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Large recoil momenta in the D(e,e′p)n reaction [1]

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Abstract

The D(e,e′p)n reaction cross section has been measured for recoil momenta ranging from 17 MeV/c up to 950 MeV/c at momentum transfers between 600 MeV/c and 700 MeV/c. At recoil momenta above 400 MeV/c, the gross features of the cross section are only reproduced if virtual nucleon excitations are included in the calculations. © 1998 Published by Elsevier Science B.V.

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As the only bound two-baryon system, the deuteron has always played a crucial role in the investigation of strongly interacting particles. Since one can calculate the deuteron structure with high accuracy, this system serves as testing ground for

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different models of the nucleon-nucleon force. Using the electromagnetic interaction, the deuteron has been studied from the beginning of nuclear physics. In the last 15 years electron accelerators have become available which feature increasingly high duty factors up to the CW accelerators with a duty factor of 1.0. This permits the detailed study of the photo- and electro-disintegration of the deuteron with high precision in kinematical regions which have been unreachable so far.

The D(e,e′p)n reaction has been used to obtain information on the spectral function of the deuteron which, in the plane wave impulse approximation (PWIA), is related to the cross section as follows:

$$\frac{d^6\sigma}{d\omega d\Omega_e d\Omega_p dT_p} = \kappa \cdot \sigma_{ep} \cdot S(E,p_i)$$

Here, σ_{ep}describes the elementary electron proton (off-shell) cross section for scattering an electron off a moving bound proton [1]. The factor κ is a kinematical factor, and $S(E,p_i)$ is the spectral function which describes the probability of finding a proton with the separation energy E and an initial momentum p_i. In this approximation, the initial momentum of the proton is opposite equal to the momentum of the recoiling non-observed neutron. The experiments reaching the highest missing momenta have been carried out at Saclay for missing momenta up to 500 MeV/c [2,3] and recently at NIKHEF [8] for missing momenta up to 700 MeV/c. The three momentum transfers used in the Saclay experiment were between 350 and 450 MeV/c for missing momenta below 330 MeV/c and 280 MeV/c for recoil momenta between 295 and 500 MeV/c. For the NIKHEF experiment they where between 360 MeV/c and 600 MeV/c.

In the one-photon exchange limit, the above cross section is written as follows:

$$\frac{d^6\sigma}{d\omega d\Omega_e dT_p d\Omega_p} = \sigma_{\mathrm{Mott}}(v_L R_L + v_T R_T + v_{LT} R_{LT} \cos\phi + v_{TT} R_{TT} \cos 2\phi)$$

The functions R_i and R_{ij} are response functions. They consist of combinations of transition matrix elements of the components of the electromagnetic current operator and contain the spectral function.

In recent experiments the longitudinal (R_L), transverse (R_T) and longitudinal-transverse interference (R_{LT}) response functions have been determined at recoil momenta between 0 and 220 MeV/c [4,5,7]. The momentum transfer dependence of R_L, R_T and R_{LT} has been measured at Saclay for recoil momenta between 0 and 150 MeV/c [9]. In a recent experiment at SLAC the cross section and R_{LT} have been determined at very large momentum transfers for recoil momenta up to 200 MeV/c [10]. These experiments studied the deuteron structure functions at relatively small missing momenta (below 230 MeV/c). In order to study the deuteron structure at short inter-nucleon distances and the effects of meson exchange and isobar currents, cross sections at large missing momenta and large momentum transfers are needed.

In this letter we report on cross section measurements covering recoil momenta from 17 MeV/c up to 950 MeV/c measured at momentum transfers between 600 MeV/c and 700 MeV/c.

This experiment has been carried out at the three-spectrometer facility [11] at the Mainz microtron MAMI using spectrometer B to detect electrons and spectrometer A to measure protons. The incident beam energy was $E_{\mathrm{inc}} =$ 855.11 MeV, and the electron scattering angle was kept constant at $\theta_e = 45°$. The momentum acceptance of the electron spectrometer was $\Delta p/p = \pm 7.4\%$ and the one of the proton spectrometer $\Delta p/p = -5, +15\%$ with respect to the corresponding reference momenta. The rectangular entrance slit of the electron spectrometer defined an angular acceptance of $d\theta_e = \pm 20 mr$ in the scattering (horizontal) plane, and $d\phi_e = \pm 70 mr$ in the vertical plane. The proton spectrometer had an acceptance of $d\theta_p = \pm 75 mr$ and $d\phi_p = \pm 70 mr$. The momenta of the outgoing protons varied between 550 MeV/c and 690 MeV/c. The recoil momenta were varied by changing the energy transfer ω from 180 MeV to 600 MeV and by varying the proton angle θ_p between 51.61° and 100°. Care was taken to perform the experiments such, that they can be extended in future experiments to determine the response function R_{LT} separately. The central settings of the spectrometers are listed in Table 1.

In order to measure the large missing momenta with the given momentum transfer and to detect the resulting proton momenta within the momentum ac-

Table 1
Central settings of the spectrometers. p_{ref} is the reference momentum of the spectrometers

Setting	electron arm		proton arm		Symbols
	θ_e degrees	p_{ref} MeV/c	θ_p degrees	p_{ref} MeV/c	
1	45	674.9	51.61	578.3	filled
2	45	657.2	59.98	599.1	open
3	45	657.6	70.13	569.5	filled
4	45	606.7	80.00	578.8	open
5	45	576.4	85.00	578.8	filled
6	45	537.0	90.00	578.7	open
7	45	507.8	100.00	538.0	filled
8	45	405.7	100.00	617.6	open
9	45	332.5	100.00	617.6	filled
10	45	255.5	100.00	640.6	open

ceptance of spectrometer A, the angle between the momentum transfer and the outgoing proton had to be continuously increased. In order to provide also the increasing energy of the undetected recoiling neutron, the energy transfer had to be increased, covering the region between quasi-elastic scattering and Δ excitation in inclusive scattering.

We used a liquid-deuterium target. The target cell consisted of a cylinder with a diameter of 2 cm made of HAVAR with a wall thickness of 6.5 μm, corresponding to 10 mg/cm^2. The deuterium target thickness was 310 mg/cm^2. The liquid deuterium was continuously circulated by means of a fan immersed in the liquid, thus preventing the liquid at the intersection with the electron beam from boiling. Since the beam diameter was typically of the order of 0.2 mm, the beam was wobbled horizontally by ± 3.5 mm and vertically by ± 2.5 mm with a frequency of 3.5 kHz horizontally and 2.5 kHz vertically. This further reduced the risk of boiling. The current in the wobbler coil was measured on an event by event basis which allowed us to reconstruct the beam position for each event in order to correct for energy losses in the target. In addition, the corresponding kinematical corrections could be applied. We therefore obtained at low missing momenta a missing energy resolution of 0.45 MeV (FWHM) which degraded to 2 MeV with increasing recoil momentum, as one has to include increasingly large recoil energies in the calculation of the missing energy. With this target system, beam currents between 2 μA and 40 μA could be used. The effective target thickness has been determined using elastic scattering via D(e,e′d) measurements and normalizing to the data of Platchkov et al. [12] and Auffret et al. [13]. These normalization measurements were performed in regular intervals during the experiment. We found a current dependence of the target thickness of 0.1 %/μA. The normalization factor varied between 1.082 at 5μA and 1.12 at 40μA. Contributions to this factor are the effect of wobbling (4%), the 3% hydrogen admixture to the deuterium gas, and losses of recoil deuterons due to nuclear reactions, estimated to be less than 3%. The systematic error of the measured cross sections has been determined to be about 6.2%. It contains contributions from the uncertainty in the elastic deuteron cross Section (2%), estimated deuteron losses (2.5%) and the uncertainty of the normalization factor (1.7%) for the different data sets.

Due to the large acceptances of the spectrometers, large regions in the kinematic variables have been sampled for each spectrometer setting. In order to compare the cross sections obtained with theoretical calculations, it is necessary to average the calculated cross sections for each bin in missing momentum over the measured kinematical range which contributes to this bin. This can be achieved with the same Monte Carlo calculation used to determine the acceptance volume of each setting. However, due to the time required to theoretically calculate a cross section, this procedure cannot be applied directly. Instead, H. Arenhövel [14] has calculated the cross section on a grid of 21021 points in the center-of-mass variables E_{np}, q^2_{cm} and θ_{cm}, i.e. in the total kinetic energy of the nucleons in the two-nucleon center-of-mass system, the momentum transfer and the angle between the final n-p pair and the momentum transfer. The calculations cover a range in E_{np} from 40 MeV to 540 MeV in steps of 12.5 MeV, in q^2_{cm} from 7.2 fm^{-2} to 9.4 fm^{-2} in steps of 0.22 fm^{-2}, and in θ_{cm} from 0° to 180° in steps of 2.5° and 5.0°. These ranges cover the region of kinematic values sampled in this experiment. The cross section for an arbitrary set of values within this range is obtained by interpolating the four response functions over the three variables using spline interpolation. We have verified that the interpolated values and the calculated values agree to within 0.5% over the whole measured range. This interpolation is fast enough to be implemented in a Monte Carlo calculation where the cross section is sampled over the kinematic ranges associated with each bin in missing momentum. The averaged cross sections obtained are then compared to the experimental ones.

The calculation of R. Schiavilla [15] has not been performed for a similar grid, since in this case the time required to calculate a kinematic point is prohibitively large. In order to compare his calculation to our measurement, we have calculated the average kinematic values for each bin of missing momentum and performed the calculation for these averaged kinematic values. Applying the two different methods to Arenhövel's calculation, we found that the results agree to within 3%.

To interpret the experimental cross sections within the frame work of the Plane Wave Impulse Approximation (PWIA) the data are first shown and compared to the calculation in the form of the reduced cross section:

$$\sigma_{\text{red}} = \frac{\sigma_{\text{exp}}}{f_{\text{rec}} \cdot \kappa \cdot \sigma_{CC1}}$$

Here, σ_{CC1} is the electron-proton off-shell cross section of de Forest [1], κ is a kinematic factor which depends on the variables with respect to which the coincidence cross section is differential, and f_{rec} is the recoil factor that arises from the integration over missing energy. If PWIA is valid, the reduced cross section is identical to the momentum distribution. The experimental cross section has been extracted by fitting the missing energy peak for the deuteron breakup on top of a linear background for each bin in missing momentum over a missing energy region between -2 MeV and 10 MeV. In Fig. 1, experimental reduced cross sections are compared to the calculated deuteron momentum distribution $n(p)$ using the Paris potential and to reduced cross

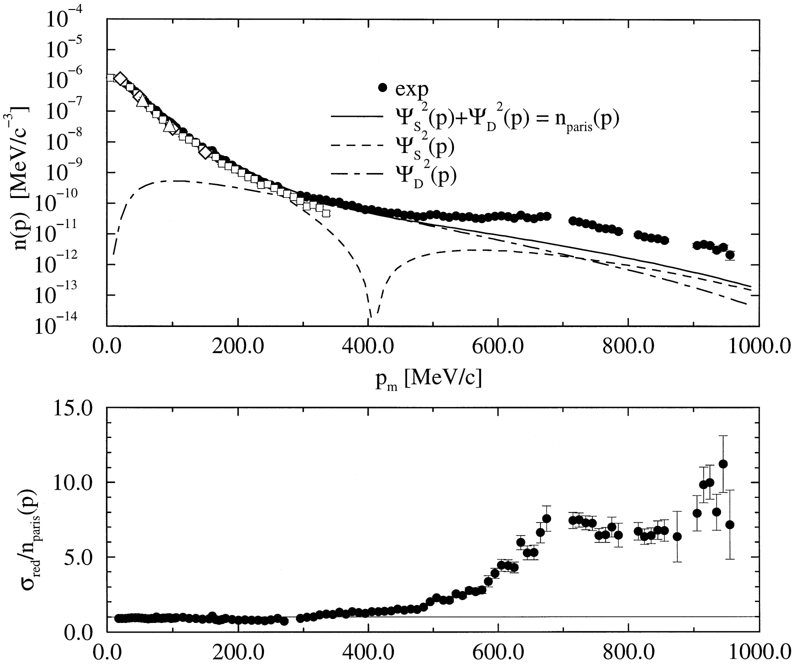

Fig. 1. Top: The reduced cross sections compared to the momentum distribution calculated with the Paris potential [14]. The open squares are data from Ref. [2], the open diamonds from Ref. [9] and the open triangles are from Ref. [6]. The dashed line shows the contribution of the S-state and the dash-dotted line shows the one from the D-state. Bottom: The ratio between the reduced cross sections and the Paris momentum distribution.

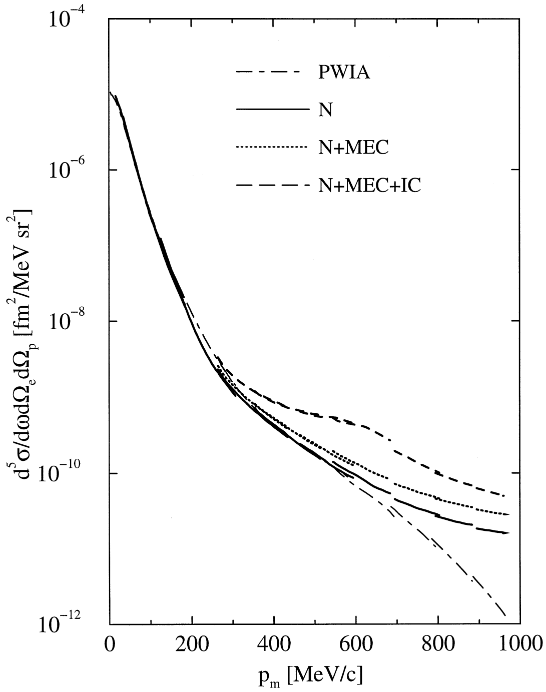

Fig. 2. Calculated D(e,e′p)n cross sections by Arenhövel [14]. The dash-dotted line shows the PWIA results. The solid curve (N) corresponds to cross sections including also FSI. The short-dashed ones (N + MEC) include in addition meson exchange currents and the long-dashed curves (N + MEC + IC) include meson exchange currents and isobar currents.

sections from experiments carried out at Saclay [2,9] and at MIT [6]. The reduced cross section of kinematic setting 27 of Ducret et al. [9], which is closest to the kinematics measured in this experiment, agrees within 4% with our value. This is well within the statistical and systematic error of the two measurements. The reduced cross sections extracted from other experiments [6,2] are generally smaller than ours by typically 5% to 15%. This could be attributed to final state interaction effects since these experiments have been performed at considerably smaller momentum transfers. At missing momenta below 200 MeV/c our cross sections are about 10% below the PWIA value which agrees with the general result of Bulten et al. [10] measured at SLAC using momentum transfers starting at 1.2 GeV/c.

The individual contributions from the S-state and from the D-state are also shown in Fig. 1. The D-state contribution dominates for internal nucleon momenta between 300 MeV/c and 700 MeV/c. Between 400 MeV/c and 450 MeV/c the cross section is practically entirely due to the D-state part of the deuteron wave function.

The data follow closely the PWIA result up to recoil momenta of 350 MeV/c. For larger momenta, the cross section becomes increasingly larger than the PWIA calculation. This can be seen even better in the bottom part of Fig. 1, where the ratio between the experimental cross section and the PWIA calculation is displayed.

At these large missing momenta final state interaction (FSI) and non nucleonic degrees of freedom become increasingly important as can be seen in Fig. 2. The solid line shows the cross section where, in contrast to PWIA, the FSI has been taken into account. The short-dashed line shows the cross section when meson exchange currents (MEC) are included and the additional effects due to isobar currents (IC), dominated by the Δ transition current, are shown by the long-dashed curve. The effect of meson exchange currents continuously increase with increasing miss-

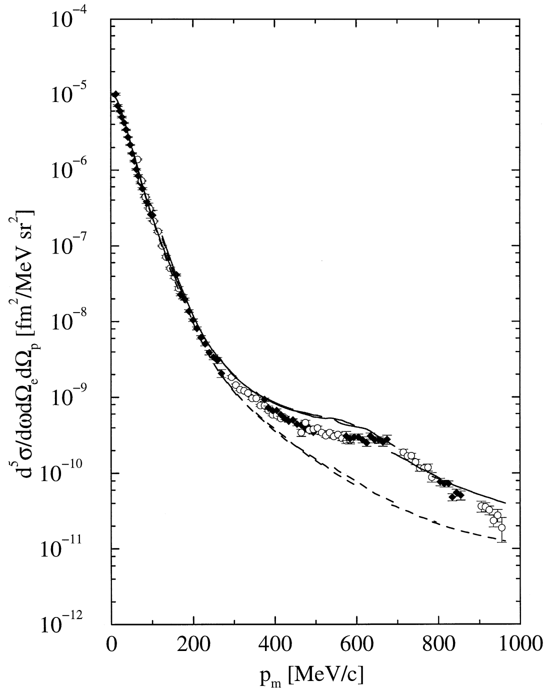

Fig. 3. Comparison of the measured D(e,e′p)n cross section to the calculation by Arenhövel [14] with (solid curve) and without (dashed curve) MEC and IC.

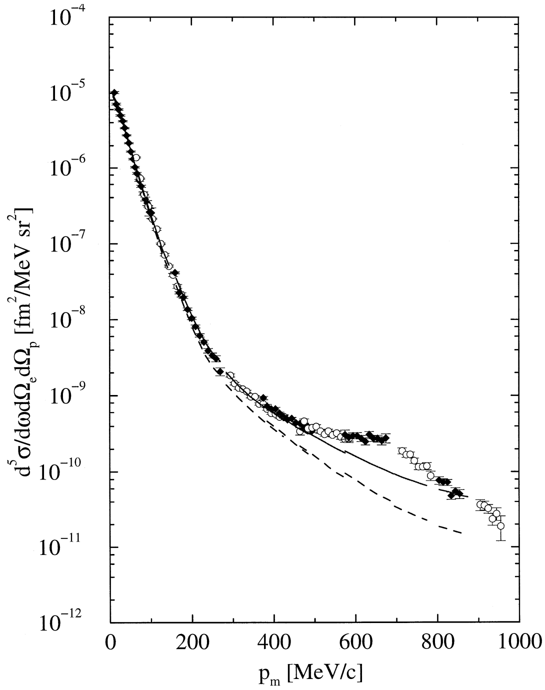

Fig. 4. Comparison of the measured D(e,e′p)n cross section to the calculation with Schiavilla's code [15] with (solid curve) and without (dashed curve) MEC and IC.

ing momentum while the contributions from isobar currents dominate at missing momenta around 600 MeV/c and slowly decrease with increasing missing momenta above 700 MeV/c. At the largest observed missing momenta, isobar currents change the cross section by about the same factor as meson exchange currents. Except for the PWIA cross section, in the calculations shown in Fig. 2 contributions to the cross sections due to relativistic corrections to the current operator have not been included.

At missing momenta above 500 MeV/c, we indeed observe a strong enhancement of the measured cross section as compared to the simple PWIA calculation. From Fig. 3, we see that a calculation by Arenhövel which also includes relativistic corrections shows a similar structure if isobar currents are included. Although the location and magnitude of the calculated structure does not fully agree with the experimental finding, the gross features are reproduced.

In Fig. 4, the measured cross sections are compared to a calculation performed by Schiavilla [15,17]. In this calculation the Argonne V_{18} potential has been used. In the lower curve only FSI has been taken into account, while in the upper one MEC as well as IC have been included. The calculation with FSI (lower curve) agrees within a few percent with Arenhövel's one, and also agrees very well with the data up to missing momenta of 400 MeV/c. At larger p_m, however, the calculated cross sections falls below the experimental data. This deficiency of the calculation at high missing momenta is likely to be due to the lack of a dynamic treatment of isobar currents.

In summary, we have measured the D(e,e′p)n cross section over a wide range of missing momenta. At recoil momenta below 350 MeV/c, the measured cross sections are well reproduced by calculations. At missing momenta above 350 MeV/c, the agreement between theory and experiment worsens continuously. At high missing momenta the general features of the experimental cross sections can only roughly be reproduced by a calculation including a dynamical excitation of the Δ resonance.

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