Analysis of the Singlet and Triplet Contributions to the Total-Cross-Section Differences $\Delta\sigma_T$ and $\Delta\sigma_L$ in *p-p* Scattering between 1 and 3 GeV/*c*

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(Received 13 November 1979)

The data from measurements of the total-cross-section differences $\Delta\sigma_T$ and $\Delta\sigma_L$ for *p-p* scattering and the spin-averaged total cross sections are analyzed to determine the singlet (σ_s^T) and (σ_t^T) cross sections. The structures observed in $\Delta\sigma_T$ and $\Delta\sigma_L$ near 1.3 GeV/*c* are found to result primarily from increases in σ_s^T and σ_t^T. These increases are shown to be consistent with the Mandelstam model of pion production. No resonantlike behavior is required to describe the structures in $\Delta\sigma_T$ and $\Delta\sigma_L$.

PACS numbers: 13.75.Cs

Measurements of total-cross-section differences for proton-proton scattering in pure spin states, both transverse, $\Delta\sigma_T = (\sigma\uparrow\downarrow - \sigma\uparrow\uparrow)$,[1] and longitudinal, $\Delta\sigma_L = (\sigma\rightleftarrows - \sigma\rightrightarrows)$,[2] have exhibited momentum-dependent structure for proton laboratory momenta between 1 and 2 GeV/*c*. These data are illustrated in Fig. 1(a) with upright and inverted triangles. The structures, especially that in $\Delta\sigma_L$, have been the source of much discussion and have been interpreted[3,4] as indicating a $^3F_3$ dibaryon resonance near 1.5 GeV/*c*.

These cross-section differences, and the spin-averaged total cross section, σ_{tot}^T, can be expressed in terms of the imaginary part of the three helicity amplitudes evaluated at $t=0$ (Ref. 5):

$$\sigma_{\text{tot}}^T = (\pi/q^2)\,\text{Im}[\varphi_1(0)+\varphi_3(0)], \quad (1)$$

$$\Delta\sigma_T = (-2\pi/q^2)\,\text{Im}[\varphi_2(0)], \quad (2)$$

$$\Delta\sigma_L = (2\pi/q^2)\,\text{Im}[\varphi_1(0)-\varphi_3(0)]. \quad (3)$$

Here q is the center-of-mass proton momentum; φ_1, φ_2, and φ_3 are three of the five independent helicity amplitudes with the partial-wave expansions[6]

$$\varphi_1(0) = \sum_{J\text{ even}} \{(2J+1)R_J + JR_{J-1,J} + (J+1)R_{J+1,J} - 2[J(J+1)]^{1/2}R^J\}, \quad (4)$$

$$\varphi_2(0) = \sum_{J\text{ even}} \{-(2J+1)R_J + JR_{J-1,J} + (J+1)R_{J+1,J} - 2[J(J+1)]^{1/2}R^J\}, \quad (5)$$

$$\varphi_3(0) = \sum_{J\text{ even}} \{(J+1)R_{J-1,J} + JR_{J+1,J} + 2[J(J+1)]^{1/2}R^J\} + \sum_{J\text{ odd}}(2J+1)R_{JJ}. \quad (6)$$

With appropriate groupings, the three observables can be expressed in terms of three partial cross sections σ_s^T, σ_t^T, and σ_i^T:

$$\sigma_{\text{tot}}^T = \sigma_s^T + \sigma_t^T, \quad (7)$$

$$\Delta\sigma_T = 2(\sigma_s^T - \sigma_i^T), \quad (8)$$

$$\Delta\sigma_L = 2(\sigma_s^T + 2\sigma_i^T - \sigma_t^T), \quad (9)$$

where σ_s^T is the singlet contribution

$$\sigma_s^T = \sum_{J\text{ even}} \sigma_J, \quad (10)$$

σ_t^T is the triplet contribution

$$\sigma_t^T = \sum_{J\text{ even}} (\sigma_{J-1,J} + \sigma_{J+1,J}) + \sum_{J\text{ odd}} \sigma_{JJ}, \quad (11)$$

and σ_i^T is the contribution of the spin-triplet terms of even J and their interference I,

$$\sigma_i^T = \sum_{J\text{ even}} \left(\frac{J}{2J+1}\sigma_{J-1,J} + \frac{J+1}{2J+1}\sigma_{J+1,J} - I\right). \quad (12)$$

The partial cross sections are defined in terms of the amplitudes by

$$\sigma_j = (\pi/2q^2)(2j+1)2\,\text{Im}(R_j), \quad (13)$$

$$\sigma_{j\pm 1,j} = (\pi/2q^2)(2j+1)2\,\text{Im}(R_{j\pm 1,j}), \quad (14)$$

$$I = (\pi/2q^2)^2[j(j+i)]^{1/2}2\,\text{Im}(R^j). \quad (15)$$

With the data of Refs. 1 and 2 and σ_{tot}^T from Refs. 7 and 8, the points in Fig. 1(b) have been extracted for momenta at (or near) which data for the three cross sections exist. The points below 0.9 GeV/*c* have been calculated from the phase shifts of an analysis by Bugg *et al.*[9] of a data base which contains extensive spin-dependent observables. Additional points at 1.0, 1.1, and 1.3 GeV/*c*, plotted as open circles, were obtained by estimating values which yield a smooth momentum dependence for σ_s^T, σ_t^T, and σ_i^T, and reproduce

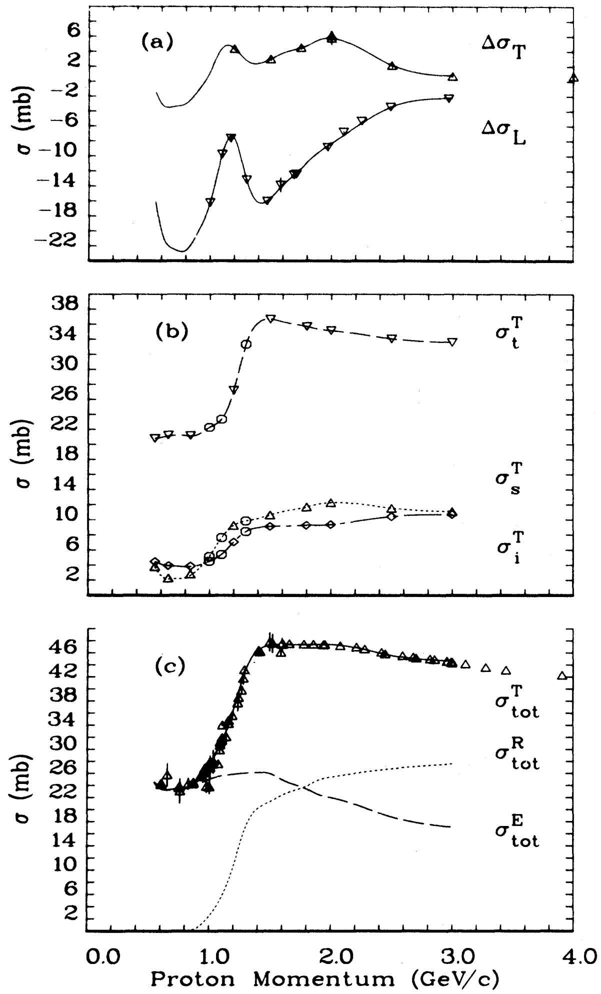

FIG. 1. The momentum dependence of (a) the cross-section differences $\Delta\sigma_T$ and $\Delta\sigma_L$ (the data are from Refs. 1 and 2; the curves are described in the text); (b) the singlet ($\sigma_s{}^T$), triplet ($\sigma_t{}^T$), and triplet-interference (σ^T) cross sections, as described in the text; (c) the spin-averaged total cross sections, $\sigma_{tot}{}^T$ (triangles), $\sigma_{tot}{}^E$ (dotted line), and $\sigma_{tot}{}^R$ (dashed line).

the values of $\sigma_{tot}{}^T$ and $\Delta\sigma_L$.

The three partial cross sections each exhibit an increase above 0.9 GeV/c, with the largest increase occuring in the triplet contribution $\sigma_t{}^T$. These increases are caused by the sharp rise in the spin-averaged ($\sigma_{tot}{}^T$) cross section near 1.2 GeV/c [Fig. 1(c)] which is primarily due to the increases in the cross sections for the three pion-production reactions $pp \to pp\pi^0$; $pn\pi^+$; and $d\pi^+$. It is suggestive that the structures observed in $\Delta\sigma_T$ and $\Delta\sigma_L$ between 1 and 2 GeV/c are caused by the momentum dependence of pion production from the initial singlet and triplet partial waves. It is interesting to note, however, that $\sigma_t{}^T$ rises faster than $\sigma_s{}^T$, which is counter to the intuition that the angular momentum barrier for the p-wave nucleon Δ would tend to inhibit the rapid turnon of inelasticity in the ${}^3P$ and ${}^3F$ partial waves, compared to the absence of such a barrier in the ${}^1D_2$ partial wave.

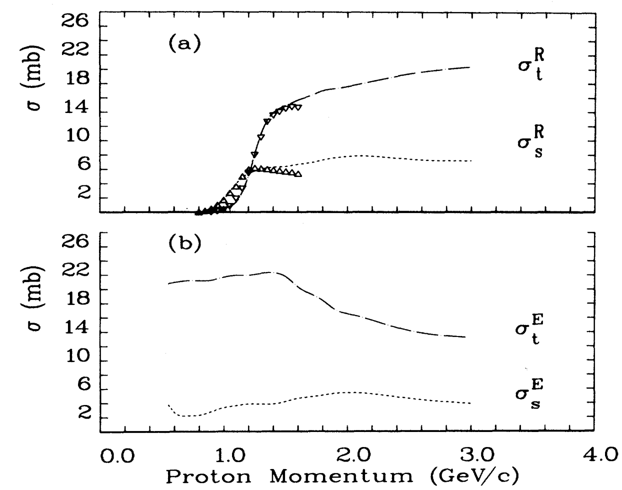

FIG. 2. The momentum dependence of (a) the inelastic cross sections $\sigma_s{}^R$ (dashed line) and $\sigma_t{}^R$ (dotted line), where symbols are results from Ref. 11; (b) the elastic cross sections $\sigma_s{}^E$ (dashed line) and $\sigma_t{}^E$ (dotted line).

To test the hypothesis that the pion-production channels are responsible for these observed increases, it is necessary to separate the cross sections of Fig. 1(b), $\sigma_x{}^T$ ($x = s, t, i$) into elastic ($\sigma_x{}^E$) and inelastic or reaction ($\sigma_x{}^R$) cross sections. A separation for $\sigma_s{}^T$ and $\sigma_t{}^T$ is obtained from the inelastic spin-averaged total cross sections $\sigma_{tot}{}^R$ and an assumed momentum dependence for $\sigma_s{}^R$ since $\sigma_{tot}{}^R = \sigma_s{}^R + \sigma_t{}^R$, $\sigma_x{}^T = \sigma_x{}^E + \sigma_x{}^R$, and $\sigma_{tot}{}^T = \sigma_{tot}{}^E + \sigma_{tot}{}^R$. The spin-averaged total inelastic cross sections are well determined from threshold to near 1.3 GeV/c and are taken from Ref. 7. Above this momentum, values for $\sigma_{tot}{}^R$ have been taken from Ref. 10.

The momentum dependence illustrated by the dashed curve in Fig. 2(a) for the singlet reaction of the analysis of single-pion production by Mandelstam[11] from threshold to 1.2 GeV/c. Above 1.2 GeV/c the momentum dependence was taken to be that of $\sigma_s{}^T$. With this curve, and the curves for $\sigma_s{}^T$, $\sigma_t{}^T$, and $\sigma_i{}^T$, and $\sigma_{tot}{}^R$ illustrated in Figs. 1(b) and 1(c), all the remaining curves of Figs. 1 and 2 are determined via the above relationships. The curves in Fig. 1(b) represent smooth interpolations between the points. Note that the sharp rise in the resulting inelastic triplet cross sections ($\sigma_t{}^R$) in Fig. 2(a) coincides with that of the total triplet cross sections (σ_t^T) in Fig. 1(b). The elastic singlet (σ_s^E) and triplet (σ_t^E) cross sections illustrated in Fig. 2(b) show no dramatic momentum dependence. Small increases do occur in the regions where the inelastic cross sections are increasing rapidly reflecting the unitarity coupling of the elastic and inelastic channels as indicated in the calculations of Kloet and Silbar.[12]

In Fig. 2(a) the upright and inverted triangles refer to the results of Mandelstam for pion production from initial singlet and triplet partial waves, respectively, and are taken from graphs contained in Ref. 11. The agreement with the momentum dependence of the inelastic cross sections which provide the increases in σ_s^T and σ_t^T in the region from threshold to near 1.4 GeV/c is impressive. Above 1.4 GeV/c the assumptions in Mandelstram's analysis are no longer expected to be valid,[13] and double-pion production must also be considered.

The important consideration is that the Mandelstam model predicts that the singlet partial waves produce pions at a lower momenta than do the triplet partial waves. Recall in this model that pion production occurs through an intermediate nucleon-delta (N-Δ) system in either an "s or p state", where Δ is the $T=\frac{3}{2}$, $J^\pi=\frac{3}{2}^+$, 1232-MeV pion-nucleon resonance. The "s state" which has $J^\pi=2^+$ is formed only by the $l=2$ initial singlet partial wave; the "p state" with $J^\pi=0^-$, 1^-, 2^-, or 3^- is formed by $l=1$ or 3 initial triplet partial waves.

A crucial test of the momentum dependence of the inelastic cross sections of Fig. 2(a) would lie in a complete energy-dependent phase-shift analysis which includes the $\Delta\sigma_T$ and $\Delta\sigma_L$ data and constrains the elasticities to reproduce the cross sections proposed here. Arik and Williams[14] have performed an analysis at 1.26 and 1.66 GeV/c were constrained to those of Amaldi *et al.*[15]; at 1.66 GeV/c the elasticities in the low partial waves were allowed to vary. The resulting inelastic singlet and triplet cross sections at 1.66 GeV/c were 6.57 and 16.3 mb, respectively. Bugg[16] has performed additional phase-shift analyses on the data at 0.99 and 1.10 GeV/c of Ref. 9. With $\Delta\sigma_L$ included in the data base, the resulting inelastic singlet and triplet cross sections are 1.52 and 0.06 mb at 0.99 GeV/c, and 4.07 and 1.40 mb at 1.1 GeV/c. These values are in excellent agreement with those of Fig. 2(a).

In summary, the structures observed in $\Delta\sigma_T$ and $\Delta\sigma_L$ between 1 and 2 GeV/c are due to increases in singlet, triplet, and triplet-interference cross sections occurring at differing momenta. Theoretical calculations should attempt to reproduce these cross sections as illustrated in Fig. 1(b) rather than the cross-section differences which are very sensitive to small changes in the momentum dependence of the sharp increases in the cross sections.

A separation into elastic and inelastic contributions to the singlet and triplet cross sections has been proposed which easily accomodates the data and is in close agreement with the analysis of Mandelstam[11] for single-pion production, and in agreement with phase-shift analyses[14,16] at 0.99, 1.10, and 1.66 GeV/c. With the proposed interpretation of the data, no resonant behavior is required to describe the structures observed in $\Delta\sigma_T$ and $\Delta\sigma_L$ between 1 and 2 GeV/c. These structures result primarily from pion production through the N-Δ system in a relative angular momentum state of $L=0$ being initiated at lower momenta than when the N-Δ is in a relative angular momentum state of $L=1$.

The author would like to acknowledge valuable discussions with B. E. Bonner, W. R. Gibbs, R. Ransome, and P. J. Riley. This work was supported in part by the U. S. Department of Energy.

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Excitation of Unnatural-Parity States in ^{12}C by 800-MeV Polarized Protons

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(Received 28 February 1980)

Cross sections and analyzing powers have been measured for 800-MeV proton inelastic transitions to unnatural-parity states in ^{12}C. Data for the 15.11-MeV 1^+, $T=1$ state are well explained by a distorted-wave impulse-approximation calculation based on proton-neutron charge-exchange cross sections. Negative analyzing powers were observed for the first time at 800 MeV, for the 12.71-MeV 1^+, $T=0$ state. Values of A_y appear to be characteristic of the isospin transfer, and support isospin assignments for states at 18.3 and 19.4 MeV.

PACS numbers: 25.40.Ep, 24.70.+s, 25.40.Rb, 27.20.+n

Recent nucleon-nucleon experiments suggest that spin-dependent terms in the proton-proton scattering amplitude are significant around 800 MeV,[1] yet previous evidence for excitation of unnatural-parity states in inelastic proton scattering in this energy region is scant.[2,3] These levels with parity $(-1)^{J+1}$ require a spin transfer, ΔS, of 1; first-order excitation of such states thus depends entirely on the spin-dependent terms. Here we report differential cross sections to low-spin unnatural-parity states in ^{12}C which are comparable in magnitude to those observed at much lower energies. In addition, large negative values of the analyzing power, A_y, have been seen for the first time at 800 MeV; the magnitude of A_y appears characteristic of the isospin transfer.

Angular distributions of $d\sigma/d\Omega$ and A_y were measured with the 800-MeV polarized beam at the Clinton P. Anderson Meson Physics Facility with use of the High Resolution Spectrometer. Scattered particles were detected in an array of drift chambers and scintillation detectors that have been described previously.[4] Energy resolution was generally about 120 keV. Data in several angle bins were summed to give an angular resolution of 0.34° for most of the data shown. Absolute cross sections accurate to ± 15% were determined by comparison with previous elastic scattering data for ^{12}C.[4] The transverse polarization of the beam was monitored continuously with a hydrogen polarimeter; it averaged about 0.75.

A spectrum taken at 2.3° with a spin-down incident beam is shown in Fig. 1. With the exception of the highly collective 4.44-MeV 2^+ state, the unnatural-parity transitions to the states at 12.71 MeV ($1^+, T=0$) and 15.11 MeV ($1^+, T=1$) dominate the spectrum. The two strong states at 18.3 and 19.4 MeV are also apparently unnatural-parity transitions. A state at 19.4 MeV has been identified in electron scattering as a 2^-, $T=1$ state.[5] States at these energies observed in pion scattering have been tentatively assigned 2^-, $T=0$ and 2^-, $T=1$, respectively, but with considerable isospin mixing.[6] Many other states have also been observed in this energy region.[7] At larger angles, the ^{12}C spectrum is dominated by natural-parity states.

The angular distributions for the two 1^+ states are noticeably different from each other, as shown in Fig. 2. Both, however, ar similar to the corresponding data at 122 MeV.[8] The absolute cross sections for the two states are each within a factor of 2 of the 122-MeV values; the 800-MeV values are mostly larger. For the $T=1$ state, A_y is close to zero (as it is also for the $\Delta T=1$, $\Delta S=1$ transition in ^6Li measured in the same experiment). The $T=0$ state, however, has a significantly negative A_y at small momentum transfer, in contrast to the uniformly positive