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# Spin Density Matrix Elements in hard exclusive electroproduction of $\omega$ mesons

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Spin density matrix elements (SDMEs) have been determined for exclusive $\omega$ 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. The resulting SDMEs are compared to those for $\rho^0$ production. A sizable contribution of unnatural parity exchange amplitudes is found for exclusive $\omega$ meson production.

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## 1. Spin Density Matrix Elements in the reaction $e+N \to e+\omega+N$

The angular distribution of the decaying products in the reaction $e+p \to e+p+\omega$, where $\omega$ decays as $\omega \to \pi^+\pi^-\pi^0(\to 2\gamma)$ depends on Spin Density Matrix Elements (SDMEs). The SDMEs describe the distribution of final spin states of the produced $\omega$ meson. These elements depend on helicity amplitudes for the angle and momentum dependent transition process between the initial spin state of the virtual photon and the final spin state of the produced vector meson.

In the $\gamma^* N$ CM frame, the spin density matrix $r^{\alpha}_{\lambda_V \lambda'_V}$ is given by the von Neumann formula [1]:

$$r^{\alpha}_{\lambda_V \lambda'_V} \sim \rho_{\lambda_V \lambda'_V} = \frac{1}{2\mathcal{N}} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N} \rho^{U+L}_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N; \lambda'_\gamma \lambda_N}, \quad (1.1)$$

where $\rho^{U+L}_{\lambda_\gamma \lambda'_\gamma}$ is the spin density matrix of the virtual photon, $F_{\lambda_V \lambda'_N; \lambda_\gamma \lambda_N}$ is the helicity amplitude, $\mathcal{N}$ is a normalization factor, and $\lambda_V, \lambda_\gamma, \lambda_N$ are the helicities of the vector meson, virtual photon and nucleon, respectively, and $\alpha$ denotes different polarization states of the virtual photon.

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 linear contribution of nucleon-helicity-flip amplitudes to SDMEs (as they are suppressed by a factor $(\alpha)^2 = (\frac{\sqrt{-t'}}{M})^2$, where $t'$ is a measure of the transverse momentum of the vector meson with respect to the direction of the virtual photon). This reduces the number of amplitudes to nine: the helicity conserving amplitudes $T_{00}$, $T_{11}$, $U_{11}$, and the helicity non-conserving amplitudes $T_{01}$, $T_{10}$, $T_{1-1}$, $U_{01}$, $U_{10}$, $U_{1-1}$, where we used the 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 unpolarized target there are 23 SDMEs; 15 which do not depend on beam polarization, and 8 which depend on beam polarization. They are determined from a fit of the angular distribution of pions in the decay $\omega \to \pi^+\pi^-\pi^0$.

The values of the SDMEs can serve to establish the hierarchy of the helicity amplitudes that are used to describe exclusive $\omega$ production. They are also used to test the SCHC hypothesis and to investigate the contribution of the unnatural parity exchange mechanism in $\omega$ production.

## 2. Experiment

The data were accumulated at the HERMES experiment at DESY using the 27.6 GeV longitudinally polarized positron or electron beam in the HERA storage ring, scattered off a hydrogen or deuterium target. Selected events consisted of exactly three tracks (scattered lepton, positive and negative pion) and two clusters in the calorimeter (the neutral-pion decay photons).

The "exclusivity" of the omega production is characterized by missing energy $\Delta E = \frac{M_X^2 - M_p^2}{2M_p}$, with the missing mass squared $M_X^2 = (p+q-p_{\pi^+}-p_{\pi^-}-p_{\pi^0})^2$ , where p, q, $p_{\pi^+}$, $p_{\pi^-}$ and $p_{\pi^0}$ are the four-momenta of the proton, virtual photon and each of the three $\omega$-decay pions, respectively.

For the exclusive reaction the target nucleon remains intact, which corresponds to ΔE =0. On the left panel of Fig. 1 the missing energy, ΔE, distribution is shown by the red histogram , with a clearly visible exclusive peak. The blue histogram represents semi-inclusive deep inelastic scattering (SIDIS) background obtained from a Pythia Monte Carlo simulation and normalised to data. It



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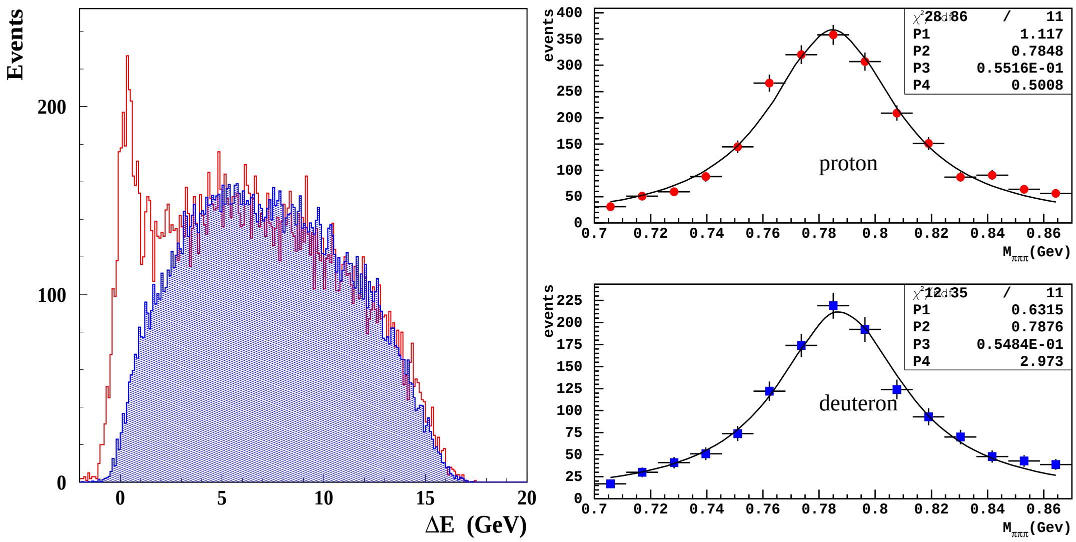


**Figure 1:** Left panel: the $\Delta E$ distribution of data for exclusive $\omega$ production (red line) is compared with the SIDIS $\Delta E$ distribution from PYTHIA (shaded area). Right panel: Breit-Wigner fit of the $\omega \to \pi^+\pi^-\pi^0$ invariant mass distributions for data collected on a hydrogen target (top) and on a deuterium target (bottom), after application of all cuts for the selection of exclusive diffractive $\omega$ mesons. A good agreement of the fit results with PDG values of the $\omega$ mass (m =782.65 MeV) is observed.

was used to determine the fraction of background under the exclusive peak. The fraction of background is about 20%. On the right panel of Fig. 1 the invariant mass of three pions is shown, after applying all constraints for the selection of the exclusive $\omega$ meson.

## 3. Results

The SDMEs of the $\omega$ 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. 2. The presented 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 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 agree within their statistical uncertainties. The presented SDMEs are multiplied by certain numerical factors in order to allow 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, see equation 39 in ref. [2].

On Fig. 3 the comparison of $\omega$ and $\rho^0$ [2] SDMEs is shown. One can see that the SDMEs $r^1_{1-1}$ and Im$r^2_{1-1}$ of class A, have opposite sign for $\omega$ and $\rho^0$. The SDME $r^1_{1-1}$ is negative for the

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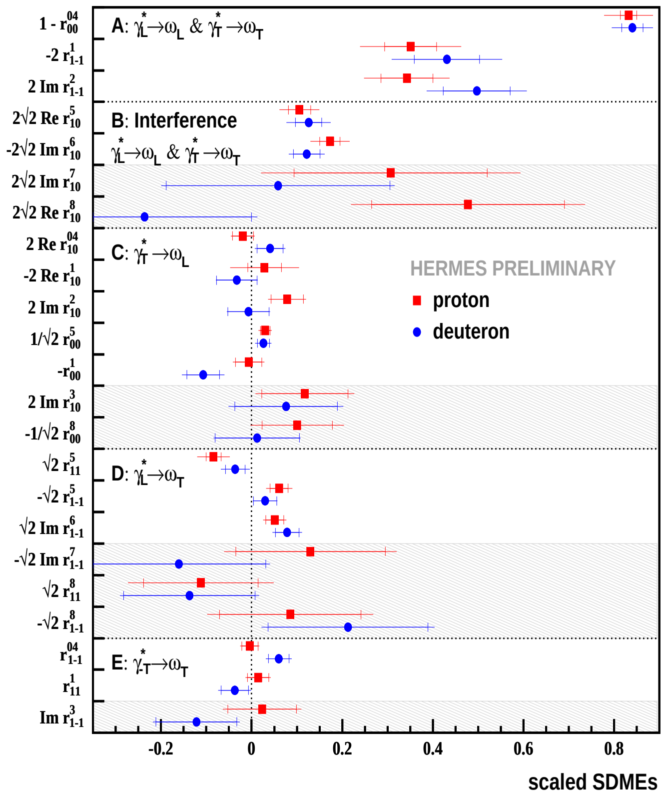


**Figure 2:** The 23 SDMEs extracted from $\omega$ data: proton ( circles) and deuterium (squares) in the entire HERMES kinematics with $\langle Q^2 \rangle = 2.42$ GeV$^2$ and $\langle -t' \rangle = 0.796$ GeV $^2$. The SDMEs are multiplied by prefactors in order to represent the normalized leading 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.

$\omega$ meson and positive for $\rho^0$. $\mathrm{Im} r^2_{1-1}$ is positive for $\omega$ and negative for $\rho^0$. In terms of helicity amplitudes these two SDMEs are written as:

$$r^1_{1-1} = \frac{1}{2\mathscr{N}} \widetilde{\sum} \{ |T_{11}|^2 + |T_{1-1}|^2 - |U_{11}|^2 - |U_{1-1}|^2 \} \tag{3.1}$$

$$\mathrm{Im}\{r^2_{1-1}\} = \frac{1}{2\mathscr{N}} \widetilde{\sum} \{ -|T_{11}|^2 + |T_{1-1}|^2 + |U_{11}|^2 - |U_{1-1}|^2 \}, \tag{3.2}$$

where $\widetilde{\sum} = \frac{1}{2} \sum_{\lambda'_N \lambda_N}$ following the notation in ref. [2].

The equations 3.1 and 3.2 imply the following inequalities:
$|U_{11}|^2 + |U_{1-1}|^2 > |T_{11}|^2 + |T_{1-1}|^2$ for $\omega$ meson (from eq. 3.1)
$|T_{1-1}|^2 + |U_{11}|^2 > |T_{11}|^2 + |U_{1-1}|^2$ for $\omega$ meson (from eq. 3.2).

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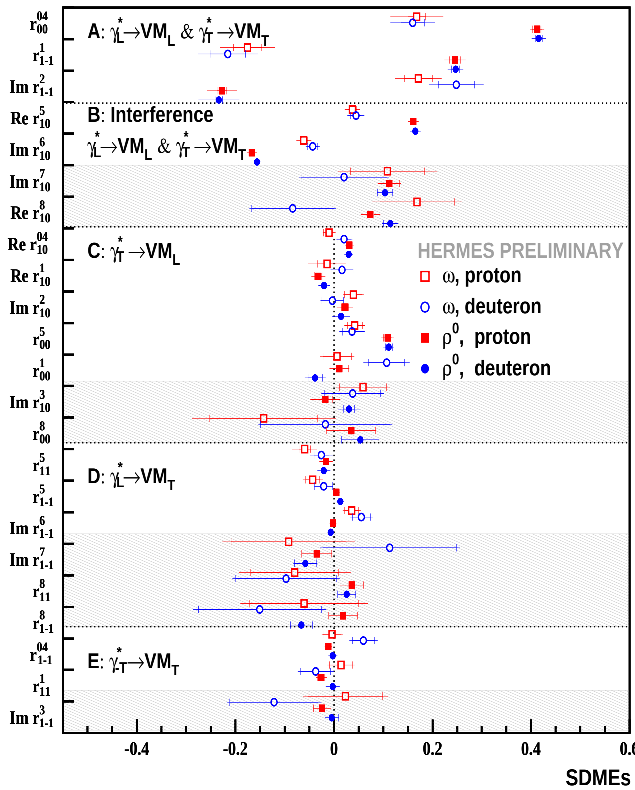


**Figure 3:** Comparison of the 23 SDMEs extracted from $\omega$ and $\rho^0$ [2] data: proton ( circles) and deuterium (squares) in the entire HERMES kinematics with $\langle Q^2 \rangle = 2.42$ GeV$^2$ and $\langle -t' \rangle = 0.796$ GeV $^2$. The inner error bars represent the statistical uncertainties, 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.

At small $t'$ the double spin-flip amplitudes $U_{1-1} \approx T_{1-1} \approx 0$. This implies that $|U_{11}|^2 > |T_{11}|^2$ for the $\omega$ meson, whereas $|T_{11}|^2 > |U_{11}|^2$ for the $rho^0$ meson. Thus the unnatural parity amplitude $U_{11}$ gives the dominant contribution for the $\omega$ meson, while the natural amplitude $T_{11}$ gives the main contribution for the $\rho^0$ meson. It suggests large UNP exchange for $\omega$ meson production.

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## References

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