Deuteron Electrodisintegration in the Δ-Resonance Region

A. Pellegrino,[1,2,*] H. Arenhövel,[3] H. P. Blok,[1,2] D. van Dierendonck,[4] G. E. Dodge,[1,2,†] W. H. A. Hesselink,[1,2] E. Jans,[2] N. Kalantar-Nayestanaki,[5] W.-J. Kasdorp,[2] L. Lapikás,[2] J. J. van Leeuwe,[2] W. Leidemann,[6] A. Misiejuk,[4] C. J. G. Onderwater,[1,2] G. van der Steenhoven,[2] R. Starink,[1,2] J. J. M. Steijger,[2] J. A. Templon,[1,2,‡] J. L. Visschers,[2] T. Wilbois,[3,§] P. Wilhelm,[3] H. W. Willering,[4] and D. M. Yeomans[4]

[1]*Department of Physics and Astronomy, Free University, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*

[2]*NIKHEF, P.O. Box 41882, 1009 DB Amsterdam, The Netherlands*

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

[4]*Department of Subatomic Physics, University of Utrecht, P.O. Box 80.000, 3508 TA Utrecht, The Netherlands*

[5]*KVI, Rijksuniversiteit Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands*

[6]*Dipartimento di Fisica, Università di Trento, I-38050 Povo (Trento), Italy*

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The differential cross section and the transverse-transverse interference structure function for the reaction $^2\mathrm{H}(e,e'p)n$ have been determined at an *np* invariant mass of 2.16 GeV. The data, covering a 40° range in the proton emission angle, indicate that Δ excitation and subsequent $N\Delta$ interaction is the dominant reaction mechanism. Calculations performed within an $N\Delta$ coupled-channel approach reproduce the cross section data, but underestimate the f_{TT} results by 30 to 40 percent. [S0031-9007(97)03090-1]

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Deuteron electrodisintegration in the Δ-resonance region offers an excellent probe to investigate the dynamics of the Δ isobar in a nuclear system. While at low energy transfer the deuteron response is reproduced by microscopic calculations based on realistic *NN* potentials, at higher energy transfer the first nucleon resonance, the Δ or P_{33} baryon, plays an important role. This has been illustrated in several theoretical studies [1,2].

Many electron scattering experiments have been devoted to deuteron disintegration in quasifree kinematics. Of these, the exclusive $(e,e'p)$ measurements have provided the most detailed information on the deuteron structure. In the unpolarized $(e,e'p)$ reaction, the information on the dynamics of the two-nucleon system is contained in four structure functions: the longitudinal f_L, the transverse f_T, and the interference terms f_{LT} and f_{TT}. Measurements of the differential cross section and in some cases of the individual structure functions f_L, f_T, and f_{LT} [3–15] have provided stringent tests of the existing theoretical models [16–19]. In particular, the f_L and f_T data were reproduced by the existing calculations [7,10], while the f_{LT} data pointed to the need for a relativistic form of the current operator [8,11–14]. The measurement of f_{TT} is more difficult, since it requires the detection of protons outside of the electron scattering plane. Hitherto, only one measurement [6] has been reported, at very low transferred energy and momentum $(\omega, |\mathbf{q}|) = (18\ \mathrm{MeV}, 160\ \mathrm{MeV}/c)$; the f_{TT} results were not significantly different from zero.

Although the effects of Δ isobar currents (IC) are small in quasifree kinematics, they are expected to become important at higher excitation energies. In the Δ-resonance region, which corresponds to an *np* invariant mass W_{np} of about 2.17 GeV, one has to treat the Δ isobar and the nucleon degrees of freedom in a coupled-channel (CC) approach, as was shown for *NN* scattering in Ref. [20], and for electromagnetic deuteron break-up first in Ref. [21] and more recently in improved calculations in Refs. [22,23]. These models predict that the $^2\mathrm{H}(e,e'p)n$ reaction in the Δ-resonance region is almost purely transverse in character and therefore the structure functions f_T and f_{TT} essentially generate the entire cross section. These structure functions in turn are predicted to have the characteristic features of a dominant M1 multipole transition. The measurement of f_T and, in particular, of f_{TT}, which is predicted to be essentially zero if IC are neglected, can thus be considered as a strong test of the theoretical treatment of Δ degrees of freedom. Such a study is not only of interest for a proper description of medium effects on the Δ propagation in the deuteron, but is also a prerequisite for the understanding of electron-induced two-nucleon knockout from a complex nucleus.

The Δ excitation in the deuteron has not been much covered by electrodisintegration measurements, mainly due to the small cross sections and the correspondingly small $(e,e'p)$ coincidence yields. Turck-Chieze *et al.* [4] measured the angular distribution of the in-plane cross section at a relatively low invariant mass $W_{np} = 2.057$ GeV; Breuker *et al.* [5] and more recently Boden *et al.* [9] have studied the cross section as a function of the invariant mass at a fixed proton emission angle.

In the present study, the $^2\mathrm{H}(e,e'p)n$ differential cross section was measured at $W_{np} = 2.16$ GeV. Detecting the emitted protons with a large-solid-angle apparatus over a range of 40° both in and out of plane, we determined the f_{TT} structure function with significant systematic accuracy and statistical precision.

The experiment was performed with the electron beam extracted from the Amsterdam Pulse Stretcher (AmPS) at

NIKHEF, at an incident energy of 525 MeV. The average beam current and duty factor were 2 μA and 60%, respectively. A cryogenic deuterium target with a nominal thickness of 240 mg/cm^2 was used. The scattered electrons were detected in the QDQ magnetic spectrometer [24], which had a 9.6 msr solid angle, 9% momentum bite, and was positioned at $\theta_e = 30°$. The transferred four-momentum in the laboratory frame was $(\omega, |\mathbf{q}|) = (312\ \text{MeV}, 357\ \text{MeV/c})$. The emitted protons were detected with the highly segmented plastic-scintillator array HADRON4. This detector consists of 94 scintillator elements, subtends a solid angle of 550 msr, and accepts protons with energies from 25 to 160 MeV. To keep the count rate and the dead time in the individual detector elements below 1 MHz and 5%, respectively, a 2.6 mm thick Pb sheet was placed in front of the detector; this changed the energy acceptance to 50–175 MeV. The position of the proton detector was kept fixed at a central angle $\theta_{np}^{\rm CM} = 117°$, where $\theta_{np}^{\rm CM}$ is defined as the angle between the relative momentum of the final-state *np* pair and $\boldsymbol{q}$, in the center-of-mass frame of the *np* pair. The 550 msr acceptance roughly corresponds to a range of about 40° both in and out of the reaction plane; this permitted the measurement of proton emission within the range $99° < \theta_{np}^{\rm CM} < 134°, 162° < \phi_{np}^{\rm CM} < 198°$, in one geometrical setup. The azimuthal angle $\phi_{np}^{\rm CM}$ is defined as the angle between the reaction plane, spanned by the *np* relative momentum and $\boldsymbol{q}$, and the electron scattering plane.

The HADRON4 detector was calibrated by exploiting the continuous energy spectrum of protons from the inclusive reaction ^{2}H(e, p). The relations between the energy losses of the protons in the various detector layers were used for the identification of the protons and for the measurement of their energies. Distributed laser and test-pulse signals were used to determine the dead times of the front-end electronics of the individual scintillator channels. Inefficiencies due to hadronic interactions and multiple scattering of the protons and to the effect of the discriminator thresholds were determined by simulating the response of the detector in a Monte Carlo procedure using the code GEANT [25]. All these inefficiencies were corrected for in the analysis of the coincidence data. The final state was unambiguously identified as an *np* state on the basis of the measured missing-energy spectrum. This spectrum was corrected for accidental coincidence events; the ratio of real to accidental events was typically 4:1. The contribution of coincidence events originating at the metallic walls of the target cell (≈10%) was determined in a measurement performed with an empty target cell and was subtracted in the off-line analysis. The data were corrected for radiative effects by using an unfolding procedure based on the method described in Ref. [26]. The net effect of this correction on the differential cross section is on average 11%. Finally, the ^{2}H$(e, e'p)n$ reaction yield was determined by integrating the so-called "break-up" peak in the missing-energy spectrum, centered around the value of the binding energy of the deuteron. The achieved accuracy of 1 MeV in the position of the break-up peak reflects the quality of the energy calibration and of the determination of the proton emission angle. The total statistical error in the measured ^{2}H$(e, e'p)n$ cross section ranges from 1.9% to 2.7%. This includes the statistical precision in the subtraction of accidental coincidences and events originating at the walls of the target cell. The total systematic error is 4.8%. The largest contribution (3.5%) to the systematic error stems from the uncertainty in the integrated luminosity, which was determined by measuring the differential cross section for elastic scattering of electrons off deuterium. The measured ^{2}H$(e, e'p)n$ cross section is displayed in Fig. 1(a) as a function of the polar angle $\theta_{np}^{\rm CM}$. Only the statistical errors are shown.

The interference terms in the differential cross section

$$\frac{d^5\sigma}{d|\boldsymbol{k}'^{\rm L}|d\Omega_e^{\rm L}d\Omega_{np}^{\rm CM}} = C\{\rho_L f_L + \rho_T f_T + \rho_{LT} f_{LT} \times \cos\phi_{np}^{\rm CM} + \rho_{TT} f_{TT} \cos 2\phi_{np}^{\rm CM}\} \quad (1)$$

can be extracted from the cross sections measured at different $\phi_{np}^{\rm CM}$ values. Theoretical calculations in Refs. [23,27] predict that the differential cross section varies by roughly 3%–6% in the $\phi_{np}^{\rm CM}$ range 162°–198°. This small variation demands high experimental precision in determining f_{TT} and great care with respect to the

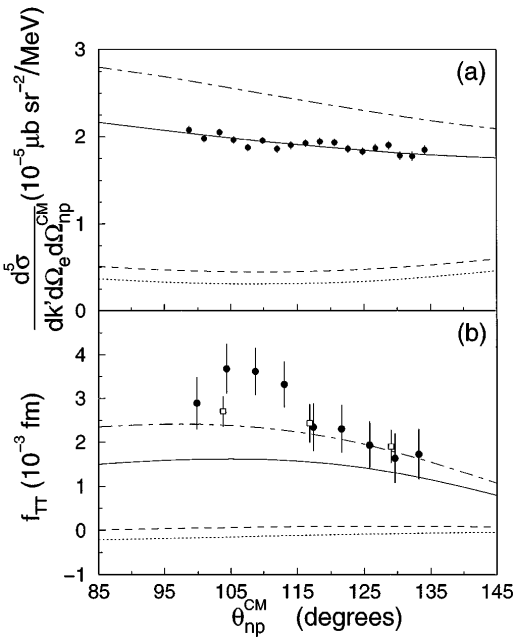

FIG. 1. Differential cross section (a) and f_{TT} structure function (b) for the ^{2}H$(e, e'p)n$ reaction as a function of $\theta_{np}^{\rm CM}$. Only statistical errors are shown. In (b), the full dots and the open squares represent the results of the analysis based on Eq. (2) and of the fit of function (1) to the data, respectively. The various curves represent calculations by Wilbois *et al.* Dotted curve: *N*; dashed curve: *N* + MEC; full curve: *N* + MEC + IC, calculated within the CC model; dot-dashed curve: same as the full curve, but calculated in IA.

systematic errors. Moreover, in our kinematics, f_{LT} is expected to be small with respect to f_{TT}; the aforementioned calculations predict $f_{LT} \simeq \frac{1}{10} f_{TT}$. Assuming this ratio for f_{LT}/f_{TT}, one finds that, over the covered ϕ_{np}^{CM} range, the contribution to the variation of the differential cross section of the LT term relative to that of the TT term is roughly 2.5%. Hence, assuming that the LT term can be neglected, f_{TT} can be directly extracted from the cross section data.

We have determined f_{TT} with two different procedures. In the first procedure, f_{TT} is extracted from the cross sections in-plane and at ϕ_- and ϕ_+, which correspond to the average values of the lowest and highest $\Delta\phi_{np}^{\mathrm{CM}}$ experimental bins, respectively. Using Eq. (1) and neglecting the LT term, one then obtains

$$f_{TT} \simeq \frac{2\sigma_{\phi_0} - \sigma_{\phi_+} - \sigma_{\phi_-}}{C\rho_{TT}(2\cos 2\phi_0 - \cos 2\phi_+ - \cos 2\phi_-)}. \quad (2)$$

The distribution of f_{TT} as a function of $\theta_{np}^{\mathrm{CM}}$ in 4.5° bins, obtained with this procedure, is represented in Fig. 1(b) by the full circles. The error bars are statistical and include the effects of the subtraction of accidental coincidence events and of events originating at the walls of the target cell. Systematic uncertainties which can cause artificial variation of the cross section with ϕ_{np}^{CM} were treated with great care. The crucial point is that the data at all ϕ_{np}^{CM} angles were taken in one geometrical setup. This restricts the causes of artificial ϕ_{np}^{CM} cross-section variation to measured quantities which explicitly depend on the proton out-of-plane angle. From the possible contributors, the following were measured to have no ϕ_{np}^{CM}-dependent effect on the cross section to within the specified accuracy: background from $(e, e'p)$ events originating at the target-cell walls (0.25%); reconstruction inefficiencies due to hadronic interactions or multiple scattering of the protons (0.4%); and detector alignment (0.1%). Only the dead times and the discriminator threshold of the front-end electronics of the detector elements measuring the proton out-of-plane angle generate a ϕ_{np}^{CM} dependence. The dead times were determined with great precision (0.3%) with the laser and test-pulse system. The results are shown in Fig. 2(a). The effect of the discriminator thresholds on f_{TT} is limited to a detection region of about 4.5° around $\theta_{np}^{\mathrm{CM}} = 106.6°$. In this region, due to the segmentation of HADRON4 and to the correlation between the kinetic energy of the emitted proton and $\theta_{np}^{\mathrm{CM}}$, protons are stopped at the borders of the last two scintillator layers in HADRON4 and produce in the last layer signals smaller than the discriminator thresholds. This effect is accounted for in the Monte Carlo simulations. The systematic uncertainty in this correction amounts to about 0.5%. The overall systematic error in the value of f_{TT} due to the effects mentioned above is 14%, with an additional 13% systematic error for the data points at 104° and 109°.

To assess the correctness of the assumption that the LT term can be neglected in comparison to the TT one in Eq. (1), we also fitted the ϕ_{np}^{CM} distribution of the differential cross section to the data without neglecting f_{LT}, by taking the quantity $\rho_L f_L + \rho_T f_T$ and the structure functions f_{LT} and f_{TT} as fit parameters. The fits were made for $\theta_{np}^{\mathrm{CM}}$ bins of 9° to increase the statistical precision of the data. As an illustration of the precision achieved in the experiment, in Fig. 2(b) the cross sections, measured for three bins in $\theta_{np}^{\mathrm{CM}}$, are displayed as a function of ϕ_{np}^{CM}. The f_{TT} values deduced from the fits are represented in Fig. 1(b) by the open squares. They are consistent with those obtained by applying Eq. (2), although the parameters $\rho_L f_L + \rho_T f_T$ and f_{LT} are fully correlated and cannot be determined unambiguously. This is due to the limited ϕ_{np}^{CM} range of the data and to the weak dependence of the LT term on ϕ_{np}^{CM}. Moreover, we determined that the neglect of the LT term can lead to a systematic underestimate of f_{TT} of at most 15%.

In Fig. 1, the data are compared to recent NN-$N\Delta$ coupled-channel calculations including explicit pion degrees of freedom [23]. The underlying NN potential used was the OBEPQ-B version of the Bonn model [28]. The $\gamma N\Delta$ coupling was fixed at the photon point by a fit to pion photoproduction data on the nucleon under the assumption of a vanishing nonresonant contribution to the $M_{1+}^{3/2}$ multipole [22]. This led to a good description of the total cross section for deuteron photodisintegration [29–31]. For the q_μ^2 dependence of the $\gamma N\Delta$ coupling, the usual dipole form was adopted. The calculation denoted

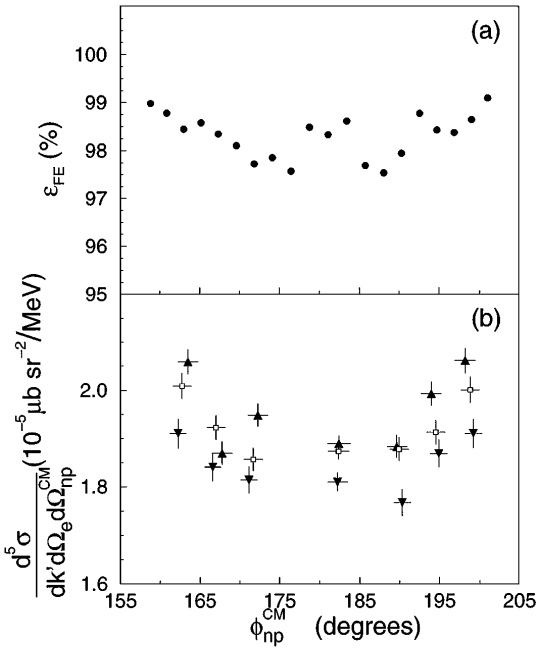

FIG. 2. (a) Efficiency of the front-end electronics of the ϕ_{np}^{CM}-measuring detector elements. The precision of the measurement is determined by the number of laser and test-pulse sampling signals and is about 0.3%. (b) Differential cross sections for the $^2\mathrm{H}(e, e'p)n$ reaction as a function of ϕ_{np}^{CM}, at given values of $\theta_{np}^{\mathrm{CM}}$. The average values of $\theta_{np}^{\mathrm{CM}}$ are 104° (top-up triangles), 117° (open squares), and 130° (top-down triangles), respectively. Only statistical errors are shown.

as "N" (dotted curve) in Fig. 1 is restricted to purely nucleonic currents including Siegert operators. Adding explicit meson-exchange currents (MEC) leads to the dashed curve. The dot-dashed curve represents the calculations in which the Δ isobar is included through a perturbative treatment, referred to as impulse approximation (IA). The solid curve corresponds to the dynamical treatment within the CC approach. Note that this also modifies the purely nucleonic components and thus affects all matrix elements, not only the IC contributions.

The comparison between the data and model calculations unequivocally demonstrates the dominant role of the Δ isobar. Moreover, the differential cross section, which is dominated by f_T, is very well described by the CC approach while the IA overestimates it by roughly 25%. A similar behavior was found in deuteron photodisintegration. It clearly shows that, due to the strong coupling between the NN, $N\Delta$, and $NN\pi$ channels, a nonperturbative treatment is mandatory. The observed agreement gives strong confidence that the main features of the model are correct, so that this interaction model may be used in more complex nuclei. The simultaneous investigation of f_T and f_{TT} provides an additional and even more sensitive test of the underlying dynamics; both structure functions contain the same matrix elements but in different combinations, which in general results in a stronger destructive interference effect in f_{TT}. The larger sensitivity of f_{TT} becomes evident in the comparison of the theoretical results with and without IC. While the agreement with the IA is not meaningful because of its failure for the differential cross section, the underestimation of the data by 30%–40% by the CC points to some remaining deficiency in the theoretical treatment. The uncertainties in the electromagnetic transition form factors are not critical for these small momentum transfers, and also the model dependence of the used NN potentials cannot account for the observed discrepancy. Possible sources may be a model dependence of the $N\Delta$ interaction, missing relativistic contributions, and the neglected retardation in the NN sector, although retardation is included in the $N\Delta$ sector.

In summary, we have measured the differential cross section for electrodisintegration of the deuteron at $W_{np} = 2.16$ GeV over a 40° range in the proton emission angle. Furthermore, from the out-of-plane data we have performed the first determination of the transverse-transverse interference structure function f_{TT} with significant statistical precision and systematic accuracy. The experimental results are conclusive regarding the dominant role of the Δ isobar and provide a stringent test for the dynamical treatment of the Δ degrees of freedom in the theoretical models. The results of a coupled-channel calculation, including explicit pion, nucleon, and Δ degrees of freedom, are in agreement with the cross section data. However, the f_{TT} data are systematically underestimated by 30% to 40%. Further theoretical studies are needed to clarify the observed discrepancies.

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*Present address: Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22603 Hamburg.
†Present address: Department of Physics, Old Dominion University, Norfolk, Virginia 23529.
‡Present address: Department of Physics and Astronomy, University of Georgia, Athens, Georgia 30602.
§Present address: Institut für Theoretische Physik, Universität Hannover, D-30167 Hannover.

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