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The cross section for the ^{3}He$(e, e'd)p$ reaction has been measured for a range of missing momentum p_m at incident electron energies of 370 and 576 MeV and for values of the three-momentum transfer q of 412, 504, and 604 MeV$/c$. The longitudinal and transverse structure functions have been separated for $q = 412$ and 504 MeV$/c$. The data are compared to exact three-body Faddeev calculations and calculations based on a covariant, gauge-invariant diagrammatic expansion. In general, fair to good agreement is observed, but there are some differences between the data and the calculations, especially for the q dependence and for the transverse structure function W_T. [S0031-9007(98)07247-0]

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Many nuclear properties can be described successfully within a mean-field approach. However, phenomena like the depletion of spectroscopic strength and the occurrence of bumps at missing energies characteristic of two-nucleon emission in $(e, e'p)$ reactions indicate that correlations between nucleons, i.e., the motion of two nucleons relative to each other and as a pair inside a nucleus, also play an essential role. The $(e, e'd)$ reaction has proven to be a sensitive tool for the investigation of proton-neutron (pn) correlations in nuclei. It has been studied on the nuclei ^{3}He [1,2], ^{4}He [3,4], ^{6}Li [4–6], and ^{12}C [4,7]. In a semimicroscopic distorted-wave impulse approximation (DWIA) [4] the cross section for the $(e, e'd)$ reaction can be approximately written as $d^6\sigma/dE_{e'}d\Omega_{e'}dE_d d\Omega_d = K\sigma_{e,pn}(q)S_{pn}(E_m, p_m, p_d)$. Here the cross section for scattering of an electron from a pn pair in the nucleus $\sigma_{e,pn}$, which depends on the momentum transfer q, reflects the relative proton-neutron motion, i.e., the relative pn wave function. The distorted spectral function S_{pn}, which depends on the missing energy E_m, the missing momentum p_m, and the momentum of the final deuteron p_d, contains the information about the center-of-mass (c.m.) motion of the pn pair within the nucleus, modified by the final-state interaction (FSI). Even though this formula is an approximation, it indicates that the relative and the c.m. behavior of the pn wave function in a nucleus can be studied separately by measuring the q and p_m dependence of the $(e, e'd)$ cross section.

This approach has proven to be successful for the ^{6}Li$(e, e'd)^4$He reaction [4–6], and for transitions in the ^{12}C$(e, e'd)^{10}$B reaction [4,7], including one in which the initial pn pair was in a $T = 1$ state. However, the data for the ^{4}He$(e, e'd)^2$H reaction [3] could not be explained within the above-mentioned DWIA framework.

For the three-nucleon system exact calculations for the ground state and the continuum are now available. By confronting those with detailed accurate experimental data one now can learn about the description of the $(e, e'd)$ process and the pn motion in the nucleus ^{3}He. A first experiment was performed by Keizer *et al.* [1], which indicated that in parallel kinematics the q dependence of the cross section for $q = 350$, 380, and 450 MeV$/c$ follows within error bars that of the elastic electron-deuteron cross section $\sigma_{e,d}$. This is surprising, since the virtual photon can also interact with a $T = 1$ pn pair in ^{3}He, which process has a different q dependence from that of the elastic channel. More recently this reaction was investigated by Tripp *et al.* [2], who determined the longitudinal and transverse structure functions for small values of the missing momentum at a value of q of 420 MeV$/c$, and demonstrated that the coupling of the virtual photon to the $T = 1$ pn pair enhances the transverse structure function considerably. However, no comparison to three-body calculations was made.

In this Letter we present extensive cross-section data for the ^{3}He$(e, e'd)p$ reaction, corresponding to an E_m value of 5.5 MeV, taken in parallel kinematics for missing

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momenta up to 200 MeV/c, and values of the transferred momentum q of 412, 504, and 604 MeV/c. Since the data comprise both the q and p_m dependence of the reaction, different parts of the pn motion in the nucleus ^{3}He can be studied. The cross sections were measured at two beam energies, so that a separation of the longitudinal (W_L) and transverse (W_T) structure functions could be performed. Those structure functions, which result from different components of the nuclear current, have a different sensitivity to the various aspects of the reaction. For instance, the coupling of the virtual photon to a $T = 1$ pn pair, transforming it into a deuteron, involves a spin flip and thus is purely transverse, whereas the coupling to an initial $T = 0$ pair, which resembles elastic $e - d$ scattering, is dominantly longitudinal at our values of q (see also [2,7]). Furthermore meson exchange currents (MECs) will mainly contribute to W_T, whereas according to the three-body calculations the effects of FSI on W_L are different from the ones on W_T (see later). The measured cross sections and structure functions are compared to the results from three-body calculations and from a covariant and gauge-invariant diagrammatic approach.

For the definition of the structure functions we follow Raskin and Donnelly [8], who write the differential cross section for the unpolarized $(e, e'd)$ reaction as

$$\frac{d^5\sigma}{dE_{e'}d\Omega_{e'}d\Omega_{d'}} = C\,(v_L W_L + v_T W_T + v_{LT} W_{LT} \cos\phi + v_{TT} W_{TT} \cos 2\phi), \quad (1)$$

where W_L, W_T, W_{LT}, and W_{TT} are the longitudinal, transverse, and interference structure functions, respectively. The latter are zero in parallel kinematics. The factor C contains the Mott cross section and kinematical factors. The kinematical factors v_i are given in Ref. [8].

The experiment was performed with the extracted electron beam from the pulse-stretcher ring AmPS [9] at NIKHEF. The beam energies were 370 and 576 MeV, and the current was about 6 μA. The scattered electrons were detected with the QDD (quadrupole-dipole-dipole) spectrometer and the knocked-out deuterons with the QDQ (quadrupole-dipole-quadrupole) spectrometer [10].

A cryogenic gas target [11] operating at 20 K and 1.5 Mpa was used, which was filled with a mixture of ^{3}He and ^{4}He gases. In this way data were collected simultaneously for the three reactions: $^3\mathrm{He}(e, e'd)p$, $^4\mathrm{He}(e, e'd)^2\mathrm{H}$, and $^4\mathrm{He}(e, e'd)pn$. Results on the latter two reaction channels will be published separately.

The experimental energy resolution varied between 0.3 and 2.0 MeV, depending on the kinematics, which was sufficient to separate the different reaction channels. The absolute ^{3}He and ^{4}He target thicknesses were determined by comparison of the measured elastic scattering cross sections to calculated ones [12,13]. During the $(e, e'd)$ measurements the total target thickness was monitored through the singles rate of either one of the spectrometers. Checks with elastic scattering before and after each set of $(e, e'd)$ measurements were consistent to within 2%.

The data analysis included the following steps. First, the deuterons were separated from protons and tritons by using the pulse height from the scintillators in the QDQ spectrometer. Next, the particle vectors at the target were reconstructed. Since an extended target was used, this reconstruction and the acceptances of both spectrometers depend on the position of the interaction point along the beam. By using energy and momentum conservation the values of E_m and p_m were calculated from the particle vectors. Next, the accidental coincidences were subtracted. As a result of the high duty factor of the extracted beam, the real-to-random ratio was high, ranging from 15 to 1640 depending on the kinematics. Then, the data were normalized to the target thickness, the integrated charge, and the experimental detection volume, and corrected for detection inefficiencies. The detection volume was obtained by a Monte Carlo simulation, which uses the measured optical properties of the spectrometers, including the vertex-position dependent angular acceptances of the spectrometers. Finally, the data were radiatively unfolded. The systematic uncertainty amounts to about 3% for the cross sections and 4%–5% for the structure functions.

The cross section measured in our kinematical setting covers an appreciable range in p_m, as a consequence of the angular and momentum acceptances of the spectrometers. However, for the different values of p_m the values of q and of the kinematical factors in the cross-section expression of Eq. (1) vary slightly around the central values. A Monte Carlo simulation was performed to determine the average values of the kinematical factors and of q for the different p_m bins within one measurement. Then, the cross sections for the different p_m bins were recalculated to a common q value by using the q dependence of the cross section as measured in this experiment. The correction changed the cross section by typically a few percent.

The measured cross sections are shown in Fig. 1 as a function of the missing momentum p_m at the reference q values of 412, 504, and 604 MeV/c. The experimental data are compared to the calculations of van Meijgaard and Tjon [14], Golak *et al.* [15,16], and Nagorny *et al.* [17]. The results of van Meijgaard and Tjon are based on exact solutions of the Faddeev equations for the three-body system, employing a central local NN interaction, the spin-dependent Malfliet-Tjon I-III potential, in the unitary pole expansion (UPE). Since this interaction contains only s-wave forces, the ground-state wave function of ^{3}He includes only s waves. Furthermore, a relativistic current operator is used. The calculations of Golak *et al.* are also based on the solution of the Faddeev equation, but employ the Bonn-B potential, which leads to additional d waves in the ground-state wave function and a more realistic description of the deuteron. A nonrelativistic current operator is used. Both groups do not include MEC effects.

Nagorny *et al.* use a quite different approach [17], which is based on including the electromagnetic field in the strongly interacting system in a fully relativistic and gauge-invariant way [18]. Two covariant sets of diagrams, including pole, "contact," and one-loop diagrams, are used, which provide both nuclear-current conservation and inclusion of the dominant FSI and MEC effects in a form that is consistent with the nuclear dynamics. They were generated by "minimal insertion" of the electromagnetic field into all external/internal lines and also directly into the 3- and 4-point nuclear vertices, which produces various contact currents in accordance with Ward-Takahashi identities [19]. The strong form factors in the covariant nuclear vertices $^3\mathrm{He} \to pd$ and $^3\mathrm{He} \to ppn$ are taken as the positive-energy states in the laboratory frame through the solutions of the Faddeev equations with the Reid soft-core potential. The electromagnetic form factors in the completely relativistic γNN, γdd, and $\gamma^3\mathrm{He}^3\mathrm{He}$ vertices are taken from standard parametrizations of experimental form factors.

The calculated cross sections are also presented in Fig. 1. All calculations describe the measured cross sections, which decrease by a factor of about 500 going from the lowest to the highest measured value of p_m, and a factor of 50 from the lowest to the highest value of q, rather well.

Focusing first on the data at $q = 412$ MeV$/c$, where the largest range in p_m was covered, one can conclude that the c.m. motion of the pn pair in ^{3}He is fairly well described in all calculations, since the p_m dependence of the cross sections, though influenced by FSI and many-body currents, mainly reflects this c.m. motion.

At the higher q values one becomes sensitive to the high-momentum part of the relative pn wave function. Here there are some interesting differences between the various calculations. In the calculation of van Meijgaard and Tjon the cross section at low p_m is smaller than in the calculations by Golak *et al.* and by Nagorny *et al.* This difference can be related to the use of a different NN potential. At higher values of q coupling to the d waves of the pn system becomes more important and, as mentioned, these are not contained in van Meijgaard and Tjon's calculation. Evidently there is also a coupling with the c.m. motion of the d waves, since the difference between the two calculations depends on p_m.

A comparison of the PWIAS (symmetrized plane wave impulse approximation) and full calculations by Golak *et al.* (see Fig. 1) shows the importance of FSI effects for the different kinematics. Here PWIAS means that the photon can couple to one of the nucleons in the detected deuteron, or to the undetected proton. However, the contribution of the latter is negligible in the present kinematics. For increasing missing momentum the cross section is strongly reduced by FSI. For increasing values of q, which in parallel kinematics corresponds to higher values of the c.m. energy, the difference between PWIAS and the full calculation decreases, confirming the general view that FSI effects become less important at higher energies.

The q dependence of the cross sections is summarized in Fig. 2. Here the reduced cross sections at $p_m = 50$ MeV$/c$, obtained by interpolating the measured data and dividing by the factor C [see Eq. (1)], have been plotted together with the calculated ones. For clarity the 576 MeV points have been multiplied by a factor of 10. The slope of the data is different at the two energies, indicating a different behavior of the longitudinal and transverse parts of the cross section with q. The corresponding curve for $\sigma_{\mathrm{ed}}(q)$ is steeper even than the 576 MeV data. This different behavior is not unexpected, since the cross section on ^{3}He gets also $T = 1$ contributions. The q dependence of Nagorny's calculation at 576 MeV is slightly too steep, whereas that of Golak's calculation is a little too shallow. The data at 390 MeV of Keizer *et al.* [1]

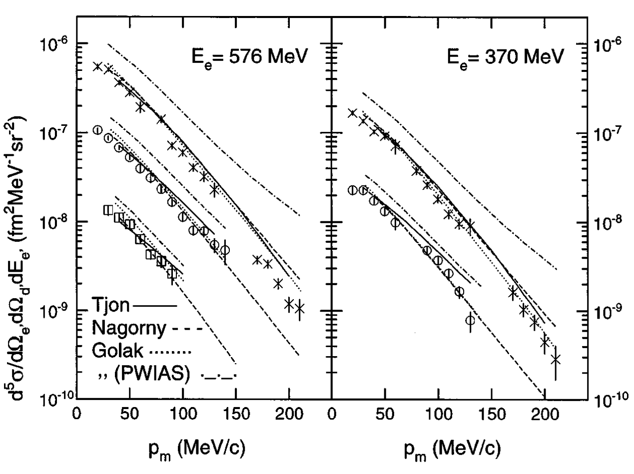

FIG. 1. Cross section for the $^3\mathrm{He}(e, e'd)p$ reaction as a function of the missing momentum p_m for transferred momenta q of 412 (crosses), 504 (circles), and 604 (squares) MeV$/c$, and for beam energies of 576 MeV (left) and 370 MeV (right). The curves are the results of the calculations of van Meijgaard and Tjon [14] (solid line), Golak *et al.* [15] (dotted line), and Nagorny *et al.* [17] (dashed line). The dot-dashed line is for the PWIAS calculation of Golak *et al.*

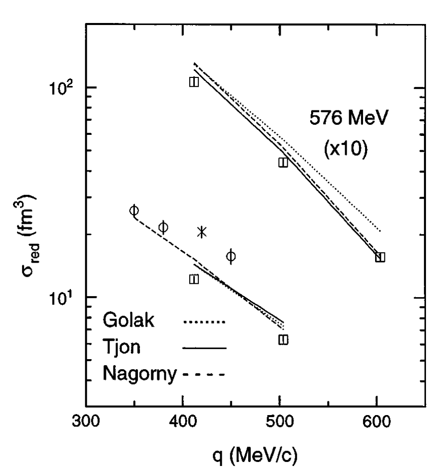

FIG. 2. The q dependence of the (reduced) cross sections at $p_m = 50$ MeV$/c$ in comparison with the theory. Squares: Our data; circles: Ref. [1]; cross: Ref. [2].

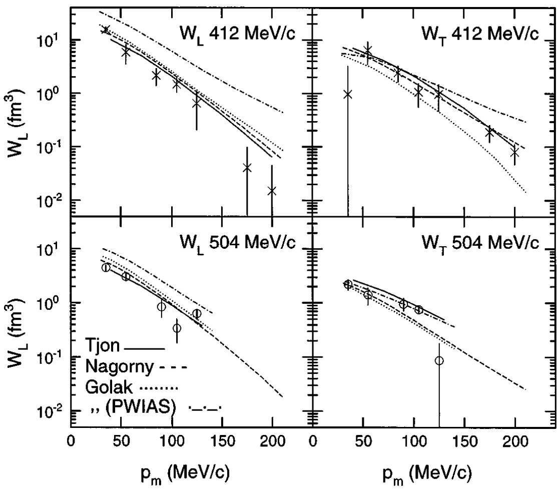

FIG. 3. The longitudinal (left) and transverse (right) structure functions for the ^{3}He$(e, e'd)p$ reaction as a function of the missing momentum p_m for transferred momenta q of 412 and 504 MeV/c.

and the 382.5 MeV data of Tripp *et al.* [2] have also been included. Since these energies are close to our 370 MeV and the factor C has been divided out, these data can be directly compared. There is a fairly large discrepancy with Tripp's point and the highest q point of Keizer. Close inspection of the original data shows that the p_m distribution of Ref. [1] at $q = 450$ MeV/c differs markedly from the one at $q = 380$ MeV/c, which is described fairly well by the theory. The data of Ref. [2] were obtained at three p_m values. Their data at $p_m = 62$ MeV/c agree nicely with ours, but those at 24 and 42 MeV/c are considerably higher.

Given the differences between the calculations for the cross sections it is instructive to inspect the structure functions. The longitudinal and transverse structure functions have been separated, both for the experimental and the theoretical cross sections, using Eq. (1). The results are shown in Fig. 3. The slope of the data is clearly different for W_L and W_T. As mentioned earlier, W_L is due to the interaction of the virtual photon with a $T = 0$ pn pair, whereas W_T gets its largest contribution from the interaction with a $T = 1$ pn pair.

All calculations agree fairly well with each other and with the data for W_L, but they differ considerably for W_T. The ratio W_T/W_L is smaller (and less in agreement with the data) in Golak's calculations than in those of Tjon. The latter must be accidental, since the *NN* potential used by Golak is more complete than the one used by Tjon. The underestimation of W_T in Golak's calculations may then be due to the neglect of MECs, since the calculations by Nagorny, in which these are implicitly included, give a better description of the W_T data, while his description of the W_L data is similar to that of Golak.

At small values of p_m there is a distinct difference in the influence of FSI on W_L and W_T. There FSI strongly reduces W_L, presumably due to an overall loss of flux into other (i.e., breakup) channels, whereas W_T is much less affected. Given the appreciable influence of FSI, especially at the lower values of q, the mentioned discrepancy in the ^{4}He$(e, e'd)^2$H reaction [3,4], where the final state is more complicated and data were taken at relatively low values of q, presumably is due to FSI.

In summary, we have presented experimental data on the ^{3}He$(e, e'd)$ reaction with a detailed comparison to two modern three-body calculations and to a quite different approach based on a covariant and gauge-invariant diagrammatic expansion. Fair to good agreement is observed for the cross sections and for the longitudinal structure function W_L. Hence the c.m. motion of the pn pair in ^{3}He, in both the $T = 0$ and the $T = 1$ states, seems to be adequately described. As for the relative pn motion: at larger values of the momentum transfer q the influence of d waves becomes noticeable. For the transverse structure function W_T the theoretical calculations differ more from each other. Combined with the data this suggests that meson-exchange currents have to be included in the Faddeev calculations.

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