Energy Variation of the Analyzing Power in the Reaction $p_{pol} + p \to d + \pi^+$

A. Saha, Kamal K. Seth, D. Kielczewska, S. Iversen, M. Kaletka, D. Barlow, and D. Smith
Northwestern University, Evanston, Illinois 60201

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Precision measurements of the analyzing powers for the reaction $p_{pol} + p \to d + \pi^+$ have been made at $\simeq 550$, 600, 650, 700, and 800 MeV. The data have been analyzed in terms of Legendre polynomials. It is found that excitation functions for both even and odd Legendre coefficients exhibit very similar resonant behaviors. It is concluded that the triplet amplitudes are as strongly dominated by the $\Delta(1232)$ as the well-known singlet amplitude, ${}^1D_2$, and that the data do not exhibit any anomalous behavior suggestive of dibaryon resonances.

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Great progress has been made recently in the understanding of the fundamental *NN* interaction below the threshold for single pion production.[1] This success follows from a large body of high-precision data for cross section and polarization observables in *NN* elastic scattering. In contrast, inelasticity in fundamental *NN* collisions is poorly understood and precision data for its observables have been scarce. However, the success achieved below 300 MeV and the excitement generated by the possible existence of dibaryon resonances[2] have recently spurred several experimental programs to provide detailed, high-precision data in the inelastic region. In this Letter we report on precision measurements of the analyzing power $A_{y0}(\theta)$ for the reaction $p_{pol} + p \to d + \pi^+$ at $\simeq 550$, 600, 650, 700, and 800 MeV. Since none of the existing theories of pion production are found to be successful in explaining our data, we analyze it in a phenomenological manner and show that the $\Delta(1232)$ intermediate state appears to dominate pion production separately in both singlet and triplet initial states of the *pp* system. We also note that in contrast to the results of recent phase-shift analyses the data exhibit no anomalous behavior which might be interpreted as suggesting the presence of dibaryon resonances.

The experiments reported here were done with polarized proton beams at the high resolution spectrometer facility at the Clinton P. Anderson Meson Physics Facility (LAMPF). Details of the experimental setup and the $A_{y0}(\theta)$ measurements at 800 MeV have been described elsewhere.[3] The random errors in the present measurements, $\Delta A_{y0}(\theta)$, are $\leq \pm 0.015$. These are smaller than the size of the data points in Figs. 1(a) and (b). It is estimated that additional systematic errors, primarily due to the uncertainty in the absolute value of the beam polarization, are less than $\pm 2\%$ of $A_{y0}(\theta)$.

For a beam with polarization P_b incident on an unpolarized target,[4]

$$d\sigma(\theta)/d\Omega = \sigma(\theta) \equiv \sigma_{00}(\theta) + \vec{P}_b \cdot \hat{n}\sigma_{y0}(\theta),$$

$$A_{y0}(\theta) \equiv \frac{1}{P_b}\,\frac{\sigma(\theta)\uparrow - \sigma(\theta)\downarrow}{\sigma(\theta)\uparrow + \sigma(\theta)\downarrow} = \frac{\sigma_{y0}(\theta)}{\sigma_{00}(\theta)},$$

$$\sigma_{00}(\theta) = (1/4\pi)\sum_n a_n P_n(\cos\theta), \quad n = 0, 2, 4\ldots,$$

$$\sigma_{y0}(\theta) = (1/4\pi)\sum_n b_n P_n{}^1(\cos\theta), \quad n = 1, 2, 3\ldots.$$

As is well known,[5,6] the odd associated-Legendre coefficients (b_1, b_3, b_5) relate to products of a singlet and a triplet *pp* amplitude. The even coefficients (b_2, b_4, b_6) relate only to the products of two triplet amplitudes and thus provide us with an effective "spin filter" for isolating triplet-state effects.

In order to determine the coefficients b_n from the $A_{y0}(\theta)$ data, we need to construct $\sigma_{y0}(\theta) A_{y0}(\theta) \times \sigma_{00}(\theta)$. To do this, we have made a consistent reanalysis of the available world data[7] for $\sigma_{00}(\theta)$, made smooth fits to the resulting excitation functions for the individual coefficients a_n, and interpolated the values of the coefficients a_n listed in Table I. We use these coefficients to generate $\sigma_{00}(\theta)$ and thus analyze our $\sigma_{y0}(\theta)$. The coefficients b_n so obtained and the random errors in them due to all known sources are listed in Table I. We note that the precision of our results is an order of magnitude better than that of the old CERN data[8] for $A_{0y}(\theta) = A_{y0}(\pi - \theta)$. Below 600 MeV our results are in excellent agreement with the results of comparable precision which have recently become available from A_{y0} measurements made at Schweizerisches Institut für Nuklearforschung.[9,10]

As shown in Fig. 1(c), Legendre-polynomial

TABLE I. Summary of the results for the reaction $p_{\mathrm{pol}} + p \rightarrow d + \pi^+$.

Coefficients (mb)	Proton energies (MeV) 547[a]	598[a]	648[a]	698[a]	793[a]	790[b]
a_0	2.980(50)	3.180(50)	2.810(50)	2.270(70)	1.226(10)	1.226(10)
a_2/a_0	1.045(20)	0.970(20)	0.895(15)	0.825(15)	0.795(15)	0.795(15)
$-a_4/a_0$	0.060(10)	0.145(10)	0.217(10)	0.237(10)	0.242(10)	0.242(10)
$-a_6/a_0$	0.000(10)	0.003(10)	0.020(10)	0.038(10)	0.057(10)	0.057(10)
b_1	0.894(7)	1.262(6)	1.162(7)	0.818(5)	0.291(2)	0.270(30)
b_2	0.122(6)	0.145(5)	0.144(5)	0.094(4)	0.025(2)	−0.019(29)
b_3	0.455(5)	0.503(4)	0.421(4)	0.270(3)	0.103(1)	0.045(24)
b_4	0.033(4)	0.057(3)	0.072(3)	0.066(3)	0.037(1)	−0.007(26)
b_5	0.015(4)	0.023(3)	0.014(3)	0.009(2)	0.006(1)	
b_6	0.003(4)	0.003(3)	0.003(3)	0.004(2)	0.000(1)	
χ^2/ν	0.63	0.48	0.65	0.55	0.72	0.93

[a]This experiment. The coefficients a are based on the world data in Ref. 7.
[b]Reanalysis of the $A_{0y}(\theta)$ data of Ref. 8, assuming coefficients a as listed.

analysis of our data reveals strong peaks in the energy excitation functions of both the even and the odd b coefficients. Since it is well known that single pion production is dominated by the ${}^1D_2$ state of the pp system, the peak in the odd b coefficients is no surprise. However, the peaks revealed by our experiments in the even b coefficients were unexpected and clearly indicate that the triplet states also make an important resonancelike contribution to single pion production. We also note that while the peaks in all b coefficients are essentially similar looking and strongly suggest a common origin, the peaks in the even b coefficients occur at ≈ 650 MeV, i.e., at ~ 50 MeV higher energy than those in the odd b coefficients (at $\simeq 600$ MeV).

Mandelstam[13] recognized the importance of $N\Delta(1232)$ as an intermediate state in pion production in 1958. Niskanen and co-workers[4,5] put the Δ on equal footing with the nucleon and developed a $NN \rightarrow NN$, $NN \rightarrow N\Delta$ coupled-channel formalism. In the past few years the so-called "unified theories" have been developed, in which the three coupled channels $NN \rightarrow NN$, $NN \rightarrow NN\pi$ (including $NN \leftrightarrow d\pi$), and $\pi d \rightarrow \pi d$ are treated together and the resulting set of unitary coupled equations, which have the form of Faddeev equations, are solved. Several such calculations now exist. They yield qualitatively similar results. As representative of these, in Figs. 1(a) and 1(c) we show the results from the calculations of Blankleider and Afnan,[6] along with the coupled-channel predictions of Niskanen.[5] We note that neither prediction fits our $A_{y0}(\theta)$ data or the corresponding b coefficients. Both Niskanen and Blankleider predict the ${}^1D_2$ related resonancelike enhancement in the odd b coefficients. However, neither author predicts a similar behavior for the even b coefficients, or correspondingly for the contributions of the triplet states of the initial pp system. Blankleider and Afnan[6] have noted that the success of their unified-theory calculations in obtaining NN phase shifts is poor, particularly in the triplet states. Our results suggest that this failure is directly reflected in the $pp \rightarrow d\pi^+$ channel in the failure to predict the observed enhancement in the even b coefficients.

In a model such as Niskanen's,[5] in which $NN \rightarrow N\Delta \rightarrow NN\pi$ is the dominant mechanism for pion production, the intermediate $N\Delta$ state can be expected to leave its characteristic resonance signature in contributions from both singlet and triplet states, which differ only in the relative angular momentum of the $N\Delta$. The dominant singlet state in pion production is ${}^1D_2$. It leads to $N\Delta$ in relative S state and to the characteristic peak in the odd b coefficients. The next most important state in single pion production[5] is the triplet state, ${}^3F_3$, which leads to $N\Delta$ in relative P state. It should also lead to similar peaking of the even b coefficients. The fact that Niskanen greatly underpredicts the values of both b_2 and b_4, and does not obtain a peak in either of them, suggests that his coupling potentials do not lead to enough production of the $N\Delta$ in relative P state. We note that in a recent paper Niskanen[14] has shown that the threshold for P-state $N\Delta$ production (from ${}^3P$ and ${}^3F$ initial NN states) is expected to be about 50 MeV higher than for S-state $N\Delta$ production (from ${}^1D_2$ initial NN state). Thus we

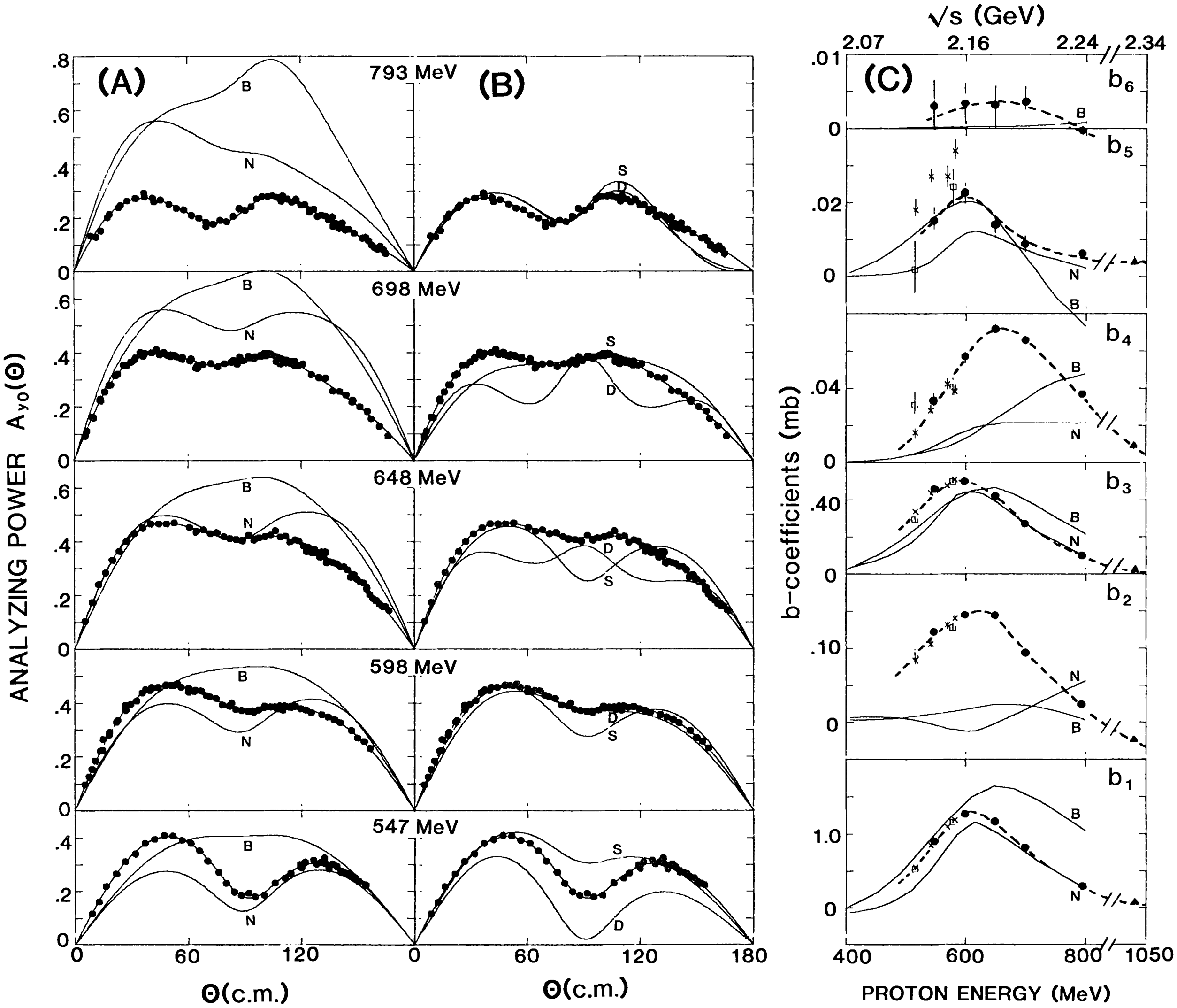

FIG. 1. Summary of the results for the analyzing power of the reaction $p_{\text{pol}} + p \rightarrow d + \pi^+$. (a) Measured $A_{y0}(\theta)$ with Legendre-polynomial fits. The other curves marked "N" and "B" refer to predictions by Niskanen (Ref. 5) and Blankleider and Afnan (Ref. 6), respectively. (b) The curves marked S and D refer to phase-shift solutions by Hiroshige *et al.* (Ref. 11). (c) Excitation functions for the coefficients b: present experiment (solid points), Ref. 9 (crosses), Ref. 10 (squares), and Ref. 12 at 1.03 GeV (triangles). The dashed curves have been drawn through the data points merely to indicate their trend.

should expect the peaks in the even b coefficients to occur at ~ 50 MeV higher energy than those in the odd-b coefficients. This is what we observe. It therefore appears that our data support the hypothesis of a common "cause," namely the $N\Delta$ intermediate state, for the peaks observed in all b coefficients, and suggest no need for exotic explanations such as dibaryon resonances.

The conjecture of dibaryon resonances arose originally from phase-shift analyses of global $NN \rightarrow NN$ data. It is therefore worthwhile to see if any evidence for dibaryons follows from phase-shift analysis of the global data in the $NN \rightarrow d\pi$ channel. Such an analysis has been recently done by Hiroshige *et al.*[11] They obtained two sets of equivalent phase shifts. The S solution was rejected because it violated unitarity. The preferred D solution possessed a $^1D_2$ enhancement and was considered supportive of a $^1D_2$ dibaryon. As shown in Fig. 1(b) our new $A_{y0}(\theta)$ data disagree with both the S and D solutions. Further, the data do not show the anomalous oscillations predicted by the *D* solution at 650 and 700 MeV. We believe that this rules out the *D* solution as well as the support this solution might have provided to the dibaryon conjecture. We believe that the inclusion of the precision data presented in this paper will impose serious restrictions on admissible phase shifts in any future analysis of the $pp \to \pi d$ channel. These results, together with the new results in the elastic channel,[2] should contribute greatly towards a definitive conclusion about dibaryon resonances.

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[1]See, e.g., R. Vinh Mau, Nucl. Phys. A374, 3c (1982).
[2]T. Kamae, Nucl. Phys. A374, 25c (1982).
[3]Kamal K. Seth *et al.*, Phys. Lett. 126B, 164 (1983).
[4]J. Niskanen, in *Polarization Phenomena in Nuclear Physics—1980*, edited by G. G. Ohlsen, AIP Conference Proceedings No. 69 (American Institute of Physics, New York, 1981), p. 62.
[5]J. Niskanen, Nucl. Phys. A298, 417 (1978), and Phys. Lett. 79B, 190 (1978).
[6]B. Blankleider and I. R. Afnan, Phys. Rev. C 24, 1572 (1981).
[7]J. Boswell *et al.*, Phys. Rev. C 25, 2540 (1982, and references therein.
[8]M. C. Albrow *et al.*, Phys. Lett. 34B, 337 (1971).
[9]J. Hoftiezer *et al.*, Schweizerisches Institut für Nuklearforschung Report No. PR-82-18, 1982 (to be published).
[10]E. Aprile *et al.*, Nucl. Phys. A379, 369 (1982).
[11]N. Hiroshige *et al.*, Prog. Theor. Phys. 68, 2074 (1982).
[12]E. Biegert *et al.*, Phys. Rev. Lett. 41, 1098 (1978).
[13]S. Mandelstam, Proc. Roy. Soc. London, Ser. A 244, 491 (1958).
[14]J. S. Niskanen, Phys. Lett. 112B, 17 (1982).