New results of exclusive $\phi^0$ and $\rho^0$ vector meson production at HERMES

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Rudiments

Spin Density Matrix Elements (SDME’s) : definitions and their determination

SDME’s and Amplitudes for $\rho^0$ and $\phi$ vector mesons

Dependencies of SDME’s on $Q^2$ and $t'$

The observables:

$$ R = \frac{\sigma_L}{\sigma_T} $$

the signatures of the Natural or Unnatural Parity Exchange amplitudes

Conclusions

Outlook
$e + p \rightarrow e' + p' + V: Rudiments$

- In one photon approximation
  $\equiv \gamma^* + p \rightarrow p' + V$

- The amplitude of this process can be factorized:
  $A = \Phi_{\gamma^* \rightarrow q\bar{q}} \otimes A_{q\bar{q} + p \rightarrow q\bar{q} + p} \otimes \Phi_{q\bar{q} \rightarrow V}$. In these three steps the interaction time ($q\bar{q}$) with target is shorter than fluctuation and formation of VM. (Collins, Frankfort and Stirman Phys. Rev D56 (1997) 2982)

- $\gamma^* + N \rightarrow \rho^0(\phi) + N'$ it is good tool to study the helicity conservation:
  - helicity state of $\gamma^*$ is easy to determine (QED)
  - $\rho^0 \rightarrow \pi^+\pi^-$ decay determines the helicity of $\rho^0$

**Kinematics:**

- $\nu = 5 \div 24 \text{ GeV}, <\nu> = 13.3 \text{ GeV}$
- $Q^2 = 0.5 \div 7.0 \text{ GeV}^2, <Q^2> = 2.3 \text{ GeV}^2$
- $W = 3.0 \div 6.5 \text{ GeV}, <W> = 4.9 \text{ GeV}$
- $x_{Bj} = 0.01 \div 0.35, <x_{Bj}> = 0.07$
- $t' = 0 \div 0.4 \text{ GeV}^2, <t'> = 0.13 \text{ GeV}^2$
Exclusive $\rho^0$ and $\phi$ Meson Production

$$e + p \rightarrow e' + p' + \rho^0 \rightarrow \pi^+\pi^-$$

$$e + p \rightarrow e' + p' + \phi \rightarrow K^+K^-$$

The exclusive events were selected from the missing energy spectra

$$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$$

for:

- $\rho^0$
- $\phi$

The background was simulated by code MC PYTHIA.
\( \rho^0 \) \& \( \phi \)-meson Spin Density Matrix Elements (SDMEs)

SDMEs: \( r^\alpha_{\lambda \rho \lambda' \rho'} \sim \rho(V) = \frac{1}{2} T_{\lambda V \lambda' \gamma} \rho(\gamma) T^{+}_{\lambda' V \lambda \gamma} \)

spin-density matrix of the vector meson \( \rho(V) \) in terms of the photon matrix \( \rho(\gamma) \)
and helicity amplitude \( T_{\lambda V \lambda' \gamma} \)

presented according to K.Schilling and G.Wolf (Nucl. Phys. B61 (1973) 381)
\( \alpha = 04, 1 - 3, 5 - 8 \) \(
\) long. or trans. photon, \( \lambda_\rho = -1, 0, 1 \) - polarization of \( \rho^0(\phi) \)

measured experimentally at \( 5 < W < 75 \) GeV (HERMES,COMPASS,H1,ZEUS)

provide access to helicity amplitudes \( T_{\lambda V \lambda' \gamma} \), which are:

- extracted experimentally from SDMEs
- calculated from GPDs:S.V.Goloskokov,P.Kroll arXiv:0708.3569 [hep-ph]27.08.07;
hep-ph/0501242
Simulated Events: matrix of fully reconstructed MC events from initial uniform angular distribution

Binned Maximum Likelihood Method: $8 \times 8 \times 8$ bins of $\cos(\Theta), \phi, \Phi$. Simultaneous fit of 23 SDMEs $r_{ij}^{\alpha} = W(\Phi, \phi, \cos(\Theta))$ for data with negative and positive beam helicity ($<|P_b|>= 53.5\%, \Psi = \Phi - \phi$)
Function for the Fit of 23 SDME $r_{ij}^{\alpha}$

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

$W^{unpol}(\cos \Theta, \phi, \Phi) = \frac{3}{8\pi^2} \left[ \frac{1}{2} (1 - r_{00}^{04}) + \frac{1}{2} (3r_{00}^{04} - 1) \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{04}\} \sin 2\Theta \cos \phi - r_{1-1}^{04} \sin^2 \Theta \cos 2\phi \\
- \epsilon \cos 2\Phi \left( r_{11}^{1} \sin^2 \Theta + r_{00}^{1} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{1}\} \sin 2\Theta \cos \phi - r_{1-1}^{1} \sin^2 \Theta \cos 2\phi \right) \\
- \epsilon \sin 2\Phi \left( \sqrt{2} \text{Im}\{r_{10}^{2}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{1-1}^{2}\} \sin^2 \Theta \sin 2\phi \right) \\
+ \sqrt{2} \epsilon (1 + \epsilon) \cos \Phi \left( r_{11}^{5} \sin^2 \Theta + r_{00}^{5} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{5}\} \sin 2\Theta \cos \phi - r_{1-1}^{5} \sin^2 \Theta \cos 2\phi \right) \\
+ \sqrt{2} \epsilon (1 + \epsilon) \sin \Phi \left( \sqrt{2} \text{Im}\{r_{10}^{6}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{1-1}^{6}\} \sin^2 \Theta \sin 2\phi \right) \right],$

$W^{long.pol.}(\cos \Theta, \phi, \Phi) = \frac{3}{8\pi^2} P_{beam} \left[ \sqrt{1 - \epsilon^2} \left( \sqrt{2} \text{Im}\{r_{10}^{3}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{1-1}^{3}\} \sin^2 \Theta \sin 2\phi \right) \\
+ \sqrt{2} \epsilon (1 - \epsilon) \cos \Phi \left( \sqrt{2} \text{Im}\{r_{10}^{7}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{1-1}^{7}\} \sin^2 \Theta \sin 2\phi \right) \\
+ \sqrt{2} \epsilon (1 - \epsilon) \sin \Phi \left( r_{11}^{8} \sin^2 \Theta + r_{00}^{8} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{8}\} \sin 2\Theta \cos \phi - r_{1-1}^{8} \sin^2 \Theta \cos 2\phi \right) \right]$
SDMEs and Amplitudes for: $\rho^0$, $\phi$

A- SCHC: $\gamma_L^* \rightarrow \rho_L^0$ and $\gamma_T^* \rightarrow \rho_T^0$

$$|T_{11}|^2 \propto 1 - r_{00}^{04} \propto r_{1-1}^1 \propto -\text{Im}\{r_{1-1}^2\}$$

B- Interference: $\gamma_L^*, \rho_T^0$

$$\text{Re}\{T_{00}T_{11}^*\} \propto \text{Re}\{r_{10}^5\} \propto -\text{Im}\{r_{10}^6\}$$

$$\text{Im}\{T_{11}T_{00}^*\} \propto \text{Im}\{r_{10}^8\} \propto \text{Re}\{r_{10}^8\}$$

C- Spin Flip: $\gamma_T^* \rightarrow \rho_L^0$

$$\text{Re}\{T_{11}T_{01}^*\} \propto \text{Re}\{r_{10}^{04}\}$$

$$\propto \text{Re}\{r_{10}^7\} \propto \text{Im}\{r_{10}^8\}$$

$$\text{Re}\{T_{01}T_{00}^*\} \propto r_{00}^5$$

$$|T_{01}|^2 \propto r_{00}^8$$

$$\text{Im}\{T_{01}T_{11}^*\} \propto \text{Im}\{r_{10}^8\}$$

$$\text{Im}\{T_{01}T_{00}^*\} \propto r_{00}^8$$

D- Spin Flip: $\gamma_L^* \rightarrow \rho_T^0$

$$\text{Re}\{T_{10}T_{11}^*\} \propto r_{11}^5 \propto r_{1-1}^5 \propto \text{Im}\{r_{1-1}^6\}$$

$$\text{Im}\{T_{10}T_{11}^*\} \propto \text{Im}\{r_{10}^7\} \propto r_{11}^8 \propto r_{1-1}^8$$

E- Double Spin Flip: $\gamma_T^* \rightarrow \rho_T^0$

$$\text{Re}\{T_{1-1}T_{11}^*\} \propto r_{1-1}^{04} \propto r_{11}^1$$

$$\text{Im}\{T_{1-1}T_{11}^*\} \propto \text{Im}\{r_{1-1}^3\}$$

$$\implies \text{Hierarchy of } \rho^0 \text{ amplitudes:}$$

$$|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \geq |T_{1-1}|, \ (0 \rightarrow L, 1 \rightarrow T)$$

$$\implies \phi \text{ meson SDMEs are consistent with SCHC, } |T_{00}| \sim |T_{11}|$$
The SDME’s dependencies on $Q^2$ for proton and deuteron data. The outer bars represent the total, the inner ones the statistical errors.
Dependencies of $\phi$ meson SDME’s on $t'$

The SDME’s dependencies on $t'$ for proton and deuteron data. The outer bars represent the total, the inner ones the statistical errors.
**Longitudinal-to-Transverse Cross-Section Ratio**

Comparison of commonly measured:

\[ R^{04} = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon} \frac{r^{04}}{1 - r^{04}} \]

where:

\[ r^{00} = \frac{\sum \{ \epsilon |T_{00}|^2 \} + }{\sigma_{tot}} \]

\[ \sigma_{tot} = \epsilon \sigma_L + \sigma_T \]

\[ \implies R^{04} \] for φ meson at HERMES is in good agreement with world data.
Natural Parity Exchange in φ Meson Leptoproduction

**HERMES PRELIMINARY**

ep(d) → e^−φp(d)

\[ U1 = 1 - r_{00}^0 + 2r_{1-1}^0 - 2r_{11}^1 \]

\[ U2 = r_{1-1}^5 + r_{11}^5 \]

\[ U3 = r_{1-1}^8 + r_{11}^8 \]

\[ \begin{align*}
U1 & = 0.02 \pm 0.07_{\text{stat}} \pm 0.16_{\text{syst}} \\
U2 & = -0.03 \pm 0.01_{\text{stat}} \pm 0.03_{\text{syst}} \\
U3 & = -0.05 \pm 0.11_{\text{stat}} \pm 0.07_{\text{syst}}
\end{align*} \]

⇒ no UPE for φ meson production, as expected
Dependencies of $\rho^0$ meson SDME’s on $Q^2$

INDICATIONS:
- green: SCHHC - $\gamma_L^* \rightarrow V_L, \gamma_T^* \rightarrow V_T$
- yellow: Single Flip - $\gamma_T^* \rightarrow V_L$
- grid: Single Flip - $\gamma_L^* \rightarrow V_T$
- blank: Double Flip - $\gamma_T^* \rightarrow V_{-T}$
Dependencies of $\rho^0$ meson SDME’s on $t'$

INDICATIONS:
- green: SCHHC - $\gamma^*_L \rightarrow V_L, \gamma^*_T \rightarrow V_T$
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HERMES PRELIMINARY
- ■ proton
- ● deuteron

$-t' \left( \text{GeV}^2 \right)$
$R^{04} = \frac{1}{\epsilon} \frac{r^{04}_{00}}{1 - r^{04}_{00}}$,

$r^{04}_{00} = \sum \{ |T_{00}|^2 + |T_{01}|^2 + |U_{01}|^2 \} / \sigma_{tot}$,

$\sigma_{tot} = \epsilon \sigma_L + \sigma_T$,

$\sigma_T = \sum \{|T_{11}|^2 + |T_{01}|^2 + |T_{1-1}|^2 + |U_{11}|^2 \}$,

$\sigma_L = \sum \{|T_{00}|^2 + 2|T_{10}|^2 \}$.

Due to the helicity-flip and unnatural parity amplitudes $R^{04}$ depends on kinematic conditions, and is not identical to $R \equiv |T_{00}|^2 / |T_{11}|^2$ at SCHC and NPE dominance.

$\implies$ Second order contribution of spin-flip amplitudes to $R^{04}$

$\implies$ HERMES $\rho^0$ data on $R^{04}$ are suggestive to R(W)-dependence
Natural-parity exchange: interaction is mediated by a particle of 'natural' parity: vector or scalar meson:

\[ J^P = 0^+, 1^- \text{ e.g. } \rho^0, \omega, a_2 \]

Unnatural parity exchange is mediated by pseudoscalar or axial meson:

\[ J^P = 0^-, 1^+ \text{ e.g. } \pi, a_1, b_1 \to \text{ only quark-exchange contribution} \]

No interference between NPE and UPE contributions on unpolarized target

Extracted from SDMEs:

\[ U_2 + iU_3 \propto (U_{11} + U_{1-1}) * U_{10} \]

\[ U_2 = r_{11}^5 + r_{1-1}^5 \]

p: \[ U_2 = -0.012 \pm 0.006_{\text{stat}} \pm 0.012_{\text{syst}} \]

d: \[ U_2 = -0.008 \pm 0.0046_{\text{stat}} \pm 0.010_{\text{syst}} \]

\[ U_3 = r_{11}^5 + r_{1-1}^5 \]

p: \[ U_3 = -0.020 \pm 0.050_{\text{stat}} \pm 0.007_{\text{syst}} \]

d: \[ U_3 = -0.021 \pm 0.038_{\text{stat}} \pm 0.011_{\text{syst}} \]

\[ U_1 \propto \epsilon |U_{10}|^2 + 2|U_{11} + U_{1-1}|^2 \]

\[ U_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{04} - 2r_{1-1}^{1} \]

p: \[ U_1 = 0.132 \pm 0.026_{\text{stat}} \pm 0.053_{\text{syst}} \]

d: \[ U_1 = 0.094 \pm 0.020_{\text{stat}} \pm 0.044_{\text{syst}} \]

p+d: \[ U_1 = 0.109 \pm 0.037_{\text{tot}} \]

\[ U_{11} \gg |U_{10}| \sim |U_{01}| \]
Conclusions

The transitions $\gamma^*_L \rightarrow \phi^0_L (\rho^0_L)$ and $\gamma^*_T \rightarrow \phi^0_T (\rho^0_T)$, are dominant for both $\rho$ and $\phi$.

SDME's: $(1 - r^{04}_{00}), \ r^1_{1-1}, \ \text{Im} \ r^2_{1-1}$, depend on $Q^2$ i.e $\sim 1/(Q^2 + m^2_v)$.

Helicity-Flip transition $\gamma^*_T \rightarrow \rho^0_L$:
Observed only for $\rho$. Regular dependence of three elements belonging to this set: $\text{Re} \{ r^{04}_{10} \}$, $\text{Re} \{ r^1_{10} \}$ and $r^5_{00}$ are nicely seen. In the case of $r^1_{00}$ and $\text{Im} \ \{ r^2_{10} \}$ dependencies are less pronounced.

Helicity-Flip transition $\gamma^*_L \rightarrow \rho^0_T$:
Very weak oscillating near zero.

Double Helicity-Flip transition $\gamma^*_T \rightarrow \rho^0_{-T}$: Very weak indication of the dependence on $Q^2$.

Dependence on target (H, D): not observed.

Only natural-Parity Exchange: only in the case of $\phi$.

Unnatural-Parity Exchange: only in the case of $\rho$.

Comparisons with other measurements: Good agreement. For measurements with higher $W$ small differences are seen due.
Determine SDME’s for samples with polarized target.
Dependencies of $\rho^0$ meson SDME’s on $Q^2$

The SDME’s as function of $Q^2$. For HRMSES data received at $W=5$ GeV for proton and deuteron targets as well as H1 and ZEUS data at $W=75$ GeV. Several SDMEs ($r_{00}^{04}, r_{1-1}^{11}, Im(r_{1-1}^2, ...)$) indicate possible $W$-dependence, in addition to $Q^2$-dependence.