Evidence for Nonnucleonic Effects in the Threshold Electrodisintegration of the Deuteron at High Momentum Transfer

S. Auffret, J.-M. Cavedon, J.-C. Clemens,[a] B. Frois, D. Goutte, M. Huet, F. P. Juster, P. Leconte, J. Martino, Y. Mizuno,[b] X. H. Phan, and S. Platchkov
Service de Physique Nucléaire à Haute Energie, Centre d'Etudes Nucléaires Saclay, F-91191 Gif-sur-Yvette, France

and

I. Sick
Department of Physics, University of Basel, Basel, Switzerland

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Deuteron electrodisintegration at threshold has been measured between $Q^2=7$ and 28 fm^{-2}. Nonnucleonic degrees of freedom are essential for the interpretation of the data. In particular, beyond 20 fm^{-2} the data provide evidence for processes beyond the conventional one-pion exchange.

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Electrodisintegration of the deuteron at threshold provides some of the most striking evidence for the presence of meson-exchange currents in nuclei.[1] The impulse-approximation part of the cross section is characterized by destructive interference between the $^3S_1$-$^1S_0$ and $^3D_1$-$^1S_0$ transitions, resulting in a deep minimum at momentum transfer $Q^2=12$ fm^{-2}. Around this value of the momentum transfer, meson-exchange currents account[2] for nearly 100% of the experimental cross section. Previous measurements[3] were carried out up to $Q^2=18$ fm^{-2}. While these data show that we do understand isovector meson-exchange currents at low momentum transfer, some discrepancies between theory and experiment appear for the highest transfers. Differences between the various theoretical predictions there become significant as well. In particular, the contributions of the shorter-range ρ exchange and the off-shell πNN form factor strongly modify the cross sections. It was not possible to isolate the contribution of these processes with the data available up to now. The extension of the measurements beyond $Q^2=18$ fm^{-2} presents a unique opportunity to investigate this short-range behavior of the meson-exchange currents. The results of such an investigation, extending the range of momentum transfer to $Q^2=28$ fm^{-2}, are reported in the present Letter.

The measurements were performed at the Saclay linear electron accelerator in the HE1 experimental hall.[4] A liquid-deuterium target was used. Data were taken at thirteen incident energies from 300 to 700 MeV and at a scattering angle of 155°. A final resolution of 1 MeV was achieved by performing an on-line reconstruction of the scattered electron trajectories. Details on the experimental procedure can be found in Auffret *et al.*[5]

Because of the thick target and the large recoil energy of the deuteron, a thorough study of the unfolding of radiative effects was carried out. We followed Mo and Tasi[6] for the Schwinger correction and kinematical recoil effects. The hadron bremsstrahlung was included according to Ref. 6 and Miller.[7] Special care was taken in the computation of the Landau straggling corrections, which are quite large in the vicinity of the elastic peak. The corrections before and after scattering were calculated separately in order to avoid uncertainties due to the significant difference between incident and scattered electron energies. Recoil energy loss was also considered when the external-bremsstrahlung corrections were computed. All of these effects were folded[8] in order to perform the radiative unfolding channel by channel. For the elastic peak, the cross section determined via the unfolding procedure was found to agree to within 1% with the cross section obtained via direct radiative correction to the integrated cross section. An experimental spectrum is shown in Fig. 1.

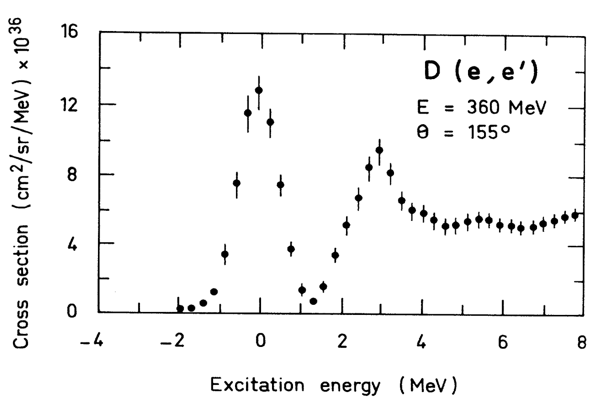

FIG. 1. Experimental spectrum for *e*-D scattering at 360 MeV and 155°, unfolded for radiative effects.

TABLE I. Experimental data for the electrodisintegration of the deuteron at threshold at a scattering angle of 155°. The results are laboratory cross sections averaged over a region of energy loss extending from threshold to a relative c.m. energy in the *n-p* system of 3 MeV.

Incident energy (MeV)	Q^2 (fm^{-2})	Average cross section (mb/sr·MeV)	Errors Stat. (%)	Errors Total (%)
300.0	6.63	3.67×10^{-8}	2.9	6.4
330.0	7.85	1.92×10^{-8}	2.5	6.2
360.0	9.15	1.02×10^{-8}	2.8	6.3
395.0	10.75	4.39×10^{-9}	4.3	7.1
430.0	12.44	2.02×10^{-9}	5.4	7.8
470.0	14.47	6.66×10^{-10}	5.9	8.2
500.0	16.06	2.92×10^{-10}	5.8	8.1
535.0	17.97	1.63×10^{-10}	7.2	9.2
570.0	19.96	6.47×10^{-11}	8.2	10.0
600.0	21.70	2.53×10^{-11}	12.9	14.1
635.0	23.80	1.15×10^{-11}	16.7	17.6
670.0	25.94	7.72×10^{-12}	24.7	25.3
700.0	27.82	3.88×10^{-12}	27.7	28.3

The cross sections were corrected for dead-time losses and for detector efficiency. Measurements at forward angles and low momentum transfer were performed to determine the absolute normalization by a comparison with existing data on the deuteron structure function $A(Q^2)$.[9] The final electrodisintegration cross sections, averaged over the region $E_{np}=0$ to 3 MeV in the *n-p* center-of-mass system, are listed in Table I. The total error includes both statistical error and an overall normalization uncertainty of 5.5%. Our new measurements improve the accuracy of the data between 10 and 18 fm^{-2} and extend the range of momentum transfer to 28 fm^{-2}. The falloff with Q^2 is exponential, apart from the two last experimental points, which seem to indicate an onset of a flattening of the cross section beyond 24 fm^{-2}. Good agreement is found with previous measurements.[3]

Figure 2 shows our data together with the theoretical prediction of Mathiot.[10] (These cross sections refer to $E_{np}=1.5$ MeV, which is approximately equal to the average cross section integrated between 0 and 3 MeV.) In this calculation the dominant $M1$ isovector transition is computed with use of the Paris potential. The contributions of the π- and ρ-meson exchange and the Δ isobar are included. The impulse-approximation result differs drastically from the data over the entire range of momentum transfer. The inclusion of pion-exchange currents alone leads to an interference minimum near $Q^2=25$ fm^{-2}; in this region short-range processes such as the ρ-meson exchange are needed to bring the theory into agreement with the data. Such processes have a typical range of 0.3 fm.

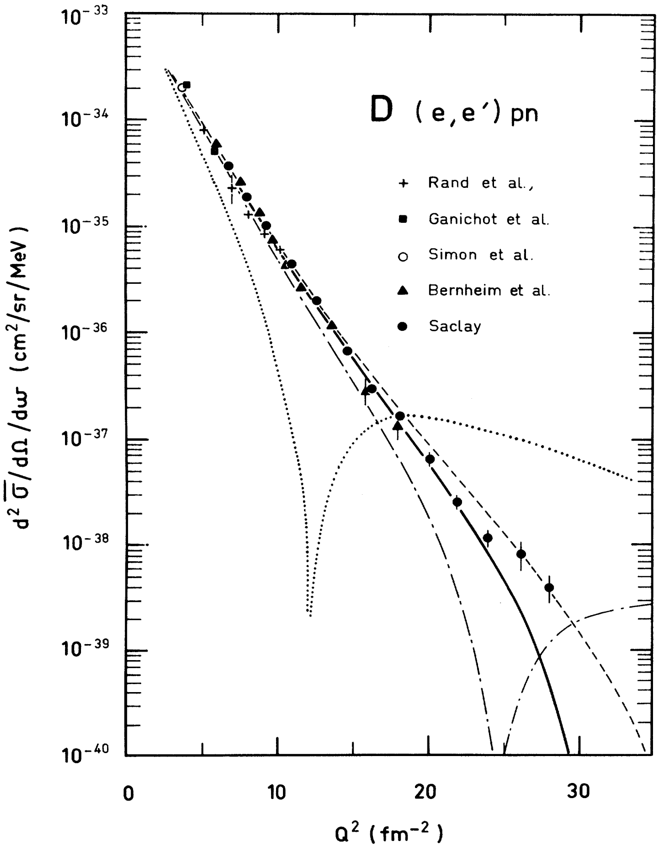

FIG. 2. Experimental cross sections from Ref. 3 and the present experiment. (The data of Rand *et al.* correspond to a different E_{np} and thus do not exactly match the present definition of $d^2\sigma/dQ\,d\omega$.) The dotted curve is the impulse-approximation result, the dash-dotted curve includes the pion-exchange contribution, and the dashed curve includes in addition the ρ-exchange contribution. The solid curve is the total result, in which the Δ-isobar contribution is also taken into account.

However, π- and ρ-meson exchange alone leads to theoretical predictions that are too large. A good agreement with our data is obtained only for the full calculation, in which the contribution of the isobar currents is also included (Fig. 2).

Brown and Rho[11] had noticed for the previously existing data that the ρ-meson exchange and the isobaric current tend to cancel the effect of the finite size of the pion. With our new data, the same observation is true up to $Q^2=28$ fm^{-2}. Although the full calculation of Mathiot is in better agreement with the experiment, it is intriguing that pointlike pion-exchange currents in addition to nucleonic contributions are still almost sufficient to describe the experimental data.

The experimental cross sections are compared with recent theoretical predictions[10,12,13] in Fig. 3. Leidemann and Arenhövel[12] have performed the most com-

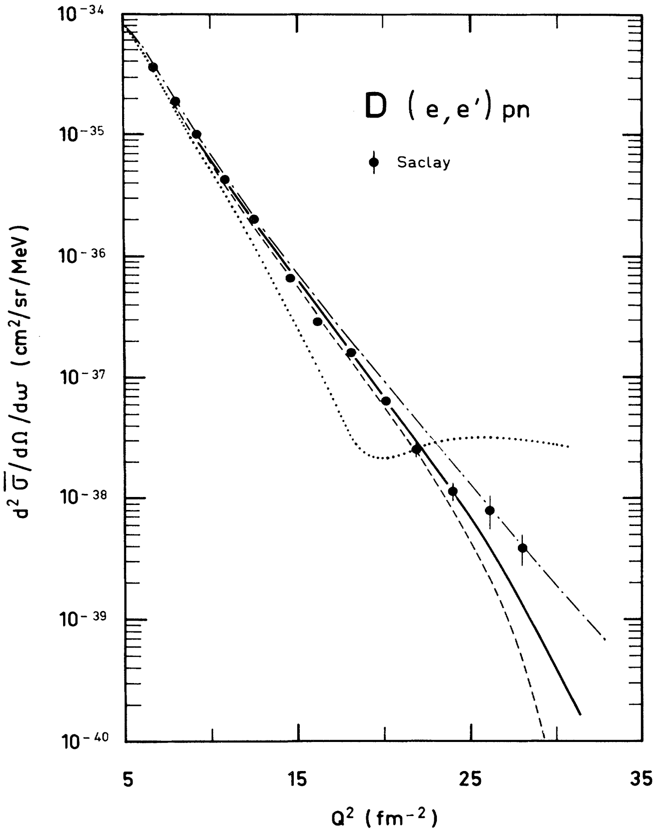

FIG. 3. Theoretical predictions of Mathiot (dashed), Riska (solid), and Leidemann and Arenhövel (dash-dotted), all calculated with F_1. The dotted curve of Leidemann and Arenhövel is calculated with G_E.

plete calculation (dotted curve); in addition to meson-exchange currents they calculate the isobar currents by including isobar components directly in the deuteron wave function. To be directly comparable to the data, the cross sections have been averaged between $E_{np} = 0$ and 3 MeV, and transition multipolarities up to $\lambda = 4$ have been included. This calculation is in satisfactory agreement with the experiment up to $Q^2 = 15$ fm^{-2}, but very large discrepancies appear in the region of our new data. The origin of this disagreement is related to the choice of the Sachs nucleon isovector form factor G_E in the expression for the meson-exchange-current operator. The same calculation performed with the Dirac F_1 form factor is in close agreement with the experimental data (Fig. 3, dash-dotted curve). A gauge-invariant choice of the isovector form factor to be used can only be obtained in a fully relativistic calculation. Different arguments for use of either F_1 or G_E have been given.[14] Adam and Truhlik[15] have recently concluded that the choice of F_1 follows from a consistent reduction of the relativistic continuity equation.

The comparison between these calculations and the data raises a fundamental problem: The internal structure of the nucleons and mesons plays a significant role at the spatial scale that our experiment was able to probe. This is usually accounted for by use of phenomenological form factors for the πNN and ρNN vertices. In the calculation of Mathiot, for example, the monopole cutoff mass Λ_π was adjusted in order to reproduce the data up to 18 fm^{-2}. The value found ($\Lambda_\pi = 1.25$ GeV) implies[10] a radius $r_0 = 0.5$ fm for the interaction region. Use of $\Lambda_\pi = 0.85$ GeV for the calculation of the electrodisintegration cross sections[11] leads to a much smaller π-exchange contribution (factor 0.5 at $Q^2 = 25$ fm^{-2}); the cross-section minimum is thus displaced from $Q^2 = 25$ fm^{-2} to $Q^2 = 19$ fm^{-2}. With the ρ-exchange and the intermediate Δ-isobar contributions being highly suppressed as well, the total result is in strong disagreement with the present data.

In order to achieve a consistency between the one- and two-body current operators, a new approach has been recently developed.[13,16] In this approach the 0^- (pionlike) and 1^- (rholike) exchange-current operators are directly derived from the nucleon-nucleon (NN) potential. As a result, an *ad hoc* choice for the vertex form factors is no longer necessary. The πNN and ρNN cutoff masses are thus implicitly included in the parametrization of the NN potential that is determined directly from nucleon-nucleon scattering data. The calculation of Riska,[13] which uses the Paris potential to construct the two-body operators, essentially agrees with the data as shown in Fig. 3.

However, the interpretation of the electrodisintegration of the deuteron at such high momentum transfer depends strongly on theoretical hypotheses which do not rely on a fundamental theory. Furthermore, mesonic degrees of freedom may no longer be the basic ones. With the spatial resolution achieved now by experiment, the internal structure of nucleons, due to quark degrees of freedom, might play a role. At present there are only a few theoretical attempts using what might be too simple approximations to provide yet reliable answers. Kisslinger,[17] for example, has proposed a hybrid model for the deuteron in which the spatial region inside a boundary radius $R_c = 0.8$ fm is described by a six-quark configuration with 5% probability. Outside the boundary radius the standard two-nucleon component is used. Yamauchi, Yamamoto, and Wakamatsu[18] divide the spatial region in a similar way around $R_c = 0.63$ fm; they incorporate the quark degrees of freedom using the resonating-group method. Their model accounts well for the $^1S_0$ and $^3S_1$-$^3D_1$ phase shifts, and for the static deuteron properties. Both calculations are in reasonable agreement with the data up to large Q^2, but they should be considered as exploratory investigations.

In conclusion, the threshold D$(e,e')pn$ reaction for $Q^2 > 20$ fm^{-2} provides evidence for processes having a shorter range than that of the conventional one-pion exchange current. These new measurements yield unique information on the role of the πNN off-shell vertex form factor and ρ-meson exchange contribution to the NN force. The size of the interaction radius found by our experiment, via the hadronic form factor, is 0.5 fm. Although the data extend to $Q^2=28$ fm^{-2}, the diffraction minimum has still not been observed. Its observation would be a crucial test of our theoretical understanding of the very short-range behavior of the NN force and of the importance of quark degrees of freedom in nuclei.

The most surprising result of this experiment is that there is not yet any evidence of a breakdown of mesonic theory, even at such high momentum transfers beyond its expected limit of validity.

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[(a)]Present address: Société Numélec, F-78320 Le Mesnil St.-Denis, France.

[(b)]Present address: EP Division, CERN, Geneva, Switzerland.

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