New Results on Spin Density Matrix Elements for $\rho^0$ at Hermes

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Outline

- Definition of Spin Density Matrix Elements (SDMEs)
- Angular Distribution of Vector Meson Decay
- The Hermes Data
- Method of SDMEs extraction
- 23 Extracted SDMEs
- Kinematical dependences of the SDMEs
- Summary
**Exclusive, Diffractive Electroproduction of $\rho^0$**

\[ e+N \rightarrow e' + N + \rho^0 \]

- Two gluon exchange mechanism at higher energies
- Quark exchange mechanism at intermediate energies
- Spin structure of the $\rho^0$ production

(How the helicity of the $\rho^0$ meson is related to the helicity of the virtual photon)

- Spin Density Matrix Elements (SDMEs)

\[ Q^2 = -q^2 = -(k - k')^2 \]
\[ W^2 = (q+p)^2 \]
\[ t = (q+v)^2 \]
Spin-Density Matrix of the Vector Meson

\[ \rho(V) = \frac{1}{2} T \rho(\gamma) T^+ \] – Spin-density matrix of the vector meson \( \rho(V) \) in terms of the photon spin density matrix \( \rho(\gamma) \) and helicity amplitude \( T \)

\[ \rho^{\alpha}_{\lambda_V \lambda_{V'}} = \frac{1}{2N} \sum_{\lambda_{\gamma} \lambda'_{\gamma}} T_{\lambda_{\gamma} \lambda'_{\gamma}} \sum_{\lambda_{\gamma} \lambda'_{\gamma}} \rho^{\alpha}_{\lambda_V \lambda'_{V}} T^*_{\lambda'_{V} \lambda'_{V}} \] – spin-density matrix elements of the vector meson

\[ T_{\lambda_{\gamma} \lambda'_{\gamma} \lambda_{N} \lambda'_{N}} = \langle \lambda_{V} \lambda'_{N} | J^{(em)} e^{(\lambda_{\gamma})} | \lambda_{N} \rangle \] – helicity amplitudes

where \( \lambda_V, \lambda_{\gamma}, \lambda_N \) – helicity of the vector meson, photon and proton
\( J^{(em)} \) – electromagnetic current, \( e^{(\lambda)} \) – photon polarization vector
\( \lambda_{\gamma} = 0 \) – longitudinal polarization, \( \lambda_{\gamma} = \pm 1 \) – transverse polarization

\[ \sum_{\lambda_{\gamma} \lambda'_{\gamma}}^{\alpha} \] – \((\alpha=0,\ldots,8)\) nine hermitian matrices representing states of photon polarization
\( \alpha = 0 \) – unpolarized transverse photon \quad \alpha = 1,2 \) – linear polarization
\( \alpha = 3 \) – circularly polarized photon \quad \alpha = 4 \) – longitudinal photon
\( \alpha = 5,6,7,8 \) – longitudinal- transverse interference terms
Spin Density Matrix Elements (SDMEs)

- It is not possible to separate contributions from longitudinal and transverse photon at constant beam energy.
- We measure SDMEs – $r^{\alpha}_{\lambda_v \lambda'_v}$

$$r^{04}_{\lambda_v \lambda'_v} = \frac{\rho^0_{\lambda_v \lambda'_v} + \epsilon R \rho^4_{\lambda_v \lambda'_v}}{1 + \epsilon R} \quad R = \frac{\sigma_L}{\sigma_T} \quad \epsilon - \text{polarization parameter}$$

$$r^{\alpha}_{\lambda_v \lambda'_v} = \frac{\rho^a_{\lambda_v \lambda'_v}}{1 + \epsilon R} \quad \alpha = 1, 2, 3$$

$$r^{\alpha}_{\lambda_v \lambda'_v} = \sqrt{R} \frac{\rho^a_{\lambda_v \lambda'_v}}{1 + \epsilon R} \quad \alpha = 5, 6, 7, 8$$

- SCHC – s-channel helicity conservation
  - helicity of the virtual photon = helicity of the vector meson
  - $T_{01} = T_{10} = T_{-10} = T_{0-1} = T_{-11} = T_{1-1} = 0$
  - $T_{00} \neq 0$, $T_{11} \neq 0$, $T_{-1-1} \neq 0$
  - $r^{04}_{00}, \text{Re}\{r^1_{1-1}\}, \text{Im}\{r^2_{1-1}\}, \text{Re}\{r^5_{10}\}, \text{Im}\{r^6_{10}\}, \text{Im}\{r^7_{10}\}, \text{Re}\{r^8_{10}\} \neq 0$

- NPE - Natural Parity Exchange process dominance
  - the exchange particle have quantum numbers ($J^p = 0^+, 1^-, 2^+ \ldots$)
  - $T_{00}, T_{11} = T_{-1-1}, T_{01} = -T_{0-1}, T_{10} = -T_{-10}, T_{1-1} = T_{-11}$
Decay Angles Definition

\( \gamma^* p \) – center-of-momentum frame

\( \Phi \) - the azimuthal production angle of \( \rho^0 \) meson

\( \rho^0 \) – rest frame

\( \theta, \varphi \) – polar and azimuthal decay angle of the meson \( \pi^+ \) relative to the \( \rho^0 \) spin quantization axis, which is along the direction opposite the direction of the recoiling target \(-p'\)
Decay Angular Distribution in terms of SDMEs

\[ W(\cos \Theta, \phi, \Phi) = W^{unpol} + W^{long.pol.} \]

\[ W^{unpol}(\cos \Theta, \phi, \Phi) = \frac{3}{4\pi} \left[ \frac{1}{2}(1 - r_{00}^{04}) + \frac{1}{2}(3r_{00}^{04} - 1) \cos^2 \Theta \right.\]

\[ - \sqrt{2} Re(r_{10}^{04}) \sin 2\Theta \cos \phi - r_{1-1}^{04} \sin^2 \Theta \cos 2\phi \]

\[ - \epsilon \cos 2\Phi \left( r_{11}^{1} \sin^2 \Theta + r_{00}^{1} \cos^2 \Theta - r_{1-1}^{1} \sin^2 \Theta \cos 2\phi \right) \]

\[ - \epsilon \sin 2\Phi \left( \sqrt{2} Im(r_{10}^{2}) \sin^2 \Theta \sin \phi + Im(r_{1-1}^{2}) \sin 2\Theta \sin 2\phi \right) \]

\[ + \sqrt{2} \epsilon(1 + \epsilon) \cos \Phi \left( r_{11}^{5} \sin^2 \Theta + r_{00}^{5} \cos^2 \Theta - \sqrt{2} Re(r_{10}^{5}) \sin 2\Theta \cos \phi - r_{1-1}^{5} \sin^2 \Theta \cos 2\phi \right) \]

\[ + \sqrt{2} \epsilon(1 + \epsilon) \sin \Phi \left( \sqrt{2} Im(r_{10}^{6}) \sin 2\Theta \sin \phi + Im(r_{1-1}^{6}) \sin^2 \Theta \sin 2\phi \right) \]

\[ W^{long.pol.}(\cos \Theta, \phi, \Phi) = \frac{3}{4\pi} P_{beam} \left[ \right.\]

\[ \sqrt{1 - \epsilon^2} \left( \sqrt{2} Im(r_{10}^{3}) \sin 2\Theta \sin \phi + Im(r_{1-1}^{3}) \sin^2 \Theta \sin 2\phi \right) \]

\[ + \sqrt{2} \epsilon(1 - \epsilon) \cos \Phi \left( \sqrt{2} Im(r_{10}^{7}) \sin 2\Theta \sin \phi + Im(r_{1-1}^{7}) \sin^2 \Theta \sin 2\phi \right) \]

\[ + \sqrt{2} \epsilon(1 - \epsilon) \sin \Phi \left( r_{11}^{8} \sin^2 \Theta + r_{00}^{8} \cos^2 \Theta - \sqrt{2} Re(r_{10}^{8}) \sin 2\Theta \cos \phi - r_{1-1}^{8} \sin^2 \Theta \cos 2\phi \right) \]

15 unpolarized SDMEs

8 polarized SDMEs
**Information about Hermes Experimental Data**

- Polarized positron (electron) beam of energy $E=27.6$ GeV
- The average lepton beam polarization was 0.53 for both positive and negative beam helicities
- Targets: Hydrogen, Deuterium
- Data collected in years 1996-2000

**Selection of Diffractive Exclusive $\rho^0$ Events**

- Event has only 3 tracks, scattered lepton and two pions $\pi^+ \pi^-$
- The $\rho^0$ meson is selected by mass constraints
  
  $0.6 < M_{\pi^+\pi^-} < 1.0$ GeV
  and veto constraints $M_{K^+K^-} > 1.06$ GeV
- Diffractive events were selected by requiring $-t' = t - t_{\text{min}} < 0.6$ GeV

- Exclusive events $-1 < \Delta E = \frac{M_x^2 - M_{\text{targ}}^2}{2M_{\text{targ}}} < 0.6$ GeV
- 9600 – events H, 16000 – events D

**SIDIS background subtraction**

δE distributions for exclusive diffractive $\rho^0$ production for different kinematical bins (circles), compared to SIDIS background calculated by PYTHIA MC (histogram)
Extraction of SDMEs

SDMEs were determined by minimizing the difference between 3-dimensional matrix of data and a sample of MC events.

1. 3-dimensional matrix of data in variables \((\cos(\theta), \varphi, \Phi)\) binned in \((8, 8, 8)\) bins

2. 3-dimensional matrix of background events

3. 3-dimensional matrix of MC events generated with uniform angular distribution, reweighted with angular distribution function \(W(\cos(\theta), \varphi, \Phi)\) which depends on the SDMEs

\((1) - (2)\) was fitted by \((3)\) with a binned Maximum Likelihood Method where SDMEs were treated as free parameters.
Fitted Angular Distribution

- Closed circles represent measured data
- MC distribution fitted to the data
- isotropically generated events used as an input for the fits

\[ \psi = \varphi - \Phi \]
23 Unpolarized and Polarized SDME on Hydrogen and Deuterium

\[ 1.0 < Q^2 < 5.0 \text{ GeV}^2 \]
\[ 3.0 < W < 6.3 \text{ GeV} \]
\[ \langle Q^2 \rangle = 1.86 \text{ GeV}^2 \]
\[ \langle W \rangle = 5.0 \text{ GeV} \]
\[ \langle t' \rangle = 0.130 \text{ GeV}^2 \]

Inner error bar - statistical
outer – total

Elements which violate SCHC

\[ \text{Re}\{r_{10}^{04}\}, \text{Re}\{r_{10}^1\}, \text{Im}\{r_{10}^2\}, r_{00}^5 \]
The $Q^2$-dependence of the 15 unpolarized SDMEs

four $Q^2$ bins
$(0.7 - 1.0 - 1.4 - 2.5 - 5.0) \text{ GeV}^2$

- Perturbative QCD
- 2 gluon exchange only
- Generalized parton distribution
- Regge model

HERMES PRELIMINARY

- proton
- deuteron
- I. Ivanov et al., pQCD
- Goloshkov et al., GPD
- S. Manayenkov, Regge
The -t'- dependence of the 15 unpolarized SDME four -t' bins 
(0.0 − 0.05 − 0.10 
− 0.2 − 0.4) GeV$^2$
1.0 < Q$^2$ < 5.0 GeV 
-t’ dependence observed for: 
Re\{r_{10}^{04}, r_{10}^{04}, Re\{r_{10}^{1}\}, 
Im\{r_{10}^{2}\}, r_{00}^{5}\} 
HERMES PRELIMINARY 
-\text{proton} 
-\text{deuteron} 
-t' (GeV$^2$)
Test of NPE dominance

\[ 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1} = 0 \quad \text{For NPE} \]
Longitudinal-to-Transverse Cross-Section Ratio

\[ R_{\rho}^{SCHC} = \frac{1}{\varepsilon} \times \frac{r_{04}^{04}}{1 - r_{00}^{04}} \]

HERMES PRELIMINARY \( <W> = 5 \text{ GeV} \)

- ▐ proton
- ○ deuteron

\[ R = \sigma_L / \sigma_T \]

\* CLAS \( <W> = 2.1 \text{ GeV} \)
△ DESY \( <W> = 2.6 \text{ GeV} \)
★ CORNELL \( <W> = 3.5 \text{ GeV} \)
□ NMC \( <W> = 14 \text{ GeV} \)
◇ COMPASS \( <W> = 14 \text{ GeV} \)
★ E665 \( <W> = 18 \text{ GeV} \)
÷ ZEUS \( <W> = 50 \text{ GeV} \)
★ H1 \( <W> = 75 \text{ GeV} \)
Summary

- 23 SDMEs were obtained with the Likelihood method for $\rho^0$ production on proton and deuteron targets.
- No significant deviation is seen between the SDMEs from proton and deuteron data and their kinematic dependences.
- Violation of SCHC was shown for non-zero values of several SDMEs on hydrogen and deuterium.
- 15 unpolarized SDMEs were extracted for four $Q^2$ bins and four $-t'$ bins for proton and deuteron. Several clean kinematic dependences of SDMEs on $Q^2$ and $-t'$ are observed.
- Test of Natural Parity Exchange was performed for different kinematic bins. An indication of unnatural parity exchange amplitudes is seen in the proton data.
- $R^\text{SCHC}$ was obtained for four $Q^2$ bins under the assumption of SCHC