Summary

The two-nucleon part of the strong interaction, the nucleon-nucleon (NN) force, provides the dominant part of the binding among nucleons inside a nucleus. The interaction features an attractive long-range part (at distances larger than approximately 1 fm) and a strongly repulsive part at shorter inter-nucleon distances. The interaction induces correlations among the nucleons bound in nuclei. Recently, various theoretical models of the NN interaction have been proposed describing accurately the binding energy of the deuteron and the NN scattering data. However, these models give different results for both ground-state and breakup properties of three-nucleon systems.

Study of the ^{3}He$(e, e'pp)$ reaction provides a tool to investigate the reaction mechanism of the two-nucleon knockout reaction and to test predictions based on bound-state wave-functions calculated with different potential models. Exact calculations of the exclusive breakup cross section show that domains in phase space exist where the reaction is primarily driven by one-body hadronic currents. The cross section in these domains is dominated by coupling of the virtual photon to the proton emitted with a small angle with respect to the momentum transfer. This opens the possibility that measurements of the ^{3}He$(e, e'pp)$ cross section in these domains may give information on the initial-state wave function. However, breakup can also be induced by coupling of the virtual photons to mesons (meson-exchange currents or MECs) or via excitation of the Δ resonance in an intermediate state (isobar currents). Although their contribution to the reaction cross section is suppressed in the case of direct two-proton knockout, they are expected to play an important role at higher values of the neutron momentum in the final state. Variation of the virtual-photon characteristics, especially the energy transfer to the system, provides an experimental way to investigate their importance.

The ^{3}He$(e, e'pp)$ reaction can thus be used to investigate the effects of nucleon-nucleon correlations and currents in ^{3}He. This work describes such an exclusive

^{3}He$(e, e'pp)$ experiment and a comparison of the results with continuum Faddeev calculations performed with various models of the NN interaction.

The experiment was carried out with the high duty-cycle electron beam extracted from the Amsterdam Pulse Stretcher facility AmPS; the incident electron energy was 564 MeV and the beam current amounted to 0.5–1.5 μA. A cryogenic, high-pressure ^{3}He gas target was used with a thickness of 270 mg/cm^2. Scattered electrons were detected in the high-resolution QDQ magnetic spectrometer, the two emitted protons in the large-solid-angle scintillator arrays HADRON3 and HADRON4. Cross sections were determined for three values of the three-momentum transfer of the virtual photon (q=305, 375, and 445 MeV/c) at an energy transfer value ω of 220 MeV. At q=375 MeV/c, measurements were performed over a continuous range in energy transfer from 170 to 290 MeV.

The data are compared to results of continuum Faddeev calculations performed by Golak *et al.*, that account for the contributions of rescattering among the emitted nucleons. These calculations include both one-body hadronic currents as well as contributions due to the coupling to π and ρ mesons in an intermediate state. Since at present no framework exists to solve the three-body problem in a Lorentz-covariant manner, all parts of the calculation were performed in a non-relativistic fashion to maintain internal consistency. Various potential models were used in the calculations: Bonn-B, charge-dependent (CD) Bonn, Nijmegen-93 and Argonne v_{18}.

The angular dependence of the ^{3}He$(e, e'pp)$ cross section shows a strong back-to-back correlation, which is a signature of a direct two-proton emission mechanism that leaves the neutron with a low momentum in the final state; the width of the angular distribution reflects the momentum distribution of the neutron. Presentation of the data as a function of the missing or neutron momentum, p_m, shows that the cross section decreases exponentially as a function of p_m.

In the missing-momentum region below approximately 100 MeV/c, and at energy transfer values well below the Δ resonance, the ^{3}He$(e, e'pp)$ reaction is likely dominated by direct knockout of correlated proton pairs, as the contributions from MECs and intermediate Δ excitation are suppressed. Calculations performed with only a one-body hadronic current operator show a fair agreement with the data obtained at $p_m \lesssim 100$ MeV/c at $\omega = 220$ MeV and q=305 MeV/c. Measurements performed at q=375 MeV/c show similar results. The inclusion of

MECs in the current operator only has minor effect on the calculated strength. It can therefore be concluded that at ω=220 MeV and $p_m < 100$ MeV/c the cross section is dominated by direct knockout of two protons via a one-body hadronic current. At higher p_m values, from 120 to 320 MeV/c, a discrepancy of about a factor of five is observed between the data and calculations with a one-body current operator only. Contributions due to MECs increase the calculated strength by up to 35% only.

The influence of intermediate Δ excitation depends on the invariant mass of the nucleon pair plus the photon. To investigate these isobar currents, measurements were performed in the domain ω=170–290 MeV. This range corresponds for $p_m < 100$ MeV/c to invariant masses $W_{p'_1 p'_2}$ between 2055 and 2120 MeV/c^2. An increase of the measured cross section by almost 50% is seen over this range in energy transfer, presumably reflecting the increased importance of the Δ resonance. Theoretical predictions including MECs and isobar currents underestimate the data at the higher ω values by about a factor of two. No strong influence of the energy transfer on the contribution of MECs is seen. The contribution of the Δ isobar in the calculation was performed within the 'static' approximation, which does not incorporate the propagation and decay width of the Δ isobar. Calculations of the $^{16}O(\gamma, pn)$ cross section and of exclusive deuteron electrodisintegration at high momentum have shown that such an approximation leads to a sizeable underestimation of the strength in the Δ resonance region and lack of resonant behaviour in the calculated cross section.

At higher neutron momentum values, data and theoretical predictions differ up to a factor of five for all values of ω. Within the range of energy transfer values probed in this experiment, the high p_m domain is expected to be strongly influenced by contributions from intermediate Δ excitation in the proton-neutron pair. The magnitude of the isobar contribution to the cross section depends on the invariant mass of the system involved, which for the pn pair in this experiment amounts to approximately 2150 MeV/c^2, which corresponds to the position of the resonance in deuteron electrodisintegration. A further indication for the importance of intermediate Δ excitation as a process contributing to the $^3He(e, e'pp)$ cross section in the p_m domain above 100 MeV/c was seen in the dependence of the cross section on the forward proton emission angle γ_1. The strong increase of the cross section with increasing γ_1 reflects the angular dependence of intermediate Δ excitation as seen in calculations of the $^{16}O(\gamma, pn)$ cross section and of coherent π^0 photoproduction.

Comprehensive treatment of the Δ degree-of-freedom within the continuum Faddeev framework is therefore necessary before quantitative conclusions can be drawn from the data measured at high p_m or high ω values.

The continuum Faddeev calculations account for rescattering effects among the outgoing nucleons via a multiple-scattering series based on realistic NN potentials. Within specific regions of phase space, where two nucleons are emitted with comparable momentum vectors, these rescattering processes strongly influence the cross section. Data from such specific 'FSI configurations' therefore provide a good tool to check the calculations in this respect.

For a pn 'FSI configuration' in the kinematic setting at $\omega = 220$ MeV and $q = 445$ MeV/c good agreement between data and calculations as a function of the pn momentum difference was found. Data obtained at ω=275 MeV and q=375 MeV/c confirmed this result, although the absolute magnitude of the cross section is underestimated, probably due to lack of isobar contributions in the current operator.

Information on the wave function of ^{3}He may be obtained in the domain $\omega \approx 220$ MeV and $p_m < 100$ MeV/c, if a direct knockout mechanism and coupling to one specific proton is assumed. Calculations indicate that, within the acceptance of this experiment, the cross section is dominated by coupling of the photon to the forward proton, which implies that, in absence of rescattering, the nucleon momenta in the initial state can be reconstructed. This suggests a presentation of the cross section as a function of the observable $p_{diff,1}$, which can be related to the relative momentum of the constituents of the two-proton pair in the initial state. The observed decrease of the cross section as a function of this relative momentum reflects the behaviour of the wave function and is well reproduced by calculations at low p_m. Although calculations performed with different models of the NN interaction, lead to different predictions of the slope and magnitude of the cross section in this domain. The statistical and systematic uncertainty of the data, as well as the sizeable changes induced in the predictions by the MECs and (yet unknown) isobar contributions, do not permit to express preference for any one of the potential models considered.

Larger differences between the wave functions calculated from the various NN potentials are observed at high centre-of-mass momentum values and for relative momenta above 400 MeV/c per nucleon. In order to be able to draw quantitative conclusions on the details of the NN interaction from ^{3}He$(e, e'pp)$ data, more high accuracy data should be obtained in the region of direct two-proton knockout over a larger range in pp relative momenta. Increase of the momentum transfer may further reduce the influence of isobar currents and rescattering, although it should be noted that this will lead to more severe problems with regard to the available calculations, which are performed in a non-relativistic framework. Also the investigation of the high p_m region offers possibilities, as in this region larger differences between the wave functions calculated with the various potential models exist. However, this awaits either a better theoretical treatment of the high p_m domain, or experimental means to isolate the contribution of isobar currents to the cross section. In this respect separation of the ^{3}He$(e, e'pp)$ cross section in its contributing structure functions and an investigation of the complementary reaction ^{3}He$(e, e'pn)$ will provide valuable information for better understanding the processes involved.