# Measurements of Spin-Correlation Parameter $A_{NN}$ and Analyzing Power at 90° for $p_{pol}p_{pol} \rightarrow d\pi^+$ between 500 and 800 MeV

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Measurements of the spin observables $A_{NN}(90°)$ and $A_{N0}(90°)$ for the reaction $pp \rightarrow d\pi^+$ between 500 and 800 MeV are presented and compared with previous measurements and with predictions from theories and a partial-wave analysis. These are the first available measurements of $A_{NN}$ above 590 MeV.

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In the energy region above the pion production threshold the study of the two-body inelastic reaction $pp \rightleftarrows \pi^+ d$ has been a subject of considerable theoretical[1] and experimental[2–10] interest. The two-body final state makes this reaction relatively easy to separate from background and it can be studied in either direction. Many measurements of the cross section[2] as well as the analyzing power[3–6] have been made in the energy range 400 to 1300 MeV. The $d\pi^+$ system has also been studied with polarized deuterons in both the elastic channel and the $pp$ final state, including both vector[7,8] and tensor[9,10] polarization measurements. Two tensor analyzing power ($T_{20}$) measurements in the elastic channel[9,10] are in sharp disagreement with each other, as a result in part of the considerable difficulty of these measurements. Several theoretical treatments[11–13] are available and partial-wave analyses (PWA's)[14–17] now provide predictions based on previous measurements for all of the observables.

From 500 to 800 MeV the $pp \rightarrow d\pi^+$ cross section decreases from approximate equality with the $pp \rightarrow np\pi^+$ cross section to about 8% of the latter. Because the $d\pi^+$ reaction couples to many of the same channels as $np\pi^+$, it remains an important part of the inelastic process for nucleon-nucleon collisions in an energy region where there has been considerable conjecture[15,18] about the existence of highly inelastic dibaryon resonances [e.g., $^1D_2$ ($\sim$2150 MeV/$c^2$), $^3F_3$ ($\sim$2220 MeV/$c^2$)]. It is appropriate, therefore, to look for structure in either the singlet or the triplet amplitudes for the $d\pi^+$ channel as a manifestation of these states. Measurements of the spin-correlation parameter $A_{NN}(90°)$ and analyzing power $A_{N0}(90°)$ for the reaction $pp \rightarrow d\pi^+$ at 500, 600, 650, 733, and 800 MeV are reported here, and are a subset of angular distribution measurements[19] for this reaction for c.m. angles $30° \lesssim \theta_\pi^* \lesssim 110°$, a complete report of which will appear in a subsequent paper. These results, together with those of a companion experiment[20] in which the spin-correlation parameters $A_{LL}$ and $A_{SL}$ were measured for the same reaction at the same energies, can be used to extract individually the energy dependence for the moduli of one singlet and two triplet amplitudes for $\theta_\pi^* = 90°$.

The reaction was studied with a vertically polarized proton beam and proton target at the Clinton P. Anderson Meson Physics Facility (LAMPF). A magnetic spectrometer was used to detect deuterons, and a recoil arm was used for pion detection. Time of flight (TOF) for each of the particles was measured with large scintillator planes at the end of each arm and a small scintillator at the entrance of the spectrometer which set the start timing for event triggers. The spectrometer also consisted of two $x$-$y$ pairs of multiwire proportional chambers (MWPC's) in front of a C magnet and

 

TABLE I. Experimental results and singlet and triplet amplitudes derived from them.

| $T_p$ (MeV) | $A_{NN}$ | $A_{N0}$ | $\lvert T_2 \rvert$ | $\lvert T_6 \rvert$ | $\lvert S \rvert$ | $\Delta(S,T_6)$ (deg) |
|---|---|---|---|---|---|---|
| 500 | −0.929 | −0.039 | 0.053 | 0.183 | 0.342 | −5.0 |
| | ± 0.040 | ± 0.030 | ± 0.015 | ± 0.008 | ± 0.004 | ± 4 |
| 600 | −0.992 | 0.366 | 0.022 | 0.273 | 0.398 | 25.5 |
| | ± 0.020 | ± 0.016 | ± 0.022 | ± 0.009 | ± 0.005 | ± 2 |
| 650 | −1.026 | 0.444 | 0.00 | 0.326 | 0.326 | 30.0 |
| | ± 0.025 | ± 0.016 | ± 0.020 | ± 0.006 | ± 0.005 | ± 1.5 |
| 700 | −0.993 | 0.389 | 0.018 | 0.326 | 0.278 | |
| | ± 0.030 | ± 0.013 | ± 0.035 | ± 0.007 | ± 0.006 | |
| 733 | −0.972 | 0.328 | 0.031 | 0.288 | 0.221 | |
| | ± 0.055 | ± 0.030 | ± 0.029 | ± 0.008 | ± 0.006 | |
| 800 | −0.953 | 0.252 | 0.035 | 0.267 | 0.172 | 19.2 |
| | ± 0.015 | ± 0.012 | ± 0.005 | ± 0.005 | ± 0.007 | ± 1.4 |

two larger *x-y* MWPC pairs following this magnet. The pion tracks were registered by two MWPC's mounted on a recoil cart in front of a large scintillator plane. The momentum and TOF measurements from the spectrometer allowed for clear separation of deuterons from protons while the TOF measurement and the pulse-height information from the recoil cart provided significant discrimination of fast pions from slower heavier particles.

The target cryostat containing propanediol, $(CH_2)_3(OH)_2$, was in a 2.5-T field that caused deflection of both the incident beam and the outgoing charged products. Corrections to the observed angles were made for these deflections in inverse proportion to either the measured or the assumed momentum of the particles.

Beam polarization was monitored with an in-line polarimeter that measured asymmetry for both left-right and up-down scattering with four sets of double-arm coincidences. This device was calibrated against the beam polarization measured at the ion source by the quench-ratio method.[21] Since the beam had only vertical polarization, the up-plus-down coincidence rate gave a secondary check of the beam intensity that could be compared with the output of an ion chamber, the primary beam flux monitor. The target polarization was measured with an integrating NMR system that was read out at 2- to 3-min intervals. The absolute NMR calibration was obtained through the measurement of the thermal equilibrium NMR signal strength with the microwave enhancement turned off and the temperature of the target raised from its operating value (0.5 K) to 1 K. These calibrations were usually done during accelerator energy changes, thereby allowing periodic monitoring of any drifts in the NMR electronics. A check on this procedure was also provided by measurements of the known analyzing power[21] for *pp* elastic scattering. The relative precision and absolute accuracy of the NMR system were estimated to be ± 4% and ± 7%, respectively.

The values of $A_{NN}(90°)$ and $A_{N0}(90°)$ given in Table I and obtained in this experiment are shown in Figs. 1 and 2, respectively, along with the results of other experiments.[3-6] These values are the result of Legendre polynomial fits to the $A_{NN}$ data and associated Legendre polynomial fits to the $A_{N0}$ data. The errors given are the uncertainties of the

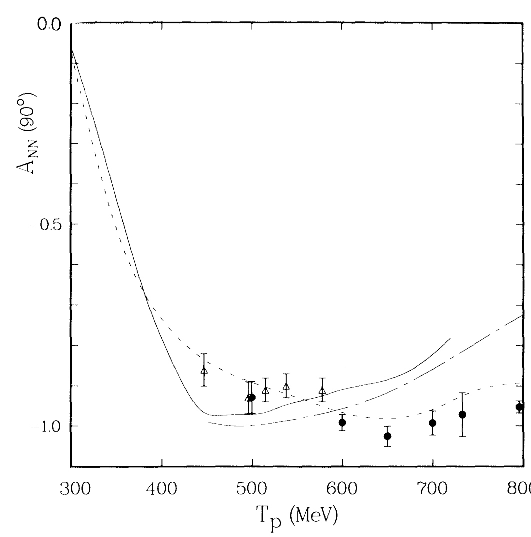


FIG. 1. Spin-correlation parameter $A_{NN}(90°)$: triangles, Aprile *et al.* (Ref. 5); circles, this experiment. The solid line is from Ref. 11, the dot-dashed line is from Ref. 12, and the dashed line is the PWA of Ref. 14 (see Ref. 17).

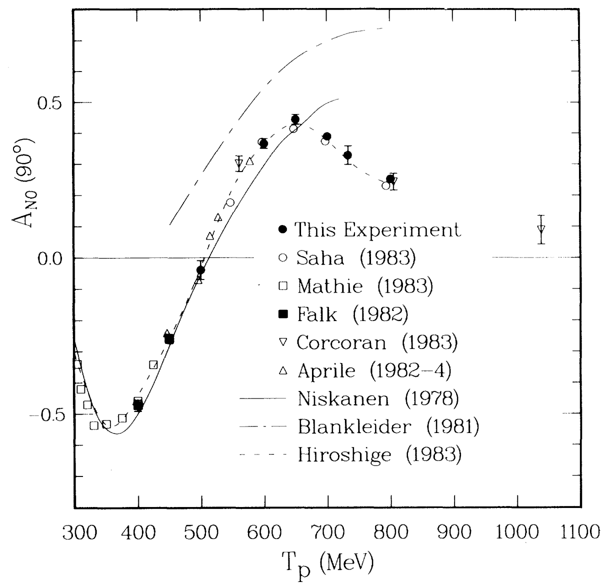


FIG. 2. Analyzing power at 90° from several experiments (Refs. 4–6) as indicated. The curves are as labeled in Fig. 1.

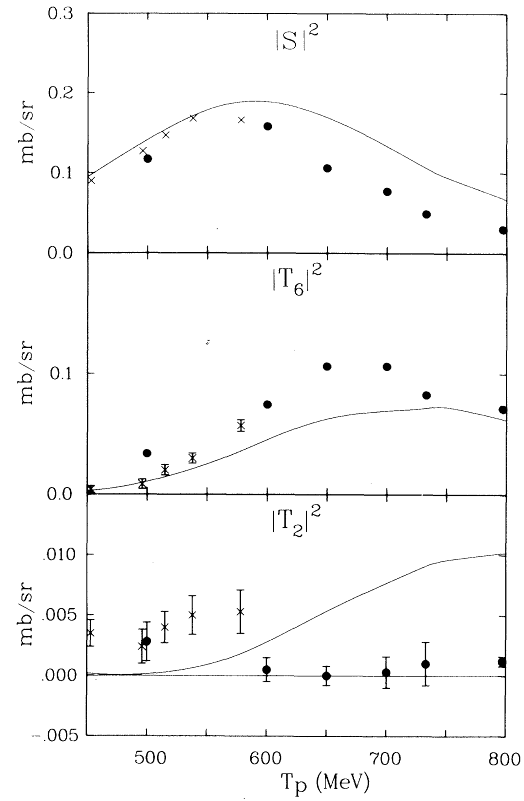


FIG. 3. Energy dependence of the moduli of the singlet and two triplet amplitudes at 90°: crosses, Aprile *et al.* (Ref. 5); circles, this experiment. Solid curves are from Ref. 12.

individual points near 90°. Also shown in Figs. 1 and 2 are the predictions of a recent PWA[17] and also the predictions of two theoretical calculations.[11,12] The data base for the PWA[17] includes the $A_{NN}$ results of this experiment and those of Ref. 20 which provide the only available data above 590 MeV. The good agreement seen in Fig. 1 is a result of the inclusion of these data; an earlier PWA[14] without the present experimental results gave very poor agreement above 600 MeV. In the latest PWA solution the $^1D_2$ partial wave continues to be dominant and peaks near 570 MeV, while the $^3F_3$ has a broad peak centered close to 640 MeV. While the PWA analyses[16,17] give a fair description of these data, there is considerable lack of agreement with theoretical predictions.[11–13]

The moduli of the singlet ($S$) and the triplet ($T_2$ and $T_6$) amplitudes at 90° in the notation of Foroughi[1] are completely determined by $A_{LL}(90°)$ and $A_{NN}(90°)$, are given by

$$|S|^2 = \sigma_{00}(90°)[1 - A_{LL}(90°)],$$

$$|T_2|^2 = \tfrac{1}{2}\sigma_{00}(90°)[1 + A_{NN}(90°)],$$

$$|T_6|^2 = \sigma_{00}(90°)[A_{LL}(90°) - A_{NN}(90°)],$$

and the phase $\Delta$ between the triplet $T_6$ and singlet $S$ amplitudes is given by

$$\tan(\Delta) = A_{N0}(90°)/[-A_{SL}(90°)].$$

The results for the moduli are given in Table I [the $\sigma_{00}(90°)$ values used were obtained from a fit by Saha *et al.*[4] to the data of Ref. 2]. The errors given are the statistical errors associated with only the spin-correlation measurements. The $\Delta$ values given by the present $A_{N0}(90°)$ results and the $A_{SL}(90°)$ values from Refs. 5 and 20 at 500, 600, 650, and 800 MeV are also tabulated in Table I. In Fig. 3 the amplitude moduli are compared with the theoretical predictions of Ref. 12, which do show the expected[22] singlet and triplet peaking near 600 and 670 MeV, but underestimate the triplet peak and overestimate the singlet peak. These peaks are expected from the $^1D_2$ partial wave feeding an $S$-wave $N\Delta$ intermediate state which has a threshold near 575 MeV, and from the five $NN$ triplet waves ($^3P_{1,2}$, $^3F_{2,3,4}$) feeding the $P$-wave $N\Delta$ intermediate states which have thresholds near 650 MeV.

The theoretical treatments in Refs. 11 and 12 differ somewhat from each other, but they both fail to treat spin relativistically.[23] Reference 12 treats the $P_{11}$ $\pi N$ amplitude as a combination of a pole and nonpole part whereas Garcilazo[23] had moderate success in fitting the vector and tensor polarization data[7–10] by using an empirical $P_{11}$ amplitude. Finally, in view of Foroughi's claim[1] that $|T_6|^2$ is not affected by a predicted coupled triplet $P$ dibaryon (2.18–2.20 GeV) but $|T_2|^2$ is, these results along with vector polarization measurements[24] provide the experimental input necessary to distinguish "... between threshold effects and resonances."[1] However, the shortcomings of these conventional theories may account for their disagreement with the experimental data.

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