SPIN STRUCTURE OF $\rho^0$ PRODUCTION IN $\pi^+ n \rightarrow \pi^+ \pi^- p$

ON TRANSVERSELY POLARIZED TARGET.

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ABSTRACT

We study pion production in reaction $\pi^+ n \rightarrow \pi^+ \pi^- p$ on transversely polarized target at 5.98 GeV/c with dipion masses below 1000 MeV and momentum transfer $-t = 0.2 - 0.4 \text{(GeV/c)}^2$. We present new results for moduli of six $P$-wave nucleon transversity amplitudes obtained in a model independent Monte Carlo amplitude analysis of the data. We find unexpected structures within $\rho^0$ mass range in the mass dependence of the moduli. The mass spectra show narrow dips associated with peaks at the same dipion mass in the amplitude of opposite nucleon transversity. These narrow structures are not observed in the nucleon spin averaged partial-wave intensities which show the expected $\rho_0$ peak. The $\rho^0$ production is suppressed in the amplitudes corresponding to unnatural $t$-channel exchange and dipion helicity $\lambda = \pm 1$. 

1
Following the discovery of resonances in hadron interactions it was always believed that the production and decay processes of resonances were separate events. For instance, the reaction \( \pi^+ n \rightarrow \pi^+ \pi^- p \) was thought of as a two step process: \( \pi^+ n \rightarrow \rho^0 p \) followed by \( \rho^0 \rightarrow \pi^+ \pi^- \). In this picture the S-matrix elements factorize into production and decay matrix elements

\[
T(\pi^+ n \rightarrow \pi^+ \pi^- p) = T(\pi^+ n \rightarrow \rho^0 p)\phi(\rho_0)T(\rho_0 \rightarrow \pi^+ \pi^-) \tag{1}
\]

where \( \phi(\rho_0) \) is a \( \rho_0 \) propagator leading to the Breit-Wigner description of dipion mass dependence of modulus of each production amplitude \( |T(\pi^+ n \rightarrow \pi^+ \pi^- p)|^2 \) as well as the production cross-section.\(^1\) It is expected from (1) that the same \( \rho^0 \) resonance peak seen in the spin averaged cross-section will appear also on the level individual spin-dependent production amplitudes. The factorization hypothesis (1) also implies that the mass spectrum of the decaying resonance does not depend on the nucleon spin.

In this report we present experimental evidence against the factorization hypothesis (1). We use the data from measurement\(^2\) of \( \pi^+ n \uparrow \rightarrow \pi^+ \pi^- p \) reaction at 5.98 GeV/c with dipion mass below 1000 MeV and momentum transfer in the range \(-t = 0.2 - 0.4 \text{ (GeV/c)}^2\) to determine in a model independent way the moduli of all production amplitudes. We find that the mass spectrum depends on dimeson helicity \( \lambda \) and on the spin of the recoil nucleon. Moreover, the mass spectra show unexpected structures within the \( \rho^0 \) mass region which correlate the spectra corresponding to opposite nucleon spins. As the result of these structures, the mass spectra on the level of amplitudes cannot be fitted to a Breit-Wigner form as
expected from the factorization hypothesis (1).

The angular distribution of the produced dipion system is described in terms of spin density matrix (SDM) elements. For dipion masses below 1000 MeV dipion spin states $J = 0$ ($S$-wave) and $J = 1$ ($P$-wave) dominate and the experiments on transversely polarized target measure 6 unpolarized and 9 polarized SDM elements. These observables are expressed in terms of nucleon transversity amplitudes.\textsuperscript{3,4} There are two $S$-wave amplitudes ($S$ and $\overline{S}$), and six $P$-wave amplitudes. The $P$-wave amplitudes $L, \overline{L}$ have dipion helicity $\lambda = 0$ while $U, \overline{U}$ are combinations of $\lambda = \pm 1$. The amplitudes $S, \overline{S}, L, \overline{L}$ and $U, \overline{U}$ all describe $\pi$ and $A_1$ unnatural exchanges. The $P$-wave amplitudes $N, \overline{N}$ are natural $A_2$-exchange amplitudes. The amplitudes $S, \overline{S}, L, \overline{L}, U, \overline{U}, N, \overline{N}$ ($S, L, U, N$) have recoil nucleon spin up (down) relative to the scattering plane.

Amplitude analysis\textsuperscript{3,4} expresses 8 normalized moduli and 6 cosines of relative phases in terms of SDM elements. There are two similar solutions. However, in number of mass bins the solutions are unphysical.\textsuperscript{3,4} To filter out the unphysical solutions we have used a Monte Carlo approach. In each $(m, t)$ bin we randomly varied SDM elements 30,000 times within their experimental errors and performed amplitude analyses for each selection. Unphysical solutions were rejected and the physical solutions produced a continuous range of values for the moduli, cosines of relative phases and for partial wave intensities. In each range we calculated average value of the corresponding quantity. In general, the Monte Carlo amplitude analysis is in agreement with previous results.\textsuperscript{3,4} The details will be published elsewhere.\textsuperscript{5}

In Fig. 1 we present the solution 1 for the unnormalized moduli $|\overline{A}|^2 \Sigma$ and
$|A|^2 \Sigma$ of $P$-wave amplitudes $A = L, N, U$. Here $\Sigma = \frac{d^2\sigma}{dm dt}$ is the reaction cross section taken from Ref. 2. We also show partial wave intensities $I_A = (|A|^2 + |A|^2) \Sigma$. The solution 2 is similar.

First we look at the amplitudes $|\bar{L}|^2 \Sigma$ and $|L|^2 \Sigma$. For dipion helicity $\lambda = 0$ the pion production proceeds predominantly with recoil nucleon spin up as $|\bar{L}|^2$ is larger than $|L|^2$. The mass spectrum of the recoil nucleon spin up amplitude $|\bar{L}|^2 \Sigma$ shows a dip at 757 MeV and a peak at 807 MeV. The opposite behaviour is seen in the nucleon spin down amplitude $|L|^2 \Sigma$ which peaks at 757 MeV and has a dip at 807 MeV. These correlated structures within $\rho_0$ mass region do not appear in the partial wave intensity $I_L$ which shows a structureless $\rho^0$ peak.

Next we note that $|N|^2 \Sigma$ has a resonance like structure while $|\bar{N}|^2 \Sigma$ is smaller and does not peak. The spectrum of $|N|^2 \Sigma$ shows a peak at 782 MeV which is associated with a dip in $|\bar{N}|^2 \Sigma$ at the same mass. The partial wave intensity $I_N$ again shows a structureless peak expected from a $\rho^0$ resonance.

The amplitudes $|\bar{U}|^2 \Sigma$ and $|U|^2 \Sigma$ are small and do not show a clear $\rho^0$ peak. However, a small peak in $|\bar{U}|^2 \Sigma$ at 757 MeV is associated with a dip in $|U|^2 \Sigma$ at the same mass. The intensity $I_U$ is small and suggests a broad bump with an estimated width of 240 MeV. The $\rho^0$ production is suppressed in this amplitude.

The most remarkable feature of the $P$-wave amplitudes is the existence of correlated dips and peaks in the mass spectra of opposite nucleon spins in the $\rho^0$ mass region. The pairs of amplitudes with opposite recoil nucleon transversities ($\bar{L}$ and $L$, $\bar{N}$ and $N$, $\bar{U}$ and $U$) behave as a two-level system. The dip or hole in one spectrum signifies a depopulation of that spectrum in a narrow mass band which is
compensated by excess population (peak) in the mass spectrum of opposite nucleon
transversity in the same mass band.

The narrow structures observed in the moduli of production amplitudes in $\rho^0$
mass region represent a new information on pion production and raise the question
what is a hadron resonance. While partial wave intensities $I_L, I_N$ and $I_U$ can be
fitted with the Breit-Wigner formula, the same cannot be said about the moduli. A
resonance which is a pole in the amplitude would lead to simple resonance peaks in
all moduli without structures within their widths. We also note that the usual model
of meson resonances as $q\bar{q}$ bound states does not predict their hadronic widths.\textsuperscript{6}

It is interesting to note that dips in a broader spectrum are well known in
nonlinear laser spectroscopy where the phenomenon is called "hole-burning" or
"cross-over resonances".\textsuperscript{7} Consider a medium in which each atom can absorb only
one definite frequency, but in which different atoms can absorb different frequen-
cies. Such a situation can result, for example, from the Doppler effect and leads to
Doppler-broadened frequency distribution of the ground state population. When
the medium is irradiated by a narrow band radiation, only atoms that can absorb
the radiation frequency are excited. A "hole" centered at the radiation frequency is
burned in the frequency distribution of ground state population and a corresponding
peak appears in the excited state population distribution.

The unusual behaviour of the moduli suggests the existence of a process which
correlates the pion production in $\rho^0$ mass region to the recoil nucleon spin (transver-
sity). The process is possibly long range. Given the width of $\rho^0$ meson is 150 MeV,
its mean free path is $ct \approx 1.32 \, fm$. The dips in the amplitudes $|\overline{L}|^2 \Sigma$ and $|L|^2 \Sigma$
are about 20 MeV wide, which would seem to indicate a force range of some 9–10 fm.

In the quark model the spin of a hadron is due to spins of valence quarks. However, recent measurements of polarized distribution function in muon-nucleon deep inelastic scattering\(^8,9\) suggest that valence quarks do not carry nucleon spin. It was suggested that the nucleon spin is due to polarized gluons or polarized \(q\bar{q}\) sea. The observed dependence of pion production on nucleon spin may be connected to the nucleon spin puzzle.

The results presented in Fig. 1 correspond to momentum transfer \(-t = 0.2–0.4\) (GeV/c).\(^2\) Elsewhere\(^10\) we found considerable variations in the \(t\)-evolution of mass dependence of bounds on moduli. This suggests that the narrow dips and peaks observed in the moduli will evolve with \(t\).

In conclusion, we found that the \(\rho^0\) mass spectra on the level of production amplitudes in \(\pi^+n \rightarrow \pi^+\pi^-p\) are not simple Breit-Wigner peaks as suggested by the factorization picture (1). Instead we observe in \(\rho^0\) mass region narrow dips associated with peaks in the amplitude with opposite nucleon transversity. These unexpected structures represent a new information about the dynamics of pion production and raise questions about the nature of hadron resonances. These new phenomena should be further investigated experimentally at the recently proposed hadron facilities such as the Canadian KAON Factory.

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REFERENCES


FIGURE CAPTIONS

Figure 1: Mass dependence of unnormalized moduli of \( P \)-wave production amplitudes and associated partial wave intensities in reaction \( \pi^+n_\uparrow \to \pi^+\pi^-p \) at 5.98 GeV/c and for \(-t = 0.2 - 0.4 \) (GeV/c).\(^2\) The results are in the \( t \)-channel dipion helicity frame.
Fig. 1