Spin Density Matrix Elements in Exclusive Diffractive ρ° Electroproduction.

The HERMES collaboration

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In a scattering process like the one depicted in Figure 1, where there are two particles in the initial state and two particles in the final state all the a-priori unknown action of the scattering process is indicated by the shaded blob. The goal of any experiment that can be described in such a way is to learn something about the underlying unknown processes. In the particular case under study here, the two particles a and c are a virtual photon generated by the electron scattering process and a ρ° meson, respectively. While b and d are the target proton in the initial state and the recoil ground state proton in the final state. In

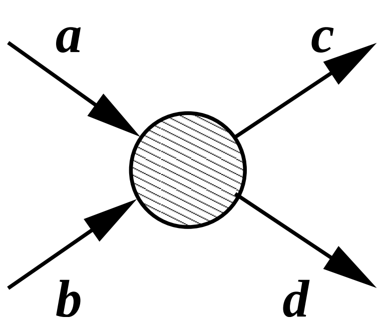

Figure 1: Process $a + b \rightarrow c + d$.

the HERMES experiment the initial virtual photons are produced by scattering a 27.6 GeV electron or positron beam delivered by the HERA accelerator off a gaseous Hydrogen target. The longitudinal polarization of the lepton beam amounts to about 50%. That means that the number of leptons with their spin aligned with their momenta is 3 times larger than the number of leptons with their spin oriented in the opposite direction. Consequently the virtual photons (particle a) will be polarized also. Particle c is a ρ° meson which is not stable and decays immediately into a $\pi^+\pi^-$ pair almost all the time. The pion pairs are detected and their 4-momenta measured allowing the reconstruction of the energy and momentum of the initial ρ° meson. The ρ° meson is a vector particle with spin one like the photon. Because the pions are spin zero particles the angular decay distribution of the pions with respect to the initial momentum of the parent ρ° meson is directly related to the polarization of the parent ρ°-meson. At the same time correlations between the initial virtual photon polarization and the final state ρ° polarization are reflected in the angular distributions of the ρ° mesons with respect to the momentum of the initial photon. The fact that the photon and the ρ°-meson have the same spin provides additional constraints in understanding these correlations.

Moreover, the virtual photon can fluctuate into a quark anti-quark pair, referred to as the hadronic structure of the photon. In such a situation these quarks can interact with the target with a coupling constant that is much stronger than the electromagnetic coupling. In addition these quark anti-quark pairs have quantum numbers of a vector particle like the ρ° enhancing the probability of its production in the final state. This scenario is called vector-meson dominance (VMD). Models that use this picture to describe the vector-meson production cross section are for example based on Regge phenomenology, where analytic properties of scattering as a function of angular momentum are investigated. A more recent view of the underlying physics is described by the so-called handbag diagram together with the concept of generalized parton distributions (GPD). This approach is expected to be a good description at sufficiently high photon virtuality Q^2, the difference between the squared energy and the squared momentum of the virtual photon that gets exchanged between the scattering lepton and the target, also referred to as the squared mass of the virtual photon. The GPDs describe the momentum distributions of quarks in the nucleon as a function of the quark's radial distance from the center of the nucleon.

Because the total angular momentum is conserved in any scattering process and the spins of the two initial and final state particles are also the same in this case, the choice of describing the scattering process in terms of helicity amplitudes is quite natural. The particle's helicity is the projection of its spin on its momentum axis. These amplitudes are defined with respect to the photon-proton center of mass frame and are categorized by the helicity states of the initial and final state particles. Conservation of parity or total angular momentum provides relations between helicity amplitudes reducing the total number of independent amplitudes. Combining helicity amplitudes into sums or differences lead to combinations related to exchange mechanisms with natural-parity (NP) and unnatural-parity (UP), i.e. with the quantum numbers which fulfill the relation $(-1)^J$ and $(-1)^{(J+1)}$, respectively, where J is the total angular momentum. Such a choice is very helpful in analyzing the experimental data to determine the strength with which given helicity amplitude combinations contribute to the scattering process. In particular NP and UP states are orthogonal and hence are useful to disentangle the different contributions of the helicity amplitudes. The strength of these amplitudes is reflected in the shape of the angular distributions of the particles in the final state with respect to a chosen reference frame. From a fit of these angular distributions to a series of combinations of helicity amplitudes squared it can be determined which amplitudes or rather which combinations of amplitudes contribute to the scattering process with which strength. Since these amplitude combinations represent certain assumptions about the quantum numbers exchanged in the process it is possible to learn more about the underlying physical processes.

In order to relate the angular-dependent differential cross section of the process $\gamma^\star N \rightarrow \rho^\circ N \rightarrow \pi^+\pi^- N$ to the polarization of the initial virtual photon the photon-spin-density matrix is needed in combination with the helicity amplitudes. The photon-spin-density matrix describes the polarization state of the initial photons and is normalized to the flux of transverse photons. The convolution of helicity amplitudes with the photon-spin-density matrix is the ρ°-spin-density matrix. Because in this experiment the contribution from longitudinal and transverse photons can not be disentangled only combinations of the ρ°-spin-density matrix elements can be determined directly. These combinations are generally referred to as spin-density matrix elements or SDMEs for short. The labeling of the SDMEs are generally done in the following way: $r^{\alpha}_{\lambda_V \lambda_{V'}}$ where $\alpha = 1, 2, ...8$ denotes the polarization state of the virtual photon and λ_V the polarization state of the ρ° meson. To be more specific $\alpha = 0$ refers to unpolarized photons, $\alpha = 1, 2, 3, 4$ to linear and circular polarization states and $\alpha = 5, 6, 7, 8$ to interference terms. The one exception to this labeling scheme is $r^{04}_{\lambda_V \lambda_{V'}}$ which is a combination of terms with $\alpha = 0$ and $\alpha = 4$ and is related to the ratio of longitudinal to transverse virtual photon cross sections and reflects that fact that the longitudinal and transverse components of the cross section can not be disentangled in this experiment.

The data provided by the HERMES detector are analyzed by looking for events that have only two pions and the scattered lepton in the spectrometer. The scattered lepton in combination with the beam lepton information defines the 4-momentum of the virtual photon and the two pions have to fulfill the requirements to be the decay products of a parent ρ°-meson. The combination of all this information is then tested for compatibility with the kinematic requirements of the process where the initial target proton remains intact and in the ground state after the scattering. This data is then binned in the variables Φ, ϕ and Θ, which are the angles between the lepton scattering plane and the ρ° production plane, the angle between the ρ° production plane and the decay-meson plane and the angle between the recoil nucleon and the decay pion in the photon-nucleon center of mass frame respectively (see Fig. 2). These angular distributions of events are shown in Figure 3. The circle points represent the data. The dotted histogram represents a Monte Carlo simulation where electro-produced exclusive ρ° mesons generated uniformly over the full solid angle are tracked by GEANT through the simu-

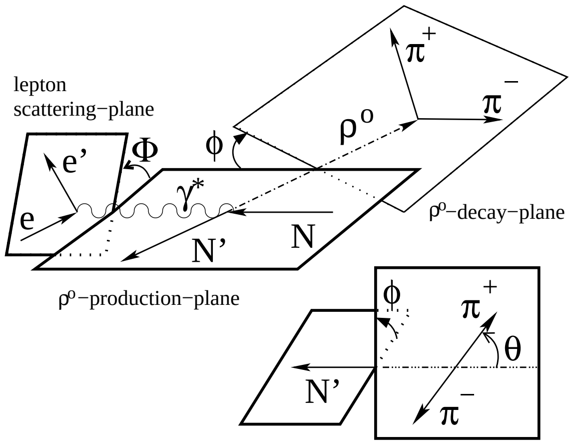

Figure 2: Kinematics of exclusive electro-production of ρ° mesons.

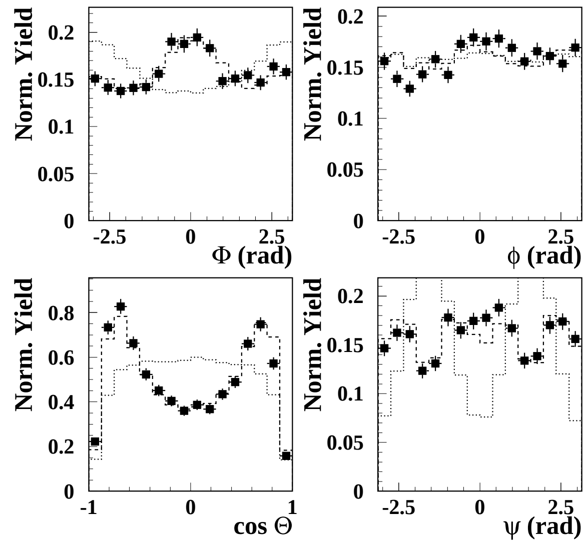

Figure 3: Angular distribution of exclusive ρ°-meson production in Φ, ϕ, $\cos(\Theta)$ and $\Psi = \phi - \Phi$ as a consistency check. The dashed histogram is the result of the fit.

lated HERMES detector and digitized and finally reconstructed and analyzed by the reconstruction and data analysis software. The dashed histogram is the result of fitting a parametrized cross section to the data with the parameters being the strength of the 23 contributing SDMEs each of which follows a distinct angular modulation in Φ, ϕ or $\cos(\Theta)$. Fifteen of these SDMEs are independent of the beam polarization while eight depend on the polarization of the incident electron beam.

The results of the extracted SDMEs confirm that s-channel helicity conservation (SCHC) is approximately fulfilled. Some of the helicity-flip amplitudes are statistically significantly different from zero, i.e, a small but significant deviation from the hypothesis of s-channel helicity conservation is observed. This means that there is a non negligible contribution of helicity-flip amplitudes to the cross section where the helicity between the initial photon and the final vector meson changes.

It is found that the helicity conserving amplitudes dominate the cross section followed by the interference between longitudinal and transverse helicity-conserving amplitudes. The contributions of helicity-flip amplitudes are much smaller with the transverse to longitudinal ($\gamma^\star_T \rightarrow \rho^\circ_L$) amplitude dominating over the longitudinal to transverse ($\gamma^\star_L \rightarrow \rho^\circ_T$) amplitude. The smallest contribution result from double helicity-flip amplitudes of the form $\gamma^\star_{-T} \rightarrow \rho^\circ_T$. This behavior confirms a hierarchy in ordering the SDMEs, which originates from the hierarchy in ordering helicity amplitudes that was expected from earlier considerations.

Combinations of the extracted SDMEs can be used to test certain hypotheses about the nature of the exchange particle in the scattering process through the relation between certain quantum numbers like parity and total angular momentum. The results of these tests can be investigated as a function of kinematic variables like the virtuality of the photon Q^2 and the 4-momentum transfer squared t'. Natural-parity exchange is related to the exchange of a particle with quantum numbers like the pomeron, sometimes referred to as gluon-exchange. In contrast, unnatural-parity exchange (UPE) is related to the exchange of mesons like π or ρ and is also referred to as quark-exchange. The non zero results of some SDMEs and in particular a combination thereof suggest a small contribution of UPE to the cross section. Putting this result in perspective to other even lower-energy experiments at SLAC and DESY and much high-energy experiments like ZEUS and H1 suggests a possible dependence of the UPE contribution on the total available energy W^2 of the hadronic system in the final state.