Failure of s-Channel Helicity Conservation in A_1^- Production*

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A study of the A_1^- density-matrix elements shows that s-channel helicity is not conserved in the process $\pi^-p \to A_1^-p$ between 5 and 25 GeV/c. Instead the A_1^- density-matrix elements have simple behavior in the t-channel helicity frame. A new analysis of the A_1^- cross section as a function of the incident π^- momentum is also presented.

The conservation of s-channel helicity for squares of momentum transfer less than 0.4 (GeV/c)^2 in ρ^0 photoproduction has recently been reported.[1] In the reaction $\gamma p \to \rho^0 p$ at 2.8 and 4.7 GeV/c, it was shown that the ρ^0 maintained the polarization of the photon with its spin aligned along its direction of motion. Gilman, Pumplin, Schwimmer, and Stodolsky[2] have suggested that s-channel helicity conservation may be a general property of diffractive processes. In particular, if s-channel helicity is conserved in the process $\pi N \to A_1 N$, then the A_1 meson should be produced with spin component equal to zero along its direction of motion in the overall center-of-mass system. The A_1 density matrix element ρ_{00} should therefore be equal to 1 in the s-channel helicity frame and the other A_1 density-matrix elements should be equal to zero.

We have investigated the question of s-channel helicity conservation for the reaction $\pi^-p \to A_1^-p$ at incident π^- momenta ranging from 5 to 25 GeV/c.[3-9] The data for our analysis come from

Table I. List of experiments with the number of $\pi^- p \to p\pi^+\pi^-\pi^-$ events at each momentum.

Momentum (GeV/c)	No. of events	Group
5	14134	University of Illinois (Refs. 3,4)
7	5483	Toronto-Wisconsin (Ref. 5)
7.5	10904	University of Illinois (Ref. 4)
11	3403	Genova-Hamburg-Milano-Saclay (Ref. 6)
13	2150	Harvard University (Ref. 7)
20	3680	Harvard University (Ref. 7)
25	2119	University of Wisconsin (Ref. 8)

the reaction $\pi^- p \to p\pi^+\pi^-\pi^-$ observed in hydrogen bubble chambers. In Table I we have listed the various experiments from which the data have been obtained and the number of events at each momentum. A partial-wave decomposition of the 3π system produced in this reaction has shown that there is a strong spin and parity 1^+ component in the 3π mass region 1.0 to 1.4 GeV.[4,9] In particular, the spin and parity 1^+ dominates the 3π system in the 1.0- to 1.2-GeV mass interval. In what follows we define the A_1^- to be the spin and parity 1^+ component of the 3π system in the 1.0- to 1.2-GeV mass region. With this mass definition the non-1^+ contributions are small and we can therefore study the A_1^- qualitatively by examining the decay angular distributions for all 3π events. After this qualitative investigation, we make a quantitative determination of the 1^+ density-matrix elements, and we use these results to decide the question of s-channel helicity conservation for A_1^- production. We find that s-channel helicity is not conserved in the reaction $\pi^- p \to A_1^- p$. We find instead that the A_1^- density-matrix elements remain simpler in the t-channel helicity (Gottfried-Jackson) frame; that is, in this reference frame the helicity-0 state dominates and the A_1^- density-matrix elements are independent of Δ^2 and incident π^- momentum.

We have examined the decay of the A_1^- in both the t-channel helicity (Gottfried-Jackson) and s-channel helicity frames. We use the standard definitions of the coordinate axes in the 3π rest system for these two frames. For the t-channel helicity frame, the z axis points along the incident π^- momentum and the y axis is along the normal to the production plane (cross product of the outgoing proton momentum with the incident π^- momentum). For the s-channel helicity frame, the z axis points opposite to the direction of the outgoing proton momentum and the y axis is again along the normal to the production plane.

The two coordinate systems therefore differ by a rotation about the y axis. The rotation angle is 0° for $\Delta^2 = \Delta_{min}^2$ and hence near $(\Delta^2)' \equiv \Delta^2 - \Delta_{min}^2 = 0$ we expect the results for the two frames to be identical; for $(\Delta^2)'$ near 0.4 $(\text{GeV}/c)^2$ the rotation angle is about 60° and we expect significant differences.

If s-channel helicity is conserved in the reaction $\pi^- p \to A_1^- p$, then the A_1^--decay angular distributions in the s-channel helicity frame must have the properties of a 1^+ state with z component of spin equal to 0 decaying into three pions. We have therefore examined the polar and azimuthal angular distributions of the π^+ in the s-channel and t-channel helicity frames for all 3π events in the mass region 1.0-1.2 GeV. Events with $p\pi^+$ mass in the N^{*++} (1.16-1.32 GeV) region have been excluded.

In Fig. 1, the distribution of the π^+ azimuthal angle φ is shown for the two frames for the $(\Delta^2)'$

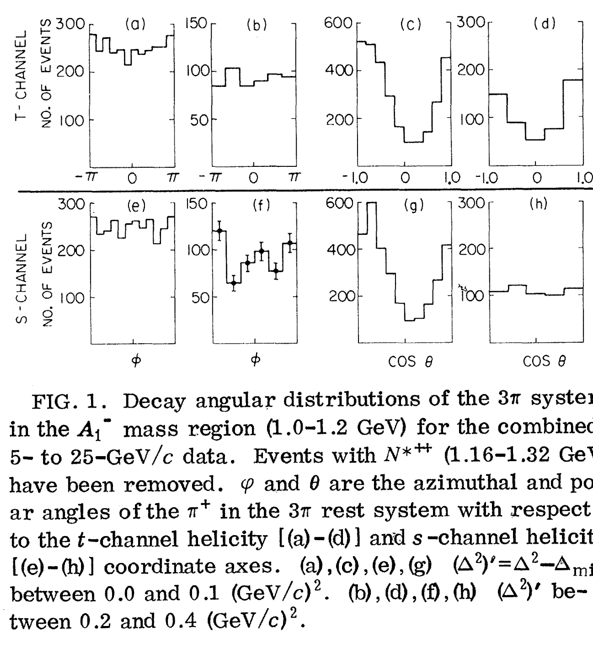

FIG. 1. Decay angular distributions of the 3π system in the A_1^- mass region (1.0-1.2 GeV) for the combined 5- to 25-GeV/c data. Events with N^{*++} (1.16-1.32 GeV) have been removed. φ and θ are the azimuthal and polar angles of the π^+ in the 3π rest system with respect to the t-channel helicity [(a)-(d)] and s-channel helicity [(e)-(h)] coordinate axes. (a),(c),(e),(g) $(\Delta^2)' = \Delta^2 - \Delta_{min}^2$ between 0.0 and 0.1 $(\text{GeV}/c)^2$. (b),(d),(f),(h) $(\Delta^2)'$ between 0.2 and 0.4 $(\text{GeV}/c)^2$.

intervals 0.0-0.1 and 0.2-0.4 $(\mathrm{GeV}/c)^2$. The φ distribution should be isotropic for a 1^+ state with z component of spin equal to 0. We see that this is the case for both the t-channel and s-channel helicity frames for $(\Delta^2)'$ between 0.0 and 0.1 $(\mathrm{GeV}/c)^2$. For the 0.2- to 0.4-$(\mathrm{GeV}/c)^2$ $(\Delta^2)'$ interval, however, the φ distribution in the s-channel helicity frame is not isotropic while that for the t-channel frame is consistent with being isotropic.

Figure 1 also shows the $\cos\theta$ distribution for the π^+, where θ is the polar angle of the π^+. The $\cos\theta$ distribution for a 1^+ S state with z component of spin equal to 0 should have an approximate $\cos^2\theta$ behavior.[9] The $\cos\theta$ distribution in both frames exhibits an approximate $\cos^2\theta$ behavior for $(\Delta^2)'$ between 0.0 and 0.1 $(\mathrm{GeV}/c)^2$. (The asymmetry in the $\cos\theta$ distribution is primarily due to the interference of the 0^- and 1^+ states.) For the 0.2- to 0.4-$(\mathrm{GeV}/c)^2$ $(\Delta^2)'$ interval, however, the approximate $\cos^2\theta$ behavior is maintained in the t-channel helicity frame whereas the s-channel helicity $\cos\theta$ distribution has departed from this behavior, having in fact become isotropic. Thus the decay angular distributions in the 3π mass region 1.0 to 1.2 GeV indicate a breakdown of s-channel helicity conservation in A_1^- production.

One may perhaps be tempted to dismiss the conclusions drawn above from the 3π decay angular distributions and to attribute the observed effects to contributions from J^P states other than 1^+, to the interference between states of different spins and parities, or to the N^{*++} cut. We can avoid these difficulties by using a partial-wave analysis method which properly takes into account all of these effects and isolates the spin and parity 1^+ component of the 3π system.

We have therefore made a partial-wave analysis of the 3π system in the manner described previously for the A_2^- in the University of Illinois data.[4,9] In this analysis, the 3π system is decomposed into contributions from several J^P and J_z states. (The possibility of interference between states of different spins and parities is also taken into account.) For each spin and parity state we consider decay into $\pi\rho$ and $\pi\epsilon$ with all possible orbital angular momenta allowed by parity and angular momentum conservation. The ϵ is taken here to be a 0^+ $(\pi^+\pi^-)$ system with mass 765 MeV and width 400 MeV.[9] In the 3π mass region 1.0 to 1.2 GeV, we find that an adequate fit is obtained by including the J^P states 0^-, 1^+, 2^-, and 2^+, with the spin and parity 1^+ accounting for 75% of the events.[10] In both the experimental data and the theoretical expressions, events in the interval corresponding to N^{*++} ($p\pi^+$ mass between 1.16 and 1.32 GeV) were excluded. The relevant results of our partial-wave analysis with regard to the question of s-channel helicity conservation are contained in the density-matrix elements for the A_1^-, the spin and parity 1^+ component of the 3π system in the mass region 1.0 to 1.2 GeV.[11]

The A_1^- density-matrix elements are given in Table II as a function of $(\Delta^2)'$ for the t-channel and s-channel helicity frames for both the "low-energy" data (sum of 5-, 7-, and 7.5-GeV/c) and the "high-energy" data (sum of 11-, 13-, 20-, and 25-GeV/c).[12] If s-channel helicity is conserved in A_1^- production, then ρ_{00} in the s-channel helicity frame must be equal to 1 and all other A_1^- density-matrix elements must be equal to 0. We see that this is not even approximately true for $(\Delta^2)'$ between 0.1 and 0.4 $(\mathrm{GeV}/c)^2$. In particular, for the 0.2- to 0.4-$(\mathrm{GeV}/c)^2$ $(\Delta^2)'$ interval, ρ_{00} is approximately equal to 0.44 for both the "low-energy" and "high-energy" data and the deviation from 1 in both cases is significant. It is important to note that both ρ_{00} and $\mathrm{Re}\rho_{10}$ in the s-channel helicity frame show that there is no trend towards s-channel helicity con-

Table II. A_1^- density matrix elements.

		t-channel helicity frame $\Delta^2-\Delta_{min}^2$			s-channel helicity frame $\Delta^2-\Delta_{min}^2$		
		0.0–0.1 $(\mathrm{GeV}/c)^2$	0.1–0.2 $(\mathrm{GeV}/c)^2$	0.2–0.4 $(\mathrm{GeV}/c)^2$	0.0–0.1 $(\mathrm{GeV}/c)^2$	0.1–0.2 $(\mathrm{GeV}/c)^2$	0.2–0.4 $(\mathrm{GeV}/c)^2$
ρ_{00}	Low-energy[a]	0.94 ± 0.02	0.93 ± 0.05	0.87 ± 0.07	0.89 ± 0.02	0.74 ± 0.03	0.41 ± 0.06
ρ_{00}	High-energy[b]	0.96 ± 0.05	0.95 ± 0.12	0.98 ± 0.20	0.94 ± 0.05	0.77 ± 0.08	0.46 ± 0.13
$\mathrm{Re}\rho_{10}$	Low-energy	-0.08 ± 0.01	-0.13 ± 0.02	-0.09 ± 0.03	0.16 ± 0.01	0.28 ± 0.02	0.31 ± 0.04
$\mathrm{Re}\rho_{10}$	High-energy	-0.10 ± 0.02	-0.13 ± 0.04	-0.06 ± 0.07	0.15 ± 0.02	0.28 ± 0.05	0.35 ± 0.08

[a]Low energy is the sum of the 5-, 7-, and 7.5-GeV/c data.
[b]High energy is the sum of the 11-, 13-, 20-, and 25-GeV/c data.

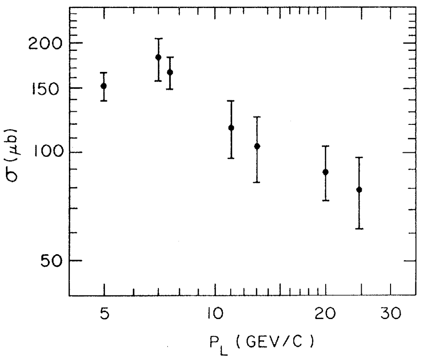

FIG. 2. The cross section for the reaction $\pi^- p \to A_1^- p$ as a function of the incident π^- momentum with the A_1^- as defined in the text. The cross sections have not been corrected for unseen decay modes of the A_1^-.

servation with increasing momentum. We therefore find that s-channel helicity is not conserved in the process $\pi^- p \to A_1^- p$. We see instead that the A_1^- density-matrix elements remain simpler in the t-channel helicity frame with $\rho_{00} \sim 0.9$ and $\mathrm{Re}\rho_{10} \sim -0.1$ independent of Δ^2 and incident π^- momentum. In the t channel, the helicity-0 state dominates and $\mathrm{Re}\rho_{10}$, although small, is significantly different from 0.

We have determined the A_1^- cross section at each incident π^- momentum using the number of A_1^- events[13] determined by the partial-wave analysis and the cross sections for the reaction $\pi^- p \to p\pi^+\pi^-\pi^-$. Figure 2 gives the cross section for the reaction $\pi^- p \to A_1^- p$ as a function of the incident π^- laboratory momentum.[14] The cross section, $\sigma(A_1^-)$, falls off slowly with increasing laboratory momentum p_L. If we parametrize this dependence with the form $\sigma(A_1^-) \propto p_L^{-N}$, then we obtain a value for N of 0.42 ± 0.11.[15]

In conclusion, we have shown that s-channel helicity is not conserved in the process $\pi^- p \to A_1^- p$ for incident π^- momenta between 5 and 25 GeV/c. We find no trend toward s-channel helicity conservation with increasing incident π^- momentum. We find instead that the A_1^- density matrix elements are simpler in the t-channel helicity frame with $\rho_{00} \sim 0.9$ and $\mathrm{Re}\rho_{10} \sim -0.1$ independent of Δ^2 and incident π^- momentum.

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[10]The percentage of events with spin and parity 1^+ is found to be roughly 75% independent of incident beam momentum and $(\Delta^2)'$ [up to $(\Delta^2)' = 0.4$ (GeV/c)^2] within the statistical errors. The other important spin and parity component, $J^P = 0^-$, is also found to be peripherally produced. The contribution of the spins and parities 2^- and 2^+ in the 3π mass region 1.0 to 1.2 GeV is small and their removal from the fit does not affect any of our results. These states are important above 1.2 GeV and were included in our analysis of the A_1^- in this region. (A study of the spin and parity 1^+ in the 3π mass region 1.2 to 1.4 GeV shows that our results concerning the question of s-channel helicity conservation for A_1^- production are not 3π-mass dependent.) The spin and parity 1^- has previously been shown to be insignificant in the 1.0- to 1.4-GeV mass region (see Refs. 4 and 9). The 1^+ state decays predominantly into $\pi\rho$ via S wave. If we remove the $\pi\epsilon$ decay mode (approximately 20% of the total 1^+), our results concerning the question of s-channel helicity conservation are not affected although the fit to the data becomes poorer.

[11]See comment on mass dependence in Ref. 10.

[12]We have considered only $(\Delta^2)'$ up to (0.4 GeV/c)^2 since there are very few events for larger $(\Delta^2)'$. The A_1^- density-matrix element ρ_{1-1} is equal to $-\rho_{11}$ within errors and $\mathrm{Im}\rho_{10}$ is equal to zero within errors for both the s-channel and t-channel helicity frames. These statements are true independent of $(\Delta^2)'$ and incident π^- momentum.

[13]The A_1^- is again defined as the 1^+ component of the 3π system in the mass region 1.0 to 1.2 GeV. We have further imposed the restriction $(\Delta^2)' < 0.7$ (GeV/c)^2.

[14]We attribute the apparent rise in the A_1^- cross section between 5 and 7.5 GeV/c to statistics or possible systematic errors in the absolute cross-section normalization. K. Paler [Nucl. Phys. B18, 211 (1970)] has shown that the A_1^- cross section is falling between 2.7 and 8.0 GeV/c. We find a reasonable χ^2 for the fit to the A_1^- cross section as described in the text.

[15]A simple model assuming "Pomeranchukon" and "meson" exchange would give a dependence for $\sigma(A_1^-)$ of the form $A + B/p_L$. If we were to adopt such a model, we would assign approximately 71% of the "high-energy" A_1^- cross section to "Pomeranchukon" exchange compared to 48% for the "low-energy" A_1^-. We do not see, however, any trend towards s-channel helicity conservation in going from the "low-energy" to the "high-energy" data. As noted above, the A_1^- density-matrix elements are independent of the incident π^- momentum.