Study of Spin Density Matrix  
in Exclusive Diffractive $\rho^0$ Meson Production at HERMES

S. I. Manayenkov  
on behalf of HERMES collaboration,  
Petersburg Nuclear Physics Institute

QCD06 Conference,  
3-7 July 2006, Montpellier, France

CONTENTS

- Physics Motivation
- Reaction $e + N \rightarrow e' + \rho^0 + N$
- The HERMES Experiment
- Method of Data Processing

Results:

- Spin Density Matrix Elements $r_{\lambda\rho\lambda'}$  
- Longitudinal-to-Transverse Cross-Section Ratio  
- $t'$-dependence of SDMEs  
- Test of Unnatural-Parity Exchange  
- Summary & Outlook
Physics Motivation

- $\gamma^* + N \rightarrow \rho^0 + N'$ is a perfect reaction to study the spin structure of $\rho^0$ QCD production mechanism: spin state of $\gamma^*$ is known; decay $\rho^0 \rightarrow \pi^+ + \pi^-$ is self-analysing.
- Measurement of $s$-channel helicity violation shows itself in spin-flip amplitudes.
- Hierarchy of spin non-flip amplitudes is measured via $\sigma_L/\sigma_T$ ratio. For spin-flip amplitudes it can be estimated via SCHC violating spin density matrix elements (SDMEs).
- $\rho^0$ production mechanisms can be tested by comparing resulting SDMEs with calculations, where two-gluon (Pomeron) exchange dominates.
- $q\bar{q}$-exchange with isospin 1 can be observed in case of difference between proton and deuteron data.
- Observation of unnatural parity ($P = -(-1)^J$) exchange points to importance of $q\bar{q}$-exchange mediated by pion.
Reaction $e + N \rightarrow e' + \rho^0 + N'$

**Photon-Nucleon CMS**

- **First:** $e \rightarrow e' + \gamma^*$ (QED)
  Spin-density matrix of the virtual photon $\rho(\gamma^*)$

- **Second:** $\gamma^* + N \rightarrow \rho^0 + N$ (QCD)
  Helicity amplitudes in CMS of $\gamma^*N$
  
  $T_{\lambda\rho\lambda'_{\rho}};\lambda\gamma\lambda_{N} = T_{\lambda\rho\lambda_{\gamma}}$

  Vector-meson (VM) spin-density matrix
  
  $\rho(V) = T\rho(\gamma^*)T^+$

  Free parameters $\rho^\alpha(V) = T\sum^\alpha T^+$

  If contributions of transverse and longitudinal photons are not distinguished $\rho^\alpha(V) \Rightarrow r^\alpha(V)$

- **Third:** $|\rho^0; 1m \rangle \rightarrow |\pi^+\pi^-; 1m \rangle \Rightarrow Y_{1m}(\theta, \phi)$
Kinematics of Exclusive $\rho^0$ Production

- $\nu = 5 \div 24$ GeV, $\langle \nu \rangle = 13.3$ GeV
- $Q^2 = 1.0 \div 5.0$ GeV$^2$, $\langle Q^2 \rangle = 2.3$ GeV$^2$
- $W = 3.0 \div 6.5$ GeV, $\langle W \rangle = 4.9$ GeV
- $x_{Bj} = 0.01 \div 0.35$, $\langle x_{Bj} \rangle = 0.07$

$$\Delta E = \frac{M_X^2 - M_p^2}{2M_p} \text{ with } M_X^2 = (p + q - v)^2$$

Background is subtracted with the help of MC (PYTHIA)

Clean exclusive peak
• **Monte Carlo Events:** 3-dimensional matrix of fully reconstructed MC events at initial uniform angular distribution.

• **Binned Maximum Likelihood Method:** $8 \times 8 \times 8$ bins of $\cos(\Theta), \phi, \Phi$. Simultaneous fit of 23 SDMEs for data with negative and positive beam helicity ($< P_b > = 53.5\%$).

→ agreement of fitted angular distributions with data
- No statistically significant difference between proton and deuteron.
- S-Channel Helicity Conservation (SCHC): Non-zero: $T_{11}$, $T_{-1-1}$, $T_{00}$.
- Violation of SCHC: enlarged points ($2 \div 5 \sigma$).
  Linear contribution of spin-flip amplitudes $T_{01}, T_{10}, T_{1-1}$.
- Indication on hierarchy of amplitudes:
  $T_{00} \sim T_{11} \gg T_{01} > T_{10} \sim T_{1-1}$
Longitudinal-to-Transverse Cross-section Ratio

HERMES PRELIMINARY $\langle W \rangle = 5$ GeV
- □ proton
- ◆ deuteron

\[ R = \frac{\sigma_L}{\sigma_T} \]
\[ \sigma_L = \frac{1}{2} \sum \lambda_N \lambda_N' \left[ |T_{00}|^2 + |T_{10}|^2 + |T_{-10}|^2 \right] \]
\[ \sigma_T = \frac{1}{2} \sum \lambda_N \lambda_N' \left[ |T_{11}|^2 + |T_{01}|^2 + |T_{-11}|^2 \right] \]

Second order contribution of spin-flip amplitudes (violating SCHC).

SCHC approximation
\[ R^{SCHC} = \frac{|T_{00}|^2}{|T_{11}|^2} \approx \frac{r_{00}^{04}}{\epsilon (1 - r_{00}^{04})} \]
L-T Cross-Section Ratio at SCHC and NPE

- SCHC approximation: \( R^{SCHC} = \frac{1}{\epsilon} \left\{ \frac{1}{1 - 7.04} - 1 \right\} \)

- Natural Parity Exchange Dominance: \( R^{NPE} = \frac{1}{\epsilon} \left\{ \frac{1}{2r_1 - 1} - r_0 - 1 \right\} \)

\( R^{NPE} \) has statistical errors greater than \( R^{SCHC} \)

- \( R^{NPE} \) is the upper limit for \( R \) (\( R \leq R^{NPE} \))
Calculations of Kinematic Dependences

  pQCD. Two-gluon (Pomeron) exchange, $\rho$-meson wave function with $S$- and $D$-waves (Coulomb-like and Gaussian functions). Amplitudes: $T_{00}, T_{11}, T_{01}, T_{10}, T_{1-1}$.

  Generalized Parton Distributions (GPD), Gaussian $\rho$-meson wave function (S-wave). Amplitudes: $T_{00}, T_{11}, T_{01}$.

  Regge Phenomenology. Exchanges with Pomeron, $\rho, \omega, f, A_2$. Parton-hadron duality. Amplitudes: $T_{00}, T_{11}, T_{01}, T_{10}, T_{1-1}$.

- Special calculations for the HERMES kinematics.
Reasonable agreement for a majority of SDMEs at low $t'$.  
- The most crucial disagreement with data for Models 2, 3: $r_{00}^{04}$, $r_{1-1}^1$, Im$\{r_{1-1}^2\}$, and for Model 1 Re$\{r_{10}^5\}$, Im$\{r_{10}^6\}$.  
- No model describes well all unpolarized SDMEs.  
- Quark-exchange or/and many-Pomeron exchanges are probably important.  
- Extraction of amplitudes from the data is needed.
Test of Unnatural-Parity Exchange

- Natural and Unnatural Parity Exchanges
  \[ NPE: \quad P = (-1)^J \]
  \[ UPE: \quad P = -(1)^J \]
  NPE in the \( t \)-channel (Pomeron, \( \rho \), \( \omega \), \( f_2 \), \( A_2 \), ...) dominate and UPE (\( \pi \), \( A_1 \), ...) are suppressed at high energies

- \( T_{\lambda_\rho \lambda_N'; \lambda_\gamma \lambda_N} = T_{\lambda_\rho \lambda_N'; \lambda_\gamma \lambda_N}^N + T_{\lambda_\rho \lambda_N'; \lambda_\gamma \lambda_N}^U \)
  No interference between NPE and UPE contributions to SDMEs \( r_{\lambda_\rho \lambda_\rho'}^\alpha \)
  for unpolarized target

- \( U_1 = 0.112 \pm 0.033_{\text{stat}} \pm 0.049_{\text{syst}} \) (H), \( U_1 = 0.059 \pm 0.026_{\text{stat}} \pm 0.047_{\text{syst}} \) (D)
Summary

- 15 unpolarized and, for the first time, 8 polarized SDMEs are obtained.

- Violation of SCHC is observed both for proton and deuteron data with $2 \div 5 \sigma$.

- Kinematic dependences of SDMEs are measured for 4 bins in $Q^2$ and $t'$. No statistically significant difference between proton and deuteron data is found. No noticeable natural-parity $q\bar{q}$-exchange with $I = 1$ is observed.

- $R = \sigma_L/\sigma_T$ is obtained under assumption of SCHC and NPE, and is in agreement with world data.

- $t'$-dependence of SDMEs is compared to theoretical models. Agreement is found for the majority of the unpolarized matrix elements, but no model describes well all SDMEs.

- Unnatural parity exchange is seen for the proton with $2 \sigma$.

Outlook

- Extraction of helicity amplitudes from the data is in progress.

- Factor of $\sim 4$ in the experimental statistics is expected.