Deuteron Breakup in the ^{2}H$(e,e'p)$ Reaction at Low Momentum Transfer and Close to Threshold

P. von Neumann-Cosel,[1,*] A. Richter,[1] G. Schrieder,[1] A. Shevchenko,[1] A. Stiller,[1,†] and H. Arenhövel[2]

[1]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

[2]*Institut für Kernphysik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany*

(Received 26 October 2001; published 6 May 2002)

Deuteron breakup has been studied in a ^{2}H$(e,e'p)$ coincidence experiment at low momentum transfer and for energies close to threshold. The longitudinal-plus-transverse $(L + T)$ and longitudinal-transverse (LT) interference cross sections are deduced. Nonrelativistic calculations based on the Bonn potential and including leading order relativistic contributions, meson exchange currents, and isobar configurations describe the $(L + T)$ data well. Surprisingly, large deviations of 30% to 45% are observed for the LT contribution.

DOI: 10.1103/PhysRevLett.88.202304 PACS numbers: 25.30.Fj, 25.10.+s, 27.10.+h

The electromagnetic deuteron breakup—photo- and electrodisintegration—is a subject of continuing interest because the two-body system provides the simplest nuclear system for which many aspects of the strong interaction can be studied in great detail in the framework of effective degrees of freedom, e.g., realistic meson exchange potentials, the role of meson exchange (MEC) and isobar (IC) currents, and the question of relativistic effects (RC). Over the years a wealth of experimental information has been accumulated for deuteron photodisintegration through measurements of total and differential cross sections and polarization observables as well [1].

Electrodisintegration provides even further-reaching information because it allows independent variations of energy and momentum transfer. With the availability of continuous wave electron beams a new quality of data is emerging from ^{2}H$(e,e'p)$ coincidence experiments. However, even in the low energy domain between breakup and pion production threshold we have very little experimental information on the longitudinal and transverse structure functions and the interference ones which govern the coincidence cross sections. While the longitudinal structure function f_L is determined by the realistic NN interaction model alone and almost independent of MEC, the latter play an important role in the transverse structure function f_T and, e.g., have been extensively investigated in threshold experiments covering a wide range of momentum transfers (for a review, see Ref. [2]). Similarly, the interference structure functions f_{LT} and f_{TT}—although much more difficult to measure—contain interesting information. For example, f_{LT} shows a pronounced sensitivity to relativistic effects while the role of IC can be tested in f_{TT}.

Most coincidence experiments of deuteron electrodisintegration so far have been performed in the quasielastic regime and for high energy transfers [3–10] except for one measurement [11] at relatively low momentum transfer $q = 0.33$ fm^{-1} and an excitation energy $E_x \approx 18$ MeV. The present study aims at a kinematical regime of even lower q and energies closer to the breakup threshold which is hitherto experimentally unexplored.

The present measurements were performed at the superconducting Darmstadt electron linear accelerator S-DALINAC [12] at an incident electron energy $E_0 = 85$ MeV. Some additional data were taken at $E_0 = 50$ MeV. Scattered electrons were observed at an angle $\Theta_e = 40°$ with a QCLAM magnetic spectrometer providing a large solid angle of about 35 msr [13]. Coincident protons resulting from the breakup of ^{2}H were simultaneously detected with 7 $\Delta E - E$ Si telescopes capable to identify protons with energies up to 16 MeV. Further details of the $(e,e'p)$ detection setup can be found in Refs. [14,15]. The kinematic variables are described in the inset of Fig. 1. Because a strong variation of the cross sections with the proton emission angle Θ_p (defined relative to the momentum transfer in the center-of-mass frame) was expected, the solid angles varied between about 2 msr at forward angles and 15 msr at $\Theta_p \approx 90°$,

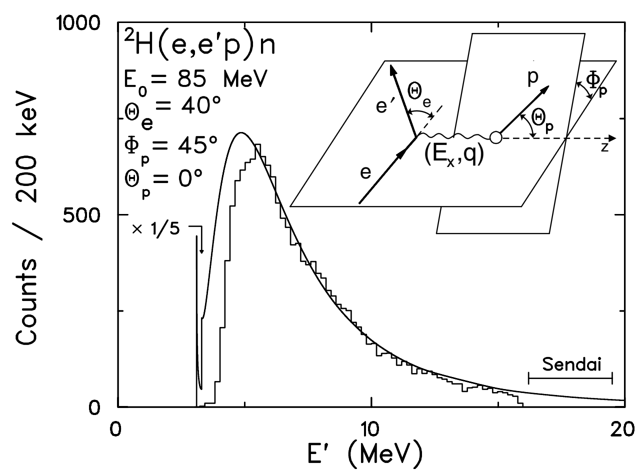

FIG. 1. Spectrum of the ^{2}H$(e,e'p)$ reaction at $E_0 = 85$ MeV, $\Theta_e = 40°$, $\Theta_p = 0°$, and $\Phi_p = 45°$ as a function of the transferred energy E'. The solid line represents calculations described in the text normalized to the data. For better visibility the result is divided by a factor of 5 for $E' < 3.3$ MeV. The energy region accessible in a previous experiment at Sendai for a similar momentum transfer [11] is indicated. The kinematic variables of the experiment are defined in the inset.

such that approximately constant counting rates were observed at all angles. The telescopes were mounted on a three-axis goniometer to permit in addition a variation of the azimuthal angle Φ_p. For a decomposition of the structure functions data were taken for values $\Phi_p = 0°$, 45°, 135°, and 180°. For each azimuthal angle two different goniometer settings were measured resulting in a total of 14 data points for the polar angular correlations.

Targets were made of deuterated polyethylene $[(C_2H_4)_n]$ with a thickness of 1–1.5 mg/cm^2. Absolute cross sections were determined by normalizing to elastic scattering on deuterium and carbon, and independently by a measurement of the total collected charge in a Faraday cup. Because of the sensitivity to the heat induced by the large electron energy loss, the target was periodically moved by a wobbling device [16] and beam currents were limited to about 1 μA. Calibration runs were repeated after a few hours of coincidence data taking.

The experimental cross sections contain statistical and systematical uncertainties. The latter were estimated from Monte Carlo simulations of the data allowing for variations of the normalization between different runs ($\leq$10%) and geometrical effects such as beam position on target, solid angle of the proton telescopes, etc. ($\leq$5%). The large body of results precludes full publication in the present paper. However, cross sections for some of the examples discussed below are given in Table I as examples. Complete tables are available; see Ref. [17].

The experiment has been kinematically complete and the ^{2}H excitation could be reconstructed from the data for each set of proton emission angles (Θ_p, Φ_p). Figure 1 displays as an example the experimental spectrum as a function of the transferred energy E' observed at $\Theta_p = 0°$ and $\Phi_p = 45°$. Because of high singles count rates it was necessary to set a hardware threshold in the proton counters which affects the data for energies $E' < 6$ MeV. Radiative corrections to the spectra were performed following the approach of Ref. [18]. However, because the data do not extend down to the breakup threshold, theoretical spectra computed within the model outlined below had to be used to determine the necessary corrections as a function of excitation energy.

The experimental results are compared to a nonrelativistic calculation [19,20], using for the NN interaction the Bonn one-boson exchange potential model in r space [21]. Effects of the final state interaction (FSI), MEC, and IC are included. Furthermore, the most important leading order relativistic contributions from the spin-orbit current and the kinematic boost are also added [22,23], providing a reasonable description of elastic electron scattering [24]. At the low momentum transfer studied here, the choice of a specific realistic potential leads to small variations of less than 0.5% only.

The result of such a calculation is shown in Fig. 1 as a solid line. Good agreement is obtained between the measured and the calculated spectra for transferred energies above about 6 MeV. A similar description is achieved at other polar angles not shown here. The hardware threshold discussed above necessitated a restriction of the further analysis to excitation energies (after transformation to the center-of-mass system) $E_x = 8$–16 MeV. Nevertheless, compared to the previous experiment in [11], energies considerably closer to the breakup threshold could be investigated.

The polar angle dependence of the double differential coincidence cross section is displayed in Fig. 2 for the excitation energy bin $E_x = 8$–10 MeV as an example. Additionally, an angle set measured at $E_0 = 50$ MeV is shown. For both electron energies the angular correlations are very well described by the theoretical model, with respect to the shape as well as on an absolute scale.

An in-depth comparison between experiment and theory requires a decomposition into the different structure functions f_L, f_T, f_{LT}, and f_{TT}. Unlike, e.g., in Ref. [3], the analysis is performed here in terms of the measured triple-differential cross sections which can be written schematically as

$$\frac{d^3\sigma}{dE_x d\Omega_e d\Omega_p} = \frac{d^3}{dE_x d\Omega_e d\Omega_p}(\sigma_L + \sigma_T + \sigma_{LT}\cos\Phi_p + \sigma_{TT}\cos 2\Phi_p). \qquad (1)$$

The partial cross sections in Eq. (1) are the products of purely kinematical factors and the structure functions f discussed above (for details see, e.g., Ref. [19]). By variation of Φ_p it is possible to separate the interference terms σ_{LT} and σ_{TT} from the longitudinal-plus-transverse cross sections $(\sigma_L + \sigma_T)$

TABLE I. Double-differential cross sections $d^2\sigma/d\Omega_e d\Omega_p$ (nb/sr^2) of the reaction ^{2}H$(e, e'p)$ at $E_0 = 85$ MeV and $\Theta_e = 40°$ as a function of the polar proton emission angle Θ_p for an excitation energy bin $E_x = 8$–10 MeV.

Θ_p	$\sigma(\Phi_p = 45°)$	$(\sigma_L + \sigma_T)$	σ_{LT}	Θ_p	$\sigma(\Phi_p = 45°)$	$(\sigma_L + \sigma_T)$	σ_{LT}
1.2°	142(5)	140(5)	−1.48(15)	79.9°	1.7(17)	5.3(10)	−1.93(9)
14.7°	110(5)	125(4)	−16.7(16)	154.1°	31.5(92)	20.8(25)	10.5(14)
28.3°	70(3)	89(3)	−25.0(19)	161.4°	23.1(45)	22.5(16)	8.0(11)
41.8°	23.7(33)	50(2)	−25.0(14)	167.8°	22.0(56)	24.0(25)	5.37(73)
54.9°	8.9(21)	20.5(11)	−19.2(12)	174.2°	29.1(80)	25.0(33)	2.61(36)
67.7°	0.28(28)	6.7(9)	−10.5(12)	179.5°	24.2(80)	25.0(36)	0.28(4)

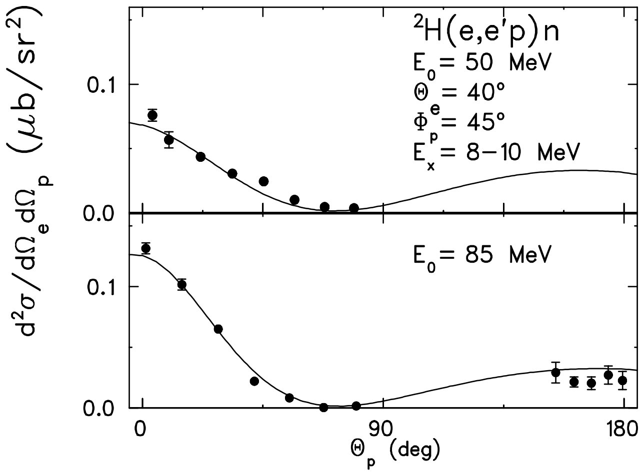

FIG. 2. Double-differential cross sections of the ^{2}H$(e, e'p)$ reaction at $E_0 = 50$ and 85 MeV for an excitation energy bin $E_x = 8-10$ MeV of the breakup spectra (see Fig. 1) as a function of the polar proton emission angle Θ_p. The solid lines represent theoretical predictions described in the text.

$$(\sigma_L + \sigma_T) = \frac{1}{2}[\sigma(\Phi_p = 45°) + \sigma(\Phi_p = 135°)], \tag{2}$$

$$\sigma_{LT} = \frac{1}{\sqrt{2}}[\sigma(\Phi_p = 45°) - \sigma(\Phi_p = 135°)], \tag{3}$$

$$\sigma_{TT} = \frac{1}{2}[\sigma(\Phi_p = 0°) + \sigma(\Phi_p = 180°)] - \frac{1}{2}[\sigma(\Phi_p = 45°) + \sigma(\Phi_p = 135°)]. \tag{4}$$

The decomposition of these various pieces was the main goal of the present experiment. A decomposition of σ_L and σ_T by a Rosenbluth separation would require additional data. In order to perform the summations/subtractions of Eqs. (2)–(4), the experimental angular correlation data (see Fig. 2 and [25] for examples) were fitted with Legendre polynomials up to order four.

The resulting $(\sigma_L + \sigma_T)$ cross sections are presented in Fig. 3 as a function of Θ_p for $E_x = 8-10$ MeV. The values are given relative to the one at $\Theta_p = 0°$ to make the comparison with model calculations independent of the absolute normalization of the data. Reasonable agreement with the theoretical predictions is observed. The σ_L and σ_T contributions to the latter are shown as dashed and dash-dotted lines in Fig. 3. Transverse cross sections are relevant only near $\Theta_p = 90°$. The underprediction of the experimental data point closest to $\Theta_p = 90°$, where σ_T dominates, seems to be a systematic feature observed at all excitation energies although partly less pronounced. The excitation energy dependence of the $(\sigma_L + \sigma_T)$ cross

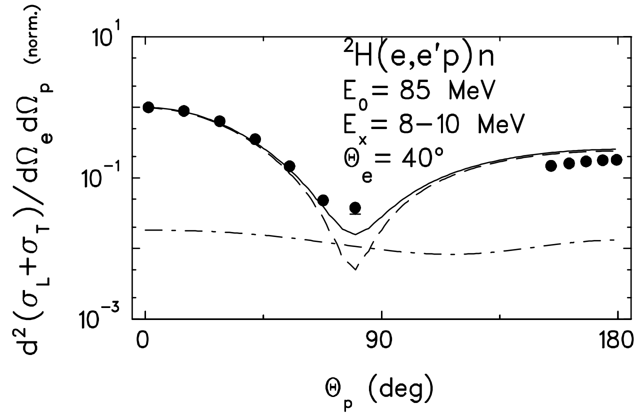

FIG. 3. Sum of the double-differential longitudinal and transverse cross sections $(\sigma_L + \sigma_T)$ of the ^{2}H$(e, e'p)$ reaction at $E_0 = 85$ MeV for an excitation energy bin $E_x = 8-10$ MeV as a function of the polar proton emission angle Θ_p. The dashed and dash-dotted lines are theoretical predictions for σ_L and σ_T (see text), and the solid line is the sum of both.

sections after integration over the proton emission angle is also well accounted for by the theoretical results [25].

Angular correlations of the σ_{LT} term are presented in Fig. 4 for different excitation energy bins. The cross sections are again normalized to $(\sigma_L + \sigma_T)$ at $\Theta_p = 0°$. The experimental results show a pronounced minimum around 30° and indicate a zero crossing near 90°. The theoretical

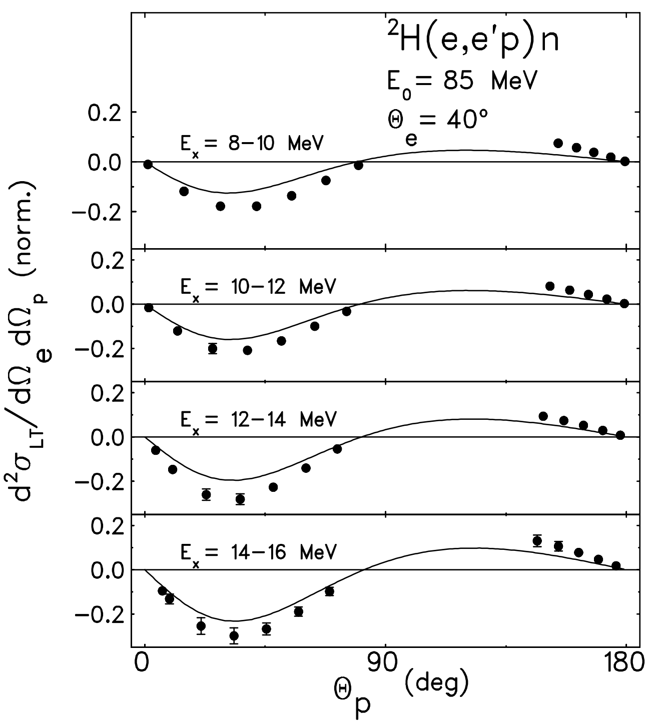

FIG. 4. Double-differential longitudinal-transverse interference cross sections σ_{LT} of the ^{2}H$(e, e'p)$ reaction at $E_0 = 85$ MeV for various excitation energy bins as a function of the polar proton emission angle Θ_p. The solid lines represent theoretical predictions described in the text.

predictions can reproduce the experimental angular correlations qualitatively. However, the absolute values are significantly underpredicted over the whole experimentally covered excitation region. The ratio between experiment and theory at the minimum of the angular correlation varies between 1.3 and 1.45.

At present, the standard nuclear theory in the framework of effective degrees of freedom does not offer any simple explanation for such a large discrepancy. It should be noted that theoretical difficulties in the description of the LT structure function already appeared for data measured at higher q. Although fully relativistic calculations generally improve the comparison [3,5–8], significant differences remain (for a comprehensive review see Ref. [26]). At the low q of the present experiment already the conventional nonrelativistic approach without MEC, IC, and RC accounts for 99% of the final result for σ_{LT}, leaving no room for further improvement. On the other hand, the experimental uncertainties estimated above are too small to explain the large difference between data and calculation. The most critical error source lies in the absolute normalization of the cross sections measured at different azimuthal angles Φ_p. However, the very good cancellation obtained in Fig. 4 for the data points near $\Theta_p = 0°$ and 180°, where helicity conservation requires that σ_{LT} vanishes, makes such an explanation unlikely.

The contributions of the σ_{TT} term are predicted to be more than an order of magnitude smaller than the σ_{LT} term. Since it must be extracted from the subtraction of large numbers measured at different azimuthal angles [cf. Eq. (4)] the uncertainties of the present data are too large for a meaningful comparison to theory.

To summarize, a study of deuteron breakup in the ^{2}H$(e, e'p)$ reaction at low momentum transfer and for excitation energies approaching the threshold has been presented. The $(\sigma_L + \sigma_T)$ data are in good agreement with calculations based on the Bonn potential and including FSI, MEC, IC, and RC effects. However, there are hints that the transverse part may be systematically underestimated. Furthermore, large deviations are observed near the minimum of the σ_{LT} angular correlations around $\Theta_p \simeq 30°$ over the whole excitation energy range investigated, providing another example for the importance of out-of-plane measurements of interference terms [27] as a sensitive test of the NN interaction. At present, there exists no explanation of this surprising result in the framework of the conventional nuclear theory.

It is an open question whether an alternative interpretation can be offered by effective field theory (for calculations of electromagnetic processes on deuterium see [28–31]). However, the results related to the reaction studied here [29,31] do not differ substantially from those of the conventional approach. Experimentally, a separation of σ_L and σ_T and a further approach towards the threshold [e.g., with a recently developed setup for $(e, e'n)$ experiments [32]] would be of particular interest.

We are indebted to H.-D. Gräf and the S-DALINAC team for their efforts to provide excellent electron beams. Useful discussions with H. Schmieden, R. P. Springer, and J. M. Udias are acknowledged. This work has been supported by the DFG under Contracts No. FOR 272/2-1 and No. SFB 443.

*Email address: vnc@ikp.tu-darmstadt.de
†Present address: EDS, D-63067 Offenbach, Germany.

[1] H. Arenhövel and M. Sanzone, Few-Body Syst. Suppl. **3**, 1 (1991).
[2] R. Gilman and F. Gross, nucl-th/0111015.
[3] M. van der Schaar *et al.,* Phys. Rev. Lett. **66**, 2855 (1991); **68**, 776 (1992).
[4] J. E. Ducret *et al.,* Phys. Rev. C **49**, 1783 (1994).
[5] F. Frommberger *et al.,* Phys. Lett. B **339**, 17 (1994).
[6] H. J. Bulten *et al.,* Phys. Rev. Lett. **74**, 4775 (1995).
[7] D. Jordan *et al.,* Phys. Rev. Lett. **76**, 1579 (1996).
[8] W.-J. Kasdorp *et al.,* Phys. Lett. B **393**, 42 (1997); Few-Body Syst. **25**, 115 (1998).
[9] A. Pellegrino *et al.,* Phys. Rev. Lett. **78**, 4011 (1997).
[10] K. I. Blomqvist *et al.,* Phys. Lett. B **424**, 33 (1998).
[11] T. Tamae *et al.,* Phys. Rev. Lett. **59**, 2919 (1987).
[12] A. Richter, in *Proceedings of the 5th EPAC,* edited by S. Meyers *et al.* (IOP, Bristol, 1996), p. 110.
[13] H. Diesener *et al.,* Phys. Rev. Lett. **72**, 1994 (1994).
[14] P. von Neumann-Cosel *et al.,* Phys. Rev. Lett. **78**, 2924 (1997).
[15] H. Diesener *et al.,* Nucl. Phys. **A696**, 272 (2001).
[16] D. Hoffmann *et al.,* Nucl. Instrum. Methods **118**, 321 (1974).
[17] All experimental data can be found in tabular form at http://qclam.ikp.physik.tu-darmstadt.de/eng/exp_deep.
[18] H. Crannell, Nucl. Instrum. Methods **71**, 208 (1969).
[19] W. Fabian and H. Arenhövel, Nucl. Phys. **A314**, 253 (1979).
[20] H. Arenhövel *et al.,* Phys. Rev. C **52**, 1232 (1995).
[21] R. Machleidt *et al.,* Phys. Rep. **149**, 1 (1987).
[22] T. Wilbois *et al.,* Few-Body Syst. **15**, 39 (1993).
[23] F. Ritz *et al.,* Phys. Rev. C **55**, 2214 (1997).
[24] H. Arenhövel *et al.,* Phys. Rev. C **61**, 034002 (2000).
[25] P. von Neumann-Cosel *et al.,* in Proceedings of the INPC 2001, Berkeley (to be published).
[26] S. Gilad *et al.,* Nucl. Phys. **A631**, 276c (1998).
[27] Z.-L. Zhou *et al.,* Phys. Rev. Lett. **87**, 172301 (2001).
[28] J.-W. Chen *et al.,* Nucl. Phys. **A644**, 245 (1998).
[29] M. J. Savage *et al.,* Nucl. Phys. **A652**, 273 (1999).
[30] D. B. Kaplan *et al.,* Phys. Lett. B **449**, 1 (1999).
[31] M. Walzl and U.-G. Meißner, Phys. Lett. B **513**, 37 (2001).
[32] S. Strauch *et al.,* Phys. Rev. Lett. **85**, 2913 (2000).