A MEASUREMENT OF THE
ANALYSING POWER OF THE
\( pn \rightarrow pp(1S_0)\pi^- \) REACTION.

By
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B.A., Oxford University, 1986

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Department of Physics

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
June 1988
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Department of PHYSICS

The University of British Columbia
Vancouver, Canada

Date JUNE 15, 1988.
Abstract

A measurement of the analysing power of the $\bar{p}n \rightarrow pp(1S_0)\pi^-$ reaction, at an incident proton energy of 400 MeV, has been conducted at TRIUMF for pion centre-of-mass angles $56^\circ < \theta^*_{\pi} < 86^\circ$. The detection of pions, using a pion magnetic spectrometer, and the detection of the two protons, using arrays of NaI bars and thin plastic scintillators, are discussed with respect to the maximisation of an event yield where the two protons are in a relative $^1S_0$ angular momentum state. The off-line event definition and the tests employed in the examination of the event set for background and accidental events are also presented in conjunction with the methods employed in the reduction of P-wave contamination. The predictions of a Monte Carlo simulation of this reaction for both S- and P-wave events are compared to the experimental quantities to discover the ratio of the yields for the two partial-waves. A partial-wave analysis\(^1\) has determined the reaction amplitude set for this reaction to a two-fold ambiguity. The results of this experiment show that the analysing power varies dramatically from approximately $-0.85$ at $\theta^*_{\pi} \approx 63^\circ$ to $+0.64$ at $\theta^*_{\pi} \approx 83^\circ$. This variation is dissimilar to the form of the analysing power for one solution set and is similar to that for the other.

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By the way, I apologise, in advance, for the flagrant use of any blatant pleonasm, pedantry or catachrestic passages.
Dedicated to the Memory
of
Florence Ponting
1885-1987
Chapter I

Some Background to this Experiment

The meson exchange theory of nuclear forces, as proposed by Yukawa in 1935 [1] describes the nucleon-nucleon interaction in terms of the emission of a quantum, by one nucleon, and its immediate absorption on another. The range of the nuclear force implies that the mass of the quantum is $m \approx 300m_e$, which is in good agreement with the mass of the pi-meson or pion. It is now generally accepted that this exchange of virtual pions, "$NN \leftrightarrow NN\pi$", is a major source of the nucleon-nucleon interaction. In this context, therefore, the study of the emission from, or the absorption on two nucleons, of real "on-shell" pions is of the utmost importance in the investigation of the nucleon-nucleon interaction especially in the short-range, high momentum region of the inter-nucleonic wavefunction [2].

I.1 The $NN \rightarrow NN\pi$ Reactions

There are seven independent reactions of single pion production from (and subsequently, by time reversal symmetry, pion absorption on) nucleon pairs. According to the formalism of Gell-Mann and Watson [3] the cross sections of these reactions may be reduced to four independent cross sections, $\sigma_{if}$, which represent transitions between the initial and final isospin states of the two nucleons. These reactions and cross sections are given in table I [4,5].

All but one of the cross sections, $\sigma_{if}$, are dominated by the delta-nucleonic resonance, which couples to both a nucleon and a pion: $\pi NN \leftrightarrow \Delta N \leftrightarrow NN$. The fourth process (of cross section $\sigma_{01}$) does not proceed via the $\Delta N$ intermediate...
Table I: $NN \rightarrow NN\pi$ Reactions and their Corresponding Cross Sections. $\sigma_{10} = \sigma_{10}(d) + \sigma_{10}(np)$.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma_{10}(d)$</th>
<th>$\sigma_{10}(np) + \sigma_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow d\pi^+$</td>
<td>$\sigma_{10}(d)$</td>
<td>$\sigma_{10}(np) + \sigma_{11}$</td>
</tr>
<tr>
<td>$pp \rightarrow np\pi^+$</td>
<td>$\sigma_{11}$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow pp\pi^0$</td>
<td>$\sigma_{11}$</td>
<td></td>
</tr>
<tr>
<td>$np \rightarrow d\pi^0$</td>
<td>$\frac{1}{2}\sigma_{10}(d)$</td>
<td></td>
</tr>
<tr>
<td>$np \rightarrow np\pi^0$</td>
<td>$\frac{1}{2}[\sigma_{10}(np) + \sigma_{01}]$</td>
<td></td>
</tr>
<tr>
<td>$np \rightarrow nn\pi^+$</td>
<td>$\frac{1}{2}[\sigma_{11} + \sigma_{01}]$</td>
<td></td>
</tr>
<tr>
<td>$np \rightarrow pp\pi^-$</td>
<td>$\frac{1}{2}[\sigma_{11} + \sigma_{01}]$</td>
<td></td>
</tr>
</tbody>
</table>

Table II: The Allowed Quantum Numbers for Pion Absorption: $NN\pi \rightarrow NN$

<table>
<thead>
<tr>
<th>$\sigma_{if}$</th>
<th>Absorbing $NN$ Spin</th>
<th>$L_{(\pi-2N)}$</th>
<th>$J^\pi$</th>
<th>$L_{\Delta N}$</th>
<th>$L_{NN}^\prime$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{10}$</td>
<td>1</td>
<td>0</td>
<td>1$^-$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>0$^+$</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2$^+$</td>
<td>0,2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1$^-$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2$^-$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_{11}$</td>
<td>0</td>
<td>0</td>
<td>0$^-$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2$^-$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_{01}$</td>
<td>0</td>
<td>1</td>
<td>1$^+$</td>
<td>No $\Delta$</td>
<td>0,2</td>
</tr>
</tbody>
</table>

state due to isospin non-conservation.

For small incident particle kinetic energies ($\lesssim 600$ MeV), each $\pi NN(\leftrightarrow \Delta N) \leftrightarrow NN$ reaction may be meaningfully analysed in terms of transitions between angular momentum states. Table II [2] gives the allowed quantum numbers for the various $\sigma_{if}$ for pion absorption, where $L_{(\pi-2N)}, L_{\Delta N}$ and $L_{NN}^\prime$ are the relative orbital angular momenta in the pion-two-nucleon, delta-nucleon and nucleon-nucleon systems, and $J^\pi$ is the total angular momentum and parity.
I.2 The $pn \leftrightarrow pp(^1S_0)\pi^-$ Reaction

The two-body process $\pi^+d \leftrightarrow pp$, has been the process most studied over the past decade (see, for example, reference [6]). It has the advantage over the other modes that it leads to well-defined quantum numbers that may be determined experimentally and utilised theoretically. It is generally thought that this process is dominated by the $L_{\Delta N} = 0$ channel and that all other $L_{\Delta N} \geq 1$ channels are strongly suppressed.

The investigation of pion absorption on a ($T = 1, {\bar{S}S}$) nucleon pair provides complementary information to that of the $\pi^+d \leftrightarrow pp$ process, as it allows the isospin zero ($\sigma_0i$) channel to be studied for which an intermediate state involving a delta resonance is disallowed. The ratio of the cross sections of these two reactions,

$$R \equiv \frac{d\sigma(\pi^+, pp)}{d\sigma(\pi^-, pn)}$$

has been measured at various energies and angles [7,8,9,10] and has been shown to be approximately $R \simeq 10 - 20$ from zero to 165 MeV. Given the assumption that the strengths of these transitions are determined by isospin coupling alone this ratio is found to be $R = 2$ [2]. Hence the experimental data indicate that a strong isospin dependence exists in pion absorption processes. This dependence has been investigated in models concerned with rescattering through delta or nucleon intermediate states [11,12,13], and in models using $(\pi^-, \rho-, \sigma-, \omega-)$ meson exchange theory [13]. As yet, however, no completely satisfactory model has produced values of $R$ in agreement with those of experiment.

The angular distribution of $(\pi^-, pn)$ has been shown [9] to be asymmetric about $\theta^*_p = 90^\circ$ in contrast to the symmetric distribution for the $(\pi^+, pp)$ reaction\(^1\). This asymmetry has been explained [14] as being due to the

\(^1\)The $(\pi^+, pp)$ angular distribution is necessarily symmetric about $90^\circ$ as a direct consequence that it may only proceed via the isospin 1 ($L_{(\pi-2N)} = 0$) channel
interference between odd and even partial waves, which indicates that both the isospin 0 and isospin 1 amplitudes contribute to the reaction (see table II). For odd partial waves delta formation cannot occur and it is suggested that the intermediate state may involve an $N^*(P_{11})$ isobar [11]. For even partial waves, it is suggested that $L_{\Delta N} \neq 0$, delta-resonance intermediate states contribute significantly [12]. Further measurements of the $\pi^-pp \leftrightarrow pn$ reaction, therefore, provide important information concerning isospin dependences, reaction channels and resonances unavailable via the $(\pi^+, pp)$ reaction.

I.3 Partial Wave Analyses of the $pn \leftrightarrow pp(1S_0)\pi^-$ Reaction.

A partial wave analysis of the angular distribution of reference [9] has recently been performed [15] which involved the use of the phase shift and mixing parameters of $pn$ elastic-scattering and invoking Watson's theorem [16,17]. This analysis determines the set of amplitudes for $pp(1S_0)\pi^- \rightarrow pn$, ($L_{(\pi-2N)} \leq 1$) to a two-fold ambiguity. The two solutions for the amplitude set share the same values of the differential cross section and the same value of the s-wave ($L_{(\pi-2N)} = 0$) amplitude. The two solutions differ in the ratio of the amplitudes for the two p-wave ($L_{(\pi-2N)} = 1$) processes ($L'_{NN} = 0$ and $L'_{NN} = 2$) and in the predicted angular dependence of the polarisations of the outgoing nucleons. These two solutions are shown in figure 1 where two different databases of phase shift and mixing angles (of Bugg [18] and of Arndt [19]) have been used.

There are several methods of distinguishing between these two types of

---

Watson's theorem arises from the hypothesis of the unitarity of the $S$-matrix: the probability amplitude for final state $j$, if the initial state of the process is $i$, is $S_{ji}$, which is also an element of the $S$-matrix; hence the unitarity condition is

$$\sum_j S^*_{ji}S_{ji} = \delta_{ii}$$
Figure 1: The Analysing Power of the $pn \rightarrow pp(1S_0)\pi^-$ Reaction for the Partial Wave Analysis Solutions of Reference [15]. The two solutions are found using the different $pn$ elastic scattering databases of Bugg [18] and of Arndt [19].
solutions. One method is the measurement of the analysing power of $\vec{n}p \rightarrow pp\pi^-$, where the two-proton state is kinematically constrained to being a $^1S_0$ state. This has the disadvantages of requiring a large amount of beam time and the difficulty of folding in the neutron energy spectrum into the event kinematics. Another is the coincident measurement of two nucleons from pion absorption on $^3$He (see, for example, reference [20]) where the polarisation of one of the nucleons is also measured. This method has the advantage that no kinematical constraints are needed to require that the absorbing $T = 1$ nucleon pair are in a relative S-state, yet has the disadvantage that, again, a large amount of beam time is required for the measurement. One further method, that being the measurement of the analysing power of $\vec{p}n \rightarrow pp\pi^-$ (again where the protons are constrained to a $^1S_0$ state), is described in the remaining chapters of this thesis.

There are several aspects of figure 1 that have a direct bearing on the experimental techniques of distinguishing between the two solutions. Firstly, it can be seen that a measurement of the analysing power over a wide angular range, with reasonable statistics, can distinguish between the two solutions. This experimental distinction is facilitated by the rapid variation of solution 1 over a small angular range, and the large difference in magnitude between the solutions. Secondly, it should not be unexpected, especially for solution 2, if data points do not completely agree with the theoretical expectations since the form of the theoretical curve is particularly sensitive to the $^3S_1 - ^3D_1$ mixing angle, $\epsilon$. The choices of the angles, $\theta^*_\odot$, ($55^\circ < \theta^*_\odot < 85^\circ$), at which the analysing power was to be measured were reached as a result of these considerations.

As stated earlier, the major difference between the two types of solutions is the relative fraction of the $^3S_1$ to the $^3D_1$ state for the outgoing $pn$ nucleons. Approximate values for the probabilities of the three allowed states ($L(\pi-2N) \leq 1$) are given in table III, together with the same probabilities as calculated using a
Table III: Approximate Probabilities for the Allowed Angular Momentum States, for the $pp(^1S_0)\pi^- \rightarrow pn$ Reaction. Solutions 1 and 2 are derived using the phase shifts and mixing angles of reference [18]. The Quark Model prediction is for $r_0 = 0.85$ fm (see Appendix A).

<table>
<thead>
<tr>
<th></th>
<th>Solution 1</th>
<th>Solution 2</th>
<th>Quark Model Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3S_1$</td>
<td>0.58</td>
<td>0.10</td>
<td>0.81</td>
</tr>
<tr>
<td>$^3D_1$</td>
<td>0.35</td>
<td>0.83</td>
<td>0.04</td>
</tr>
<tr>
<td>$^3P_0$</td>
<td>0.07</td>
<td>0.07</td>
<td>0.15</td>
</tr>
</tbody>
</table>

From these probabilities, it can be seen that solution 1 and the quark model are in qualitative agreement, in that both predict large values for the $^3S_1$ probability. An experimental selection of solution 2 over solution 1 would therefore rule out the quark model for this reaction.
Chapter II

The Experiment

This experiment was performed at the Tri-University Meson Facility (TRIUMF) in July and in November, 1987, after a test run of the \(^2\)He arm in February of the same year. The TRIUMF BL1B proton channel was used, providing a 400 MeV polarised beam at 0.1 nA. This was a two-arm experiment, using the TRIUMF quadrupole- quadrupole-dipole (QQD) spectrometer as the pion detector and planes of plastic scintillators and NaI bars (the \(^2\)He Arm') for the detection of the two protons (see figure 2). The kinematics of this reaction, and the cross sections for S- and P-wave protons in the final state, were investigated using a Monte Carlo program, which is discussed in Appendix B.

II.1 The 1B Beamline

The 1B beamline is commonly used during low intensity and polarised beam operation of the cyclotron. The beam derives from beamline 1 and is deflected by two 43° magnets into the 1B experimental area. At 400 MeV, the maximum beam current is \(\simeq 10\) nA which is two orders of magnitude larger than the current used for this experiment, which was limited by the tolerance of the NaI bars to pile-up of elastically scattered protons. This beam was stripped from the circulating cyclotron current by a 0.001" carbon whisker. Given the small ratio of 1B current to cyclotron current we were prone to significant increases in the relative beam background for slight changes in the cyclotron radio-frequency, and this was
Figure 2: A Schematic of the Experimental Configuration
monitored for the duration of the experiment.

II.1.1 The 1B Polarimeter

The polarisation of the beam was measured using an in-beam polarimeter situated between the 43° bending magnets. This polarimeter is identical in design to the TRIUMF 4B polarimeter described in reference [23]. The polarisation measurement relies on the left-right asymmetry of $p - p$ elastic scattering from a thin CH$_2$ target at 17° in the lab. Each arm of the two arm polarimeter consists of two forward scintillators at 17° to the beam on one side, and, on the other, a recoil detector whose acceptance is sufficiently large to detect the recoil protons for a large range of beam energies.

If the forward scintillators are denoted by $LB,LF$ and $RB,RF$, and the recoil detectors are $LR$ and $RR$, for the left and right arms, then a left (or right) $p - p$ elastic ‘event’ is $LB.LF.LR$ (or $RB.RF.RR$). Accidental counts, defined by the coincidence of the forward scintillators with a beam-burst-delayed signal from the recoil scintillator, are subtracted to give count rates ‘LEFT’ and ‘RIGHT’ in the two arms. Given that the analysing power of the CH$_2$ target at 400 MeV is 0.43, the polarisation of the beam is given by

$$P_{beam} = \frac{1}{0.43} \frac{(LEFT - RIGHT)}{(LEFT + RIGHT)}$$

Throughout the experiment the spin of the beam particles was cycled through the spin ‘UP’, ‘DOWN’ and ‘OFF’ nominal settings. Logic signals corresponding to true or accidental coincidences in either of the two polarimeter arms were gated according to these nominal spin settings and were recorded by HEX scalers which were read onto magnetic tape during, and after, each run. The
cumulative totals of LEFT and of RIGHT events for all runs were then found and
the polarisation of the beam $P_{\text{beam}}$ was calculated for the three spin settings.
Moreover, the sum of LEFT and RIGHT counts for the spin settings gave a
measure of the beam charge for a particular spin, and was used in the final
calculations of analysing powers. The 1B Secondary Emission Monitor (SEM)
was not used for this purpose as its operation at low beam intensities is unreliable.

II.2 The $^2\text{He}$ Arm

The most important design factor that was considered during the planning of this
experiment, was the choice of phase-space covered by the particle detectors. The
final choice was made to optimise the ratio of S-wave cross-section to the
cross-section of all other partial-waves (predominantly P-wave) so as to immitate
the time-reversed reaction of pion absorption upon the $T = 1$ ($^1S_0$) nucleon pair of
$^3\text{He}$. It was realised that this may be achieved by limiting the magnitude of the
difference of the momenta of the two protons. This limit was imposed by the use
of a small solid-angle proton detector (limiting the opening angle of the protons),
and by limiting the kinetic energies of each of the protons by the requirement that
the particles be stopped within the detector.

The detector that provided such specifications, and that was immediately
available was a segmented, seven-bar, position-sensitive, sodium iodide (NaI(Tl))
scintillating detector (the specifications of which may be found in Table IV). This
detector differs in many respects from its prototype [24] in terms of its dimensions
and physical characteristics. This present detector has been used in the detection
of low energy gamma rays and muons [25] but this was the first time in which
they have been used for the detection of higher energy protons and deuterons.
Table IV: The Specifications of the NaI Bars

<table>
<thead>
<tr>
<th></th>
<th>NaI Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Bars</td>
<td>Seven</td>
</tr>
<tr>
<td>Length</td>
<td>35.6 cm</td>
</tr>
<tr>
<td>Width</td>
<td>4.42 cm</td>
</tr>
<tr>
<td>Thickness</td>
<td>5.08 cm</td>
</tr>
<tr>
<td>Stopping Energies :</td>
<td></td>
</tr>
<tr>
<td>Protons</td>
<td>115 MeV</td>
</tr>
<tr>
<td>Deuterons</td>
<td>155 MeV</td>
</tr>
<tr>
<td>Resolutions :</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>± 4 MeV</td>
</tr>
<tr>
<td>for 400 MeV protons</td>
<td>± 1.4 cm</td>
</tr>
</tbody>
</table>

The position of the NaI array with respect to the two planes of plastic scintillators is shown in figure 3.

The NaI bars were placed approximately 1.20 m from the target so that they subtended angles between 4° and 21° to the beam direction (z-axis) at the target. The array was aligned parallel to the vertical (y-) axis providing discrete positional information along the horizontal (x-) axis, dependent solely on which of the bars fired. Vertical position information and the energy deposition of each particle were deduced from the integrated pulse heights from photo-multiplier tubes at the ends of the bars, and from the knowledge that a significant attenuation of the light signal occurs along each bar.

II.2.1 The Calibration of the NaI Bars

The calibration of the NaI bars, relied on the measurement of the integrated pulse-heights from the photo-multiplier tubes at each end of the bars. These measurements were given by the number of channels above pedestal of the analogue-to-digital converters (ADCs) for each tube. It was noted on-line that the widths of the pedestals were unexpectedly large due to an oscillatory background.
Figure 3: A Schematic of the $^2$He Arm
signal whose amplitude was significant in comparison with the signal amplitude. This background signal was observed, using an oscilloscope, to consist of the fundamental and first two harmonics of a 60 Hz waveform (60, 120 and 180 Hz), and was thought to be due to ground-loops in the mains power-supply circuits in the experimental area. Various possible sources of this background ‘hum’ were investigated on-line yet this search was ultimately unsuccessful.

It was felt to be important to reduce the widths of these pedestals since the widths correspond directly to uncertainties in energy and position. A method was found off-line (see Appendix C), which resulted in the reduction in the FWHM of the ADC pedestals (and hence in the reduction of the uncertainty in the energy and position calibration) by between 25% and 50%. The resulting energy and position resolutions of the bars (for proton elastics) were approximately 4 MeV and 1.5 cm, respectively.

For this experiment, it was assumed that the integrated pulse height (ADC channels above pedestal) varied exponentially with distance, as measured from each photo-multiplier tube [26]. Supposing that the attenuation coefficient for a bar $i$ is $\alpha^i$, and that a particle stops at a distance $x$ (measured from the top of the bar), depositing energy $E$, then one can hypothesise that the integrated pulse-height from the uppermost tube is,

$$\Delta_u^i = G_u^i E \exp \left( -\frac{\alpha^i x}{L} \right)$$

and that similarly for the lowermost tube,

$$\Delta_d^i = G_d^i E \exp \left( -\frac{\alpha^i (L - x)}{L} \right)$$

where $G_u^i, G_d^i$ are the gains of the tubes, and $L$ is the length of each bar. From
these equations one can calculate the independent parameters, $E$ and $x$:

$$\frac{x}{L} = \frac{1}{2\alpha^i} \left( \alpha^i + \log_e \left( \frac{G^i_u \Delta^i_u}{G^i_d \Delta^i_d} \right) \right)$$  \hspace{1cm} (5)$$

$$E = \sqrt{\exp(\alpha^i) \frac{\Delta^i_u \Delta^i_d}{G^i_u G^i_d}}$$  \hspace{1cm} (6)$$

To obtain the calibration constants $G^i_u, G^i_d, \alpha^i (i=1,7)$ one must have at least two calibration points each in position and in energy. Initially it was thought that both elastically scattered protons and deuterons emanating from $pp \rightarrow d\pi^+$ could be used for such a purpose. Elastically scattered protons were perceived as being of use, due to their high count rate and ease of identification, and would provide a low energy calibration point (400 MeV protons deposit 37 MeV in 5.08 cm of NaI). Deuterons from $pp \rightarrow d\pi^+$ would be of use due to a relatively clean $\pi^+$ trigger from the pion spectrometer, and would provide a high energy calibration point (the maximum energy deposited by deuterons in 5.08 cm of NaI is 155 MeV).

However, it was found that $pp \rightarrow d\pi^+$ deuterons were of no use in providing calibration constants for $\pi^-$ final states, since a change in the polarity of the pion spectrometer — from detecting $\pi^+$ to $\pi^-$ — altered the gains in the NaI bars, due to significant fringe fields from the spectrometer dipole magnet and insufficient magnetic shielding around the NaI tubes. Thus $pp \rightarrow d\pi^+$ could provide a calibration for $\pi^+$ reactions but not for $\pi^-$ reactions such as $pn \rightarrow pp\pi^-$.  

The calibration coefficients were obtained using elastically scattered protons which passed through the NaI bars and were sampled by two narrow (2.54 $\times$ 0.318 $\times$ 50 cm) scintillators equidistant from the reaction plane at $x = x_1, x_2$. These “proton elastics” originated from any of the $pp \rightarrow pp$, $pn \rightarrow pn$ or $pd \rightarrow pd$ reactions. For any bar, the maximum spread of energies deposited in the bar by protons originating from these reactions was approximately $\pm 0.9$ MeV.
This method provided only two low energy calibration points, these being the energy deposited by these elastically scattered protons and the zero ADC pulse height (pedestal). From equations (3) and (4)

\[
\alpha^i = \frac{L}{\Delta x} \log_e \left( \frac{\Delta^i_u(x_1)}{\Delta^i_u(x_2)} \right), \quad \alpha^i = \frac{L}{\Delta x} \log_e \left( \frac{\Delta^i_d(x_2)}{\Delta^i_d(x_1)} \right)
\]

and,

\[
G^i_u = \frac{\Delta^i_u(x_{1,2}) \exp(\alpha^i x_{1,2}/L)}{E_{el}}, \quad G^i_d = \frac{\Delta^i_d(x_{1,2}) \exp(\alpha^i (L - x_{1,2})/L)}{E_{el}}
\]

where \(E_{el}\) is the energy deposited by an elastically scattered proton, and which is a function of angle.

The gains \(G^i_{u,d}\) were found to vary not only for different polarities of the pion spectrometer but also for different spectrometer angles so that the twenty-one calibration coefficients were calculated from proton elastic scattering data for every configuration, and indeed for every run. Table V shows these coefficients for two spectrometer configurations. The errors in determining \(\alpha^i\) and \(G^i_{u,d}\) were approximately 6% and 3%. It should be noted that the greatest change in gains occurred for those bars that were closest to the spectrometer magnets (i=7,6,5...).

After the calibration of each run, it was noted that the maximum energy, as deduced from the calibration, deposited in the bars by deuterons, was larger than its maximum possible value by approximately 30%, and that, for the \(pn \rightarrow pp\pi^-\) reaction the energy balance between initial and final states differed from zero by approximately 20 MeV. This could not be explained as being due to the inaccuracy of calculating, from the calibration, energies far above the energies of the two calibration points used. This overestimation in the energy scale implies a non-linearity in the integrated pulse height from each bar with respect to the amount of light produced in the bar. This effect could be explained as being due
Table V: Gains and Attenuation Coefficients for Two Different QD Configurations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>α'</th>
<th>G'_{u}</th>
<th>G'_{d}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>2.31</td>
<td>6.54</td>
<td>5.22</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2.26</td>
<td>6.50</td>
<td>6.21</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2.64</td>
<td>6.79</td>
<td>7.01</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>2.05</td>
<td>4.69</td>
<td>5.83</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>2.21</td>
<td>5.49</td>
<td>5.91</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>2.33</td>
<td>5.88</td>
<td>6.72</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>2.55</td>
<td>7.90</td>
<td>6.92</td>
</tr>
</tbody>
</table>

QD: Positive Polarity, \( \theta_{\pi} = 35.3^\circ \)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>α'</th>
<th>G'_{u}</th>
<th>G'_{d}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>2.44</td>
<td>6.83</td>
<td>6.23</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2.37</td>
<td>6.71</td>
<td>7.11</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2.60</td>
<td>7.33</td>
<td>7.16</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>2.06</td>
<td>5.59</td>
<td>5.98</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>2.23</td>
<td>6.86</td>
<td>5.48</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>2.42</td>
<td>8.63</td>
<td>6.07</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>2.59</td>
<td>9.37</td>
<td>5.79</td>
</tr>
</tbody>
</table>

QD: Negative Polarity, \( \theta_{\pi} = 43.5^\circ \)
to a non-linearity in the amount of light produced in the scintillator per unit energy deposited, or as being due to a non-linearity in the photo-multiplication process. Given that the former process has not been reported\footnote{Whereas plastic scintillators have been shown to be non-linear at low proton energies \cite{27}, NaI(Tl) has been shown to be linear for proton energies greater than 1 MeV \cite{28,29}}, the latter seems the more likely, but has not been proven.

This observation was used to provide a third, higher-energy, calibration point, this being the maximum possible energy that could be deposited in the NaI bars by deuterons. The calibration was then treated as being a quadratic in energy where the energy deposited in each bar is given by

$$E' = E(1 - E/b)$$

where \(E\) is given by equation (6) and \(b\) is a constant of order 1000. This had the desired results of reducing the calibration energy of the deuterons to its expected range, and of balancing the initial and final state energies for the \(pn \rightarrow pp\pi^-\) reaction.

The NaI bar ADCs were gated in three different ways. The first 'NORMAL' gates were set at 550 ns wide, and these ADCs were the ones used in the determination of energies and positions. The 'EARLY' gates were 20 ns wide and were gated such that the gate terminated at the commencement of the 'NORMAL' gate. The 'LATE' gates started at the end of the 'NORMAL' gates and were 30 ns wide. These 'EARLY' and 'LATE' gated ADC values were used to distinguish between valid events and those events for which pile-up had occurred in the bars. An 'EARLY' or 'LATE' gated ADC value above pedestal would indicate pile-up due either to neutrons or to protons that had, for some reason, evaded detection by the pile-up gates. All the signals from the NaI photo-tubes were passed.
through a clipping-box which reduced the pulse-height of the signals in the tails.

II.2.2 The $\Delta E$ and Veto Scintillators

The hardware trigger for the $^2$He arm was provided by two planes of $\frac{1}{8}$" plastic scintillators, one plane on the upstream side, and one plane on the downstream side of the NaI bars. Each plane was segmented four-ways in a chequered pattern, so as to reduce the count-rate in any single base. Each upstream ($\Delta E$) scintillator, in the hardware trigger, was put into anti-coincidence with its corresponding downstream (VETO) scintillator to provide triggers on particles stopping in the NaI bars. Since we were attempting to trigger on two protons, the hardware trigger requirement was for either one of $\Delta E_i, VETO_i (i = 1, 4)$ with the $\Delta E$ threshold at a high setting (corresponding to two protons passing through a single $\Delta E$), or for two of $\Delta E_i, VETO_i (i = 1, 4)$ with each $\Delta E$ threshold at lower settings (corresponding to two protons passing through separate $\Delta E$ counters). The low $\Delta E$ thresholds were set above the mean signal from $(p, p)$ elastics, to discriminate against the majority of these particles, save those in the tail of the energy-loss spectrum.

As with the calibration of the NaI bars, the calibration of the $\Delta E$ ADCs also used passing elastically scattered protons. Since the energy-loss of these particles in the $\Delta E$ scintillators is comparable with the maximum energy transfer to an electron at 400 MeV [30], the energy loss spectrum corresponds neither to a Gaussian, nor to a Landau, but instead to a Vavilov distribution. Knowing the ADC channel number corresponding to the most probable energy-loss, the channel number corresponding to the mean energy-loss was calculated, using the form of this distribution [30]. Thus, the $\Delta E$ ADCs were calibrated in energy using the
pedestal and the mean energy-loss channels as calibration points. For $pn \rightarrow p\pi^-$ protons over the energy range of interest in this experiment (40 to 120 MeV), the distribution is Gaussian and the mean energy-loss was taken as the value of the most probable energy-loss.

Pulses from each $\Delta E$ scintillator were fed into pile-up gates (PUGs) gated for 550 ns after the end of the first signal pulse, which is the width of the NaI 'NORMAL' gates. A signal during this time period would indicate that particles, dissociated with the particles that caused the original trigger, had impinged upon the $^2$He detection system. Four bits, corresponding to the four $\Delta E$ PUGs were set in a C212 pattern unit, according to whether the tests for these multiple hits (or 'pile-up') were passed, and were written to tape as part of the event word.

II.3 The Pion Spectrometer

The detector of the emitted pion was the quadrupole-quadrupole- dipole (QQD) spectrometer [31]. The design and operation of the QQD, and the techniques involved in the analysis of QQD data, have been extensively reviewed elsewhere [32,33,34,35], and it is our intention here to describe only those details of the spectrometer which are particularly pertinent to this experiment, and to refer the interested reader (if there be such a person) to the aforementioned references.

The QQD is a low-energy pion spectrometer for energies $\leq 100$ MeV. It was originally designed to consist of a dipole (BT), which spatially separates pions according to their momenta, and two quadrupoles, one of which focusses in the horizontal direction (QT1), and the other (QT2) in the vertical direction. However, as is present custom, the spectrometer was reduced to a mere QD by the removal of QT1. Even though this quad increases the effective solid-angle of the
Table VI: Specifications of the QQD Spectrometer

<table>
<thead>
<tr>
<th>QQD Spectrometer</th>
<th>16 msr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Angle</td>
<td>± 20%</td>
</tr>
<tr>
<td>Momentum Acceptance</td>
<td>$\pm 20%$</td>
</tr>
<tr>
<td>Momentum Resolution</td>
<td>$\frac{P}{\Delta P} = 1000$</td>
</tr>
<tr>
<td>Momentum Range</td>
<td>$\leq 200$ MeV/c</td>
</tr>
<tr>
<td>Focal Plane:</td>
<td></td>
</tr>
<tr>
<td>Dispersion</td>
<td>$-1.06$ cm/%</td>
</tr>
<tr>
<td>Radial Magnification</td>
<td>$-0.54$</td>
</tr>
<tr>
<td>Tilt Angle</td>
<td>$72^\circ$</td>
</tr>
<tr>
<td>Path Length</td>
<td>$2.28$ m</td>
</tr>
<tr>
<td>Angular Range</td>
<td>$30 - 135^\circ$</td>
</tr>
</tbody>
</table>

spectrometer, it does reduce the resolution of the target traceback and, in this experiment, would have obstructed the rotation of the spectrometer to small angles ($\leq 35.3^\circ$). The paths of those particles that pass through the spectrometer were monitored by three multi-wire proportional chambers (henceforth referred to as wire chambers) and a single drift chamber (see figure 2). The information from these chambers was used to calculate two separate measurements of the particle momentum and to provide a cut on those pions that had decayed along the length of the spectrometer. Scintillators at both the entrance and the exit of the QD, with the firing of at least two out of the three wire chamber anodes, provided the hardware trigger for this arm. The specifications of the spectrometer are given in table VI.

The QD position-resolution detectors, for this experiment, were of two types: a drift chamber, closest to the target, and three wire chambers, two positioned downstream of the dipole magnet, and the third positioned before the dipole magnet (see figure 2).
The three wire chambers\(^2\) (labelled WC3,4,5) consist of three planes of equally spaced parallel wires. The central (anode) plane is set at a high positive potential with respect to the outer (cathode) planes which are grounded. The anodes lie horizontally, whereas the cathodes lie vertically in one plane and horizontally in the other. For each cathode plane wires are soldered onto a common delay line at which the signal is divided. Time-to-digital converters (TDCs) time the delay at each end of the delay line, and position information is given by the difference between the two TDC values. The sum of the TDC values gives a peaked distribution, whose width is twice the electron drift time in the chamber. To eliminate misfires this sum is gated about this peak for every delay line and values within this gate are taken to correspond to valid 'hits' (the 'CHECKSUM' test).

This information is required to be converted to appropriate spatial units (\(\text{mm}\)) and to be offset to define the centre of the chamber. The conversion factor is found by noting that the y-direction cathode plane spectrum is highly irregular, and appears as a "picket-fence" structure [35]. This is understood by considering that an electron avalanche about an anode capacitively couples strongly only to its immediate (y-direction) cathode neighbour (producing a peak in the y-direction spectrum), and not to those (y-direction) cathodes that are next nearest (producing troughs in the spectrum). Hence the inter-peak distance in the TDC difference spectrum corresponds to the anode separation distance. Since the design of horizontal and vertical cathode planes are equivalent, the conversion factors are taken to be the same for the two perpendicular directions.

The backend wire chambers, WC4 and WC5, are segmented along the

\(^2\)The dimensions and operating characteristics of these chambers may be found in reference [33]
horizontal axis into three sections, which are equal in area, and identical in design, whereas the frontend wire chamber, WC3, is unsegmented. The offsets for the y-direction, and for the x-direction for WC3 and the central sections of WC4 and WC5, were found by centering the observed position spectra about the origin. Those x-direction offsets that remained, were found by matching the spectra until a continuous non-overlapping position spectrum was obtained. A more usual method, which uses a set of pion events for which two segments of the wire chamber fire [35], was not used, since the data set was too small, and an improved position resolution was not required.

The usual QQD configuration includes a frontend wire chamber situated between the QT1 position and the target. This was replaced by a drift chamber which was thought to exhibit greater efficiency and durability of the high flux rates of this experiment. This chamber is shown in figure 4. It consists of four sections, the outer two 12.5 mm wide, and the inner two 12.25 mm wide, and is identical in construction in the horizontal and vertical directions. Electrons, ionised by a passing particle, drift in the directions shown, and produce a signal pulse at the anode which is connected to a TDC. The drift velocity remains constant so that the TDC value gives a direct measure of the particle position. The factors used to convert TDC channels to a known distance scale (mm) are found knowing the physical dimensions of the chamber. The drift chamber position spectra exhibit a 0.5 mm wide dead zone at their centre corresponding to the central anode pair region.

The two planes of scintillators (E1 and E2) at the exit window of the QD were meantimed and together defined the start of the TDCs. The scintillator (cautiously nicknamed HOPE at a particularly bad time in the experiment),
Figure 4: The Frontend Drift Chamber of the QD. The arrows indicate the direction of the drift of negative ions.
placed at the entrance of the QD, provided part of the event trigger and was particularly useful in discriminating pions from electrons in the QD, by a time-of-flight method.

II.4 The Target and Appurtenances

The target for the \( pn \to pp\pi^- \) reaction was liquid deuterium, acting as a quasi-neutron target under the assumption that the accompanying proton acts as a spectator particle. The target itself, was an upright cylinder 5 cm in diameter and 7 cm high, with vertical walls of 0.005" kapton and metal end caps. The target system allowed for the filling and emptying of this vessel so that data could be taken for an empty target. To reduce multiple scattering of the beam, the target was placed in an evacuated scattering vessel. This was made to be part of the beamline, although for safety reasons a thin (0.001") stainless steel window separated the target vacuum from that of the cyclotron.

A thin kapton window, on the QD side of the apparatus allowed for the exit of pions from the vessel. On the side of the \(^2\text{He} \) arm, protons were allowed to propagate, undergoing no multiple scattering, in a large, 85 cm length, evacuated barrel, whose exit window (0.05" of stainless steel) lay close to the plane of the \( \Delta E \) scintillators.

II.5 Data Acquisition

The hardware trigger definition was a coincidence between the two arms of the experiment. For the detection of \( pn \to pp\pi^- \) reactions, as stated previously, the hardware trigger was given by

\[
((\Delta E_i \cdot \text{VETO}_i)_{\text{hi}}^{1/4} \cdot \text{or} \cdot (\Delta E_i \cdot \text{VETO}_i)_{\text{lo}}^{2/4}) \cdot ((2/3 \cdot \text{Anodes}) \cdot \text{HOPE.E1.E2}) \tag{10}
\]
Here, the 1 and 2/4 refer to the number of $\Delta E$ scintillators that were required to fire, and the $hi$ and $lo$ refer to the $\Delta E$ discriminator threshold settings. The gate for the $^2$He trigger was set at 80ns, so that accidental events from the subsequent beam burst were written to tape to give an indication, off-line, of the final accidental event rate.

For the $pn \rightarrow pp\pi^-$ reaction, the analysing power was measured for two pion angles. These angles were 35.3° (corresponding to a central QD momentum of $p_0 = 186.9$ MeV/c), and 43.5° ($p_0 = 173.7$ MeV/c).

For each run, proton elastic events were also written to tape, to be used in the calibration of the $^2$He arm. This trigger type was a coincidence between any $\Delta E$ scintillator (set at a minimum discrimination threshold), and one of the narrow scintillators (dimensions given on page 15), positioned behind the NaI bars.

We also required $pp \rightarrow d\pi^+$ events to be written to tape. This event type was useful in a check of the experimental procedures and the off-line analysis, used in the measurement of the $pn \rightarrow pp\pi^-$ analysing power, since the analysing power of the $pp \rightarrow d\pi^+$ reaction is fairly well known. The pion arm trigger remained, for this $\pi^+$ reaction, as it was for the $\pi^-$ reaction. For the $^2$He arm, the trigger was altered to be one in which only a single $\Delta E$ (at a low threshold) fires. Hence, the trigger was

\[
(\Delta E_i.VETO_i)^{1/4}.((2/3\text{Anodes}).\text{HOPE.E1.E2})
\]

For any event, the generation of a look-at-me (LAM) caused the TDC values for the chambers and scintillators, and the ADC values for the chambers, scintillators and NaI bars, to be read into the buffer of the STARBURST data pre-processing unit. The event word, containing these values and the C212 pattern unit bits, was then written to magnetic tape by a PDP11/34 computer. In
addition, HEX scaler values were written to tape every five minutes. These scalers were used to record the rates of the $^{2}$He scintillators and the wire-chamber anodes, the trigger event rate, and the polarimeter event rates for the various nominal settings of the beam spin. The PDP11/34 was also used for on-line analysis of the events. Off-line, the data was analysed on the VAX/VMS system using both existing programs, and original programs written especially for this experiment.
Chapter III

Analysis

Data taking during this experiment was limited to approximately sixty hours, due to a lengthy set-up procedure and major problems associated with the cryogenic target and the beam-tune. The data that was written to tape was ultimately found to have a signal-to-noise ratio of order 1%. Those processes that were considered to have possibly contributed to this noise, either directly or indirectly in association with another process, are listed in table VII. Further background may have arisen due to nuclear reactions between hadrons produced by these reactions and nuclei in the NaI bars.

However, it should be noted that the excellent off-line software discrimination of pions versus electrons and muons in the pion spectrometer immediately precludes the direct participation of all these types of events in the final 'event' data set. For convenience, the off-line analysis was separated into two sections, corresponding to each of the two arms of the experiment.

III.1 Event Definition in the \(^2\)He Arm

The ultimate aim of the analysis of the \(^2\)He arm data was to define those events for which two protons, emanating from the \(pn \rightarrow pp\pi^-\) reaction, were stopped within the NaI bars, without any other particle, from any other reaction or beam-burst, impinging on the \(^2\)He arm detectors. Such spurious particles would deposit energy in the system resulting in erroneous designations of the proton energies.

One concern was that delta-rays (secondary electrons emitted on the impact
Table VII: Possible Sources of Background

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>THRESHOLD MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow pp$</td>
<td>$-$</td>
</tr>
<tr>
<td>$pd \rightarrow pd$</td>
<td>$-$</td>
</tr>
<tr>
<td>$pn \rightarrow pn$</td>
<td>$-$</td>
</tr>
<tr>
<td>$pp \rightarrow d\pi^+$</td>
<td>287.52</td>
</tr>
<tr>
<td>$pp \rightarrow np\pi^+$</td>
<td>292.30</td>
</tr>
<tr>
<td>$pn \rightarrow d\pi^0$</td>
<td>275.06</td>
</tr>
<tr>
<td>$pn \rightarrow nn\pi^+$</td>
<td>292.49</td>
</tr>
<tr>
<td>$pn \rightarrow pn\pi^0$</td>
<td>279.82</td>
</tr>
<tr>
<td>$pd \rightarrow t\pi^+$</td>
<td>206.76</td>
</tr>
<tr>
<td>$pd \rightarrow ^3\text{He}\pi^0$</td>
<td>198.70</td>
</tr>
</tbody>
</table>

of the beam on the target) might be sufficiently energetic to reach the $^2\text{He}$ arm detectors. However, it was calculated that the maximum delta-ray energy is $T_{\delta}^{\text{max}} \simeq 1.1$ MeV, which is below the threshold required to pass through the (0.05" thick) stainless steel window of the vacuum enclosure ("barrel"), downstream of the target.

Events were chosen for which the pion in the spectrometer, and the protons in the $^2\text{He}$ arm originated from the same beam-burst. This test was applied by gating the $\Delta E$ TDCs, whose start is defined by the back scintillators of the QD, on particles from the first beam-burst. The event was rejected if, apart from time-outs, any $\Delta E$ TDC value lay outside this range. On the other hand, if the TDC value lay within the range, the detection by the $\Delta E$ was considered valid (a "valid" $\Delta E$). Those events for which any pile-up gate bit was set were also rejected. The criterion that particles be stopped within the NaI bars was applied by requiring that no VETO ADC be above its pedestal value. The final requirement of the $^2\text{He}$ arm scintillators was that either one or two $\Delta E$ detectors must be "valid".

Once the NaI bars had been calibrated, using the methods described in
chapter II, a cut on the energy deposition in each bar was made. The lower limit on this energy was chosen to be 40 MeV which is higher than the mean energy loss in the bars of 400 MeV elastically scattered \((p, p)\) protons. The higher limit was chosen to be 120 MeV, which is the maximum energy-loss of a proton in a bar, plus the energy resolution of the detector. All events for which the energy-loss fell between these limits in two of the bars were retained for further analysis, whilst the remainder were rejected. This test effectively rejects all events for which both protons were stopped within a single bar. This was done as insufficient information was obtained to calculate the energies and co-ordinates of the protons in these 'same-bar hits'. Another test that was applied, was that the positions in the bars, as deduced from the calibrations, may not be within one inch of each other in the vertical direction in adjacent bars. This test was applied to disallow events that scatter from one bar to an adjacent bar, depositing greater than 40 MeV in each. One final test on the NaI bar information ensured that for each bar that fired, the particle position \((x, y, z)\) in the bar corresponded to a "valid" \(\Delta E\) scintillator which lay on a line defined by the origin (the target position) and \((x, y, z)\). Thus each particle detected by the NaI bars, was paired with a single "valid" \(\Delta E\) scintillator.

These tests, however, do not discriminate between particle types, and, for this, one further test was required. One common technique used to distinguish particle types, is to choose events which lie within a characteristic region of an \(E - \Delta E\) plot (energy deposited in a NaI bar versus energy deposited in a \(\Delta E\) scintillator). However, given the complexity of the detecting system (7 '\(E'\)-counters and 4 '\(\Delta E'\)-counters), a variation of this \(E - \Delta E\) method was employed. For an energy-loss \(E_{i}^{\text{bar}}\), of a particle within a bar, the energy-loss, \(\Delta E_{i}\) of that particle (assuming that the particle is a proton) in \(\frac{1}{8}\)'' of scintillator was calculated, where the energy-loss in an intervening aluminium window was
Figure 5: The $E - \Delta E$ Test for the $^2$He Arm. The Ratio, $R$ is the ratio of the calculated energy-loss of the two protons in the $\Delta E$ scintillators given the energy-loss in the NaI bars, compared with the actual energy-loss.

accounted for. The sum, $\Delta E^{\text{calc}} = \Delta E_1 + \Delta E_2$ was then the calculated energy-loss of the two protons in the $\Delta E$ scintillators and was compared to the sum of the energy-losses, $\Delta E^{\text{real}}$, as deduced from the calibration of the $\Delta E$ ADCs. A ratio $R$ was formed where

$$ R = \frac{\Delta E^{\text{calc}}}{\Delta E^{\text{real}}} \quad (12) $$

For stopped protons this ratio is centred on unity (see figure 5). Those events for which $R \ll 1$, or $R \gg 1$ do not correspond to two stopped protons, and were rejected by a cut on $R$. These tests constituted the off-line software event definition of a low energy ($40 \leq E \leq 120$ MeV) proton pair.
III.2 Event Definition in the QD

The definition of a valid pion was made by ensuring that the particle that passed through the spectrometer originated within the target, was not an electron and did not decay in flight.

The drift and wire chamber coordinates were calculated for which the wire chamber CHECKSUM test (see page 22) were passed and each anode fired. The drift chamber was considered to have been valid if the calculated coordinates lay within the physical chamber limits.

The coordinates in the first two chambers (DC and WC3) were used to calculate the vertex coordinates \((x_0', y_0')\) of the reaction. These coordinates are a projection of the vertex position onto a plane perpendicular to the QD axis and defined by its axis of rotation. The quadrupole magnet, QT2, that was positioned between these chambers focused in the \(y'\) direction and defocused in the \(x'\) direction, and in the following calculation was assumed to behave as a thin lens. This assumption results in the following expressions for \(x_0'\) and \(y_0'\) [35],

\[
x_0' = a_1 x_1' + a_3 x_3'
\]
\[
y_0' = b_1 y_1' + b_3 y_3'
\]

The coefficients \(a_i (i = 1, 3)\) depend solely on the separation distances between chambers, quadrupole and target and on the diverging focal length \((f_D)\).

Similarly, \(b_i (i = 1, 3)\) depend on the same separation distances and on the converging focal length \((f_C)\).

For the \(y'\)-direction calibration, \(f_C\) was varied until the centroid of the target position, \(y_0'\), was independent of the drift chamber coordinate, \(y_1'\). Using \(f_D = -f_C\)

---

1The primed coordinate system corresponds to the QD right-handed orthogonal axes reference frame. Here the \(x'\) direction is taken to be along the axis of the QD, \(y'\) is the vertical direction, and the \(x'\)-axis is positive to the left of an upright observer facing down the QD.

2Subscripts refer to the chamber number: DC=1, WC3,4,5=3,4,5

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(this is not generally true [36], but was used as a first approximation), the horizontal coordinate, \( x'_0 \), was calculated. To investigate the validity of this approximation, \((x'_0, y'_0)\) data from target empty runs was analysed — this data should mostly correspond to vertices within the walls of the target. It was found that the width of the \( x'_0 \) distribution corresponded to the physical width of the target, multiplied by the cosine of the angle at which it was viewed. Furthermore, the dependence of \( x'_1 \) on \( x'_3 \) for particles originating in the walls of the target was consistent with the coefficients \((a_1, a_3)\) used for calculating \( x'_0 \) (equation 13). This implies that the approximation \( f_C = -f_D \) was valid. From \((x'_0, y'_0)\), the polar angle (with respect to the \( z' \)-axis), \( \theta'_0 \) and the azimuthal angle \( \phi'_0 \) were obtained.

The flight path of a pion for a given momentum, is completely specified by a set of frontend coordinates, e.g. \((x'_1, y'_1, x'_3, y'_3)\) or \((x'_0, y'_0, \theta'_0, \phi'_0)\). Therefore, any coordinate in the backend of the spectrometer may be written as a power series of the form [34,35]

\[
 r_j = \sum_{i=1} \alpha_i \delta^a x^a_i y^a_i \theta^a_i \phi^a_i \tag{15}
\]

where \( r_j \) are coordinates such as \( x'_4 \) or \( x'_5 \), and

\( \delta \) is a momentum parameter related to the central momentum \( p_0 \) of the spectrometer,

\[
 \delta = \frac{p - p_0}{p_0} \tag{16}
\]

To second order in \( \delta \) this may be written [35]

\[
 r_j = A + B \delta + C \delta^2 \tag{17}
\]

with \( A, B \) and \( C \) of the form

\[
 A = \text{(polynomial of order } m_0 \text{ in frontend coordinates)}
\]

\[
 B = \text{(polynomial of order } m_1 \text{ in frontend coordinates)}
\]
\[ C = (\text{polynomial of order } m_2 \text{ in frontend coordinates}) \]

Since the dipole magnet (BT) bends only in the horizontal plane, \( y'_4 \) and \( y'_5 \) have no dependence on \( \delta \) so \( a_i = 0 \). However, \( x'_4 \) and \( x'_5 \) are dependent on \( \delta \) and these dependences may be inverted to obtain two values of \( \delta : \delta_4 \) and \( \delta_5 \).

The coefficients \( a_i \) in equation (15) are, in more normal applications of the spectrometer, obtained using elastically scattered pions from a target such as CH\(_2\). Since this experiment was undertaken on a proton channel this was impossible, and calibration data from another experiment was used [37]. For this set of data, the expansion in equation (15) was taken to, at most, fourth order \((m_0 = 3, m_1 = 3, m_2 = 1)\). This calibration was used to produce two values of the particle momentum, \( \delta_4 \) and \( \delta_5 \) per event.

At the pion energies of interest in this experiment, approximately 20% of the pions decay \((\pi \rightarrow \mu \nu)\) along the 2.28m length of the spectrometer producing muons within a cone whose half-angle is \( \approx 13^\circ \) (lab). Although, for the measurement of the analysing power of \( pn \rightarrow pp(1S_0)\pi^- \), the pion need not be required to survive along the entire length of the spectrometer, a pion 'event' was defined such that it did not decay over that length. This definition was chosen so that the software trigger was simple and that the original pion momentum may always be calculated.

If the muons, from pion decay, remain within the spectrometer, the results of the calculations of \( \delta_4 \) and \( \delta_5 \) may well be different, especially for those muons at the larger angles of the muon cone, and for those whose \( x' \)-components of momentum are largest. For this reason a cut, about zero, was made on the difference of \( \delta_4 \) and \( \delta_5 \). The events for which muons have large momentum components along the \( y' \)-axis were rejected by applying the constraint that the
relationship between \( y'_4 \) and \( y'_5 \) be linear, i.e.

\[
y'_4 - \beta y'_5 \simeq 0
\]  
where \( \beta \) is a constant. These techniques ought to eliminate all decayed pion events excepting those few events for which the decay products, \( \mu \) and \( \nu \), are forwardly scattered.

What was of greater concern, for pion detection purposes, was a contamination of electrons, presumably resulting from \( \pi^0 \)-production and decay in the target (\( \pi^0 \rightarrow 2\gamma, \gamma \rightarrow e^+e^- \)). However, the electron time-of-flight through the spectrometer was considerably shorter than for a 100 MeV pion and, on this basis, the electrons were rejected. Figure 6 shows the pion and electron time-of-flight spectrum, defined by scintillators at the entrance and exit of the QD. These cuts constituted the off-line software event definition of a pion in the spectrometer.

### III.3 Definition of a \( pn \rightarrow pp\pi^- \) Event

The data set was reduced by applying a logical AND between the software events in the two arms. The only way to ascertain whether this reduced data set was free of contamination was to apply a cut on the energy balance between the initial and final states of the reaction.

To do this, the total energy-loss of the two protons in the various materials of the apparatus, was calculated. The materials, their thicknesses, and the coefficients \( (a, b, c) \) for energy-loss,

\[
\Delta E = a + \frac{b}{E} - \frac{c}{E^2}
\]  
are listed in table VIII, in the order in which they are traversed by the particles. Here, \( E \) is the energy of the particle after it has traversed the material, depositing energy \( \Delta E \).
Figure 6: Time-of-Flight Spectrum in the QD

Table VIII: Energy Loss for Protons (40 < E < 400 MeV) in the Windows of the $^2$He Arm

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>THICKNESS (cm)</th>
<th>$a$ (MeV)</th>
<th>$b$ (MeV$^2$)</th>
<th>$c$ (MeV$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>0.127</td>
<td>1.258</td>
<td>413.9</td>
<td>4547.</td>
</tr>
<tr>
<td>Scintillator</td>
<td>0.318</td>
<td>0.5360</td>
<td>212.2</td>
<td>1775.</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.159</td>
<td>0.5204</td>
<td>203.5</td>
<td>1753.</td>
</tr>
</tbody>
</table>
These expressions are valid for thin windows where the stopping power is approximately constant across the material thickness and for a limited range of energies. To find the energy-loss in the target a different approach had to be adopted, since the target was relatively thick (2" in diameter), and the distance traversed by the particles within the target was not precisely known. As the position of the event vertex within the target was only known in two dimensions in the QD (primed) frame, an assumption was made that the beam was nominally a pencil beam travelling along the z-axis. Thus for the QD at an angle $\theta_z$ to the z-axis, the vertex position was taken to be

$$r_T = (x'_0 \cos \theta_z, y'_0, -x'_0 \sin \theta_z)$$

(20)

Using this approximation and the positions of the protons at the NaI bars, the distances traversed within the cylindrical target were found. These distances were used to find the energy-losses in the target by integrating over thin distance elements, and knowing the stopping power of the protons in liquid deuterium:

$$\frac{dE}{dx} \text{(MeV/cm)} = 0.2689 + \frac{100.7}{E} - \frac{250.8}{E^2}$$

(21)

where the unit of $E$ is MeV. This same equation was also used to find the degradation of the beam energy within the target.

The sum of the energy-losses in the elements of the $^2\text{He}$ arm for each of the two protons gives the kinetic energies, ($T_1$ and $T_2$), at the vertex, and the proton lab momenta ($p_1$ and $p_2$). The uncertainty in these energies is of the order of the energy-loss of the pion within the target ($\sim 1 \text{ MeV}$) which was not calculated. The kinetic energy of the pion, ($T_\pi$), was determined from the momentum parameter $\delta$. The pion lab momentum ($p_\pi$) was calculated from $\delta$, the vertex position and the pion position at the drift chamber.

To calculate the total energy of the final state using the experimental observables, it was necessary to calculate the kinetic energy of the spectator
proton. This was deduced from the conservation of four-momenta in the lab:

\[ \vec{p}_B + \vec{p}_T - \vec{p}_S = \vec{p}_\pi + \vec{p}_1 + \vec{p}_2 \]  

(22)

Here,

- \( \vec{p}_B \) = four-momentum of the beam particle, (the proton), \( \vec{p}_B = (E_B, \vec{p}_B) \),
- \( \vec{p}_T \) = four-momentum of the target particle, (the deuteron), \( \vec{p}_T = (m_d, 0) \),
- \( \vec{p}_S \) = four-momentum of the spectator proton, \( \vec{p}_S = (E_S, \vec{p}_S) \),
- \( \vec{p}_\pi \) = four-momentum of the final-state pion, \( \vec{p}_\pi = (E_\pi, \vec{p}_\pi) \), and
- \( \vec{p}_i \) are the four-momenta of the final-state protons (i=1,2), \( \vec{p}_i = (E_i, \vec{p}_i) \).

Therefore,

\[ \begin{align*}
\vec{p}_S & = \vec{p}_B - (\vec{p}_1 + \vec{p}_2 + \vec{p}_\pi) \\
E_S & = E_B + m_d - (E_1 + E_2 + E_\pi) \\
T_B & = T_1 + T_2 + T_\pi + T_S + (m_p + m_n + m_\pi - m_d)
\end{align*} \]  

(23, 24, 25)

where \( T_S = \sqrt{p_S^2 + m_p^2} - m_p \). Equations 24 and 25 provide independent information for the energy of the spectator particle.

The spectator momentum and energy were determined from equations (23) and (24) and a quantity, which is the difference between the left and right sides of equation (25), calculated. This quantity (labelled TDIFF), if the data correspond purely to \( pn \rightarrow pp\pi^- \) events, should be distributed about zero, with a width equal to the resolution of the detection system. Figure 7, which is the experimental distribution of TDIFF, shows an experimental width, at base, of \( \approx 10 \) MeV. It also shows that no cut on TDIFF was required as the full extent of the distribution can be explained as being due to the uncertainties in the energy-loss of the detection system.
III.4 Centre-of-Mass Quantities

The final state kinematical quantities were also calculated in the centre-of-mass frame (*), where the velocity of the centre-of-mass is

$$\beta^* = \frac{\mathbf{p_1} + \mathbf{p_2} + \mathbf{p_\pi}}{E_1 + E_2 + E_\pi}$$

and the total centre-of-mass energy, $W$, is

$$W = \sqrt{(E_1 + E_2 + E_\pi)^2 - (\mathbf{p_1} + \mathbf{p_2} + \mathbf{p_\pi})^2}$$

Further centre-of-mass quantities were calculated. These were

- the pion centre-of-mass angle with respect to $\beta^*$, $\theta^*_\pi$:

$$\cos \theta^*_\pi = \frac{\mathbf{p^*_\pi} \cdot \beta^*}{p^*_\pi \beta^*}$$
- the magnitude of the difference of the centre-of-mass momenta of the two protons in units of $m_\pi = 1$, $P$:

$$P = \frac{|P_1^* - P_2^*|}{m_\pi}$$  \hspace{1cm} (29)

- the ratio of the magnitude of the pion momentum to its maximum value, $r$:

$$r = \frac{p_\pi^*}{p_{\pi\text{ max}}}$$ \hspace{1cm} (30)

$$p_{\pi\text{ max}} = \sqrt{\frac{(W^2 - (m_\pi + 2m_p)^2)(W^2 - (m_\pi - 2m_p)^2)}{4W^2}}$$  \hspace{1cm} (31)

- the angle between the difference of the centre-of-mass momenta of the two protons, and the pion momentum, $\mu = \cos(P, p_\pi^*)$.

- and, the angle between the difference of the centre-of-mass momenta of the two protons, and $\beta^*$, $\mu_p = \cos(P, \beta^*)$.

It should be noted here that the choice of the vector $P$ is arbitrary. For the purposes of this experiment and for the Monte Carlo simulation, the vector $p_1$ is defined as being the momentum of that proton that has the greatest negative x-component of momentum in the lab. This means that proton 1 has the greatest polar angle with respect to the beam direction. This choice specifies the choice of $P$.

III.5 The Definition of the $pp \rightarrow d\pi^+$ Event

The analysis of $pp \rightarrow d\pi^+$ events was similar, but not identical to, the analysis of the $pn \rightarrow pp\pi^-$ events. Since the only difference in the spectrometer between detecting negative and positive pions is a change in the polarity of the QD dipole magnet, the definition of a $\pi^+$ was identical to that described above for $\pi^-$. To define a deuteron in the $^2\text{He}$ arm, software cuts were made such that valid events
Table IX: Energy Loss for Deuterons ($40 < E < 250$ MeV) in the Windows of the $^2$He Arm

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>THICKNESS (cm)</th>
<th>$a$ (MeV)</th>
<th>$b$ (MeV$^2$)</th>
<th>$c$ (MeV$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>0.127</td>
<td>1.838</td>
<td>683.4</td>
<td>5972.</td>
</tr>
<tr>
<td>Scintillator</td>
<td>0.318</td>
<td>0.7139</td>
<td>348.7</td>
<td>2387.</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.159</td>
<td>0.8007</td>
<td>350.2</td>
<td>2469.</td>
</tr>
</tbody>
</table>

consisted of single $\Delta E$ scintillators and single bars firing. The energy-loss equations were altered from above (see table VIII), to account for the energy-loss of deuterons in the materials (see table IX). The stopping power expression used for the energy-loss of deuterons in deuterium (cf. equation (21)), was

$$\frac{dE}{dx} (MeV/cm) = 0.3574 + \frac{185.5}{E} + \frac{76.61}{E^2}$$  \hspace{1cm} (32)$$

For similar reasons as above the calculations leading to a cut on the variable $R$ (see equation (12)), were altered to describe the deuteron energy-loss. The remaining methods used were as previously described for the $pp\pi$ final state.
Chapter IV

Results

IV.1 Analysing Powers

Analysing powers for this type of polarised beam experiment are given by the ratio of the up-down asymmetry for spin-up and spin-down protons, $\varepsilon(\theta^*_e)$, to the beam polarisation, $P_{\text{beam}}$,

$$A_y(\theta^*_e) = \frac{\varepsilon(\theta^*_e)}{P_{\text{beam}}} \tag{33}$$

where $P_{\text{beam}}$, for this experiment is given by equation (2), and $\varepsilon(\theta^*_e)$ is given by [38]

$$\varepsilon(\theta^*_e) = \frac{d\sigma/d\Omega(\uparrow) - d\sigma/d\Omega(\downarrow)}{d\sigma/d\Omega(\uparrow) + d\sigma/d\Omega(\downarrow)}. \tag{34}$$

This last equation shows the simplicity of this measurement, in that for a ratio of the cross sections no overall normalisations of cross sections are required. To normalise the cross sections with respect to each other, the numbers of events, $N$, (as defined by the tests described in Chapter III) for each spin setting, were normalised to unit computer live-time and to unit beam charge

$$\frac{d\sigma}{d\Omega}(\uparrow) = B \frac{N(\uparrow)}{LT(\uparrow) \times BEAM(\uparrow)} \tag{35}$$

$$\frac{d\sigma}{d\Omega}(\downarrow) = B \frac{N(\downarrow)}{LT(\downarrow) \times BEAM(\downarrow)}, \tag{36}$$

where $B$ is a constant for a particular experimental configuration. The live-time, $LT$, for a particular spin setting, was calculated as being the ratio of the number of non-sample events written to tape to the number of such events recorded by the HEX scalers. As mentioned on page 11, the beam charge, $BEAM$, was taken as
being proportional to the sum of the \textit{LEFT} and \textit{RIGHT} counts in the polarimeter.

These equations were used to measure the analysing powers for $\bar{p}n \rightarrow pp\pi^-$, for nominal QD settings of 35.3° and 43.5°, and for the $\bar{p}p \rightarrow d\pi^+$ at 35.3°. This last measurement was found to be

$$A_y(\theta^*_\pi = 61.0° \pm 3.0°) = -0.02 \pm 0.05$$

The “error” of the pion centre-of-mass angle, here, is the full-width of the pion angular distribution. As can be seen from figure 8, this is in full agreement with previously published data on this reaction [39]. This measurement is necessary, but not sufficient, to vindicate the methods employed, in this experiment, in the measurement of analysing powers.

\textbf{IV.2 Tests of the Contamination of the Event Set}

It was deemed prudent to examine the characteristics of the ‘event’ data set for the $pn \rightarrow pp\pi^-$ reaction to investigate the possibility of contamination by other types of reaction or accidentals. The first test that was investigated was that of applying the tests outlined previously (Chapter III) on empty-target runs for both experimental QD settings. The result of this was that no events were found which passed the ‘event’ test set. Secondly, this ‘event’ test set was applied for runs for which the $\Delta E$ TDCs were gated on next-beam-burst particles. This would then give an indication of the ‘accidental’ event rate. This rate was found to be less than 1% of the true ‘event’ data set. The third test that was applied was that of searching for ‘events’ for which the NaI EARLY or LATE gates were above pedestal, which would indicate that pile-up had occurred for that event (see page 18). The rate for this type of event was approximately 5%. From these tests it can be implied that no major contamination of the ‘event’ data set had occurred.
Figure 8: The Measured Analysing Power of the $pp \rightarrow d\pi^+$ Reaction at 400 MeV, in Comparison with Previously Published Data. This experiment: *, reference [39]: ◇.
One other indirect search for contamination was in investigating the variation of the analysing power for the two quantities that are important in the definition of the data set: the ratio $R$ (see page 31) and TDIFF (see page 38). If contamination exists in localised regions of these distributions then it might be possible to distinguish the regions by a possible difference in the analysing power with respect to the analysing power for the $pn \rightarrow pp\pi^-$ reaction. Both these quantities were investigated in this manner and no appreciable variation in analysing power was found. From this one can conclude, once more, that no appreciable contamination had occurred.

IV.3 The Comparison of the Monte Carlo with the Experimental Results

The Monte Carlo, described in Appendix B, models the $pn \rightarrow pp\pi^-$ process according to the results of previous experiments (specifically those of reference [4]), and according to the known configuration and detector resolutions of this experiment. The comparison of the Monte Carlo results with the experimental results, tests, therefore, both the underlying assumptions of the Monte Carlo and the kinematical results of this experiment.

One comparison made between the Monte Carlo results and the experimental results was the comparison of the predicted and observed event rates. The Monte Carlo predicted an event rate of approximately 143 events per hour, for an 100% efficient $^2$He detector, for the known efficiencies of the QD chambers and for the QD angle of $\theta_\pi = 44^\circ$. This compares favorably with an experimental rate of approximately 95 events per hour at this angle.

It can be seen that the kinematical results of this experiment (see figures 9, 10, 11, 12 and 13) are in very good agreement with the Monte Carlo predictions (see figures 17, 18, 19, 20, 21, 22 and 23). One exception to this is
that the experimental distribution of \(|\mathbf{p}_S|\) (figure 9) is broader than that predicted (figure 17) by the Monte Carlo. The slight error in the energy calibration of the system, which can be seen from the offset of the TDIFF spectrum (figure 7), may partially account for, but cannot fully explain, this disparity, the cause of which is unknown.

The general agreement between the experimental data and the Monte Carlo predictions gives a strong indication that the S-wave selection, at a hardware level, was extremely successful.

IV.4 The Measurement of the S- and P-wave Analysing Powers

For this type of experiment it is not possible to completely emulate pion absorption on the \(T = 1\) \((^{1}S_0)\) nucleon pair in \(^3\text{He},\) as P-wave contamination will always occur, to various degrees, as a background. As explained in Appendix B, it was expected that the S-wave events should predominate at small values of \(P,\) and the P-wave events should predominate at larger values. It was interesting to calculate the analysing power as a function of \(P\) for the reason that if the P-wave analysing power differs from that of the S-wave, then any P-wave contamination would produce a varying analysing power at large \(P.\)

The analysing power as a function of \(P\) is shown in figure 14 for both QD settings. Here \(P\) has been binned in four bins, each of width \(\Delta P = 0.3.\) There is no dramatic variation in analysing power, \(A_y,\) although a general trend of decreasing \(A_y\) for increasing \(P\) may be discernable. This would then support the contention that the P-wave contamination in the event set was indeed small.

To reduce the fraction of P-wave events in an event set, it was decided to bin events, in two bins, according to the value of \(P.\) For \(\theta_x = 35.3^\circ,\) these two bins were \(0 \leq P \leq 0.8\) and \(P > 0.8,\) and for \(\theta_x = 43.5^\circ,\) they were \(0 \leq P \leq 0.7\) and
Experimental Data: $\theta_\pi = 43.5^\circ$

![Experimental Data Graph]

Figure 9: The Experimental Momentum Distribution of the Spectator Particle
Figure 10: The Experimental Distribution of $r$

Experimental Data: $\theta = 43.5^\circ$
Figure 11: The Experimental Distributions of $\mu$ and $\mu_p$. 

Experimental Data: $\theta_\pi = 43.5^0$
Figure 12: The Experimental Distributions of $P$ for the two angle settings.
Figure 13: The Experimental Distributions of \( \cos(\theta_\pi^*) \).
Figure 14: Analysing Power as a Function of $P$. Nominal angle settings, $35.3^\circ: \Diamond$, $43.5^\circ: \ast$
According to the Monte Carlo results, binning $P$ in the 'S-wave' (low $P$) regions produces a P-wave contamination of approximately 10%. Similarly, binning in 'P-wave' (higher $P$) regions produces S-wave contaminations of approximately 50%. Thus the analysing powers that were found for the 'S-wave' event set may be considered as being the analysing powers of a highly enriched S-wave event set, and those for the 'P-wave' event set may be considered as being analysing powers of an approximately equal admixture of S- and P-wave events.

To compare with the partial-wave analysis predictions for the two types of solutions (see figure 1) it was then necessary to bin the 'S-wave' event sets according to the pion centre-of-mass angle, $\theta_\pi$. The number of (equally populated) angle bins for each QD setting was chosen to be three, which would provide a sufficient number of data points for comparison with the predictions and with reasonable statistical errors. Figure 15 shows the measured variation of the analysing power with $\theta_\pi$ for 'S-wave' events in comparison with the two partial-wave solution types. Here, the analysing power error corresponds purely to statistical error, and the $\theta_\pi$ "error" bar corresponds to the angular range over which 66% of the events in each bin are distributed. The 'P-wave' bin contained so few events that no binning according to $\theta_\pi$ was attempted. The results for both 'S-wave' and 'P-wave' bins are given in table X.

IV.5 Conclusions

Figure 15 shows the comparison of the results of this experiment with predictions produced using the $pn$ elastic scattering databases of Arndt [19] and of Bugg [18]. From this figure, it is obvious that there is no absolute quantitative agreement between the results and the predictions of either of the two solutions. However, it is also apparent that the results qualitatively follow the dramatic variation of analysing power of solution 1 and do not correspond to the slowly varying forms of
Figure 15: The Experimental Values of $A_y(\theta_\pi^*)$ in Comparison with the Theoretical Predictions using the databases of Arndt [19] and of Bugg [18].

Table X: The Experimental Results for the 'S-' and 'P-wave' bins.

<table>
<thead>
<tr>
<th>'S-' or 'P-wave'</th>
<th>$\theta_\pi^*$ (deg)</th>
<th>$A_y(\theta_\pi^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>'S-wave'</td>
<td>58.5$^{+2.0}_{-2.2}$</td>
<td>-0.48 $\pm$ 0.12</td>
</tr>
<tr>
<td>'S-wave'</td>
<td>63.2$^{+1.2}_{-0.7}$</td>
<td>-0.85 $\pm$ 0.12</td>
</tr>
<tr>
<td>'S-wave'</td>
<td>68.0$^{+4.5}_{-2.1}$</td>
<td>-0.52 $\pm$ 0.13</td>
</tr>
<tr>
<td>'S-wave'</td>
<td>72.4$^{+1.8}_{-2.6}$</td>
<td>+0.04 $\pm$ 0.10</td>
</tr>
<tr>
<td>'S-wave'</td>
<td>77.2$^{+1.4}_{-1.2}$</td>
<td>+0.31 $\pm$ 0.10</td>
</tr>
<tr>
<td>'S-wave'</td>
<td>82.7$^{+3.6}_{-2.4}$</td>
<td>+0.64 $\pm$ 0.09</td>
</tr>
<tr>
<td>'P-wave'</td>
<td>65.8$^{+3.8}_{-3.8}$</td>
<td>-0.66 $\pm$ 0.16</td>
</tr>
<tr>
<td>'P-wave'</td>
<td>78.2$^{+4.0}_{-4.2}$</td>
<td>+0.11 $\pm$ 0.09</td>
</tr>
</tbody>
</table>

54
solution 2. On this basis, a conclusion may be reached that the correct amplitude set for the \( \pi^- (1S_0)pp \leftrightarrow pn \) process is similar to the amplitude sets of solution 1 and is dissimilar to the amplitude sets of solution 2. It remains to be seen whether an amplitude set may be found which is in agreement with the results of this experiment and with differential cross section data. This experiment has not been successful in choosing between the forms of solution 1 given by the Bugg database [18] and by the database of Arndt [19].

These experimental results imply a large probability for the \( ^3S_1 \) angular momentum state for the \( pn \) nucleons of the \( \pi^- (1S_0)pp \rightarrow pn \) reaction with respect to the \( ^3D_1 \) state (see table III). This same conclusion has been reached using a quark model, described in Appendix A. Although the probabilities, as calculated from the partial-wave analysis for solution 1 and as calculated from the quark model, are not in quantitative agreement, these results would seem to encourage the refinement of the model and to lend some support to some of its inherent assumptions. The results of this experiment certainly do not rule out the use of this quark model for this reaction.

IV.6 Discussion

This experiment suffered from a dearth of data-taking time and hence suffered a paucity of events and data points. The problems associated with the NaI signal background 'hum' and with the small number of calibration points (three) for the bars, did not directly effect the results of this experiment. However, these problems should, in any future experiment, be solved or averted, since their treatment, for this experiment, was not entirely satisfactory (especially considering the non-linear calibration of the bars).

The underlying principle of the experiment was the possibility of measuring the analysing power of a single angular momentum state of a pair or outgoing
nucleons. The major success of the experiment was the assertion of this principle due mainly to the design and the use of the $^2$He arm. Any future experiments, employing a different "diproton" detector, should be at least as successful in producing an event set dominated by the $^1S_0$ state. It is suggested that other variations of a "diproton" detector could be a telescope of thick, segmented plastic scintillators and wire chambers, or a magnetic spectrometer capable of energy and position measurement for two-proton events.

Given the importance of its results, a repetition of this measurement is advised, using the experience gained from this experiment. It is suggested that a repetition should obtain improved statistics (especially over the region in which the analysing power varies dramatically) and further data points over a wide range of angles, $\theta^*_\pi$, and for different pion energies. It should be noted that measurement at large $\theta^*_\pi$ is hindered by a small cross section, and measurement at small $\theta^*_\pi$ using the QD is not possible for $\theta^*_\pi < 55^\circ$. 

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Bibliography


Appendix A

A Quark Model for the $pn \rightarrow pp\pi^-$ Reaction

The $pn \rightarrow pp\pi^-$ reaction has been investigated using a six-quark model of two nucleons [21,22]. This model describes the nucleons of a two-nucleon system as being spatially separated, without exchanging gluons or quarks at separation distances greater than a distance $r = r_0$. For $r < r_0$, it is envisaged that the nucleons overlap and may exchange gluons, and here influences of the quark-quark Pauli principle arise. It has been argued that the largest contributions of pion absorption (such as delta- or nucleonic-resonances, or mechanisms involving meson exchange) occur at small distances [22]. It is therefore appropriate to replace these contributions by quark contributions and to compare the results of the calculations with experimental data.

This model limits contributions of pion absorption to only s- and p-wave pions for energies below the threshold for the delta $(3,3)$ resonance. It predicts a total cross section which is sensitive to the value of $r_0$, and is in agreement with the experimental data [9] for $r_0 = 0.85$ fm. A qualitative agreement with the differential cross section results was also obtained, and was found to be sensitive to the value of the $^3S_1 - ^3D_1$ mixing parameter, $\epsilon$. Predictions were also made of the six-quark probabilities for the various angular momentum states of the proton-neutron system. A comparison of these probabilities with the results of this and future experiments may substantiate many of the claims made in the assumptions underlying this model.
Appendix B

The Monte Carlo Program

A Monte Carlo simulation of the $pd \rightarrow \pi^-ppp$ reaction was written to provide estimates of the experimental count rates and to investigate the behaviour of final-state kinematical variables for the S- and P-wave final state protons. The basis for this program was the PEPINES program, initially written for the NESIKA group at SIN. This is a two-body $(A + B \rightarrow \pi + D)$ Monte Carlo, where the decay of the final-state pion $(\pi \rightarrow \mu\nu)$ is included. One other provision of this program was for the multiple-scattering of particles in the various elements of the system, but magnetic fields and energy-loss or straggling effects were not included.

This program was modified to describe the experimental apparatus (detailed in Chapter 2), the software cuts (Chapter 3) and the reaction $pn^* \rightarrow pp\pi^-$. Here, for kinematical purposes, the target was considered to be a quasi-neutron, $n^* = d - p$, where the deuteron was at rest in the lab and the proton was assigned a spectator momentum whose distribution was given by the Hulthen wavefunction (see figure 16). The beam particles were given kinetic energies, according to a normal distribution about 400 MeV ($\sigma = 1$ MeV). The beam energy-loss in the target was also calculated assuming a random vertex position along the beam direction, within the target. The kinematics of this initial state were then totally specified and the total centre-of-mass energy, $W$, was calculated (see equation (27)).

For the final state, five variables were not specified by the kinematics and so were chosen in the usual Monte Carlo manner. These variables were the total
energy of the two protons in *their* centre-of-mass frame, the directions of the protons in *their* centre-of-mass frame, and the direction of the pion in the *total* centre-of-mass frame within limits set by input variables. With these quantities, and $W'$, known, the final state was completely specified and all kinematical variables were found in the three reference frames (see section A.1). The centre-of-mass quantities were needed in the calculation of the experimental cross-section, and the laboratory quantities were needed to determine whether an event could be defined by the detecting system.

An event was defined for processes in which the pion entered the QQD aperture with a momentum within the acceptance of the detector, and in which the two protons entered the $^2\text{He}$ detector aperture and were both stopped in separate NaI bars. It is possible that protons, with energies at the vertex of the reaction which are greater than the maximum energy of stopped protons in the NaI bars, may be stopped within the bars due to energy-losses in the various elements of the $^2\text{He}$ detector— this effect is included in this simulation.
The detectors are described in the program in an elementary fashion. For the pion spectrometer, no ray-tracing is undertaken, although the decay of the pion within the spectrometer, was accounted for. The efficiencies of the detecting system otherwise were considered as 100% efficient.

The experimental cross-section was calculated using the treatment of Handler [4] of the $np \rightarrow pp\pi^-$ reaction using a neutron beam. His cross-section was a function of five variables:

$T$ is the lab. kinetic energy of the incoming neutron,

$r$ is the ratio of the c.m. pion momentum to its maximum value,

$\mu_\pi$ is the cosine of the angle between the pion c.m. momentum $P_\pi^*$ and the direction of the incoming neutron $\hat{N}$,

$\mu_p$ is the cosine of the angle between the relative momentum of the two protons $P$ and $\hat{N}$, and

$\phi$ is the relative azimuth between $P$ and $P_\pi^*$.

The variables calculated by the Monte Carlo program were related to Handler's variables [4] by a Jacobian:

$$J = \frac{\partial r}{\partial M_{pp}} \frac{\partial \Omega_p}{\partial \Omega_4^*}$$

where $M_{pp}$ is the total energy of the two protons in their c.m. frame,

$\Omega_p$ is the chosen proton solid angle in the 2-proton c.m. frame, and

$\Omega_4^*$ is the proton solid angle in the total c.m. frame.

The total experimental cross-section, summed over all events $i$, is then:

$$\overline{d\sigma} = \frac{2\pi \Delta \Omega_\pi \Delta M_{pp}}{N} \sum_i d\sigma_i^n J_i D_i$$
where $\Delta \Omega_\pi$ is the pion c.m. solid angle window,

$\Delta M_{pp}$ is the range of the values of the total 2-proton c.m. energy,

$2\pi$ accounts for the choice of the direction of the protons in the 2-proton c.m. frame, bearing in mind that they are identical particles,

$N$ is the total number of trial events,

$D_i$ is the pion exponential decay factor, and [4]

\[
\frac{d\sigma}{d\Omega} = \frac{\bar{\sigma}}{16\pi^2 \Lambda_{S*} \beta_i \Omega} \frac{f_{tot}}{\beta_i \Omega} p_{\pi \max}^3 P_{\pi}^2 (S - \Omega) \tag{37}
\]

Here $\bar{\sigma} = 53.3 \pm 4.8 \mu b$

$\Lambda_{S*} = 35.25$, a normalisation factor

$\beta_i = \text{relative velocity of the incoming neutron in the c.m. frame}$

$\Omega = \sqrt{m_{\pi}^2 + p_{\pi}^2}$

$r = \frac{p_{\pi}}{p_{\pi \max}}$

$S = \text{total c.m. energy}$

$f_{tot}$ is the sum of all transition probabilities, and all energy variables are in units for which $m_\pi = 1$.

### B.1 The Kinematical Variables

The following is an outline of the kinematics used in the program.

If, in the lab. system,

$p_B = \text{four-momentum of the beam particle, (the proton), } p_B = (E_B, p_B)$,

$p_T = \text{four-momentum of the target particle, (the deuteron), } p_T = (m_d, 0)$,

$p_S = \text{four-momentum of the proton in the deuteron, } p_S = (E_S, p_S)$,

$p_\pi = \text{four-momentum of the final-state pion, } p_\pi = (E_\pi, p_\pi)$, and

$p_i$ are the four-momenta of the final-state protons $(i=1,2)$, $p_i = (E_i, p_i)$, then

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\[ \hat{p}_B + \hat{p}_T - \hat{p}_S = \hat{p}_x + \hat{p}_1 + \hat{p}_2 \]  

(38)

From this it follows that the total centre-of-mass energy, \( W \), is

\[ W = \sqrt{(E_B + m_d - E_S)^2 - (\mathbf{p}_B - \mathbf{p}_S)^2} \]  

(39)

In the 2-protons' centre-of-mass frame (*), using the same notation, the total energy in this frame, is

\[ M_{pp} = \sqrt{(E_1^* + E_2^*)^2 - (\mathbf{p}_1^* + \mathbf{p}_2^*)^2} \]  

(40)

From this quantity, one can deduce the energy of the pion in the total (**) centre-of-mass frame,

\[ E_{\pi^*}^* = \frac{W^2 + m_\pi^2 - M_{pp}^2}{2W} \]  

(41)

and the momenta of the protons in the * frame,

\[ \mathbf{p}_i^* = \sqrt{\frac{M_{pp}^2}{4} - m_b^2} \]  

(42)

These momenta, coupled with the Monte Carlo generation of their direction cosines, now totally specify the final state, and this state may now be determined in the three different frames.

### B.2 The Predictions of the Monte Carlo Program

There are several kinematical quantities that are specifically dependent on the angular momentum states of the two proton system in the final state. The most important of these are \(|\mathbf{p}_S|, r, \mu, \mu_p\) and \(P\), all of which have been defined previously above and on page 39. All of these variables were used, in comparison with the experimental data, to verify that the observed event set was that of the \(pn \rightarrow pp\pi^-\) reaction. An experimental reproduction of the Monte Carlo predictions would imply that this is, indeed, the case, and that there would be only small
contributions from other processes such as three-body processes. As an example of this, it should be noted that a large experimental event yield at large values of $|p_S|$ (see figure 17) would indicate the presence of such three-body processes.

![Monte Carlo Prediction: $\theta_\pi = 44^\circ$](image)

**Figure 17:** The Monte Carlo Prediction of the Event Yield versus Spectator Momentum $|p_S|$, for S- and P-wave protons at $\theta_\pi = 44^\circ$

The prediction for the distribution of the ratio of the pion centre-of-mass momentum to its maximum value, $r$, was also histogrammed (figure 18). This quantity served as a check on the objectives of this experiment that the pion centre-of-mass momentum be maximised, and the value of $P$ minimised, in order to maximise the S-wave event yield.

As this experiment was attempting to separate the yield for S- and P-wave proton final states, it was necessary to model the contributions from each state for the kinematical variables which are dependent on the two-proton angular
Figure 18: The Monte Carlo Prediction of the Event Yield versus $r$, for S- and P-wave protons at $\theta_\pi = 44^\circ$
momentum. As examples of this, figures 19 and 20 show the different dependences on \( \mu \) and on \( \mu_p \) of these two states. For an 100% efficient detection system subtending a solid angle of \( 4\pi \), these quantities should, for the S-wave contribution, be isotropic over the entire range. As can be seen from these figures, the isotropy is distorted by the acceptance of the detectors.

The variation of the yield for the two partial-waves was found to be most pronounced for the variable \( P \). As \( P \) approaches zero, the probability of an event being 'S-wave' approaches unity. This can be seen in figures 21 and 22, for the two angle settings of this experiment.

The overall objective of this experiment was to distinguish between the two types of solution for the variation of the \( \vec{p}n \rightarrow pp\pi^- \) analysing power as a function of the pion centre-of-mass angle, \( \theta^*_\pi \). The distribution of \( \theta^*_\pi \) is, therefore, of importance, and is shown in figure 23 for the two experimental configurations.
Figure 19: The Monte Carlo Prediction of the Event Yield versus $\mu$, for S- and P-wave protons and for S- and P-wave protons separately, at $\theta_x = 44^\circ$
Figure 20: The Monte Carlo Prediction of the Event Yield versus $\mu_p$, for S- and P-wave protons and for S- and P-wave protons separately, at $\theta_x = 44^\circ$. 

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Figure 21: The Monte Carlo Prediction of the Event Yield versus $P$, for $S$- and $P$-wave protons and for $S$- and $P$-wave protons separately, at $\theta_* = 35^\circ$
Figure 22: The Monte Carlo Prediction of the Event Yield versus $P_\tau$ for $S$- and $P$-wave protons and for $S$- and $P$-wave protons separately, at $\theta_\tau = 44^\circ$. 
Figure 23: The Monte Carlo Prediction of the Event Yield versus $\theta_\pi^*$, at the two angle settings.
Appendix C

Signal 'Hum'

The attempt to reduce the pedestal widths was based on the observation, on an oscilloscope, that the modulations of the signals from the fourteen tubes were, to various degrees, correlated, as is apparent from figure 24. Using these correlations the most probable channel for each ADC zero was calculated, for every event and for every NaI ADC.

![The Correlation of Pedestal ADC Values from Two NaI Tubes](image)

Figure 24: The Correlation of Pedestal ADC Values from Two NaI Tubes

The correlations were used to advantage in the following way. Firstly, a large set of pedestal ADC channel numbers was collected for each of the fourteen
photo-multiplier tubes. Then the correlation and degree of correlation (correlation coefficient) of each data set with each other data set was determined using a linear least-squares fitting routine. Thus for the correlation of the ADC of tube $i$ ($\Delta(i)$) with the ADC of tube $j$ ($\Delta(j)$), the equation of correlation is

$$\Delta(i) = m(i,j)\Delta(j) + c(i,j)$$  \hspace{1cm} (43)

where $m(i,j)$ is the correlation gradient, and $c(i,j)$ is the correlation intercept.

It should, perhaps, be stated that since the correlation coefficient $r(i,j)$ is not unity, then $m(i,j) \neq 1/m(j,i)$ and $c(i,j) \neq -c(j,i)/m(j,i)$.

Given the three matrices, $m(i,j)$, $c(i,j)$ and $r(i,j)$, and the fourteen ADC values of a single event, the correlations of one ADC signal, $\Delta(i)$ with the thirteen others $\Delta(j), j \neq i$, were then used to find the most probable value of $\Delta(i)$, using only five correlations which have the largest value of $r(i,j)$, and weighted according to $|r(i,j)|^2$, i.e.

$$\Delta(i) = \frac{\sum(m(i,j)\Delta(j) + c(i,j)) |r(i,j)|^2}{\sum |r(i,j)|^2}$$  \hspace{1cm} (44)

This procedure was followed for each of the fourteen $\Delta(i)$ and for each event in each run. Due to the possible variations in correlations throughout this experiment, the coefficients were found for each run. The reduction in the widths of the ADC pedestals may be seen in figure 25.
Figure 25: NaI ADC Spectra before and after the 'Dehumming' Process