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A HIGHLY EFFICIENT POLARIMETER FOR THE MEDIUM RESOLUTION SPECTROMETER AT TRIUMF*

O. Häusser^{1,2}, R. Henderson^{1,3}, K. Hicks¹, D.A. Hutcheon¹,
D. Clark¹, C. Günther⁵, R. Sawafte⁴, G. Waters¹

- 1) TRIUMF, 4004 Westbrook Mall, Vancouver, B.C., Canada V6T 2A3
- 2) Also affiliated with Simon Fraser University, Burnaby, B.C., Canada
- 3) Also affiliated with University of Melbourne, Melbourne, Australia
- 4) University of Alberta, Edmonton, Canada, T6G 2N5
- 5) On leave from Universität Bonn, D-5300 Bonn, F.R.G.

Abstract

A polarimeter which uses inclusive scattering from carbon has been mounted after the focal plane of the TRIUMF Medium Resolution Spectrometer. Four drift chambers measure scatterings at all azimuthal angles out to 20° in polar angle over a spectrometer momentum acceptance of $\pm 5\%$. A microprocessor rejects events with small scattering angles. The efficiency for 400 MeV protons is 4%, and for 295 MeV deuterons is 1.5%. Analyzing powers for protons are similar to those previously reported for polarimeters of this type.

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1. Introduction

Polarization transfer measurements have become an important tool in the study of nuclear reactions at intermediate energies. Some examples include studies of depolarization or spin rotation in the elastic and inelastic scattering of protons by nuclei, and spin transfer to deuterons in the $pp+dw$ reaction. In most of such cases it is necessary to use a magnetic spectrometer to select the energy, angle and type of particle of interest from a background of unwanted reaction products. Typically, counting limitations arise not from the flux through the polarimeter, which is determined by the finite spectrometer acceptance and the size of the cross section of interest, but from neutron-induced background produced by the primary beam. In such circumstances it is desirable that the polarimeter have a high efficiency.

We have built a high-efficiency polarimeter for use with the Medium Resolution Spectrometer (MRS) at TRIUMF. It is based on the classic method [1, 2, 3] of elastic and inelastic scattering of particles by thick carbon slabs, with determination of particle trajectories by means of wire chambers. We present in this paper a description of the polarimeter, with emphasis on technical improvements and performance features which have not previously been reported in the literature.

2. Mechanical construction

The MRS is a 1.4 GeV/c QD spectrometer with a vertical bend angle of 60° and a solid angle of 1-2.5 msr. The requirement that the polarimeter not interfere with normal high-resolution operation of the spectrometer meant that the polarimeter had to be placed after the

focal plane detectors (vertical drift chambers and trigger scintillators) as shown in fig. 1. Usually the focal plane is located just below VDC1; it is oriented at 45° to the optic axis, parallel to the VDC's. To ensure uniform azimuthal response the polarimeter normal must necessarily coincide with the optic axis. Therefore, the orientation of carbon scatterers and polarimeter chambers is fixed at 30° to the horizontal, and at 45° to the VDC's and the focal plane. The MRS has a broad momentum acceptance, and it was deemed important that this advantage be retained for polarization measurements; an acceptance corresponding to a momentum range $\pm 5\%$ was chosen. The dimensions and spacings of the polarimeter components (carbon scatterer, wire chambers and trigger scintillators) are determined by the momentum acceptance, and by a scattering angle in the carbon of up to 20° in both directions transverse to the particle momenta. The 30-degree inclination from the vertical could have made servicing wire chambers or changing carbon scatterers a difficult task. The solution was to mount all the elements of the polarimeter in a cage which can be rotated about a horizontal axis (fig. 2). Each element is mounted on a "tray" which can be installed through the open end of the cage, by sliding it into support rails mounted on the inner sides of the cage. The trays are bolted to the cage so that they do not slide out when it is tilted 30 degrees for data taking. The elements so mounted are:

- (1) four wire chambers, (2) as many as four slabs of carbon scatterer, (3) a trigger scintillator in front of the scatterer, and (4) a mount for steel absorber plates (used for deuteron experiments only). A large, final trigger scintillator and its four phototubes are not mounted in this fashion, but rather on a saddle-shaped mount which is

bolted atop the cage.

Geometrical data on the polarimeter cage and its components are summarized in table 1. The coordinates are chosen along the optic axis (z), parallel to the dipole field (y), and in the direction of the dispersion (x).

Access to the polarimeter was provided by addition to the spectrometer structure of a small upper platform, which also provides space for two racks of electronics and storage of unused carbon slabs. Reproducibility of cage orientation is assured by spacer bars which are inserted between it and the fixed detector tower of the spectrometer.

In the normal ("proton") mode chamber 1 is separated from chamber 2 by 40 cm, with the carbon scatterer immediately in front of the latter, with chambers 3 and 4 following with successive 20-cm separations (fig. 2). In the "deuteron" mode, chamber 4 is only 14 cm above chamber 3, and is followed by the support cradle for steel absorber plates which boost the vector analyzing power [7].

3. Detectors

Particles are tracked through the polarimeter using position information from four multi-wire chambers, each consisting of an "x" and a "y" plane. Considerations of cost lead us to choose drift chambers with delay line readout to identify the cell number, rather than a discriminator-per-wire or a TDC-per-wire system. The chamber design is, in fact, very similar to that used in the JANUS polarimeter at LAMPF [ref. 3]. Alternate anode and cathode wires form drift cells with a maximum drift distance of 4.06 mm. The anode wires are connected directly to a low-loss printed-circuit delay line having a

connected directly to a low-loss printed-circuit delay line having a signal propagation speed of 0.4 cm/ns. The difference in times at which signals reach the two ends of the delay line determines the cell number, while their average depends upon the drift time and hence upon the distance of a particle track from the nearest anode wire.

Each cathode wire is connected to one of two bus lines depending upon whether it is an "odd" or "even" wire. The ambiguity in the direction of drift was resolved in a similar way as in ref. 3 by observing the charge induced in "odd" and "even" cathode sense wires. We have introduced a double layer of cathode sense wires, with the second layer 0.5 mm above the first one. This results in a better electric field geometry near the cathode wires, in larger induced "odd" and "even" signals, and in a more reliable resolution of the 'left-right' ambiguity [see ref. 4]. Unlike the JANUS polarimeter at LAMPF [ref. 3] we obtain pulse heights for each of the "odd" and "even" cathode bus lines, and calculate corrections and differences in software; the optimized odd-even asymmetry makes it possible to resolve the ambiguity in the direction of drift. A time signal is also derived from the "odd" line. The gas mixture consists of 65% Argon, 34.5% Isobutane and 0.5% Isopropyl alcohol, and contains no freon. The detectors are operated at 2000 to 2150 V; higher voltages than these produce gas gain modes which degrade left-right differentiation. A detailed description of the drift chambers and their properties is given in reference 4.

The polarimeter trigger system consisted of two plastic

scintillators, one after the first chamber but before the carbon scatterer, and the other after the three chambers following the

interface unit. While these buffered data are being read by the MRS data acquisition computer, the system is free to respond to subsequent carbon.

4. Electronics

Signals from the two phototubes of S1 pass through discriminators and are ORed together, as are those from the four phototubes of S2. The S1-S2 coincidence provides a local trigger for the polarimeter electronics, as well as the time reference for the drift chambers. A fraction of each of the six analog signals is split off and input to an ADC channel for possible use in off-line analysis. Events of interest in a polarimeter experiment are those in which the normal spectrometer coincidence condition ("MRS") is met, as well as the coincidence involving the polarimeter trigger ("FPP"). The ADC's and TDC's for the polarimeter reside in a dedicated crate of the MRS Camac Branch; they are gated by a local "FPP" trigger and latched to avoid the delay in obtaining the slower "MRS" decision. If there is no "MRS" condition within 300 ns, a Fast Clear signal is generated automatic-ally. The MRS trigger logic also has provision for a Slow Clear, which is propagated to the FPP Camac modules and latch as well as to those of the standard MRS electronics. A clear can be issued in a third way from a microprocessor in the FPP crate which examines the FPP data to decide whether the scattering angle is too small to be of interest; then, a Clear is generated via an output register. Finally, for good events the latch is cleared by the standard MRS electronics after non-buffered modules have been read.

For good events the FPP data are buffered in microprocessor memory, and the MRS wire chamber data in the memory of its Camac

triggers and to reject bad events.

The "odd" and "even" cathode pulses are amplified, then integrated in charge-sensitive ADC's for which the 50 ns gate width is about half of the pulse width, so as to optimize the signal-to-noise ratio. Because of the variation in drift time, the S1-S2 trigger is unsuitable as an ADC gate since the resultant jitter would be greater than the gate width. Instead, the cathode timing signal from each of the eight planes is used to re-time the trigger, thus providing a jitter-free gate for each input to the ADC's (Iecroy 2249SG).

5. Event rejection by microprocessor

Fewer than one particle in ten is scattered in the polarimeter through a polar angle large enough to be useful, the others undergoing only small-angle multiple scattering which has an analyzing power of zero. To eliminate the overhead of transferring useless data along the Camac Branch, a small-angle test is performed by a microprocessor which resides in the same crate as the FPP Camac modules. Acting as an auxiliary crate controller, the microprocessor (a "Starburst", CES model 2180) reads the data from the TDC's and tests whether the event is "good" or "bad". For a "good" event the FPP data are collected in a buffer in the Starburst memory, then the Starburst issues a LAM and the MRS data acquisition computer reads this buffer via Camac along with the standard spectrometer data. For a "bad" event the Starburst causes a "fast Clear" signal to appear via an output register, resulting in a Clear of the modules and latches of the FPP and MRS (no LAM being raised). Further details concerning the programming of the Starburst are given in ref. [5].

A "good" event is one which has satisfied: (1) test for a

pulsar-generated event, or (2) a software prescaler test which is set to pass one of n events unconditionally, or (3) tests for scattering angle and collinearity, plus checksum tests on each plane. The scattering angle test is performed on the delay line time differences with a resolution of ± 4 mm corresponding to the anode wire spacing. The combination $x_1 - 2x_2 + x_4$ (where x_n is the bend-plane coordinate in wire chamber n , and similarly for the y -direction) is zero if no scattering occurred in the carbon, and is used as a test of scattering angle. If the sum of squares of deviations in the x and y directions is less than a specified amount the event is rejected as "bad". The checksum test is applied to each plane; it is the difference between the drift time as measured from the cathode time signal (corrected for propagation time along the bus line) and the measured average of times from the two ends of the delay line. Multiple-track events in which the signal at one end of the delay line is due to one track and that at the other end is due to another will fail the checksum test. The third test, a straight-line test of the x and y coordinates for chambers 2, 3 and 4, is intended to catch those multiple-track events in which the "false" track passed the checksum test; this can happen if the "false" track had a much shorter drift time than the "true" track, so that it was the first signal to reach both ends of the delay line.

The most common cause of an event being rejected is that the scattering angle is too small, for which the processing time (including TDC conversion time) is 460 μ s. The maximum time required to determine that an event is "good" is ~ 1100 μ s, which happens for only 10% of the events. This should be compared with the nearly 3 ms

spent by the acquisition computer to read and process it.

6. Data reduction

Details of data analysis vary somewhat according to the aims and running conditions of individual experiments; the broad strategy described below is common to all experiments run to date.

Analysis begins with "straight through" data, which are collected with no carbon scatterer in the polarimeter and a low dipole field to ensure full illumination of the focal plane with a continuum of particles. From such a run are extracted: (a) the relationship between position and delay line times, odd/even pulse heights for each plane, (b) the alignment of coordinates for each chamber to a common system (defined by the central wires of chambers D2 and D4, (c) the alignment of the VDC's relative to the polarimeter chambers D2 and D4. A special-purpose program does this analysis and outputs the results in the form of a file of coefficients which will be used as input by the main analysis program.

In detail, the calculations include:

(1) For each plane, a histogram of delay line time differences is accumulated, centroids of the peaks in this "picket fence" spectrum are computed, and coefficients yielding wire number as a quadratic function of time difference are determined. The quadratic terms are very small, with deviations from linear fits amounting at most to 1/3 wire separation in 110 wires.

(2) Relative gains and ADC offsets for the "odd" and "even" cathode pulse heights are obtained for each wire plane. The odd-even asymmetry is observed to fluctuate from one wire to the next (fig. 3a) because anode wires are not perfectly centered between

the cathode wires. (This geometric origin of the effect was confirmed by observation of wire spacings using a travelling microscope [ref. 4].) Very small errors produce an effect which can be a large fraction of the asymmetry due to the direction of drift, as shown in the figure. Centroids in odd-even asymmetry distributions are found and a gain factor calculated for each wire. Figure 3b shows the clear distinction between "left" and "right" drifts after these corrections are applied to the data for a plane.

(3) A distribution of delay line time sums is formed for each plane. From this a lookup table relating time sums and drift distances is formed.

The main analysis program uses this information to determine track position with good xy resolution at each of the four ppp chambers and the two focal plane chambers (VDC's). A checksum test is applied to the cathode time and the sum of delay line times of each ppp plane. The 12 planes permit a determination of x and y position and angle plus a straight-line test for particle motion before and after the carbon scatterer. It is then required that the distance of closest approach of these two trajectories be small, and that the scattering occur within the carbon. Polar and azimuthal scattering angles are computed for events which pass these tests. Finally, a cone test is applied to ensure that no false azimuthal asymmetries are introduced by finite detector sizes.

7. Performance

The position resolution of the polarimeter chambers was investigated using quastelastic protons from the $^{12}\text{C}(p,p')$ and $^{208}\text{Pb}(p,p')$

reactions to uniformly illuminate the full MRS focal plane. For these measurements the carbon slabs were removed. The straight-through protons generate distributions for $x_{234} = x_2 + x_4 - 2x_3$, and a similarly defined x_{124} which have a finite width, with contributions from the intrinsic drift process, from multiple scattering, and from geometric imperfections and misalignments of the large chambers (see fig. 4). The widths (FWHM) of these distributions for three incident proton energies are shown in table 2. For the x_{124} distributions we estimate a significant contribution from multiple scattering in the scintillator S1, which explains the increase in the widths as the proton energy decreases. The widths for x_{234} are nearly independent of proton energy, in agreement with multiple scattering estimates. From x_{234} we deduce an effective chamber resolution of 0.3 mm (FWHM) for each chamber plane which is an upper limit for the resolution of a single drift cell.

The alignment of focal plane VDC's and polarimeter chambers is critical to avoid instrumental asymmetries from incorrectly evaluated scattering angles. The difference between the x-angles for incident and outgoing straight-through protons, $\Delta\theta_x = \theta_x(\text{in}) - \theta_x(\text{out})$, is shown in fig. 5. The widths of the distributions in $\Delta\theta_x$ and $\Delta\theta_y$ are dominated by multiple scattering as can be seen from the strong energy dependence (see table 2). The widths in $\Delta\theta_x$ are slightly larger, presumably because chamber alignment in the dispersive (x) direction is more critical.

The thickness of the carbon scatterer is chosen to confine multiple scattering to small angles where nuclear scattering has a small analyzing power. The distribution of polar scattering angles

for events which have passed all the tests mentioned in the previous section are shown in fig. 6. The range of "useful" scattering angles is seen to be between 5° and 20° . The rise below $\theta = 5^\circ$ is caused by multiple scattering. (The sharp cut-off at 2° is due to a restriction of the analysis program.) The rapid falloff in the efficiency for $\theta > 20^\circ$ is caused by the finite detector size in the y-direction. It should be noted that outside the "useful" region the analyzing power is small (see also fig. 7).

The efficiency of scattering at low counting rates (< 50 kHz per wire plane) is indicated in table 3, for the specified carbon thicknesses and range of scattering angles. For the deuterons, steel absorber material is added after chamber 4 (for the energy cited this was 1.8 cm thick). In all cases the tests described in section 6 were applied to the data.

The efficiency of the detection system (wire chambers and electronics readout) is a marked function of singles rates. In contrast to the situation reported for the JANUS polarimeter at LAMPF [3] where delta rays from the carbon scatterer were the primary cause of reduced efficiency, we find that the losses are nearly the same in all chambers and seldom involve more than one plane at a time. In our case the background is largely due to electrons and soft photons created following thermalization and capture of neutrons in the walls and roof of the experimental hall. The efficiencies quoted in table 3 are for low rates in the chambers; these efficiencies drop with increasing singles rate, falling by a factor of two as chamber singles rates rise to 150 kHz. The fall-off is due to second hits occurring in one of the eight wire planes within the read out time, 230 ns on average.

Clearly, the degree of enrichment of data by event selection in the Starburst microprocessor depends on how tightly the windows are set on scattering angle and other criteria. For the typical case of a 1.5° limit on scattering in the carbon by 400 MeV protons, the enrichment factor is about 7.

The polarimeter analyzing power for protons was examined by using "polarization pumping" in which elastically scattered polarized protons were detected at an angle where the analyzing power for elastic scattering is large. For a spin zero target, the polarization is related to the beam polarization P_1 and the analyzing power A by

$$P = (P_1 + A)/(1 + P_1 * A).$$

For $P_1 > 0.7$ and $A > 0.8$ not only is the resultant polarization near 100%, but the uncertainty in it is much less than those of either the beam polarization or the analyzing power taken separately. After allowance for spin precession in the MRS dipole, the polarimeter analyzing powers measured by this technique for protons with average energies of 260 and 360 MeV, are presented in fig. 7. They are in good agreement with values found for other polarimeters of this type [6]. An estimate of possible instrumental asymmetry comes from the computed sideways component of polarization in cases where parity conservation guarantees that no such component can actually be present. The sideways component of polarization, P_x , deduced for $^{208}\text{Pb}(p,p)$ elastic scattering at $E_p = 290$ MeV [9] is shown in fig. 8 for several scattering angles. The results, when averaged over scattering angle, yield a sideways component, $\langle P_x \rangle = -0.003 \pm 0.012$, which is indicative of a very small instrumental asymmetry. The overall performance of the polarimeter can also be judged from

measurements of the polarization normal to the reaction plane, P , in the same reaction. Because of parity conservation in the strong interactions the results for P when $P_1 = 0$, shown in fig. 9b, can be directly compared to previous accurate measurements of the analyzing power, A_y , (fig. 9a) in this reaction [10]. Because of the slight difference in incident proton energy the P data are compared to predictions using a relativistic optical potential [ref. 11] obtained by fitting the A_y data. The equality, $P = A_y$, is obviously well fulfilled. Because of the large variation in the polarization P , and the wide range of singles counting rates in the chambers D1-D4, (up to 300 KHz), the comparison provides a stringent test of the polarimeter system.

At present the vector and tensor analyzing powers for deuterons are known only approximately, from thin-target measurements of inclusive scattering [7] at 200 and 400 MeV. Precise measurements using the polarized deuteron beam of Saturne II are planned.

8. Conclusions

We have built, tested, and used a high-efficiency focal plane polarimeter. Delay-line readout of drift chambers permits a resolution of 0.3 mm, at moderate hardware cost, in eight planes having a total area of 3.6 m^2 . A front-end microprocessor provides fast rejection of events where the scattering angle is too small, or where pileup has occurred. The polarimeter has been used successfully in a number of experiments at TRIUMF. These measurements have determined the spin rotation function Q in elastic proton scattering in ^{208}Pb , polarizations and spin-flip probabilities in inelastic proton scattering on ^{12}C and ^{24}Mg , and the deuteron polarization in

the p^+d^+ reaction [11].

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Table 1
Dimensions of the polarimeter components

Component	Quantity	Dimension
A) Mounting Cage:	inside volume x,y,z	110 cm x 82 cm x 90 cm
B) Drift Chambers D1-D4:	anode wire spacing	0.8128 cm
	active area x,y	89.4 cm (110 wires) x 48.8 cm (60 wires)
	separation of xy planes	0.97 cm
	separation of chambers	D1-D2 40 cm D2-D3 20 cm D3-D4 20 cm (protons); 14 cm (deuterons)
C) Trigger scintillators	active volume x,y,z	78 cm x 24 cm x 0.64 cm (S1) (52 cm + 52 cm) x 62 cm x 0.64 cm (S2).
	distance D1-S1	22 cm
	distance D4-S2	15 cm (protons)
D) Carbon scatterer:	area x,y	98 cm x 45 cm
	thickness	combination of 4.5 cm, 3x(3cm)

Table 2
Polarimeter performance for straight-through protons

Incident proton energy (MeV)	x_{234}^* FWHM (mm)	x_{124}^* FWHM (mm)	$\Delta\theta_x$ FWHM (mr)	$\Delta\theta_y$ FWHM (mr)	
maximum	minimum				
400	340	0.72	1.76	7.9	7.4
290	245	0.75	2.12	10.6	9.4
250	211	0.77	2.56	12.3	11.8

* polarimeter acceptance limits for quasielastic protons.

Table 3
Polarimeter efficiency

particle type	Average Energy (MeV)	Thickness of carbon (cm)	Range in polarangle	Efficiency %
Proton	360	10.5	5°-20°	4.0*
	260	7.5	5°-20°	2.6*
Deuteron	270	10.5	5°-20°	1.5

*Does not include trigger inefficiency, estimated to be 1% per gm/cm², due to reaction losses in the carbon.

Figure Captions

1. Schematic view of the TRIUMF MRS Focal Plane Polarimeter showing location of the FPP detectors in relation to the standard MRS focal plane detectors (VDC's).
2. The FPP support cage. Each element inside the cage is mounted on a "tray" which may be rolled into position on support rails.
3. Asymmetry $(O-E)/(O+E)$ in "odd" and "even" cathode pulse heights versus delay line time difference. Each group in time difference corresponds to one anode wire; for each anode wire the two groups of different asymmetry are due to different directions of drift. Figure 3a and 3b show the asymmetries before and after wire-by-wire software gain corrections, respectively.
4. Distribution in the "straight line test" variables $x_{234} = x_2 - 2x_3 + x_4$ (top) and $x_{124} = x_1 - 2x_2 + x_4$. The observed FWHM in x_{234} sets a limit to single-plane position resolution of 0.3 mm (FWHM).
5. Difference of the incident and outgoing particle directions with carbon scatterers removed. The width of distribution is dominated by multiple scattering in scintillator S1.
6. Distribution of polar scattering angles for protons with an average energy of 260 MeV. The events shown have passed all the tests discussed in the text.
7. Measured analyzing powers for protons as a function of polar scattering angle. The curve is the polynomial fit to previous data reported in ref. 6. The energies quoted are average energies in the carbon slabs.
8. Sideways polarization P_s observed after elastic scattering of unpolarized protons from 208Pb at $E_p = 290$ MeV.
9. Comparison of analyzing power (top) and polarization (bottom) for elastic proton scattering from 208Pb at 290 MeV with predictions of a relativistic optical model.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9