A HIGHLY EFFICIENT POLARIMETER FOR THE MEDIUM RESOLUTION
SPECTROMETER AT TRIUMF

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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 ± 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
effects include studies of depolarization or spin rotation in the
elastic and inelastic scattering of protons by nuclei, and spin
transfer to deuterons in the pppdr 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 improve-
ments 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
connected directly to 5,000 psi pressure circuit by the having a
with a minimum 100° angle of 6.00 mm. The angle wires are
at left. (2) E. After passage and cathode wires form drift cells
down to, very similar to the JAMS photomultiplier in this chamber
from a photomultiplier-per of a photocathode. The chamber
connects the drift to the readout to detect the cell number, rather
and a z photoionization of the readout to the drift
projection of the photomultiplier surface position

3. Detectors

another plane which span the vector multipliers (Figs. 2). Each element is monostated on
above detectors, and is bolted by the support frame. Over
separations (Figs. 2). In the detector section, chambers are only 1 cm
interclose with chambers and 4 following with successful 2 cm
order, with the carbon photoelectric measurement of the 1 cm
in the normal (normal) mode, chambers I am separated from carbon
spectrometers.

are inserted between it and the drift detector lower of the
perpendicularity of the potentialization is assumed by space bars which
space for two tanks of electronic space of number carbon stops.
acceptance to the photomultiplier was provided by additional to the
the direction (x), the drift is created by the drift field (y), and in the direction of
axis (z) present in the drift field (y), and in the direction of
summed in table 1. The components are chosen along the optic

4.

out of this function, but rather on a saddle-shaped mount, which is
large, final etch photoelectric and their photomultiplier are not
for spiral detectors (as for detector components (2))
(1) The etch photoelectric (1) for the cathode, and (2) a monostated
(1) Local components, (2) as many as four types of carbon detectors,
(3) Right components, (2) as many as four types of carbon detectors,
(4) Left components, (2) as many as four types of carbon detectors,
(5) Right components, (2) as many as four types of carbon detectors,
(6) Left components, (2) as many as four types of carbon detectors,
(7) Right components, (2) as many as four types of carbon detectors,
(8) Left components, (2) as many as four types of carbon detectors,
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(18) Left components, (2) as many as four types of carbon detectors,
(19) Right components, (2) as many as four types of carbon detectors,
(20) Left components, (2) as many as four types of carbon detectors.

4. Techniques

were calculated using a computer, which can be
of various components there is a difference at least.
the solution was to
in direction from the vectorial could have made selecting the chambers
both detectors transformed to the particle momentum. In the acceptance, and by a separation angle in the carbon of ap to 0°.

and graphs of the photomultiplier components (carbon photospectrums) were
to correspond to a component range, as shown in Figs. 1 to Figs. 10.
the dimensions

the advantage of the position of the periphery and for positioning measurement; in a reception
was a broad momentum acceptance, and it was deemed important that
the vertical of carbon components and photomultiplier components is used at 0°.

above vertices (as shown in Figs. 2 to Figs. 10). Usually the focal plane is located just
local plane detection (vertical) drift chambers and detector scintillator.
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% Isopropanol 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 automatically. 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
only 10% of the covariance. This should be compared with the matrix \( \mathbf{Q} \) for a good fit, since this is \( 100\% \) of the covariance. The matrix \( \mathbf{Q} \) is obtained from the covariance, and its elements are given by:

\[
q_{ij} = \frac{1}{N} \sum_{k=1}^{N} (x_{ik} - \bar{x}_i)(x_{jk} - \bar{x}_j)
\]

where \( N \) is the number of observations, \( x_{ik} \) and \( x_{jk} \) are the values of the variables \( i \) and \( j \) at observation \( k \), and \( \bar{x}_i \) and \( \bar{x}_j \) are the means of the variables.

The most common cause of an upward bias is that the correlation is underestimated due to the presence of outliers. Outliers can significantly affect the correlation coefficient, leading to an underestimate of the true correlation.

The least squares method, which is based on minimizing the sum of the squared differences between the observed and predicted values, is used to estimate the parameters of the linear regression model. The least squares method is a special case of the more general method of moments, which is used to estimate the parameters of a probability distribution.

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5. When a \% of the observed variance in the dependent variable is explained by the independent variables, the model is considered to be adequate. A good fit is obtained when the residual sum of squares is small, and the coefficient of determination (R^2) is close to 1.

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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 FPP 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 FPP 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 quasielastic protons from the $^{12}$C(p,p') and $^{208}$Pb(p,p')
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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 $P_\perp$ and the analyzing power $A$ by

$$P = \frac{(P_\perp + A)}{(1 + P_\perp^2 A)}.$$  

For $P_\perp > 0.7$ 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, $P_s$, 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, $<P_s> = -0.003\pm 0.012$, 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 $P_\perp = 0$, 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 DI-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 $^{208}\text{Pb}$, polarizations and spin-flip probabilities in inelastic proton scattering on $^{12}\text{C}$ and $^{24}\text{Mg}$, and the deuteron polarization in
<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Preparation of the Parameter Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>H_2O</td>
<td>0.7%</td>
<td></td>
</tr>
<tr>
<td>0.1N</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>0.92 x 10</td>
<td>110 cm</td>
<td></td>
</tr>
<tr>
<td>0.98 x 12</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>0.06 x 12</td>
<td>110 cm</td>
<td></td>
</tr>
</tbody>
</table>

Acknowledgments

The authors extend their appreciation to Dr. Johnson College for the use of their equipment. The results for the NIST detectors have been published elsewhere.

References

Table 3
Polarimeter efficiency

<table>
<thead>
<tr>
<th>particle type</th>
<th>Average Energy (MeV)</th>
<th>Thickness of carbon (cm)</th>
<th>Range in polarangle</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>360</td>
<td>10.5</td>
<td>5°-20°</td>
<td>4.0*</td>
</tr>
<tr>
<td></td>
<td>260</td>
<td>7.5</td>
<td>5°-20°</td>
<td>2.6*</td>
</tr>
<tr>
<td>Deuterion</td>
<td>270</td>
<td>10.5</td>
<td>5°-20°</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*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 FFP detectors in relation to the standard MRS focal plane detectors (VDC's).
2. The FFP support cage. Each element inside the cage is mounted on a "tray" which may be rolled into position on support rails.
3. Asymmetry (0-EF)/(0+EF) 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 \( x_{123} = x_1 - 2x_2 + x_3 \). 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 Si.
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 \( P_x \) observed after elastic scattering of unpolarized protons from \(^{208}\text{Pb} \) at \( E_p = 290 \text{ MeV} \).
9. Comparison of analyzing power (top) and polarization (bottom) for elastic proton scattering from \(^{208}\text{Pb} \) at 290 MeV with predictions of a relativistic optical model.