Chapter 8

Summary and outlook

Summary  At present the total angular momentum $J_q$ carried by the quarks in the nucleon is unknown. One can investigate the angular momentum carried by the quarks by using the recently developed framework of generalized parton distributions (GPDs). Within the GPD framework, it has been shown that specific observables in exclusive production processes, such as deeply virtual Compton scattering and hard exclusive meson production, are sensitive to $J_q$. By measuring these observables, one can obtain a model-dependent estimate of $J_q$. From the estimated value of $J_q$, in combination with the available data on the quark-spin contribution $\Delta g$ to the nucleon spin, information on the unknown orbital angular momentum $L_q$ of quarks inside the nucleon can be obtained.

More in particular, the $\sin(\phi - \phi_s)$ component of the transverse target-spin asymmetry $A_{UT}$ for exclusive $\rho^0$ production from a transversely polarized nucleon has been predicted to be sensitive to $J_q$. Here, $\phi$ and $\phi_s$ are the azimuthal angles of the produced $\rho^0$ meson and the transverse component of the nucleon spin, respectively, around the direction of the exchanged virtual photon. The GPD description of exclusive meson production only applies if both the exchanged virtual photon and the produced meson are longitudinally polarized. Hence, in order to compare GPD-based calculations of $A_{UT}$ with measurements, the asymmetry has to be determined for this specific case.

This thesis reports the first measurements of the asymmetry $A_{UT}$ in exclusive $\rho^0$ electroproduction from a transversely polarized proton. The asymmetry was extracted from data taken by the HERMES experiment at DESY with a polarized internal hydrogen gas target and the 27.6 GeV electron (positron) beam of HERA. These data were collected during the 2002-2005 running periods of HERMES. The exclusive $\rho^0$ production events were reconstructed from the measured information on the scattered lepton and the $\rho^0$ decay products. The recoil protons could not be detected by the HERMES spectrometer. Requirements on the invariant mass of the detected hadron pairs were used to select pions resulting from $\rho^0$ decay events. Additional requirements on the missing energy enabled the selection of exclusive events. A Monte Carlo simulation provided an estimate of the non-exclusive back-
ground contributions coming from semi-inclusive deep-inelastic scattering events. The background contribution from exclusive non-resonant events was estimated from a fit of the reconstructed invariant mass distribution for exclusive hadron pairs, but was found to be negligible.

The transverse target-spin asymmetry $A_{UT}$ was determined as a function of $\phi$ and $\phi_s$ by fits of the angular distribution of events measured with two opposite transverse orientations of the target polarization. Since $A_{UT}$ needed to be determined separately for longitudinally and transversely polarized $\rho^0$ mesons, also the dependence of the yields on the decay angle $\theta_{\pi\pi}$ was accounted for in the extraction procedure. Two different approaches were used to take this additional dependence into account. In one approach a combination of the Diehl-Sapeta [13] and Wolf-Schilling [14] formalisms was used. In this case the relevant angular distributions were effectively integrated over the $\rho^0$ decay angle $\phi_{\pi\pi}$. In the other approach the more recently developed Diehl formalism [11] for vector-meson production on a polarized target was used. In this case the dependence on the decay angle $\phi_{\pi\pi}$ was taken into account in the description of the angular distribution.

In both approaches so-called spin density-matrix elements (SDMEs) for exclusive $\rho^0$ production were used to represent the information contained in the angular distribution. The SDMEs parameterize the sensitivities of the angular distribution to the polarization states of the exchanged virtual photon and the produced $\rho^0$ meson. The SDMEs representing $\rho^0$ production on an unpolarized target and on a transversely polarized target were extracted in the Diehl formalism. This extraction is the first experimental determination of the SDMEs for a transversely polarized target. The results that were obtained for an unpolarized target were converted to the Wolf-Schilling formalism and compared with the results of an earlier analysis based on that formalism, which made use of the HERMES data taken with an unpolarized target during the 1996-2000 data taking period. The results from both analyses were found to be consistent.

From the extracted SDMEs it can be concluded that, for an unpolarized target, the amplitudes for $s$-channel helicity conserving transitions (where the helicity of the virtual photon is transferred to the produced $\rho^0$ meson) are significantly larger than those for the helicity changing transitions. However, the results indicate that also the amplitudes for the helicity changing transitions $\gamma_T^+ \rightarrow \rho L$ from transverse virtual-photon helicity to longitudinal $\rho^0$ helicity deviate significantly from zero. Considering the SDMEs for transverse target polarization, the most significant deviation was found for the SDME $n_{0+}^{0+}$ suggesting additional violation of $s$-channel helicity conservation (SCHC) through the transition $\gamma_T^0 \rightarrow \rho L$. This SDME was found to be comparable in magnitude with the observed SCHC-violating SDMEs for an unpolarized target. Overall, the extracted values of the SDMEs for transverse target polarization are within their statistical uncertainties consistent with zero.

The extracted $\sin(\phi - \phi_s)$ component of the asymmetry $A_{UT}$ for longitudinally polarized $\rho^0$ mesons was compared with available GPD-model calculations [28, 79] assuming SCHC. The calculations were found to be consistent with the data. The calculations of [28] were used to obtain a model-dependent estimate of $J^u$ under
the assumption \( J^d = 0 \). The resulting estimate \( J^u = 0.43 \pm 0.43 \) is consistent with the constraints on \( J^u \) and \( J^d \) provided by DVCS measurements [76, 77, 78] and GPD-model fits on form factor data [29, 74]. By using the available estimate \( \Delta \Sigma = 0.330 \pm 0.039 \) from [6] in combination with the obtained estimate of \( J_q \approx J^u + J^d = 0.43 \pm 0.43 \) an estimate \( L_q = 0.27 \pm 0.43 \) of the orbital momentum carried by the quarks inside the proton was obtained.

**Outlook**  
New data for the exclusive leptoproduction of \( \rho^0 \) mesons from a polarized proton are needed to increase the amount of statistics available for the asymmetry \( A_{UT} \), so that the relatively large uncertainties on the available estimates on \( J_q \) and \( L_q \) can be reduced. Such data are foreseen to be collected by the COMPASS experiment at CERN [80] and the CLAS experiment at JLab [81]. After the 12 GeV upgrade at JLab the CLAS experiment will be able to measure \( A_{UT} \) in the \( x \)-range \( 0.3 \leq x \leq 0.5 \). In this kinematic range GPD-model calculations [10] predict relatively large magnitudes of the \( \sin(\phi - \phi_s) \) component of \( A_{UT} \) assuming \( J^d = 0 \) and \( 0.1 \leq J^u \leq 0.4 \) (It should be noted, however, that the calculations of [10] did not yet take into account the contribution from gluons, which may cause a dilution of the asymmetry). At COMPASS first results already exist for the asymmetry for exclusive \( \rho^0 \) production on a transversely polarized deuteron target [80]. New data on the asymmetry are expected for a transversely polarized proton target. At COMPASS the \( x \)-range covered reaches down to \( x \approx 0.01 \) and higher values of \( Q^2 \) are reached, up to 10 GeV\(^2\), although most of the data will be taken at \( Q^2 < 5 \text{ GeV}^2 \). Together, the expected COMPASS and CLAS data will have the potential to increase the kinematic coverage and the statistical precision of the data on \( A_{UT} \) substantially. As a result these data will enable a more precise model-dependent determination of the total and the orbital angular momentum carried by quarks in the nucleon.