

Analyzing powers and spin correlations  $A_{NN}$  and  $A_{LL}$  for  $pp \rightarrow np\pi^+$  at 650 and 800 MeV

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We report first measurements of the spin correlation parameters,  $A_{NN}$  and  $A_{LL}$ , for  $pp \rightarrow np\pi^+$  above the  $\Delta$ -production threshold. Our results for this dominant inelastic channel are in good agreement with a theoretical model that does not include any dibaryon resonances.

Recent phase shift analyses<sup>1</sup> of nucleon-nucleon scattering data have found that, as energy increases above the  $N\Delta$  threshold, there is a counterclockwise looping behavior in the Argand diagrams for the  ${}^1D_2$  and  ${}^3F_3$ ,  $I=1$  partial wave amplitudes. Such loops are often indicative of underlying resonances, which in this case would be called "dibaryons." The nature of dibaryon resonances, if they exist, has generated much interest. Can the energy dependences be understood in a conventional way through the normal interactions of mesons and nucleons? Or, do the data require an interpretation in terms of a new quark substructure, such as six quarks in one bag?<sup>2</sup> In fact, these questions originally arose because of the earlier discovery of rapid energy variations in the differences of spin dependent NN total cross sections.<sup>3</sup>

Considerable theoretical work has been undertaken to answer these questions. Box diagrams involving  $N\Delta$  intermediate states have long been suspected of creating resonancelike loops in the Argand diagrams. Kloet and Tjon<sup>4</sup> have discussed in detail how this happens in a particular unitary, dynamical model for the  $NN \rightarrow NN\pi$  reaction, including the origin of dynamical poles. VerWest<sup>5</sup> has shown that some potential models exist that describe the observed rapid energy dependence in the amplitudes with an absence of nearby resonance poles. Further, several more detailed dynamical models have been developed in recent years for the coupled  $NN$  and  $NN\pi$  systems.<sup>6,7</sup> Of these, the model described in Ref. 7 has been used to calculate various spin observables for the  $pp \rightarrow np\pi^+$  reaction.<sup>8</sup> In view of the great impact that the existence of dibaryon resonances would have on the fields of nuclear and particle physics, it is important to test the predictions of such "conventional" models in detail before concluding that a new quark substructure exists.

The suggested dibaryon resonances<sup>3</sup> are expected to have large inelasticities. At 800 MeV, the  $pp \rightarrow np\pi^+$  channel accounts for over 75% of the total inelastic cross section. It is not surprising, therefore, that several experi-

mental studies of this reaction are currently underway. Shimizu *et al.*<sup>9</sup> have concluded that about 80% of the  $np\pi^+$  events originate from the  $n\Delta^{++}$  state above 600 MeV. Measurements of cross sections and analyzing powers at 800 MeV for exclusive kinematics have now been completed by Hancock *et al.*<sup>10(a)</sup> There are also now measurements of polarization transfer in the  $pp \rightarrow np\pi^+$  reaction at 800 MeV, but for inclusive kinematics.<sup>11</sup> In this paper we report the first measurements of the spin correlation parameters  $A_{NN}$  and  $A_{LL}$  for this dominant inelastic channel at incident proton energies above the  $\Delta$ -production threshold.

The experiments were carried out at LAMPF. Figure 1 shows the experimental setup for the measurement of  $A_{NN}$ , which is defined as

$$A_{NN} = \frac{1}{P_B P_T} \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)},$$

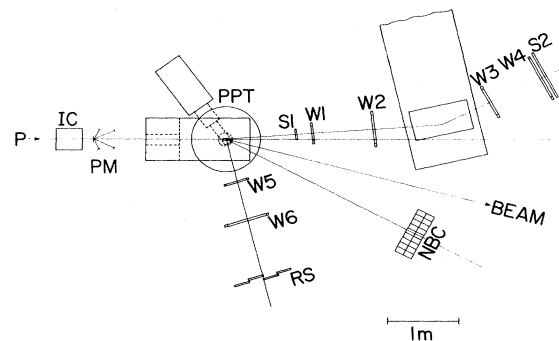


FIG. 1. Experimental setup for the  $A_{NN}$  part of this experiment. IC is an ion chamber used as a beam monitor; PM is a beam polarimeter monitor; PPT is the polarized proton target; NBC is the neutron bar counter array; S1, S2, and RS are 6 mm scintillators; and W1-W6 are multiwire proportional chambers each having an x-y pair of planes.

where  $P_B$  and  $P_T$  are beam and target polarizations and  $N(\uparrow\downarrow)$ , for example, is the normalized yield for beam polarization "up" and target polarization "down." Some details of the experimental method concerning absolute beam, target polarization measurements, and beam intensity monitoring have been reported earlier.<sup>12</sup> For the  $A_{NN}$  measurements the beam polarization was typically  $0.80 \pm 0.02$ . Target polarization was also  $\sim 0.80$  for the normal ( $N$ ) target and was measured to within  $\pm 0.02$ . For kinematically complete detection of the three-body final state in the  $pp \rightarrow np\pi^+$  reaction, it is necessary to measure five parameters for the outgoing particles. For instance, the momentum for the proton together with the  $\pi^+$  direction will, in principle, suffice. However, when a polarized proton target (hydrogen content  $\sim 9\%$ ) is used, such a five-parameter detection of the final state would not enable the separation of the  $pp \rightarrow np\pi^+$  signal from the quasifree background contamination from the nonhydrogenic components of the target material.

In these experiments all three particles (n, p, and  $\pi^+$ ) were detected in coincidence. The scattered protons were detected in a magnetic spectrometer with momentum resolution of  $\sim 2\%$ . The time of flight, along with the momentum, provided unique particle identification. Pions were detected in a "recoil arm." Nearly complete separation of charged pions from heavier charged particles in this arm was made possible by measurements of  $dE/dx$  (smaller for pions) and flight time (shorter for pions). In coincidence with a proton in the spectrometer and a pion in the recoil arm, a neutron was detected in a neutron bar counter (NBC) array,<sup>13</sup> which gave the velocity of the neutrons.

Such kinematic overdetermination was crucial in defining the signal for  $pp \rightarrow np\pi^+$  over the quasifree background. The measurements were restricted to kinematics for a  $\Delta^{++}$  mass of 1232 MeV. For every kinematic situation studied, background runs were taken with the target cryostat filled with hollow graphite beads of approximately the same density as the polarized target material. The signal-to-background ratio ranged from 4 to 10.

For the  $A_{LL}$  measurement the  $N$ -type polarized proton target was replaced with a longitudinal ( $L$ ) polarized target. It consisted of a  $^3\text{He}$  refrigerator<sup>14</sup> with the target cell

along the axis of a superconducting split-coil solenoid magnet.<sup>15</sup> The detection system was the same as described above for the  $A_{NN}$  measurements. The recoil arm was designed to move in the vertical direction because of the deflection of the protons and  $\pi^+$  due to the solenoid field. Before reaching the polarized target the beam progressively passed through a solenoid, two dipoles, and an additional auxiliary solenoid. The  $S$ ,  $N$ , and  $L$  ( $\hat{S} = \hat{N} \times \hat{L}$ ) components of the beam polarization vector at the center of the polarized target were estimated to be  $0.014 \pm 0.024$ ,  $0.255 \pm 0.024$ , and  $-0.625 \pm 0.021$ , respectively. The beam polarization direction was reversed every 2 or 3 min while the target polarization was reversed every 2 h. The average value of the target polarization for the  $A_{LL}$  measurement was  $0.74 \pm 0.02$ .

The results of this experiment for the various spin-spin correlations and the analyzing powers measured are presented in Table I. Figures 2 and 3 show these results for the 800-MeV measurements, along with theoretical calculations of these quantities with the three-body unitary model described in Refs. 7 and 8. The agreement between experiment and this theoretical model (which has essentially no free parameters and does not include explicit dibaryon resonances) is reasonably good. It is reasonable to expect that other "conventional" models (models that assume only well-understood forces between mesons and nucleons) would give similar predictions.

Outside of the  $\pi d \rightarrow \pi d$  reaction, there have been many theoretical studies of models which include explicit dibaryon resonances. Thus it is difficult to assess the extent to which the present data can differentiate between conventional dynamics and new quark substructures in the NN system. The most relevant calculation of which we are aware is that of Umland, Duck, and Mutchler,<sup>10(b)</sup> who initially thought such dibaryon degrees of freedom might be needed to explain the extensive polarization data of Hancock *et al.*<sup>10(a)</sup> It was later found that unitarization alone<sup>8(a)</sup> gave considerable improvement in the predictions of  $A_B$  (compare the dashed and solid curves for  $A_B$  and  $A_T$  in Figs. 2 and 3).

The theoretical model is well documented in the literature (Refs. 7 and 8), so only a brief description follows.

TABLE I. The measured values of  $A_B$ ,  $A_T$ ,  $A_{NN}$ , and  $A_{LL}$  for  $pp \rightarrow np\pi^+$  reaction. The errors given are statistical. Overall normalization of 4% is not included. The values predicted by the unitary model of Ref. 7 are given in parentheses.

$T_p$ (MeV)	$\theta_p$ (deg)	$\theta_{\pi^+}$ (deg)	$P_p$ (MeV/c)	$A_B$	$A_T$	$A_{NN}$	$A_{LL}$
800	18.9	40.5	970	+ 0.602 $\pm 0.050$ (+ 0.284)	- 0.567 $\pm 0.060$ (- 0.247)	- 0.765 $\pm 0.046$ (- 0.539)	0.239 $\pm 0.086$ (- 0.036)
800	21.2	48.5	987	+ 0.619 $\pm 0.109$ (+ 0.508)	- 0.435 $\pm 0.115$ (- 0.405)	- 0.583 $\pm 0.110$ (- 0.666)	(+ 0.060)
650	17.1	82.0	775	+ 0.217 $\pm 0.145$ (- 0.182)	- 0.437 $\pm 0.150$ (+ 0.198)	- 0.870 $\pm 0.153$ (- 0.975)	(- 0.897)

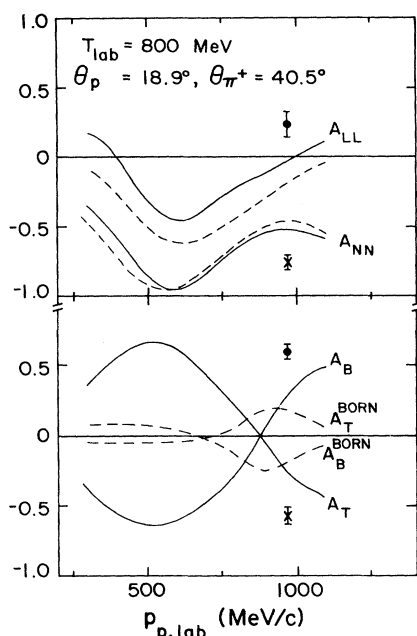


FIG. 2. Measured values of  $A_B$ ,  $A_T$ ,  $A_{NN}$ , and  $A_{LL}$  at 800 MeV for  $18.9^\circ, 40.5^\circ$  angle pair compared with predictions of the Kloeit-Silbar model. Solid curves denote the fully unitary calculations and dashed curves denote the Born approximation calculations. The upper half of the figure shows  $A_{LL}$  ( $\bullet$ ) and  $A_{NN}$  ( $\times$ ). The lower half of the figure shows  $A_B$  ( $\bullet$ ) and  $A_T$  ( $\times$ ), the analyzing powers with respect to beam and target reversals, respectively.

Basically, it is an isobar model in which the only particle interactions are between the produced pion and either of the nucleons. These forces are in the dominant  $P_{33}$  channel [which contains the  $\Delta(3,3)$  resonance] and the  $P_{11}$  channel (which contains a pole representing the nucleon as a bound state of a pion and a bare nucleon).<sup>16</sup> The isobar amplitudes are generated by (multiple) pion exchange, and their partial-wave amplitudes are obtained by solving coupled three-body Blankenbecler-Sugar integral equations. The model respects two- and three-body unitarization and uses relativistic kinematics. Crossing symmetry is not incorporated. In Ref. 8(a) there were rough estimates of how the exchange of heavy mesons, such as  $\rho$ , affected the  $A_B$  predictions. In general the effects were not large. The question of the importance of short-range forces for the  $NN \rightarrow NN\pi$  observables deserves more careful study, however.

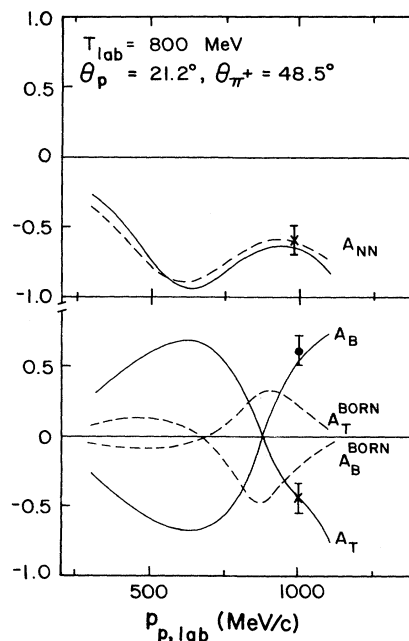


FIG. 3. Same as Fig. 2, for the 800 MeV  $21.2^\circ, 48.5^\circ$  angle pair.

Two interesting features are noteworthy in Figs. 2 and 3. Comparison of the solid (fully unitary) and dashed (Born approximation) curves shows that  $A_{NN}$  is rather insensitive to unitarization,  $A_{LL}$  is moderately so, and the beam and target analyzing powers  $A_B$  and  $A_T$  are very much so. Surprisingly, the experimental and theoretical values of the analyzing powers  $A_B$  and  $A_T$  are approximately equal and opposite. A similar approximate symmetry was noted for  $A_{LL}$  and  $A_{SS}$  in the calculations of Ref. 8(b).

To conclude, we report the first measurements<sup>17</sup> of spin-spin correlations in the dominant inelastic channel  $pp \rightarrow np\pi^+$  above the  $\Delta$ -production threshold. The results are in good agreement with a theoretical model for the reaction that does not include explicit dibaryon resonances.

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