Study of Spin Density Matrix Elements in hard exclusive electroproduction of $\phi$ meson on proton and deuteron at HERMES.

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Vector meson Spin Density Matrix Elements (SDMEs).
SDMEs and general properties of helicity amplitudes.
HERMES Experiment and data processing.
SDMEs for the integrated data.
Unnatural-Parity Exchange for $\phi$ meson.
Summary.
Spin Density Matrices in reaction

\[ e + N \rightarrow e' + \phi + N \]

- \( e \rightarrow e' + \gamma^* \) (QED). Spin-density matrix \( \rho^U = U_{\gamma, \gamma'}(\epsilon, \Phi) = U_{\gamma, \gamma'}^U + P_{\text{beam}} U_{\gamma, \gamma'}^L \) of the virtual photon is known. U - unpolarized, L - polarized beam

- \( \gamma^* + N \rightarrow \phi + N \rightarrow K^+ + K^- + N \) (QCD). Vector-meson spin-density matrix \( \rho_{\lambda V \lambda' V} \) is expressed by helicity amplitudes \( F_{\lambda V \lambda' V_1; \lambda N \lambda N}(W, Q^2, t') \). In CM frame of \( \gamma^* N \) is given by the von Neumann formula:

\[
\rho_{\lambda V \lambda' V} = \frac{1}{2N} \sum \lambda_N \lambda' N_{\lambda' N} \lambda N_{\lambda N} F_{\lambda V \lambda' V_1; \lambda N \lambda N} \rho_{\lambda N \lambda N} \rho_{\lambda' N \lambda' N} \rho_{\lambda' V \lambda' V_1} \rho_{\lambda V \lambda V_1}
\]

- \( \rho_{\lambda V \lambda' V} \) decompose into the set of nine hermitian matrices \( (3 \times 3) \Sigma^\alpha \) \( (\alpha = 0 \div 3 - \text{transv.}, 4 - \text{long.}, 5 \div 8 - \text{interf.}) \),

\[
\rho_{\lambda V \lambda' V} = \rho_{\lambda V \lambda' V}^\alpha \quad \alpha = 1, 2, 3, 5, 6, 7, 8.
\]

When we can not separate transverse and longitudinal photons, Spin Density Matrix Elements (SDMEs) are defined:

\[
r^{04}_{\lambda V \lambda' V} = \frac{\rho^{04}_{\lambda V \lambda' V}}{1 + \epsilon R}, \quad \rho^{04}_{\lambda V \lambda' V} = \frac{\rho^{04}_{\lambda V \lambda' V}}{(1 + \epsilon R)}, \quad \epsilon = 1, 2, 3,
\]

\[
r^\alpha_{\lambda V \lambda' V} = \begin{cases} 
\rho^\alpha_{\lambda V \lambda' V} \frac{(1 + \epsilon R)}{(1 + \epsilon R)}, & \alpha = 5, 6, 7, 8, \\
\sqrt{R} \rho^\alpha_{\lambda V \lambda' V} & \alpha = 1, 2, 3
\end{cases}
\]

- \( R = \frac{\sigma_L}{\sigma_T} \)
Angular distribution in reaction

\[ e + N \rightarrow e' + \phi + N \rightarrow e' + K^+ + K^- + N \]

- \( \phi \Rightarrow K^+K^- \) (conservation of \( \vec{J} \))

\[ |\phi; 1m \rangle \rightarrow |K^+K^-; 1m \rangle \Rightarrow Y_{1m}(\cos(\theta), \phi), \quad (m = \pm 1, 0) \]

Angular distribution \( W(\Phi, \phi, \cos \Theta) \) depends linearly on \( r_{\lambda_\nu \lambda'_{\nu'}}^\alpha \) and beam polarization \( P_b \).

For longitudinally polarized beam and unpolarized target there are 23 SDMEs, (15 unpolarized and 8 polarized) which are determined from the fit of angular distribution of Kaons from decay \( \phi \Rightarrow K^+K^- \).

SDMEs are bilinear combination of helicity amplitudes.
General properties of helicity amplitudes

\[ F_{\lambda_V \lambda'_N; \lambda_N \lambda_N} = T_{\lambda_V \lambda'_N; \lambda_N \lambda_N} + U_{\lambda_V \lambda'_N; \lambda_N \lambda_N} \]

- **T** - natural-parity exchange (NPE) \((P = (-1)^J)\)
- **U** - unnatural-parity exchange (UPE) \((P = -(−1)^J)\)

On unpolarized target **nucleon-helicity-flip** amplitudes are suppressed. \(T_{\lambda_V \lambda_N} = T_{\lambda_V \frac{1}{2} \lambda_N \frac{1}{2}}\)

Helicity conserving - \(T_{00}, T_{11}\), helicity non conserving - \(T_{01}, T_{10}, T_{1-1}\)

The dominance of diagonal transitions is called s-channel helicity conservation (SCHC).

\[ |T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{1-1}|^2. \]

NPE \((J^P = 0^+, 1^-)\) amplitudes \(T_{\lambda_V \lambda_N}\) (Two-gluon exchange = pomeron, \(\rho, \omega, a_2, \ldots\) reggeons = \(q\bar{q}\) exchange). UPE \((J^P = 0^-, 1^+)\) amplitudes \(U_{\lambda_V \lambda_N}\) (\(\pi, a_1, b_1, \ldots\) reggeons = \(q\bar{q}\) exchange)
Hermes Detector was Two Identical Halves of Forward Spectrometer

- Beam $e^\pm$, $P = 27.56$ GeV/c longitudinal polarization $\sim 55\%$.
- Target longitudinally, transversely polarized H or D or unpolarized gas target.
- Acceptance: $|\Theta_x| < 170$ mrad, $40 < |\Theta_y| < 140$ mrad.
- Resolution $\delta P/P \leq 1\%, \delta \Theta \leq 0.6$ mrad.
- PID: RICH, TRD, Preshower, Calorimeter.
Exclusive $\phi$-meson production at HERMES

- $W = 3.0 \div 6.3$ GeV, $<W> = 4.8$ GeV  total number of events (1996-2000)  $W^2 = (q+p)^2$
- $Q^2 = 1.0 \div 7.0$ GeV$^2$, $<Q^2> = 1.9$ GeV$^2$  Deuteron: $\rho^0 - 1038$
- $x_B = 0.01 \div 0.35$, $<x_B> = 0.08$  Hydrogen: $\rho^0 - 711$
- $0 \leq -t' \leq 0.4$ GeV$^2$, $<-t'> = 0.13$ GeV$^2$  with $t' = t - t_{min}$

$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$ with $M_X^2 = (p + q - p_{K+} - p_{K-})^2$ and $M_X$ being missing mass, p, q, $p_{K+}$, $p_{K-}$ are 4-momenta of proton, $\gamma^*$ and Kaons.

$-1.0 < \Delta E < 0.6$ GeV,

$0.99 < M_{KK} < 1.04$ GeV,

SIDIS background is subtracted using MC PYTHIA
**HERMES PRELIMINARY**

- $\phi$ proton and deuteron, $Q^2 = 1.9$ GeV, $W = 5$ GeV
- $\rho^0$ proton, EPJ C 62, 4 (2009) 659

**A:** $\gamma_L^* \rightarrow V_L^0$ and $\gamma_T^* \rightarrow V_T^0$

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

**B:** Interference $\gamma_L^* \rightarrow V_L^0$ and $\gamma_T^* \rightarrow V_T^0$

- $Re\{T_{00}T_{11}^*\} \propto Re\{r_{10}^5\} \propto -Im\{r_{10}^6\}$
- $Im\{T_{11}T_{00}^*\} \propto Im\{r_{10}^7\} \propto Re\{r_{10}^8\}$

**C:** Spin Flip: $\gamma_T^* \rightarrow \phi_L$

- $Re\{T_{11}T_{01}^*\} \propto Re\{r_{10}^{04}\} \propto Re\{r_{10}^1\} \propto Im\{r_{10}^2\}$
- $Re\{T_{01}T_{00}^*\} \propto r_{00}^5$

**D:** Spin Flip: $\gamma_T^* \rightarrow \phi_T$

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

**E:** Spin Flip: $\gamma_T^* \rightarrow \phi_{-T}$

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

**Hierarchy of $\rho^0$ amplitudes:**

$|T_{00}| \sim |T_{11}| \gg |T_{01}| \gg |T_{10}| \gg |T_{1-1}|$,  

$\Rightarrow$
**SDME of exclusive $\phi$ production for the integrated data, class A and B**

**HERMES PRELIMINARY**
- $\phi$ proton and deuteron, $Q^2 = 1.9$ GeV$^2$, $W = 5$ GeV
- $p^0$ proton, EPJ C 62, 4 (2009) 659

A, $\gamma^*_L \to \phi_L$ and $\gamma^*_T \to \phi_T$

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

SDMEs($\phi$) larger by 10% - 20% than SDMEs($\rho^0$)

$$|T_{11}/T_{00}(\phi)| > |T_{11}/T_{00}(\rho_0)|$$

B, Interference: $\gamma^*_L, \phi_T$

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

\[Im\{T_{11}T_{00}^*\} \propto Im\{r_{10}^7\} \propto Re\{r_{10}^8\}\]

if SCHC holds:

\[r_{1-1}^1 = -Im\{r_{1-1}^2\}\]

\[Re\{r_{10}^5\} = -Im\{r_{10}^6\}\]

\[Im\{r_{10}^7\} = Re\{r_{10}^8\}\]

Phase difference of $T_{11}$ and $T_{00}$

\[\tan\delta = (Im\{r_{10}^7\} + Re\{r_{10}^8\})/(Re\{r_{10}^5\} - Im\{r_{10}^6\})\]

\[\delta = 33.0 \pm 7.4 \text{ deg}\]

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

\[|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \gg |T_{1-1}|\]
SDME of exclusive $\phi$ production for the integrated data class C,D,E

C, Spin Flip: $\gamma^*_T \rightarrow \phi_L$

$$Re\{T_{11}T^*_{01}\} \propto Re\{r^4_{01}\} \propto Re\{r^1_{10}\} \propto Im\{r^2_{10}\}$$

$$|T_{01}|^2 \propto r^1_{00}$$

$$Im\{T_{01}T^*_{11}\} \propto Im\{r^3_{10}\}$$

$$Im\{T_{01}T^*_{00}\} \propto r^8_{00}$$

$\phi$ meson SDMEs are consistent with SCHC

Pronounced differences for $r^5_{00}$ and $Re\{r^4_{01}\}$ between $\rho$ and $\phi$

$$r^5_{00} \propto Re(T_{11}T^*_{01}) = |T_{01}| |T_{11}| \cos \delta_{01}$$

$$r^8_{00} \propto Im(T_{11}T^*_{01}) = |T_{01}| |T_{11}| \sin \delta_{01}$$

$$|T_{01}|(\phi) < |T_{01}|(\rho^0)$$

$T_{01} \sim 0$ in the absence of longitudinal quark motion in meson.

smaller longitudinal quark motion in the $\phi$ meson as compared to the $\rho^0$

$$|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \gg |T_{1-1}|$$
**Test of Unnatural-Parity Exchange for $\phi$ meson**

- **Signal of UPE in SDME method**
  
  $u_1(\phi) = 0.021 \pm 0.071_{\text{stat}} \pm 0.159_{\text{syst}}$

  $u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1}$

  $u_1 = \sum \lambda_N \lambda'_N \frac{2\epsilon|U_{10}|^2 + |U_{11} + U_{-11}|^2}{N}$

Summary

The SDMEs were extracted for electroproduction of $\phi$ vector meson on proton and deuteron at HERMES.

They are presented grouped into five classes according to the hierarchy of helicity amplitudes.

It was found that $|T_{11}/T_{00}|$ for $\phi$ meson is larger than for $\rho^0$ meson.

The violation of SCHC by SDMEs is not seen for $\phi$ meson.

$|T_{01}|$ is very small for $\phi$ production - smaller longitudinal quark motion in the $\phi$ meson as compared to $\rho^0$ meson.

The UPE contribution is not seen for $\phi$ meson production.