Spin Density Matrix Elements from diffractive φ meson production at HERMES

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Exclusive production of φ mesons on hydrogen and deuterium targets is studied in the HERMES kinematic region $1 < Q^2 < 7 \text{ GeV}^2$ and $3.0 < W < 6.3 \text{ GeV}$. Spin density matrix elements and their $Q^2$ and $t$ dependences are presented. These data are consistent with $s$-channel helicity conservation in exclusive φ meson production. No statistically significant evidence for the contribution of unnatural-parity-exchange amplitudes is found.

1 Introduction

Electroproduction of neutral vector mesons from nucleons is described by the interaction with the nucleon of $q\bar{q}$ pair created by virtual photon. The reaction $e + N \rightarrow e' + \phi + N'$ in the single-photon approximation is equivalent to $\gamma^* + N \rightarrow \phi + N'$, in which the $\gamma^*$ has negative squared four-momentum transfer $Q^2$ and polarization parameter $\epsilon$, the ratio of fluxes of longitudinal and transverse virtual photons. The spin transfer from the virtual photon $\gamma^*$ to the vector meson $V$ is commonly described \cite{1, 2} in terms of Spin Density Matrix Elements (SDMEs). The experimentally determined set of 23 SDMEs for the $\phi$ meson is presented here in the Schilling-Wolf \cite{1} representation. From measured values of the SDMEs one may examine $s$-Channel Helicity Conservation (SCHC) in the transition $\gamma^* \rightarrow V$. The fractional contribution of Unnatural-Parity-Exchange (UPE) amplitudes of the process $\gamma^* + N \rightarrow V + N$ in comparison with Natural-Parity-Exchange (NPE) amplitudes can also be derived from SDMEs measurements. Natural-parity exchange indicates that the interaction is mediated by a particle of “natural” parity ($J^P = 0^+, 1^-, 2^+, \ldots$), while UPE amplitudes describe the exchange of a particle of “unnatural” parity ($J^P = 0^-, 1^+, \ldots$). Since the $\phi$ meson consists mainly of strange quarks with a very small admixture of other quark flavors, it is expected that quark-exchange with the nucleon is suppressed and two- (or more) gluon exchange dominates. For $\rho^0$ meson production at HERMES kinematics, both two-gluon-exchange and quark-exchange contributions of the same order of magnitude \cite{3, 4} are needed to describe the data. Hence a comparison of SDMEs for $\phi$ and $\rho^0$ mesons allows a test of our understanding of these mechanisms. Further information about these final-state interactions can be obtained by measuring the phase difference between amplitudes.

2 Selection of exclusive $\phi$ mesons

The experiment was performed with longitudinally polarized electron and positron beams at an energy of 27.5 GeV using unpolarized hydrogen or deuterium gas targets. The decay

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products of the $\phi$ mesons ($\phi \rightarrow K^+K^-$, branching ratio $\approx 49\%$) were detected in the HERMES spectrometer [5]. The $\phi$ mesons were selected by requiring $0.99 < M_{KK} < 1.04$ GeV for the invariant mass of the two hadrons (see Fig. 1). In addition, the identification of the decay particles was required. For the data set obtained in 1996-1997, the absence of a threshold pion signal from the Cherenkov detector was required, while for the data from 2000-2002 information from the RICH [6] detector was used. 

As can be seen from Fig. 1 the non-resonant contribution under the $\phi$ meson invariant mass peak is negligible. Exclusive events were selected by the requirement: $\Delta E = (M_X^2 - M^2)/(2M) \leq 0.6$ GeV, where $M$ ($M_X$) is the mass of the nucleon (missing mass). Diffractive events were selected by the constraint $-t' < 0.4$ GeV$^2$. Here, $t' = t - t_0$, with $t$ being the squared four-momentum transfer from virtual photon to vector meson and $-t_0$ the smallest kinematically allowed value of $-t$ at fixed $Q^2$ and energy in the $\gamma^*N$ center-of-mass system ($W$). The fraction of semi-inclusive deep-inelastic scattering events in the chosen region was determined to be 1.6%.

3 Spin Density Matrix Elements

3.1 Formalism

The matrix $r_{\alpha}^{\lambda_V \lambda_N'}$ is given by $r_{\alpha}^{\lambda_V \lambda_N'} = \sum_{\lambda_N} F_{\lambda_V \lambda_N \lambda_N}^{\lambda'} \sum_{\lambda_N} F_{\lambda_V \lambda_N \lambda_N}^{\lambda'}$, where $F_{\lambda_V \lambda_N \lambda_N}$ is the amplitude of the process $\gamma^*(\lambda_N) + N(\lambda_N) \rightarrow V(\lambda_V) + N'(\lambda_N')$ (symbols in parenthesis denote particle helicities) and $N$ is the normalization factor. The amplitude $F$ may be decomposed into the sum of a NPE amplitude $T_{\lambda_V \lambda_N \lambda_N}$ and a UPE amplitude $U_{\lambda_V \lambda_N \lambda_N}$. Since the contribution to the SDMEs from the NPE amplitudes with nucleon spin flip are suppressed by a factor of about $-t'/(4M^2)$, only the NPE amplitudes with $\lambda_N = \lambda_N$ will be discussed here and the shorthand notation $T_{\lambda_V \lambda_N} = T_{\lambda_V \lambda_N \lambda_N}$ will be used below. The nine Hermitian matrices $\Sigma_{\alpha}^{\lambda \lambda'}$ are defined in [1]. The upper index $\alpha = 0$ corresponds to the unpolarized transverse photon, $\alpha = 1, 2$ to the two directions of linear polarization, $\alpha = 3$ - circular polarization, $\alpha = 4$ corresponds to the longitudinal photon and $\alpha = 5-8$ are attributable to the interference of longitudinal and transverse photons. Without using different lepton beam energies contributions of the transverse and longitudinal photons.
cannot be disentangled, hence the matrices $r_{ij}^0$ and $r_{ij}^4$ cannot be measured separately; only their combination $r_{ij}^{04} = r_{ij}^0 + cr_{ij}^4$ is determined. For this case the normalization factor $N$ can be found from the condition $\text{tr}(r^{04}) = r_{00}^{04} + r_{11}^{04} + r_{01}^{04} - 1 = 1$. Eight matrix elements of the matrices $r_{ij}^3, r_{ij}^7, r_{ij}^8$, referred to as “polarized” SDMEs, measured for the first time by HERMES, are presented in Fig. 2 (yellow background). The other 15 matrix elements, called “unpolarized,” do not require a polarized beam.

The 3-dimensional angular distribution of the scattered lepton and the decay products is described by the following angles (see detailed definitions in [7]): $\Phi$ is the angle between the $\phi$ meson production and lepton scattering planes in the $\gamma^p$ center-of-mass system. The polar $\varphi$ and azimuthal $\Theta$ angles of the decay $K^+$ are presented in the $\phi$-meson rest frame.

The extracted SDMEs will be presented based on a hierarchy of NPE helicity amplitudes: $|T_{00}| \sim |T_{11}| \gg |T_{01}| \sim |T_{-11}|$, established for the first time in Ref. [8] for $\rho^0$ production. This hierarchy is valid at asymptotically high value of $Q^2$, and was experimentally confirmed for exclusive $\rho^0$ production at HERMES kinematics [4]. The SDMEs are categorized into five classes according to this hierarchy. The two classes A and B describe only SCHC transitions. Classes from C to E contain also spin flip transitions. Class A comprises SDMEs with dominant contributions proportional to $|T_{00}|^2$ or $|T_{11}|^2$ - the helicity-conserving amplitudes describing the transitions $\gamma_L^* \rightarrow V_L$ and $\gamma_T^* \rightarrow V_T$. Class B SDMEs correspond to the interference of $T_{00}$ and $T_{11}$ amplitudes. The main terms for the unpolarized (polarized) SDMEs are proportional to the real (imaginary) part of $T_{00}T_{11}^*$. In fact, as a general rule for the classes B - E, the dominant contribution of the unpolarized (polarized) SDMEs is proportional to the real (imaginary) part of the product of two amplitudes. Class C contains SDMEs with dominant terms that are products of the $s$-channel helicity non-conserving amplitude $T_{01}$ (corresponding to the $\gamma_T^* \rightarrow V_L$ transition), and $T_{00}^*$ or $T_{11}^*$ (for $r_{00}^1$, the $T_{01}$ contribution is actually quadratic). Classes D and E are composed of SDMEs in which the main terms contain a product of the small helicity-flip amplitudes $T_{10}$ ($\gamma_L^* \rightarrow V_T$) and $T_{-11}$ ($\gamma_T^* \rightarrow V_{-T}$), respectively, multiplied by $T_{11}^*$.

### 3.2 Extracted SDMEs

The SDMEs are obtained by minimizing the difference between the 3-dimensional ($\cos \Theta, \phi, \Phi$) matrix of the data and the analogous matrix from fully reconstructed simulated events. An $8 \times 8 \times 8$ binning was used for the variables $\cos \Theta, \phi, \Phi$. The simulated events were generated with uniform angular distributions and re-weighted in an iterative procedure with the angular distribution $W(\cos \Theta, \phi, \Phi, r_{ij}^3)$ [4], where the spin density matrix elements $r_{\lambda\lambda'}^3$ were treated as free parameters. The best fit parameters were determined using a binned maximum log-likelihood method. The minimization itself and the error calculation were performed by MINUIT.

The extracted SDMEs for the kinematic region $1 < Q^2 < 7$ GeV$^2$, $3 < W < 6.3$ GeV, and $0 < -t' < 0.4$ GeV$^2$, are presented for $\rho^0$ and $\phi$ meson data in Fig. 2. The average kinematic values are $\langle Q^2 \rangle = 1.9$ GeV$^2$, $\langle W \rangle = 4.8$ GeV and $\langle -t' \rangle = 0.13$ GeV$^2$. The experimental uncertainties are larger for the eight polarized SDMEs due to the imperfect lepton beam polarization (0.53), and the small kinematic factor $\sqrt{1 - \epsilon}$ ($\langle \epsilon \rangle = 0.8$) by which the polarized SDMEs are multiplied.

In Fig. 2 the SDMEs are shown multiplied by certain factors to make the coefficients of the dominant amplitude products equal to unity. The elements of class A are presented in the figure in such a way that their main terms are proportional to $|T_{11}|^2$, in particular
1 − r_{10}^{00} is chosen. The SDMEs of class A are similar for ρ^0 and φ. The elements of class B are also close to each other for both vector mesons. For φ mesons the values of the elements of classes C, D and E fluctuate near zero supporting the validity of SCHC. For ρ^0 mesons the elements of classes C, D, E with significantly non-zero values indicate that there exists also a production mechanism which does not conserve s-channel helicity. We note, that small violation of SCHC was observed for φ production by the H1 Collaboration [9].

The dependences of φ meson SDMEs on Q^2 and t’ are shown in Fig. 3. For the presentation of the Q^2 (t’) dependence, an additional bin of 0.5 < Q^2 < 1 GeV^2 (0.4 < t’ < 1 GeV^2) is included. As seen also in Fig. 2 the SDMEs from classes A and B are non-zero (in agreement with a GPD model calculation [3]). One can see some dependence on Q^2 for these elements, however a t’ dependence is not observed. We note that the SCHC relations r_{1-1} = −\Im\{r_{21}^0\}, \Re\{r_{10}^0\}, \Re\{r_{10}^\phi\} = \Im\{r_{10}^{\phi}\} are fulfilled in every kinematic bin in Q^2 and t’. The elements from classes C to E, related to spin-flip transitions,

Figure 2: The 23 SDME’s extracted for ρ^0 production on the proton (squares) and for φ meson production on proton and deuteron (circles). The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature. The unshaded (shaded) areas indicate unpolarized (polarized) SDME’s. For easier interpretation the set of SDMEs was divided in five classes (see text).
Figure 3: The kinematic dependence of $\phi$ SDMEs on $Q^2$ and $t'$. Proton and deuteron data are combined. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature.

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should mainly depend on \( t' \); the present experimental uncertainty is insufficient to observe any dependence.

### 3.3 Phase Difference of \( T_{11} \) and \( T_{00} \)

The interference between the dominant amplitudes \( T_{11} \) and \( T_{00} \) depends on their phase difference \( \delta \) which can be evaluated as follows: \( \tan \delta = [\text{Im}\{r_{10}^7\} + \text{Re}\{r_{10}^8\}] / [\text{Re}\{r_{10}^5\} - \text{Im}\{r_{10}^6\}] \). This results in \( \delta = 33.0 \pm 7.4 \) deg, for the combined proton and deuteron \( \phi \) meson data. For the first time, the sign of \( \delta \) is determined to be positive. We note that in the GPD-based calculations of Ref. [3], the value of \( \delta \) is found to be \( \sim 3 \) degrees. This appears to be inconsistent with the above result.

### 3.4 Unnatural-Parity Exchange

Without assuming SCHC, the hypothesis of natural parity exchange in the \( t \) channel alone leads to the following relations: \( U_1 = 1 - r_{06}^{04} - 2r_{111}^{11} - 2r_{111}^{1} - 2r_{111}^{11} - 2r_{111}^{11} = 0 \), \( U_2 = r_{111}^{11} + r_{111}^{11} = 0 \), and \( U_3 = r_{111}^{11} + r_{111}^{11} = 0 \).

As presented in Fig. 4 all those relations are approximately fulfilled, indicating that UPE amplitudes do not contribute significantly to exclusive \( \phi \) meson production. A non-zero signal of UPE is evidence for the existence of quark-antiquark exchange, which is observed for exclusive \( \rho^0 \) (see Fig. 4).

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Figure 4: \( Q^2 \) dependence of the linear combinations of SDMEs \( U_1, U_2, U_3 \) for \( \phi \) and \( \rho^0 \) (only on the top panel). Values integrated over the range \( 1 < Q^2 < 7 \text{ GeV}^2 \) are presented in the first bin \( Q^2 < 1 \text{ GeV}^2 \) by open symbols. Only statistical errors are presented.