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Spin Density Matrix Elements in exclusive production of ω mesons at Hermes

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Abstract. Spin density matrix elements have been determined for exclusive ω meson production on hydrogen and deuterium targets, in the kinematic region of $1.0 < Q^2 < 10.0$ GeV^2, $3.0 < W < 6.3$ GeV and $-t' < 0.2$ GeV^2. The data, from which SDMEs are determined, were accumulated with the HERMES forward spectrometer during the running period of 1996 to 2007 using the 27.6 GeV electron or positron beam of HERA. A sizable contribution of unnatural parity exchange amplitudes is found for exclusive ω meson production.

1 Spin Density Matrix Elements

Exclusive electroproduction of vector mesons is a rich source of information on the structure of the nucleon and the production mechanism. This reaction is factorized into two subprocesses; the incident lepton radiates a virtual photon which dissociates into $q\overline{q}$ pair; this pair interacts strongly with the nucleon and forms the observed vector meson.

The angular distribution in exclusive electroproduction of vector mesons depends on Spin Density Matrix Elements (SDMEs), which are involving the spin state of the virtual photon and vector meson. The first subprocess of vector meson production, the emission of a virtual photon ($e \rightarrow e' + \gamma^*$), is described by the photon spin density matrix [1]

$$\varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma}(\epsilon, \Phi) = \varrho^{U}_{\lambda_\gamma \lambda'_\gamma} + P_{beam}\varrho^{L}_{\lambda_\gamma \lambda'_\gamma}(\epsilon, \Phi), \tag{1}$$

where U and L denote an unpolarized and polarized beam, respectively, ϵ is the ratio of fluxes of longitudinal and transverse virtual photons, and Φ is the angle between the lepton scattering and the hadron production planes. This spin density matrix can be calculated from QED. The vector meson spin density matrix $\rho_{\lambda_V \lambda'_V}$ is related to the one of the virtual photon by the helicity amplitudes $F_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N}(W, Q^2, t')$. These amplitudes describe the transition of the virtual photon with helicity λ_γ to the vector meson with helicity λ_V where λ_N, λ'_N are the helicities of the nucleon in the initial and

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final states, respectively. In the CM frame of $\gamma^* N$, the vector spin density matrix is given by the von Neumann formula [1]

$$\rho_{\lambda_V \lambda'_V} = \frac{1}{2\mathcal{N}} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N} \varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N; \lambda'_\gamma \lambda_N}. \tag{2}$$

After the decomposition of $\varrho^{L+U}_{\lambda_\gamma \lambda'_\gamma}$ into the standard set of nine $(3 \times 3)\Sigma^\alpha$ Hermitian matrices, the spin density matrix is expressed in terms of a set of nine matrices related to various polarization states of a transversely polarized photon (α from 0 to 3); to a longitudinally polarized photon (α equal to 4) and to interference terms (α from 5 to 8). When we cannot separate transverse and longitudinal photons, the SDMEs are customary defined as

$$r^{04}_{\lambda_V \lambda'_V} = (\rho^0_{\lambda_V \lambda'_V} + \epsilon R \rho^4_{\lambda_V \lambda'_V})/(1 + \epsilon R), \tag{3}$$

$$r^{\alpha}_{\lambda_V \lambda'_V} = \frac{\rho^{\alpha}_{\lambda_V \lambda'_V}}{(1 + \epsilon R)}, \alpha = 1, 2, 3, \qquad r^{\alpha}_{\lambda_V \lambda'_V} = \frac{\sqrt{R}\rho^{\alpha}_{\lambda_V \lambda'_V}}{(1 + \epsilon R)}, \ \alpha = 5, 6, 7, 8, \tag{4}$$

where $R = \sigma_L/\sigma_T$ is the longitudinal-to-transverse cross section ratio.

Usually, the helicity amplitude is decomposed into the sum of an amplitude T for natural-parity exchange (NPE) ($P = (-1)^J$) and an amplitude U for unnatural-parity exchange (UPE) ($P = -(-1)^J$), given by $F_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N}$.

For an unpolarized target there is no interference between NPE and UPE amplitudes and there is no linear contribution of nucleon-helicity-flip amplitudes to SDMEs (as they are suppressed by a factor $(\frac{\sqrt{-t'}}{M})^2$, with $t' = t - t_{min}$). This reduces the number of relevant amplitudes to nine: the helicity conserving T_{00}, T_{11}, U_{11} and the helicity non-conserving T_{01},T_{10}, T_{1-1},U_{01},U_{10}, U_{1-1}. Here we used an abbreviation $T_{\lambda_V \lambda_\gamma} = T_{\lambda_V \frac{1}{2} \lambda_\gamma \frac{1}{2}}$. The dominance of diagonal transitions is called s-channel helicity conservation (SCHC).

For a longitudinally polarized beam and an unpolarized target there are 23 SDMEs; 15 do not depend on beam polarization, and 8 depend on beam polarization.

The SDMEs are determined from the process $e + p \to e' + p' + \omega \to (\pi^+ \pi^- \pi^0 (\to 2\gamma))$ by fitting the 3-dimensional angular distribution of the pions from the omega meson decay in the angles Φ, which is the angle between the lepton scattering and ω production planes, θ and ϕ which are the polar and the azimuthal angle of a normal unit vector to the ω decay plane in the ω rest plane. Fitting is done with the maximum likelihood method.

2 Results

The SDMEs of the ω meson for the integrated data ($\langle Q^2 \rangle = 2.42$ GeV^2, $\langle W \rangle = 4.8$ GeV and $\langle -t' \rangle = 0.796$ GeV^2), where -Q^2 represents the negative square of the virtual-photon four-momentum and W the invariant mass of the photon-nucleon system, are presented in Fig.1. Those SDMEs are divided into five classes, corresponding to different helicity transitions. Class A corresponds to the transition of longitudinal virtual photons to longitudinal mesons $\gamma^*_L \to V_L$, and of transverse virtual photons to transverse mesons $\gamma^*_T \to V_T$. Class B corresponds to the interference of these two transitions. Class C corresponds to the $\gamma^*_T \to V_L$ transition, class D to the $\gamma^*_L \to V_T$ transition, and class E to the $\gamma^*_T \to V_{-T}$ transition.

The SDMEs for the hydrogen and deuterium data are found to be consistent within their statistical uncertainties. The presented SDMEs are multiplied by certain numerical factors in order to allow

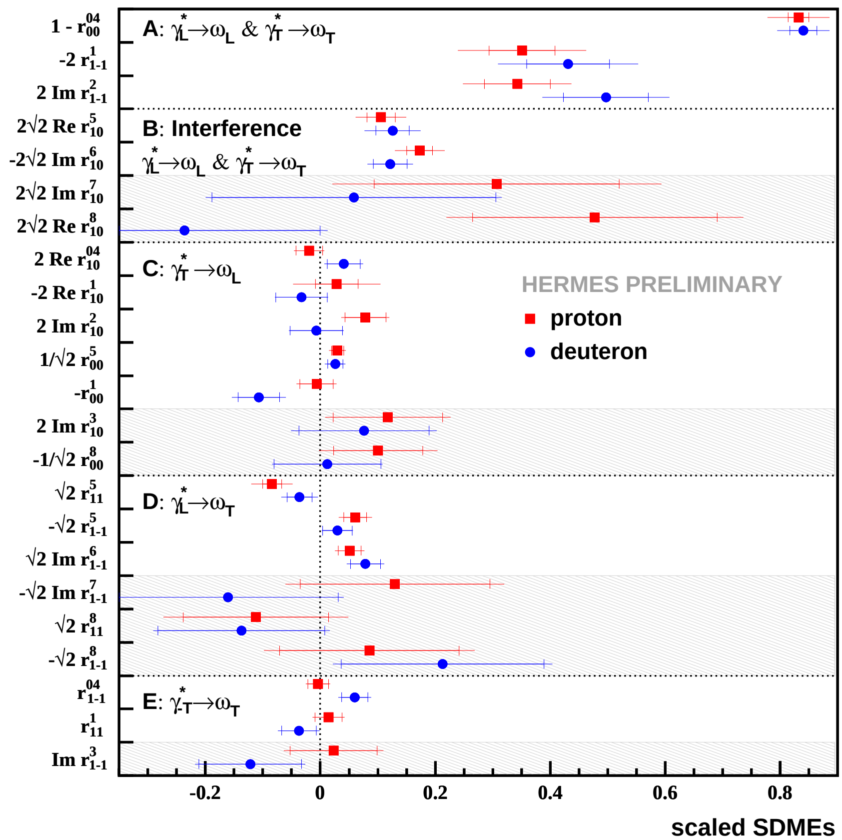

Figure 1. The 23 SDMEs extracted from ω data: proton (circles) and deuteron (squares) in the entire HERMES kinematics with $\langle Q^2 \rangle$ = 2.42 GeV^2 and $\langle -t' \rangle$ = 0.796 GeV ^{2}. The SDMEs are multiplied by prefactors in order to represent the normalized leading contribution of the corresponding amplitude. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature. SDMEs measured with unpolarized (polarized) beam are displayed in the unshaded (shaded) areas.

their comparison at the level of dominant amplitudes [2]. The 8 polarized SDMEs are presented in the shaded areas. Their experimental uncertainties are larger in comparison to the unpolarized SDMEs because the lepton beam polarization is smaller than unity and in the formula of angular distribution they are multiplied by small kinematical factors, as seen in eq. 39 of ref. [2].

If SCHC holds, the seven SDMEs of class A and B (r^{04}_{00}, $r^{1}_{1-1}, Im\{r^{2}_{1-1}\}$, Re $\{r^{5}_{10}\}, Im\{r^{6}_{10}\}$, $Im\{r^{7}_{10}\}, Re\{r^{8}_{10}\}$) are not restricted to be zero for SCHC. As we see in Fig. 1, they are non-zero. In addition, six of these SDMEs obey the relations: $r^{1}_{1-1} = -Im\{r^{2}_{1-1}\}$, Re $\{r^{5}_{10}\} = -Im\{r^{6}_{10}\}$, $Im\{r^{7}_{10}\} = Re\{r^{8}_{10}\}$, which hold mostly within one standard deviation, as it is seen from the sums $r^{1}_{1-1} + Imr^{2}_{1-1} = -0.004 \pm 0.038 \pm 0.017$, $Rer^{5}_{10} + Imr^{6}_{10} = -0.024 \pm 0.013 \pm 0.003$, $Imr^{7}_{10} - Rer^{8}_{10} = -0.060 \pm 0.010 \pm 0.044$ on hydrogen, and from the sums $r^{1}_{1-1} + Imr^{2}_{1-1} = 0.033 \pm 0.049 \pm 0.004$, $Rer^{5}_{10} + Imr^{6}_{10} = 0.001 \pm 0.016 \pm 0.015$, $Imr^{7}_{10} - Rer^{8}_{10} = 0.10 \pm 0.11 \pm 0.17$ on deuterium.

The existence of unnatural parity exchange in ω production on the proton and deuteron can be tested with a linear combination of SDMEs such that

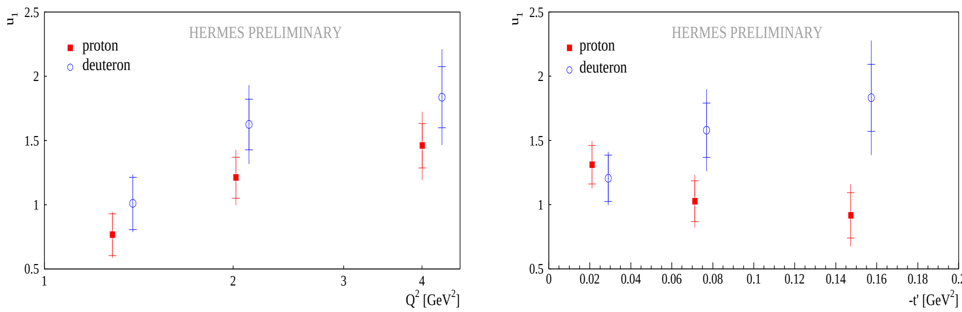

Figure 2. The Q^2 and t' dependence of the SDME combination u_1. Hydrogen is denoted by squares and deuterium by circles. The inner error bars represent the statistical uncertainties, while the outer ones indicate the statistical and systematic uncertainties added in quadrature.

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}. \tag{5}$$

This can be seen by expressing u_1 in terms of helicity amplitudes, with

$$u_1 = \sum_{\lambda_N \lambda'_N} \frac{2\epsilon|U_{10}|^2 + |U_{11} + U_{-11}|^2}{N}, \tag{6}$$

where the normalization factor is $N = N_T + \epsilon N_L$, $N_T = \sum_{\lambda_N \lambda'_N}(|T_{11}|^2 + |T_{01}|^2 + |T_{-11}|^2 + |U_{11}|^2 + |U_{01}|^2 + |U_{-11}|^2$, and $N_L = \sum_{\lambda_N \lambda'_N}(|T_{00}|^2 + |T_{10}|^2 + |T_{-10}|^2 + |U_{10}|^2 + |U_{-10}|^2)$. A non-zero result for u1 indicates the existence of UPE contributions.

In Fig.2, the Q^2 and t' dependence of the SDME combination u_1 is presented for the proton and deuteron target. It shows that u_1 is larger than unity, implying large contributions from UPE transitions. At the average kinematics the values of u_1 are 1.15± 0.09 ± 0.12, and 1.47± 0.12± 0.18 for proton and deuteron target, respectively. This suggests that at Hermes energies the quark-exchange mechanism or π^0 exchange in Regge phenomenology, plays a significant role in ω meson electroproduction.

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