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**Author**
Colton, Eugene

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Eugene Colton and Z. Ming Ma

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Separation of Isotopic-Spin 1/2 and 3/2 πN Systems
in pp → NπN Reactions at 6.6 GeV/c

Eugene Colton
Lawrence Berkeley Laboratory, Berkeley, California 94720

and

Z. Ming Ma
Department of Physics, Michigan State University, East Lansing, 48823

Abstract

Data for the reactions pp → pπ+n and pp → ppπ0 at 6.6 GeV/c are used to obtain the cross sections for the production of isotopic spin 1/2 and 3/2 πN systems as well as their mutual interference term. Invariant mass and momentum transfer projections are presented. Comparisons are made with previous results at 6.92 and 19 GeV/c.

In this paper we calculate the cross-sections for the production of isotopic spin 1/2 and 3/2 πN systems in single-pion production in proton-proton collisions utilizing charge independence. Isospin separations have been previously reported for π+p interactions at 5,1 and 8 and 16 GeV/c,2 and for pp interactions at 6.92,3 and 19 GeV/c.4,5 The data for this analysis were obtained using the Lawrence Berkeley
Laboratory 72-in. hydrogen bubble chamber exposed to an external proton beam of 6.6 GeV/c incident momentum. We utilize 6424 events of the type $pp \rightarrow p\pi^+n$ and 2539 events of the type $pp \rightarrow pp\pi^0$. The production cross sections for the two reactions are $5.73 \pm 0.35$ and $2.54 \pm 0.16$ mb, respectively.

In order to perform an isotopic-spin separation in $pp \rightarrow N\pi N$ reactions the outgoing pion must be associated with one of the outgoing nucleons. Following earlier analyses we assign the pion to a nucleon which is referred to as $N_1$, such that $N_1 \pi$ has the minimum invariant mass (MIM), i.e., $M(N_1\pi) < M(N_2\pi)$. The use of this criterion for separation yields

\[
\sigma_1 \equiv (pp \rightarrow p\pi^+n) = 2.94 \pm 0.19 \text{ mb} \\
\sigma_2 \equiv (pp \rightarrow n\pi^+p) = 2.79 \pm 0.18 \text{ mb} \\
\sigma_3 \equiv (pp \rightarrow p\pi^0p) = 2.54 \pm 0.16 \text{ mb}
\] (1)

In order to separate the different isotopic-spin contributions to reactions (1) we define $|A_{21}|^2$ to be the integrated cross section for producing the $N_1 \pi$ system with isotopic-spin 1. Then from charge independence and Bøggild et al. we have

\[
|A_3|^2 \equiv (4/3)\sigma_1 = 3.92 \pm 0.25 \text{ mb} \\
|A_1|^2 \equiv \sigma_3 + \sigma_2 - (1/3)\sigma_1 = 4.35 \pm 0.38 \text{ mb} \\
\text{Re}(A_1^*A_3) \equiv (1/\sqrt{2})[2\sigma_3 - \sigma_2 - (1/3)\sigma_1] = 0.92 \pm 0.23 \text{ mb}.
\] (2)
The average phase angle between the two isotopic-spin amplitudes, integrated over all variables is given by

$$\cos \phi_{13} = \frac{\text{Re}(A_1^*A_3)}{|A_1||A_3|} = 0.22 \pm 0.06$$

For the purpose of comparison we list in Table I the above quantities and those determined at 19 GeV/c, and at 6.92 GeV/c by Rushbrooke. The $I = 3/2$ cross sections decrease more rapidly with increasing beam momentum than do the $I = 1/2$ cross sections: whereas the ratio $|A_1|/|A_3|$ is consistent with 1.0 slightly below 7 GeV/c, it has risen to 1.8 at 19 GeV/c. The phase angle cosine [defined by eq. (3)] shows little change with increasing beam momentum, however.

In order to illustrate the invariant mass and four-momentum transfer dependence of the amplitudes defined in Eqs. (2) we show first in Figs. 1(a)–1(c) the $d\sigma/dM(N\pi)$ projections of $|A_3|^2, |A_1|^2$, and $\text{Re}(A_1^*A_3)$, respectively, as a function of $M(N\pi)$ in 40 MeV bins. Figure 1(a) indicates copious production of the $J^P = \frac{3^+}{2}$ $\Delta^{++}(1238)$ resonance with little or no significant structure at higher mass values. The $I = 1/2$ mass distribution [Fig. 1(b)] displays an enhanced region from threshold to 1.75 GeV: discernable peaks are seen near 1.45 and 1.65 GeV. We have reported on these $I = 1/2$ resonances in an earlier publication. Below 1.4 GeV the structure is similar to the $I = 1/2$ invariant mass distributions observed by the ABBCC collaboration in their study of $\pi^+p$ interactions at 8 and 16 GeV/c: The data show an excess near 1.3 GeV, which is well below the central mass value of the
first I = 1/2 πN resonance \(J^P = 1/2^+ \text{ N}(1470)\). The interference term \[\text{Re}(A_1^*A_3)\] plotted in Fig 1(c) is consistent with zero from 1.12 to 1.28 GeV and is positive elsewhere. This observation is opposite to that reported at 6.92 GeV/c; however, this discrepancy may be due in part to the values used for \(\sigma_3\) in Eq. (2): 2.54 mb at 6.6 GeV/c and 2.0 mb at 6.92 GeV/c. In any case, structure does exist in Fig. 1(c) but clearly more accurate data are required for serious studies.

The \(d\sigma/dt\) projections of \(|A_3|^2\) and \(|A_1|^2\) are given in Figs. 2(a)-2(d). The data are plotted vs. both \(t_1\) and \(t_2\) where \(-t_1\) is the four-momentum transfer squared from the appropriate incoming proton to the outgoing \(N_1\). The \(d\sigma/dt_1\) projections of \(|A_3|^2\) and \(|A_1|^2\) (Figs. 2(a) and 2(c), respectively) are markedly different. Figure 2(a) exhibits different behavior in three clearly defined regions of \(t_1\), where each behavior is mainly due to a different \(M(pn^+)\) region. Figure 2(a) is similar to the corresponding distribution observed at 19 GeV/c in that a break is seen near 0.7 GeV/c, however the break appears as a dip at 0.8 GeV at the higher beam momentum. The data in Fig. 2(c) decrease smoothly with \(t_1\) to 2.0 GeV, then fall off more rapidly. The \(d\sigma/dt_2\) projections of \(|A_3|^2\) and \(|A_1|^2\) (Figs. 2(b) and 2(d), respectively) both display a smooth drop-off with \(t_2\). The data in Figs. 2(b)-2(d) have been fit, using the least-squares method, to the function

\[
\frac{d\sigma}{dt} = Ae^{xt} + Be^{yt}.
\] (4)

The resulting confidence levels, as well as the best fit values of the parameters are listed in Table II. The small \(t\) behavior of each distribution in Figs. 2(b)-2(d) appears to be different, as evidenced by the differing values of the slope parameter \(x\). The \(y\) slope parameters are
similar in each case, however. This behavior was also observed at 19 GeV/c.5

Turning now to the question of the dominant exchange responsible for the \(|A_3|^2\) and \(|A_1|^2\) cross section, we have shown 10 that one-pion-exchange (OPE) is dominant in the reaction \(pp \rightarrow \Delta^{++}(1238)n\). In work in progress we have verified 11 that significant OPE contributions exist also at higher \(M(p\pi^+)^\) values. Thus we conclude that the \(|A_3|^2\) cross section is dominantly due to OPE, in agreement with Bøggild et al.5 In the case of the \(|A_1|^2\), it was shown earlier, 4 by means of energy independence arguments, that Pomeron exchange appears to be dominant at 19 GeV/c. If the \(I=1/2\) cross section is due mainly to Pomeron exchange at both 6.6 and 19 GeV/c, then the ratio of these cross sections should closely approximate the square of the ratio of the pp total cross sections, 12 (by the optical theorem) which is roughly \((41/39)^2 = 1.11\). From Table I we have \(|A_1|^2_{19}/|A_1|^2_{6.6} = 4.35/2.3 = 1.89 \pm 0.30\). The two ratios differ by roughly 2.5 standard deviations, indicating energy non-independence of \(|A_1|^2\) in going from 6.6 to 19 GeV/c. Therefore Pomeron exchange is not dominant in producing \(I = 1/2\ N\pi\) systems at 6.6 GeV/c. In fact, Rushbrooke 6 has shown, using the pp and pd data at 6.92 GeV/c, that the Pomeron-exchange contribution amounts to \((36^{+7}_{-11})\%\) of the total reaction amplitude.13 A similar calculation using our pp data (at 6.6 GeV/c) together with the 6.92 GeV/c pd data 6 indicates a 33% contribution.

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References and Footnotes

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8. Since pp interactions are peripheral at 6.6 GeV/c, the outgoing nucleons can be associated with the appropriate initial-state protons in nearly all cases.

9. The three regions of $t_1$ are approximately 0.05-0.7 GeV$^2$, 0.7-1.8 GeV$^2$, and 1.8-3.0 GeV$^2$. The dominant effects observed in these regions are associated with data for $M(p\pi^+)$ < 1.4 GeV, 1.4 < $M(p\pi^+)$ < 1.8 GeV and $M(p\pi^+)$ > 1.8 GeV, respectively.

11. Pole-extrapolation techniques applied to the reaction $pp \rightarrow (p\pi^+)n$, in order to determine the on-mass-shell $\pi^+p$ elastic scattering cross section, have yielded correct results up to $M(p\pi^+) = 2.02$ GeV.

12. If we invoke factorization and assume that the $N_2$ vertices are of the same type as exist in elastic scattering, then the total cross sections can be related to the $I = 1/2$ cross sections by the optical theorem.

13. The use of reactions (1) along with data for the process $pn \rightarrow pp\pi^-$ leads to a determination of the $I = 0$ exchange amplitude in $NN \rightarrow NN\pi$. See Ref. 6.
Table I. Isotopic spin cross section for the reactions $pp \rightarrow N_1 \pi N_2$ for different beam momenta.

| Momenta (GeV/c) | $|A_1|^2$ (mb) | $|A_3|^2$ (mb) | $\cos \phi_{13}$ | $|A_1|/|A_3|$ |
|----------------|---------------|----------------|------------------|----------------|
| 6.6            | 4.35±0.38     | 3.92±0.25      | 0.22±0.06        | 1.05±0.06      |
| 6.92\(^a\)     | 4.3±1.2       | 2.9±0.7        | 0.06±0.16        | 1.2±0.2        |
| 19\(^b\)       | 2.3±0.3       | 0.7±0.1        | 0.4±0.3          | 1.8±0.3        |

a. Reference 6  
b. Reference 4

Table II. Results of least-squares fits of the $d\sigma/dt$ distributions in Figs. 2(b)-2(d) to the form $Ae^{xt} + Be^{-yt}$.

| Distribution | Fit Quantity | $|A_3|^2$ [Fig. 2(b)] | $|A_1|^2$ [Fig. 2(c)] | $|A_1|^2$ [Fig. 2(d)] |
|--------------|--------------|-----------------------|-----------------------|-----------------------|
| t range (GeV\(^2\)) | 0.0-3.0      | 0.05-1.90             | 0.05-3.0              |
| confidence level (%) | 2            | 89                    | 6                     |
| A             | 18.2±1.4     | 5.7±0.9               | 16.4±1.4              |
| B             | 1.6±0.3      | 3.3±1.0               | 1.8±0.4               |
| x (GeV\(^-2\)) | -7.2±0.6     | -4.4±1.4              | -5.8±0.5              |
| y (GeV\(^-2\)) | -1.2±0.1     | -0.9±0.2              | -1.1±0.1              |
Figure Caption

Figure 1. $d\sigma/dM(N_1\pi)$ projections for $pp \rightarrow N_1\pi N_2$ at 6.6 GeV/c where $M(N_1\pi) < M(N_2\pi)$. (a) $|A_3|^2$; (b) $|A_1|^2$; (c) $Re(A_1^*A_3)$ where these quantities have been calculated using Eqs. (2).

Figure 2. $d\sigma/dt_1$ projections for $pp \rightarrow N_1\pi N_2$ at 6.6 GeV/c where $M(N_1\pi) < M(N_2\pi)$ and $-t_1$ is the four momentum transfer squared from the appropriate incoming proton to the outgoing $N_i$. (a)-(b) $t_1$ and $t_2$ projections of $|A_3|^2$, respectively; (c)-(d) $t_1$ and $t_2$ projections of $|A_1|^2$, respectively. $|A_3|^2$ and $|A_1|^2$ have been calculated using Eqs. (2).
FIGURE 2
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