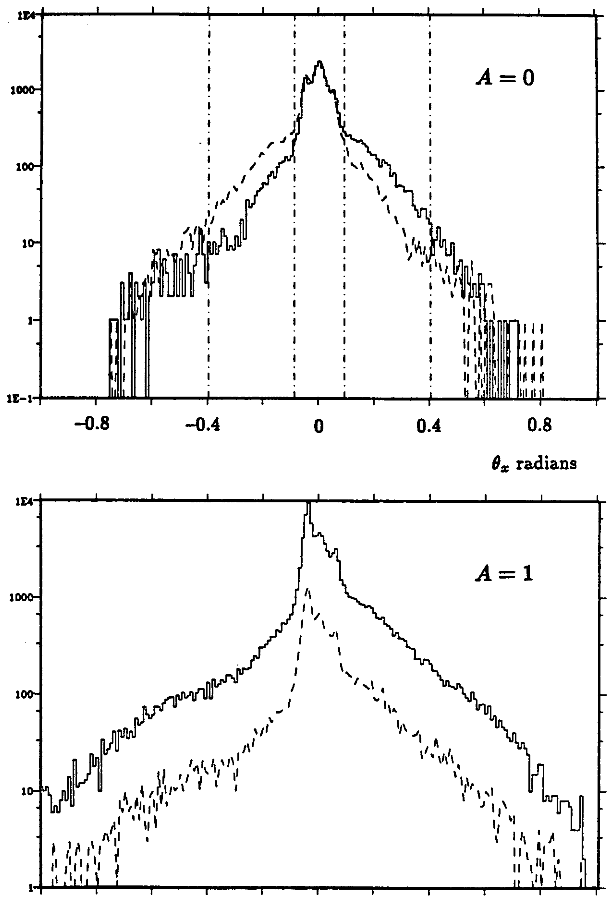

Figure 2. Representative spectra of protons scattered in the focal plane polarimeter as a function of the horizontal angle θ_x. The solid (dashed) line represents the data for spin up (down). The top (bottom) panel represents the case where $A = 0$ ($A = 1$).

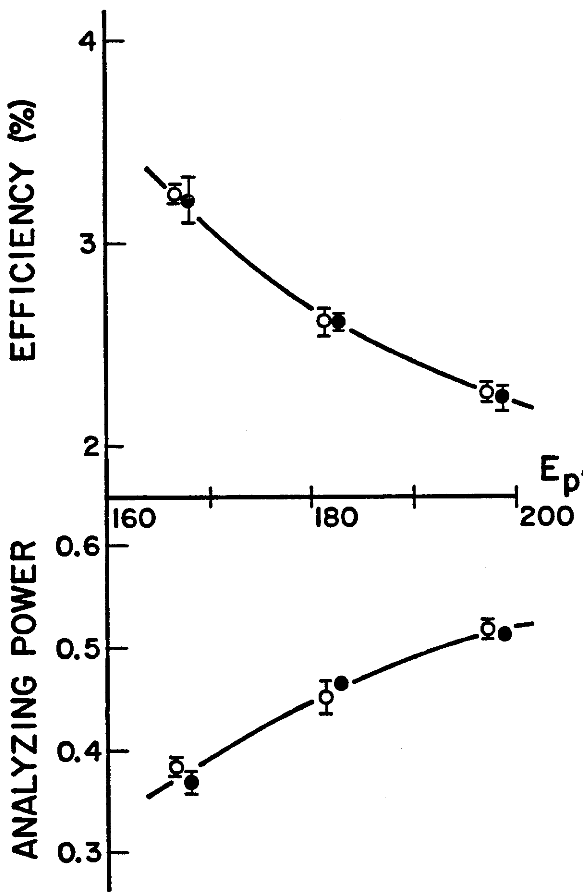

Figure 3. Values of the polarimeter efficiency and average analyzing power as a function of the energy of the scattered proton passing through the focal plane detector. The solid (open) points were measured for the case where $A = 1$ ($A = 0$). See the text for further details.

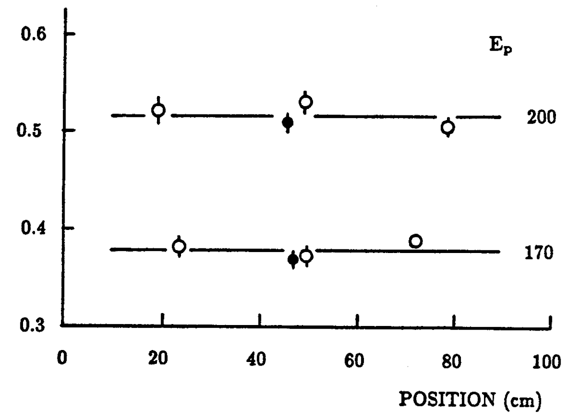

Figure 4. Focal plane position dependence of the 175 and 200 MeV measurements of analyzing power depicted in Fig. 3. The horizontal lines are averages from the calibration curve of Fig. 3 taken at an energy midway between the $A = 0$ and $A = 1$ calibration points.

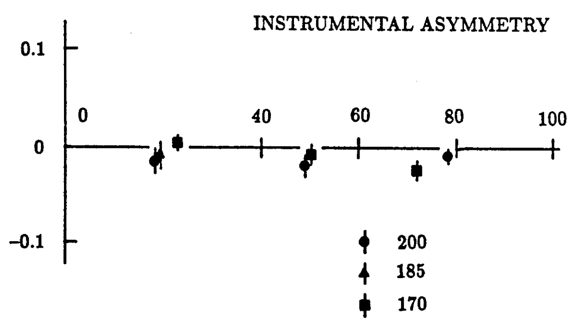

Figure 5. Position dependence of the instrumental asymmetry in the focal plane polarimeter. Various symbols denote the three different incident beam energies used.

contributions to this quantity from unequal magnitudes of the positive and negative beam polarizations, and from setting the scattering angle at a value where A is not exactly zero

$$\epsilon_{\text{inst}} = \frac{p_+ + p_- + 2(1 + p_+ p_-)A}{1 + p_+ p_- A_{FPP}^2} A_{FPP} \tag{3}$$

where p_+ and p_- are the positive and negative beam polarizations. Of these two contributions, the largest for the calibration measurements arose from values of $A < 0$, giving asymmetry values consistent with what is observed. Thus we see no evidence that there is an instrumental asymmetry in the operation of the focal plane polarimeter at the level of precision represented by these measurements.

In the case that measurements with the focal plane polarimeter are limited by the luminosity available (such as when targets must be thin to maintain high resolution), the performance of the system may be enhanced by opening the K600 entrance aperture. At the same time, the angles rejected in the hardware test and the minimum acceptable software angle need to be increased in proportion to the size of the entrance aperture. This process increases an altered figure of merit that includes the overall data acquisition rate since the average analyzing power increases with larger values of the minimum accepted value of θ_x. This figure of merit is maximal for an entrance aperture of about 2°. Scattering events suitable for investigating this mode were taken during the calibration experiment and are being analyzed.

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DETECTOR UPGRADE FOR (p,n) POLARIMETRY

W. Huang and C. Goodman
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

T.N. Taddeucci, R.C. Byrd and T.A. Carey
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

J. Rapaport
Ohio University, Athens, Ohio 45701

E.R. Sugarbaker
Ohio State University, Columbus, Ohio 43210

The detector array used for (p,n) experiments has been upgraded to achieve improved reliability and better resolution for use in neutron polarimetry as well as for simple time-of-flight spectroscopy. The original detectors were $6 \times 6 \times 40$ inch plastic scintillators coupled to 5-inch RCA 4522 photomultipliers with slightly tapered acrylic light guides.

The original packaging was mechanically unsound and the light joints frequently separated. Also, the 6-inch thickness was too great for optimal time resolution when the detectors were used in the polarimeter configuration, that is, transverse to the flight path. In anticipation of using the detectors in vertical as well as horizontal configurations for future polarimetry with different spin orientations, we desired packages that had sufficient mechanical integrity to stand up to frequent reorientation. We chose to go to 2-inch photomultipliers in CERN bases which incorporate spring loading to keep the tube pressed against the light guide. In addition we decided to remake the scintillators into $4 \times 6 \times 40$ inch bars.

The Amperex XP2262 tubes that we used have a useful photocathode diameter of only 44 mm with an area of about 15 cm^2 compared the 150 cm^2 area of the end of the scintillator. In order not to degrade the performance unacceptably by the areal mismatch we designed light guides to capture the rays making small angles with respect to the axis