NEW RESULTS ON EXCLUSIVE $\rho^0$ AND $\phi$ MESON PRODUCTION AT HERMES

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Abstract

Exclusive diffractive production of light vector mesons ($\rho^0$ and $\phi$) on Hydrogen and Deuterium targets is measured in the HERMES kinematic region of $0.5 < Q^2 < 7$ GeV$^2$ and $3.0 < W < 6.3$ GeV. Data for $Q^2$ and $W$ dependences of longitudinal cross sections are presented and compared with GPD based calculations and world data. Spin density matrix elements have been determined for exclusive $\rho^0$ and $\phi$ production. Within the given experimental uncertainties a hierarchy of relative sizes of helicity amplitudes is observed. Non-conservation of $s$-channel helicity is observed for $\rho^0$, but not for $\phi$ mesons. An indication of a contribution of unnatural parity exchange amplitudes in exclusive $\rho^0$ production is seen for proton data.

1 Introduction

Exclusive production of vector mesons such as $\rho$, $\omega$ or $\phi$ in deep-inelastic lepton scattering, see Fig. 1 a, is of particular interest as measurements of angular and momentum distributions of the scattered lepton and the vector meson decay products allow the study of the production mechanism and, in a model-dependent way, the nucleon structure. In the context of perturbative QCD (pQCD), the formalism of Generalized Parton Distributions (GPDs) has been introduced to describe the structure of the nucleon [1]. Here, at sufficiently large values of the factorization scale, exclusive meson production is assumed to be dominated by handbag-diagrams, see Fig. 1 b, which involve various GPDs, e.g. $H$, $\bar{H}$, $E$, $\bar{E}$. Experimentally, GPDs can be investigated assuming certain functional forms for GPDs with a number of adjustable parameters, and fitting these parameters through a comparison of calculated observables with experimental data [2]. The HERMES data on hard-exclusive production of vector mesons ($\rho^0$ and $\phi$) are compared with the calculations of the GK model [3]-[6] which is based on the ‘handbag factorization’.

The determination of the longitudinal cross section ($\sigma_L$) of $\rho^0$ [7] and $\phi$ meson production allows the estimation of the contributions of the two major production mechanisms involved: quark-exchange and gluon-exchange, see Fig. 1 b. For these two mechanisms, the amplitudes of $\rho^0$ and $\phi$ meson production have been calculated in the GK model and, from properly normalized bilinear combinations of amplitudes, the spin density matrix elements (SDMEs) have been obtained and compared with HERMES data.

The spin transfer from the virtual photon to the vector meson is commonly described [8] in terms of SDMEs. Those are usually described in the center-of-mass system of the virtual photon and target nucleon by the helicity amplitudes $T_{\lambda_V,\lambda_N,\lambda,\lambda_N}$ where $\lambda_V$ ($\lambda_N$) is the helicity of the vector meson (virtual photon). For longitudinal polarization
of virtual photon (vector meson) \( \lambda_{\gamma(V)} = 0 \), and \( \lambda_{\gamma(V)} = \pm 1 \) for transverse polarization. Helicities of incident \( (\lambda_N) \) and outgoing nucleon \( (\lambda'_N) \) are summed over. The full expression for the decay angular distribution is given in Ref. [8] in terms of SDMEs \( r_{ij}^\alpha \), which are related to the initial spin density matrix elements \( \rho_{\lambda\lambda'} \) of the vector meson: 

\[
\rho_{\lambda\lambda'}^\alpha = \frac{1}{2N_\alpha} \sum_{\lambda\gamma} T_{\lambda\lambda'} \Sigma^\alpha_{\lambda\gamma} T^\dagger_{\gamma\lambda'}. 
\]

Here \( N_\alpha \) denotes a normalization factor, and \( \Sigma^\alpha_{\lambda\gamma} (\alpha = 0, 1, \ldots, 8) \) are nine Hermitian matrices defined in Ref. [8]. The index values \( \alpha = 0, 1, 2, 3 \) represent transverse photons: unpolarized, the two directions of linear polarization, and circular polarization. Pure longitudinal photons correspond to \( \alpha = 4 \), while the remaining values \( \alpha = 5, 6, 7, 8 \) are attributed to the interference of longitudinal and transverse photons. Summation over final nucleon helicities and averaging over initial proton helicities is implied. As the contributions of longitudinal and transverse photons are not distinguishable at fixed beam energy, the following matrix elements (referred to SDMEs) are used [8]: 

\[
r_{04}^\alpha \equiv (\rho^0 + \epsilon R\rho^1)/(1 + \epsilon R), \quad r_{12}^\alpha \equiv \rho^\alpha/(1 + \epsilon R) \quad \text{for} \quad \alpha = 1, 2, 3, \\
r_{56}^\alpha \equiv \sqrt{R}\rho^\alpha/(1 + \epsilon R) \quad \text{for} \quad \alpha = 5, 6, 7, 8, 
\]

where \( \epsilon \) is the virtual-photon polarization parameter and \( R \equiv \frac{\sigma_T}{\sigma_L} \) is the longitudinal-to-transverse cross section ratio.

In the case of \( s \)-channel helicity conservation (SCHC), the helicity of the vector meson is the same as that of the virtual photon. The validity of SCHC was tested and, as shown below, the observation of several non-zero SDMEs for \( \rho^0 \) production indicates contributions from SCHC-violating helicity-flip amplitudes. In addition, the relative contributions of natural and unnatural-parity exchange were estimated from the combination of certain SMDEs. Natural-parity exchange (NPE) indicates that the interaction between the virtual photon and the target nucleon is mediated by a particle of ‘natural’ parity \( (J^P = 0^+, 1^-, \ldots) \) e.g. \( \rho^1, \omega, A_2 \), while ‘unnatural’ parity exchange (UnPE) denotes the contribution of exchanged mesons with \( J^P = 0^-, 1^+, \ldots \), e.g. \( \pi \) or \( A_1 \).
2 Detection of $\rho^0$ and $\phi$ Mesons and Their Longitudinal Cross Sections

In the HERMES spectrometer [9] $\rho^0$ and $\phi$ mesons are observed by detecting their decay products in the following channels: $\rho^0 \rightarrow \pi^+\pi^-$ (100%) and $\phi \rightarrow K^+K^-$ (49%), respectively. The $\rho^0$ mesons are identified [7] by requiring $0.6 < M_{\pi\pi} < 1$ GeV, with $M_{\pi\pi}$ being the invariant mass of the $\pi^+\pi^-$ system. The $\phi \rightarrow K^+K^-$ background in the $\rho^0$ spectrum is removed by the requirement that $M_{KK} > 1.04$ GeV, if the hadrons are assumed to be kaons. The $\phi$ mesons are selected by requiring $0.99 < M_{KK} < 1.04$ GeV. The absence of a signal in the Cherenkov threshold detector is required to identify kaon tracks in 1996-1997 data samples. For 1998-2000 data information from RICH detector [10] was used for kaon identification.

In order to extract information on the longitudinal production cross section, data on $R_{00}^{00}$, the longitudinal fraction of the $\rho^0$ cross section, have been used [7]. Using a parameterization of $R$, the longitudinal cross section for $\rho^0$ and $\phi$ production has been determined using $\sigma_L = \frac{R}{1+R} \sigma_{total}$, where $\sigma_{total}$ represents the total measured cross section [7]. The resulting values for $\rho^0$ and $\phi$ production are shown in Figs. 2 a and b, respectively, and are compared to the calculations of Ref. [4] and world data. The calculations for $\rho^0$ are in agreement with the data if the quark-exchange, two-gluon and sea quark interference, and the gluon-exchange contributions are included. For $\phi$ meson production only the gluon-exchange mechanism is expected to contribute, as the proton contains only a small population of $s$-quarks. Calculations based on this assumption [4] are in agreement with the data as presented in Fig. 2 b. Contributions of different mechanisms to the longitudinal cross section of $\rho^0$ and $\phi$ meson leptoproduction are also related to the following results on SDMEs.

3 Spin Density Matrix Elements

In exclusive vector meson production, the angular distributions of the scattered lepton and the vector meson decay products are described in terms of the angles: $\Phi$, the angle between the scattering plane and the $\rho^0$ production plane, $\Theta$ and $\phi$, the polar and azimuthal angles of the decay $\pi^+$ in the vector meson rest frame with the $z$-axis aligned opposite to the outgoing nucleon momentum in the $\gamma^*p$ center-of-mass system [8], see Fig. 3 a.

The SDMEs are obtained from the measured angular distributions by minimizing the difference between the 3-dimensional ($\cos \Theta, \phi, \Phi$) decay angle matrices of the data and of a sample of fully reconstructed Monte Carlo events, using the maximum likelihood method. An $8 \times 8 \times 8$ binning was used for the variables $\cos \Theta, \phi, \Phi$. The Monte Carlo events were generated with uniform angular distributions and were reweighted in an iterative procedure with the angular distribution $W(\cos \Theta, \phi, \Phi, r_{ij})$ [8], where the SDMEs were treated as free parameters. These SDMEs were determined without the assumption of SCHC. The best fit parameters were obtained using a binned maximum log-likelihood method. The minimization itself and the error calculation were performed using the MINUIT package. Angular distributions from Monte Carlo, weighted with the final SDMEs, are compared with the data in Fig. 3 b.
3.1 Hierarchy of SDMEs

The extracted SDMEs will be presented below based on the hierarchy of NPE helicity amplitudes:

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

where the subscripts denote the helicities of vector meson and virtual photon. This hierarchy was established for the first time in Ref. [17]. It is experimentally confirmed [12, 13] at the HERA collider and discussed in Refs. [3, 4, 5]. The measured 23 SDMEs are subdivided into five classes according to the hierarchy shown above. Class A includes SDMEs dominated by the helicity-conserving amplitudes \( T_{00} \) and \( T_{11} \) which describe the transitions \( \gamma_L^* \to \rho_L^0 \) and \( \gamma_T^* \to \rho_T^0 \), respectively. Class B contains SDMEs corresponding to the interference of the above two amplitudes. Class C consists of all those SDMEs in which the main term contains a linear contribution of the s-channel helicity non-conserving amplitude \( T_{01} \), corresponding to the \( \gamma_T^* \to \rho_L^0 \) transition, except \( r_{00}^1 \) for which the \( T_{01} \) contribution described above is quadratic. The classes D and E represent the SDMEs in which the main terms contain a linear contribution of the small helicity-flip amplitudes \( T_{10} \) (\( \gamma_L^* \to \rho_T^0 \)) and \( T_{-11} \) (\( \gamma_T^* \to \rho_{-L}^0 \)), respectively.

The SDMEs extracted for the kinematic region \( 1 < Q^2 < 5 \text{ GeV}^2, \ 3 < W < 6.3 \)
Figure 3a. Definition of angles in the process $\gamma^* p \rightarrow \rho^0 p$. Here $\Phi$ is the angle between the $\rho^0$ production plane and the lepton scattering plane, $\Theta$ and $\phi$ are polar and azimuthal angles of the decay $\pi^+$ in the vector meson rest frame.

Figure 3b. Angular distributions of $\rho^0$ meson production and decay. Data points represent used in the fit subsample of the proton data with positive polarization of the beam. The dotted lines are the Monte Carlo input distributions, the dashed lines are the results of the 23-parameter fit.

GeV (corresponding to $0.03 < x_{Bj} < 0.25$), and $0 < -t' < 0.4$ GeV$^2$, are presented for $\rho^0$ and $\phi$ meson data in Fig. 4. The shown SDMEs are multiplied by certain factors in order to present them according to the dominant amplitudes. 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 $1 - r_{04}^0$. The coefficients for class B are chosen to have the main contribution for the SDMEs proportional to $\text{Re}\{T_{11}T^*_0\}$ and $\text{Im}\{T_{11}T^*_0\}$, respectively. This corresponds to the general rule which is applicable to classes B to E: the dominant contribution of any element presented in Fig. 4 is equal to the real or imaginary part of a product of two amplitudes. Class C contains products $T_{01}T^*_0$ (for $r_{00}^5/\sqrt{2}$ and $r_{00}^8/\sqrt{2}$) and $T_{01}T^*_0$. The dominant contributions for classes D and E contain products $T_{10}T^*_1$ and $T_{11}T^*_1$, respectively.

The unpolarized SDMEs of class B have large values, very similar to those of class A. This suggests the presence of a substantial interference between the two dominant amplitudes $T_{00}$ and $T_{11}$ for $\rho^0$ and $\phi$ meson production. The two polarized class B SDMEs are significantly non-zero for $\rho^0$ and $\phi$ as well. As seen from Fig. 4, the values of elements in class C which contains the dominant term $T_{01}T^*_0$ are close to each other for the unpolarized SDMEs ($\text{Re}\{r_{10}^2\}$, $\text{Re}\{r_{10}^1\}$, $\text{Im}\{r_{10}^1\}$). While they are much smaller than class B SDMEs, they are still significantly larger than class D and class E SDMEs. This shows that the anticipated hierarchy is supported by the data.
HERMES PRELIMINARY

- $\rho^0$ proton, $\langle Q^2 \rangle = 1.9$ GeV$^2$, $\langle W \rangle = 5$ GeV
- $\phi$ proton and deuteron

A: $\gamma^* \rightarrow V_L^0$ & $\gamma^* \rightarrow V_T^0$

B: Interference $\gamma^* \rightarrow V_L^0$ & $\gamma^* \rightarrow V_T^0$

C: $\gamma^* \rightarrow V_L^0$

D: $\gamma^* \rightarrow V_T^0$

E: $\gamma^* \rightarrow V_{-T}^0$

Figure 4. The 23 SDMEs extracted for $\rho^0$ production on proton (squares) and $\phi$ meson production on proton and deuteron (circles) in the entire HERMES kinematics with $\langle x \rangle = 0.08, \langle Q^2 \rangle = 1.9$ GeV$^2$, $\langle -t \rangle = 0.13$ GeV$^2$. The SDMEs are renormalized to represent the leading contribution of the corresponding amplitude. 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 beam-polarization independent (dependent) SDMEs. The vertical dashed line at zero corresponds to SDMEs expected to be zero under the hypothesis of SCHC.
3.2 Test of the SCHC Hypothesis

Elements of classes C,D,E indicate non-conservation of s-channel helicity in $\rho^0$ production if they are non-zero. In particular, the SDME $r_{00}^5$ is observed to be non-zero at the level of eight standard deviations in the combined uncertainty, proving s-channel helicity non-conservation. This was already observed earlier by the HERA collider experiments [12, 13] at a lower significance level, and with high significance very recently [12]. For the first time, HERMES observes s-channel helicity non-conservation also in other class C SDMEs, in particular $\text{Re}\{r_{10}^0\}$. The beam-polarization dependent elements $r_{00}^8$ and $\text{Im}\{r_{10}^3\}$ are determined using information on the longitudinally polarized lepton beam, for the first time. Both elements are consistent with zero within large uncertainties, indicating only a small possible contribution from the term $\text{Im}\{T_{01}^0 T_{11}^1\}$.

Contrary to $\rho^0$ production, $\phi$ meson SDMEs are in agreement with s-channel helicity conservation.

3.3 Phase Difference between $T_{11}$ and $T_{00}$

The phase difference $\delta$ between the amplitudes $T_{11}$ and $T_{00}$ can be evaluated as follows:

$$\cos \delta = \frac{2\sqrt{\text{Re}\{r_{10}^5\} - \text{Im}\{r_{10}^6\}}}{\sqrt{r_{00}^{04}(1 - r_{00}^{04} + r_{11}^{11} - \text{Im}\{r_{11}^{11}\})}}.$$  \hspace{1cm} (2)

This results in the precise determination of $|\delta| = 28.1 \pm 2.8_{\text{stat}} \pm 3.7_{\text{syst}}$ degrees for $\rho^0$ data on proton. Using beam-polarization dependent SDMEs, also the sign of $\delta$ can be determined:

$$\sin \delta = \frac{2\sqrt{\text{Re}\{r_{10}^8\} + \text{Im}\{r_{10}^7\}}}{\sqrt{r_{00}^{04}(1 - r_{00}^{04} + r_{11}^{11} - \text{Im}\{r_{11}^{11}\})}}.$$  \hspace{1cm} (3)

In this way, the HERMES experiment for the first time determines the sign of $\delta$ to be positive: $\delta = 24.4 \pm 5.2_{\text{stat}} \pm 2.1_{\text{syst}}$ degrees for $\rho^0$ production.

3.4 Unnatural-Parity Exchange

Disregarding the assumption of SCHC, the hypothesis of the absence of unnatural-parity exchange (UnPE) in the $t$-channel implies that $U_1 \equiv 1 - r_{00}^{04} + 2r_{11}^{22} - 2r_{11}^{11} - 2r_{11}^{11} = 0$. The HERMES result for $\rho^0$ production on the proton, $U_1 = 0.132 \pm 0.026_{\text{stat}} \pm 0.05_{\text{syst}}$, is different from zero at a level of $2\sigma$ of the total uncertainty, demonstrating the significance of the unnatural-parity-exchange contribution. A signal of UnPE is important as evidence of quark-antiquark exchange, corresponding to a description of the polarized GPDs. The kinematic dependences of $U_1$ for the proton on $Q^2$, $t'$ and $x_{bj}$ are presented in Fig. 5 a. Although the errors are large due to the large number of SDMEs involved, all measured values of $U_1$ are positive. Note that a positive $U_1$ value of about 0.1 was recently obtained including the GPD $\tilde{H}$ in GK model calculations [5].

Contrary to $\rho^0$ production, $U_1$ values calculated from $\phi$ meson SDMEs are consistent with zero, see Fig. 5 b. This is in agreement with corresponding calculations in the GK model [5] where only two-gluon exchange was considered.
Using a maximum likelihood fit, 15 beam-polarization-independent SDMEs and, for the first time, 8 beam-polarization-dependent SDMEs are determined. The measured SDMEs are grouped according to their theoretically expected hierarchy which is observed within given experimental uncertainties. This facilitates the investigation of the relative importance of various helicity amplitudes describing different $\gamma^* \rightarrow \rho^0 (\phi)$ transitions.

Non-zero values of $\rho^0$ SDMEs corresponding to the amplitude $T_{01}$ indicate a small but statistically significant deviation from the hypothesis of $s$-channel helicity conservation.

The phase difference between the helicity-conserving amplitudes $T_{00}$ and $T_{11}$ is confirmed to be significantly non-zero. For the first time, the sign of the phase difference is precisely determined using the beam-polarization-dependent $\rho^0$ SDMEs.

The evaluation of certain relations between SDMEs provides an indication for the existence of unnatural-parity-exchange amplitudes for $\rho^0$ production, supporting a significant role of the quark-exchange mechanism in $\rho^0$ production at intermediate energies.

For the first time HERMES results on light vector meson production ($\rho^0$ and $\phi$) are...
comprehensively compared with model calculations [3]-[6] based on GPDs at kinematic values of $W = 5$ GeV and $Q^2 = 3$ GeV$^2$. It is remarkable to note that these calculations are in fair agreement with the longitudinal and full cross sections of $\rho^0$ and $\phi$ mesons, the values of most of the SDMEs and hierarchy of corresponding amplitudes, violation of SCHC in $\rho^0$ production, the $W$-dependence of $\rho^0$ and $\phi$ SDMEs and with the $\sigma_L/\sigma_T$ ratios [5, 6]. Nevertheless, HERMES data provide several constraints for a further development of this model, in particular for the phase difference in the interference of $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$ transitions, the $H$ contribution in the unnatural parity exchange amplitude, and the $E$ contribution in the transverse target-spin asymmetry of exclusive $\rho^0$ electroproduction discussed in [18].

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References


[18] S.V. Korotkov, these proceedings.