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Spin dependence of matter creation in hadron collisions

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First measurements of pion production on polarized targets in reactions $\pi^+ n_\uparrow \to \pi^+\pi^- p$ and $K^+ n_\uparrow \to K^+\pi^- p$ at 6 and 12 GeV/c and in $\pi^- p \to \pi^-\pi^+ n$ at 17.2 GeV/c provide direct information on the momentum-transfer evolution of dimeson-mass dependence of moduli squared of production amplitudes for dimeson masses below 1000 MeV and $-t \lesssim 0.6$ (GeV/c)^2. We observe significant and complex dependence of pion production processes on nucleon spin and dimeson helicity, with unexpected structures near resonant masses.

The conversion of kinetic energy of colliding hadrons into the matter of produced hadrons is a remarkable process that is characterized by conservation of total four-momentum and quantum numbers such as electric charge, baryon number, and strangeness. The comparison of total cross sections shows that this conversion process depends on the flavor content of colliding hadrons. Also, the multiplicities of produced hadrons show asymmetries in produced flavors. The question arises whether the creation of hadrons depends on spin states of colliding hadrons, and whether the produced states exhibit single-particle and multiparticle spin polarizations.

Recent experiments provided important evidence for spin dependence in hadron production processes. The total cross sections for pp scattering with parallel and antiparallel spin states show large differences[1-3] below 12 GeV/c. Measurements of these cross sections at 200 GeV/c are now in progress at Fermilab.[4] Hyperons produced with proton or meson beams show large polarization[5] at high values of Feynman x. Some polarization transfer was observed in production of Λ^0 and Σ^0 with polarized proton beams.[6-8] Dependence of cross sections on initial nucleon spin in inclusive production of mesons was found in measurements using polarized proton beams[9-13] or targets.[13-15] Significant dependence of particle production on nucleon spin was found also in deep-inelastic scattering of polarized charged leptons from polarized nucleon targets.[16-18]

At the other end of reaction complexity are single-pion production processes $\pi N_\uparrow \to \pi\pi N$ and $KN_\uparrow \to K\pi N$ on polarized nucleon targets. Such measurements are of special interest because they permit the study of spin dependence of pion creation directly on the level of production amplitudes. In this Brief Report, we present the first look at the moduli of production amplitudes in these two reactions for dimeson masses $m \lesssim 1$ GeV as a function of momentum transfer for $-t \lesssim 0.6$ (GeV/c)^2. Large and unexpected spin effects are observed.

Our work is based on the first measurements of $\pi^+ n_\uparrow \to \pi^+\pi^- p$ and $K^+ n_\uparrow \to K^+\pi^- p$ at 6 and 12 GeV/c and $\pi^- p_\uparrow \to \pi^-\pi^+ n$ at 17.2 GeV/c made at CERN.[19-22] For masses below 1 GeV the dimeson system is produced predominantly in spin states with $J=0$ (S wave) and $J=1$ (P wave). The experiments yield 15 spin-density-matrix (SDM) elements describing the dimeson angular distribution. These observables and $d^2\sigma/dt\,dm \equiv \Sigma$ can be expressed in terms of two S-wave and six P-wave nucleon transversity amplitudes[21] (NTA). In our normalization

$$|S|^2+|\bar S|^2+|L|^2+|\bar L|^2+|U|^2+|\bar U|^2+|N|^2+|\bar N|^2=1 ,$$

where $A=S,L,U,N$ and $\bar A=\bar S,\bar L,\bar U,\bar N$ are normalized amplitudes with recoil nucleon transversity "down" and "up" relative to the scattering plane. The S-wave amplitudes are S and $\bar S$. The P-wave amplitudes $L,\bar L$ have dimeson helicity $\lambda=0$ while the pairs $U,\bar U$ and $N,\bar N$ are combinations of amplitudes with helicities $\lambda=\pm 1$ and have opposite t-channel-exchange naturality.

We now focus on a subset of SDM elements consisting of pairs $(\rho_{ss}+\rho_{00}+2\rho_{11}, \rho_{ss}^y+\rho_{00}^y+2\rho_{11}^y)$, $(\rho_{00}-\rho_{11}, \rho_{00}^y-\rho_{11}^y)$, and $(\rho_{1-1}, \rho_{1-1}^y)$. We have shown elsewhere[20,21] how linear combinations of these observables determine the following combinations of moduli squared of NTA:

$$\begin{gathered} |L|^2+\tfrac{1}{3}|S|^2,\quad |U|^2+\tfrac{1}{3}|S|^2,\quad |\bar N|^2+\tfrac{1}{3}|S|^2 , \\ |\bar L|^2+\tfrac{1}{3}|\bar S|^2,\quad |\bar U|^2+\tfrac{1}{3}|\bar S|^2,\quad |N|^2+\tfrac{1}{3}|\bar S|^2 . \end{gathered} \tag{1}$$

Results (1) can be taken as upper bounds on moduli squared of P-wave NTA. The lower bounds are obtained by subtracting from each term in (1) an upper bound on $\frac{1}{3}|S|^2$ or $\frac{1}{3}|\bar S|^2$. Since amplitudes $S,\bar S,N,\bar N$ are invariant under s-to-t-channel helicity-frame transformation, we calculate in each (t,m) bin

$$\left(\tfrac{1}{3}|S|^2\right)_{\text{upper}} = \min_{\substack{A=L,U \\ s \text{ and } t}} \left\{ |A|^2+\tfrac{1}{3}|S|^2,\ |\bar{N}|^2+\tfrac{1}{3}|S|^2 \right\} ,$$

$$\left(\tfrac{1}{3}|\bar{S}|^2\right)_{\text{upper}} = \min_{\substack{A=L,U \\ s \text{ and } t}} \left\{ |\bar{A}|^2+\tfrac{1}{3}|\bar{S}|^2,\ |N|^2+\tfrac{1}{3}|\bar{S}|^2 \right\} . \qquad (2)$$

The obtained bounds are most restrictive for the *P*-wave moduli and reveal useful information about their behavior.

In Fig. 1 we present the t evolution of m dependence of moduli squared of NTA in $\pi^+ n_\uparrow \to \pi^+\pi^- p$ at 5.98 GeV/c together with the results for $\pi^- p_\uparrow \to \pi^-\pi^+ n$ at 17.2 GeV/c at $t=-0.068$ (GeV/c)^2. Each column shows the dependence of pion production on the recoil nucleon transversity for a fixed spin J, helicity λ and exchange naturality σ of the $\pi^+\pi^-$ state.

The column with $|\bar{L}|^2$ and $|L|^2$ describes the production of $\pi^+\pi^-$ state with $J=1$, $\lambda=0$, $\sigma=-1$. The nucleon transversity "up" amplitude $|\bar{L}|^2$ dominates this production at small t but it decreases with t. This decrease is accompanied by unexpected structures near ρ^0 mass indicating a complex dependence of π^- production on nucleon spin. The next two columns describe $\pi^+\pi^-$ production with $J=1, |\lambda|=1$ for the unnatural ($\sigma=-1$) and natural ($\sigma=+1$) exchange, respectively. The natural-exchange transversity "up" amplitude $|\bar{N}|^2$ is suppressed for $-t \lesssim 0.3$ (GeV/c)^2 but it rapidly increases and dominates pion production at $t \approx -0.55$ (GeV/c)^2. This rise is again accompanied by a remarkably complex dependence on nucleon spin near ρ^0 mass. The equality $|N|^2 \approx |\bar{N}|^2$ at $t \approx -0.45$ (GeV/c)^2 seen at ρ_0 mass is observed also in KN charge exchange.[23] However, the rapid changes of the ratio $|N|^2/|\bar{N}|^2$ as a function of dipion mass at larger $-t$ is entirely unexpected.[20] The bounds on *S*-wave amplitudes suggest that $J=0$ production proceeds predominantly with nucleon transversity "up" at small t. The $J=0$ production is suppressed for masses below 600 MeV at larger momentum transfer $t \approx -0.55$ (GeV/c)^2 where $J=1$ amplitudes dominate.

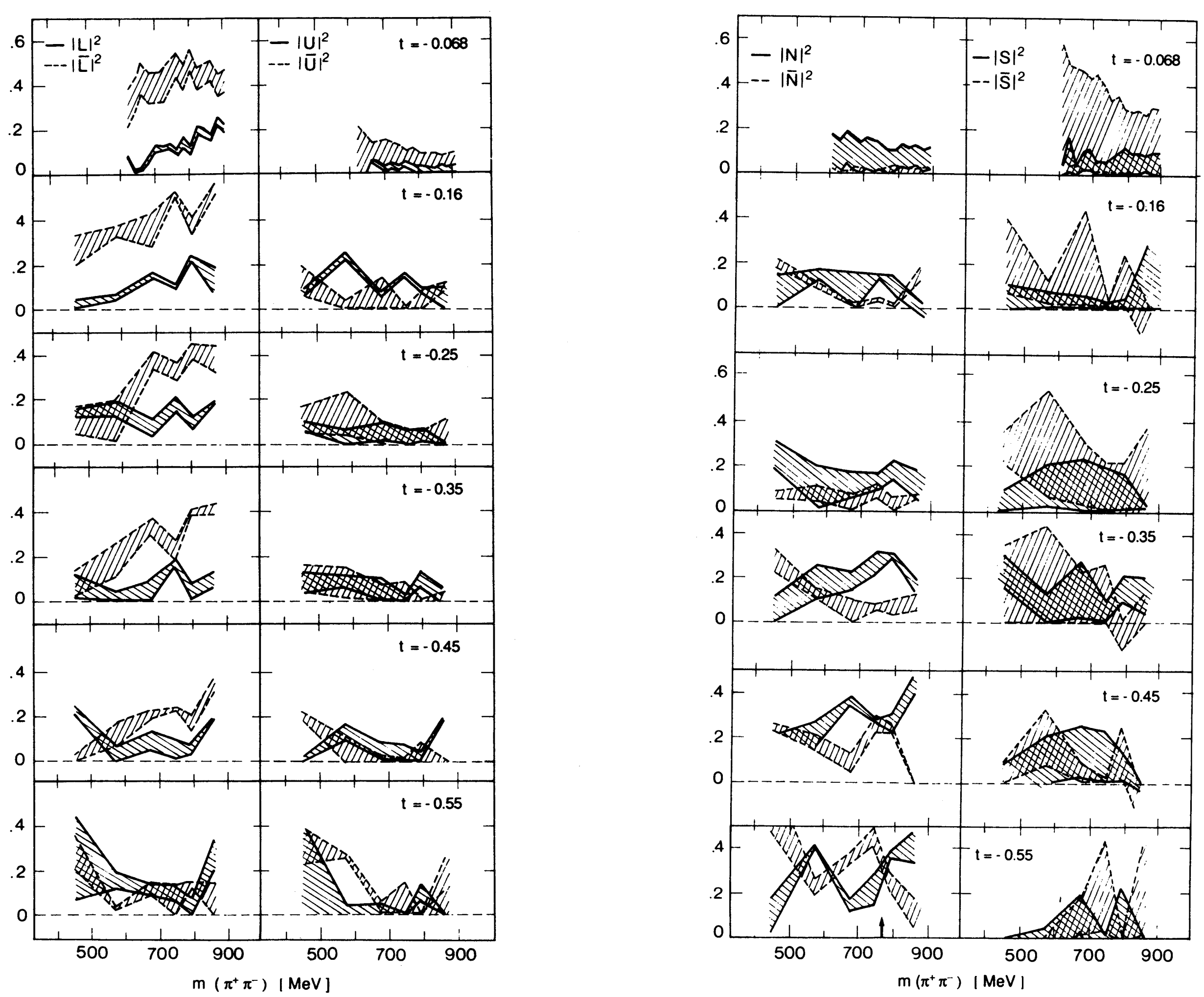

FIG. 1. The t evolution of mass dependence of moduli squared of t-channel normalized nucleon transversity amplitudes in $\pi^+ n_\uparrow \to \pi^+\pi^- p$ at 5.98 GeV/c together with the results for $\pi^- p_\uparrow \to \pi^-\pi^+ n$ at 17.2 GeV/c at $t=-0.068$ (GeV/c)^2.

The results for $\pi^+ n_\uparrow \rightarrow \pi^+ \pi^- p$ at 11.85 GeV/c and $K^+ n_\uparrow \rightarrow K^+ \pi^- p$ at 5.85 GeV/c are based on lower statistics. We found some energy dependence of the nucleon spin effects in $\pi^+ n_\uparrow \rightarrow \pi^+ \pi^- p$. Figure 2 confirms the existence of spin effects also in $K^+ n_\uparrow \rightarrow K^+ \pi^- p$ reaction and indicates additional dependence of pion production on flavor content of the incident mesons.

The bounds in Figs. 1 and 2 were shown without errors for the sake of clarity. Figures 3 and 4 show statistical errors for several interesting structures. We conclude

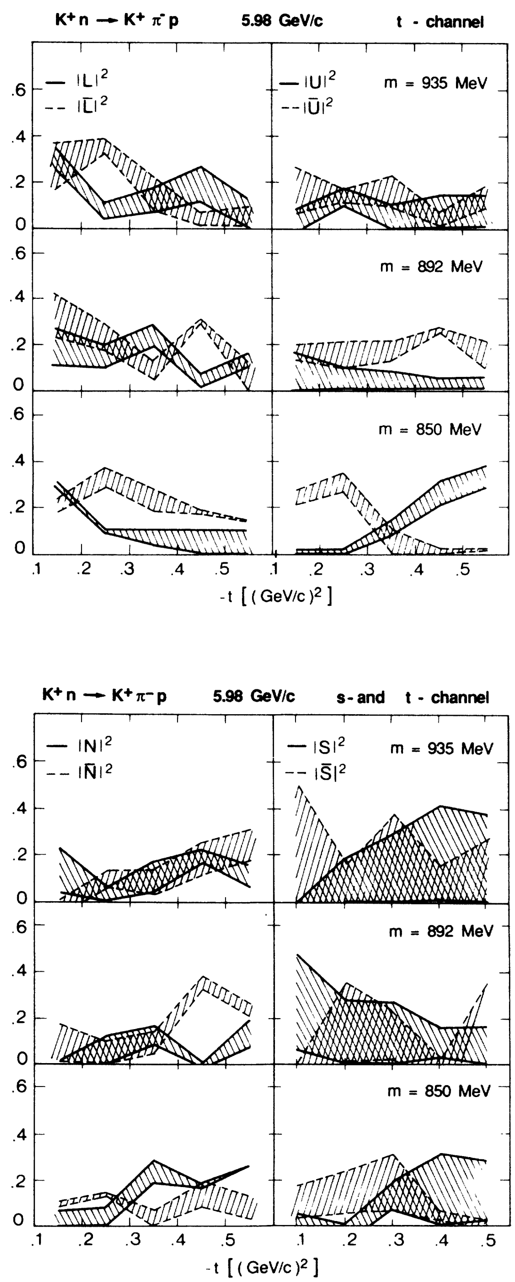

FIG. 2. The mass evolution of t dependence of moduli squared of t-channel normalized nucleon transversity amplitudes in $K^+ n_\uparrow \rightarrow K^+ \pi^- p$ at 5.98 GeV/c.

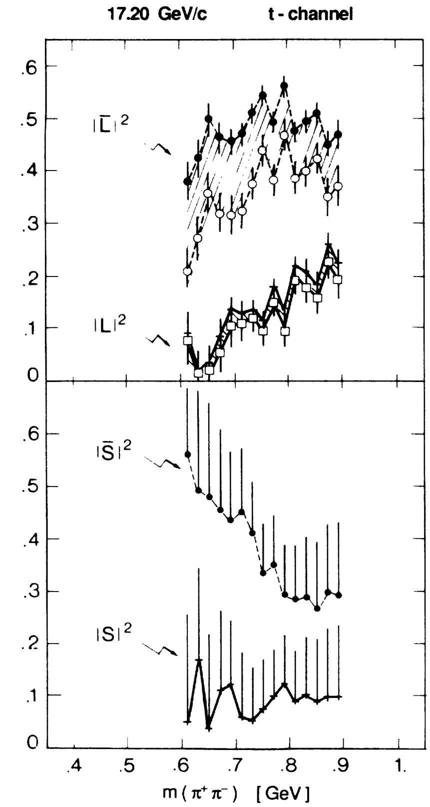

FIG. 3. Bounds with statistical errors for amplitudes with zero dimeson helicity in $\pi^- p_\uparrow \rightarrow \pi^- \pi^+ n$ at 17.2 GeV/c at small momentum transfer $t = -0.068$ (GeV/c)^2.

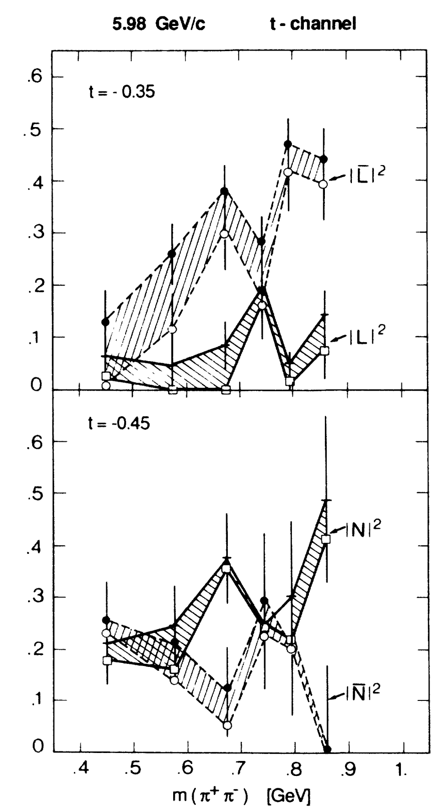

FIG. 4. Bounds with errors on P-wave amplitudes $|L|^2$, $|\bar{L}|^2$, and $|N|^2, |\bar{N}|^2$ in $\pi^+ n_\uparrow \rightarrow \pi^+ \pi^- p$ at 5.98 GeV/c showing the nucleon spin-dependent structures at large momentum transfers.

that the observed spin dependence and structures near ρ^0 and K^{*0} masses are statistically significant. The resonance peak seen in Σ is not uniformly copied on the level of unnormalized amplitudes $|A|^2\Sigma$ and $|\overline{A}|^2\Sigma$ at larger t. Instead, the t-dependent structures within the resonance width provide new information on dynamics of resonance production. At a given t, the shape of ρ^0 resonance in the unnormalized amplitudes depends on nucleon spin. The apparent position and width of ρ^0 in the unnormalized amplitudes and partial-wave cross sections[20,21] depend on vector meson helicity and exchange naturality. The commonly assumed degeneracy of resonance mass with respect to its helicity state should be further examined experimentally.

The difference of moduli of NTA is a partial-wave polarization $\tau(A)=|A|^2-|\overline{A}|^2=2\epsilon\,\mathrm{Im}(A_0A_1^*)$ where A_0 and A_1 are nucleon-helicity nonflip and flip amplitudes,[20] and $\epsilon=+1$ for $A=S,L,U$ and $\epsilon=-1$ for $A=N$. In $\pi N\to\pi^+\pi^-N$ the nonflip amplitudes S_0, L_0, U_0 exchange A_1, the flip amplitudes S_1, L_1, U_1 exchange π, and N_0, N_1 exchange A_2 quantum numbers in the t channel. The large difference in magnitude and behavior between $|L|^2$ and $|\overline{L}|^2$ in Fig. 1 is a clear signal for a strong and nontrivial A_1 exchange in the nucleon-helicity nonflip amplitude L_0. Our results suggest similar conclusion for S_0, another dimeson helicity $\lambda=0$ and nucleon-helicity nonflip amplitude in $\pi N\to\pi^+\pi^-N$. Experimental information about the structure and energy dependence of A_1 exchange in $\pi N\to\pi^+\pi^-N$ is important for understanding of the spin structure of nucleon[18] since A_1 exchange contributes to quark spin distributions[18,24,25] at small x.

The remaining SDM elements measured in $\pi N_\uparrow\to\pi^+\pi^-N$ and $K^+n_\uparrow\to K^+\pi^-p$ provide information on cosines of certain relative phases and enable a more complete amplitude analysis based on nonlinear relations. The results[19] (which are in agreement with bounds) reopened the question of low-mass scalar resonances in pion production[26] and allowed the first test of additive quark model using experimentally determined amplitudes.[27]

In conclusion, the first measurements of single-pion production using polarized targets[19–22] revealed an important and complex dependence of pion creation process on spin. The proposed advanced hadron facilities[28–33] will make possible new polarization experiments dedicated to a systematic study of the dynamical role of spin in hadron production on the level of amplitudes.[34]

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