Electron-Induced Deuteron Disintegration at Threshold

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Electroexcitation of the singlet S state of the deuteron has been measured for the range of momentum transfer $q^2 = 6$–$19\ \text{fm}^{-2}$, where meson-exchange current contributions dominate the cross section.

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For a quantitative description of nuclei, the understanding of exchange currents is of considerable importance. The nonnucleonic degrees of freedom of nuclei become prominent in particular in the interaction of nuclei with intermediate energy probes and at large momentum transfer. For a detailed study of meson-exchange currents (MEC), simple systems like the deuteron, and a simple reaction mechanism as occurs in electron scattering, are especially favorable. Here, the impulse-approximation (IA) contribution can be calculated with good confidence, and the MEC contribution isolated. As a consequence, deuteron properties measured via n-p capture, elastic form factors, and quasielastic electron scattering have received extensive attention.

Electrodisintegration at high momentum transfer and very low electron-energy loss ω is of particular interest.[1-5] As first realized by Hockert *et al.*,[2] the isovector form factor for the $M1$ transition to the (unbound) singlet S state (^1S) of the deuteron shows an exceptional sensitivity to MEC. The IA cross section near momentum transfers $q^2 = 12\ \text{fm}^{-2}$ exhibits a minimum originating from the destructive interference of ^3D-^1S and ^3S-^1S transitions. While at a low q MEC effects are not very prominent, they increase the cross section by a factor of 10 near this minimum. In this region of momentum transfer, and at an electron energy loss of less than 3 MeV above threshold, the contributions of MEC can be isolated experimentally in a particularly unambiguous way.

Available experimental data[6-8] mainly concern the low-q region. In particular, Simon *et al.*[8] give accurate data for $q^2 < 4\ \text{fm}^{-2}$. Higher-q data ($q^2 < 10\ \text{fm}^{-2}$) have been obtained in connection with an elastic electron-scattering experiment by Rand *et al.*[6] These data are given for an energy loss of 4–6 MeV above disintegration threshold, where the sensitivity to MEC is reduced as compared with the ^1S peak. In this Letter, we present an experiment on the excitation of the ^1S transition in the deuteron; the range of momentum transfer, 6–19 fm^{-2}, covers the full region of the impulse-approximation minimum where the sensitivity to meson-exchange current contributions is highest.

The experiment was performed using the Saclay ALS accelerator and the HE1 endstation.[9] Electrons of 280 to 535 MeV (the maximum energy available) with an energy spread of < 0.5 MeV were incident on a liquid deuterium target. This target could be replaced by a viewer and an iron target, allowing us to measure the contribution of the 14-mg/cm^2 stainless-steel windows. The electron-beam current was integrated with use of a Faraday cup. The cylindrical target was part of a loop filled with D_2 and cooled by liquid hydrogen. With a beam spot defocused to $2 \times 4\ \text{mm}^2$, electron-beam intensities of up to 25 μA could be used. The decrease of target density ($< 12\%$) was monitored by the target temperature and measured by determining the current dependence of the elastic cross section at forward angles. A correction of ~5% to the spectrometer solid angle was required for the extended target (1.40 cm diameter) used. This correction was determined by measuring the spectrometer acceptance with use of a thin target displaced along the beam.

Electrons scattered by 155° were energy analyzed with use of the 900-MeV/c spectrometer. The scattered electrons were detected with use of the standard focal-plane detector, consisting of two multiwire proportional chambers (MWPC), two sets of plastic scintillators, and a lucite Čerenkov counter. The relative efficiencies of individual wires of the MWPC were determined by measuring the flat part of the iron quasielastic spectrum. The overall absolute efficiency was taken from the comparison of previous measurements of ^{12}C elastic scattering and the ^{12}C cross sections.[10] Periodic checks of the apparatus were performed by measuring the deuterium elastic cross section at 45° scattering angle. The results were found to agree with the values given in the literature.[11] The overall systematic uncertainty of the cross sections is estimated to be ±7%. The data cover the region of excitation energy in the n-p system up to $E_{np}=20$ MeV and were unfolded for the radiative effects.

Two examples of the resulting spectra are shown in Fig. 1. The spectrum at 280 MeV ($q^2=6$ fm^{-2}) clearly shows the elastic peak, the peak due to the transition to the ^1S state, and the tail of the quasielastic peak. The spectrum at 410-MeV incident electron energy ($q^2=11.6$ fm^{-2}) covers the region where, at $E_{np}<3$ MeV, 90% of the cross section is due to MEC.

The cross sections as a function of four-momentum transfer q^2 are given in Table I and Fig. 2. The sensitivity to MEC being largest for the singlet-S state, we give the (normalized) integral of the cross section from threshold ($E_{np}=0$) to 3 MeV above threshold. This region includes the full ^1S peak (see Fig. 1) and allows a comparison between experiment and theory independent of finite experimental energy resolution. The cross sections given in Fig. 2 essentially measure the transverse response function; according to the calculation of Sommer,[5] the longitudinal contribution at 155° varies between 2% and 3% in the q^2 range 4–20 fm^{-2}. In Fig. 2 we also show points obtained from previous experiments.[6-8] The comparison with the data of Rand *et al.*[6] is of a qualitative nature only; these data refer to a different n-p relative energy (4 to 6 MeV) and include estimated radiative corrections only.

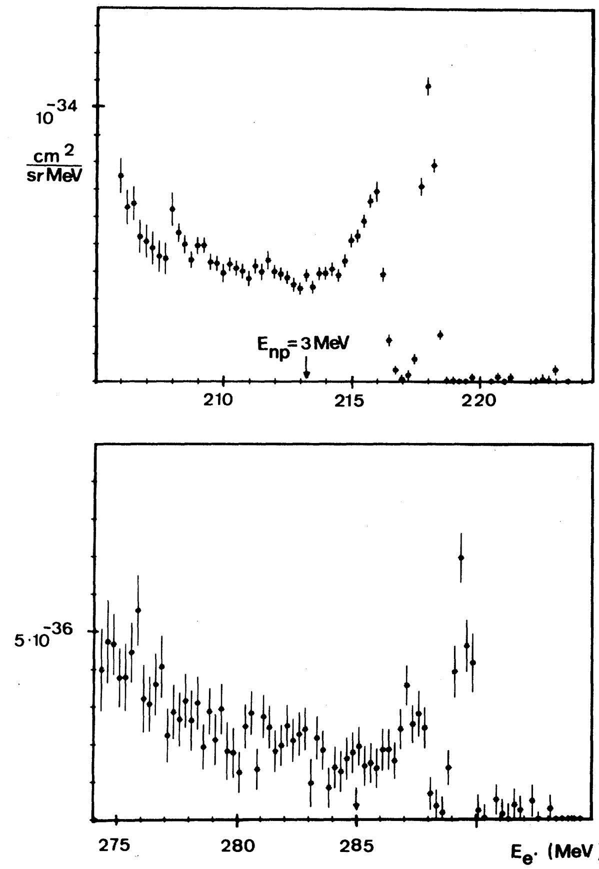

FIG. 1. Cross sections (in cm^2/sr MeV) for e-d scattering at $\theta=155°$ and electron energies of 280 and 410 MeV ($q^2=5.9$ and 11.5 fm^{-2}).

A number of theoretical calculations for the meson-exchange current contribution to the electrodisintegration of the deuteron have been published. The calculations of Hockert *et al.*[2] and of Lock and Foldy[3] include the contributions of the pionic current, pair, and Δ-excitation diagrams (for the definition of the various diagrams see, e.g., Ref. 5). For $E_{np}=3$ MeV and medium q^2 both the calculation of Hockert and the prediction of Lock for pseudoscalar π-N coupling agree quite well with our data. The more recent calculations by Fabian and Arenhövel[4] and by Sommer[5] include several additional features: treatment of final-state angular-momentum components with $l\geq2$, inclusion of πNN vertex form factors, effect of the Δ isobar component in the deuteron ground-state wave function, and the contribution of the ρ-exchange diagrams. At high q^2, these additional contributions have a large, though partly compensatory, influence on the cross section (see Ref. 5).

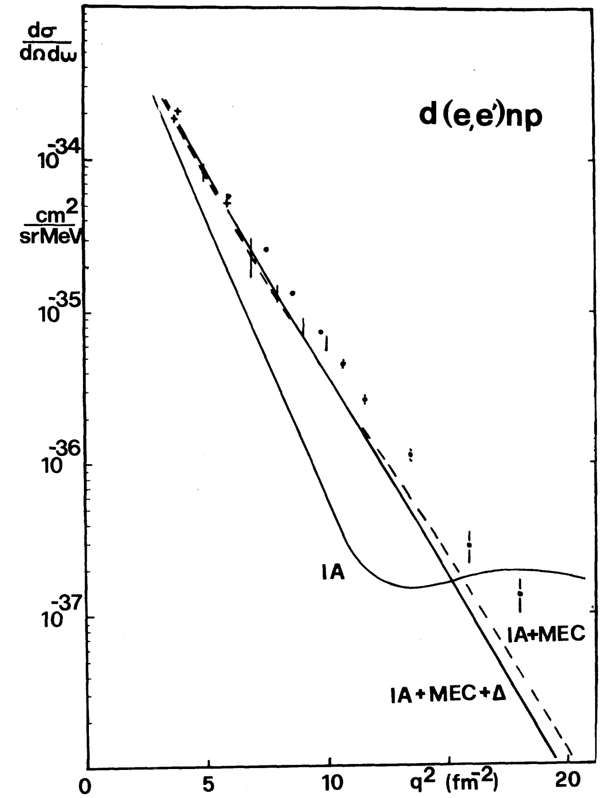

FIG. 2. Cross sections for 0–3 MeV above threshold and $\theta = 155°$. Crosses are from Refs. 7 and 8. The comparison with the bars (Ref. 6) is qualitative only (see text). The predicted curves of Fabian and Arenhövel are labeled according to the diagrams included: impulse approximation (IA), pionic current and pair (π), ρ exchange (ρ), total MEC (MEC), and ground-state isobar component (Δ).

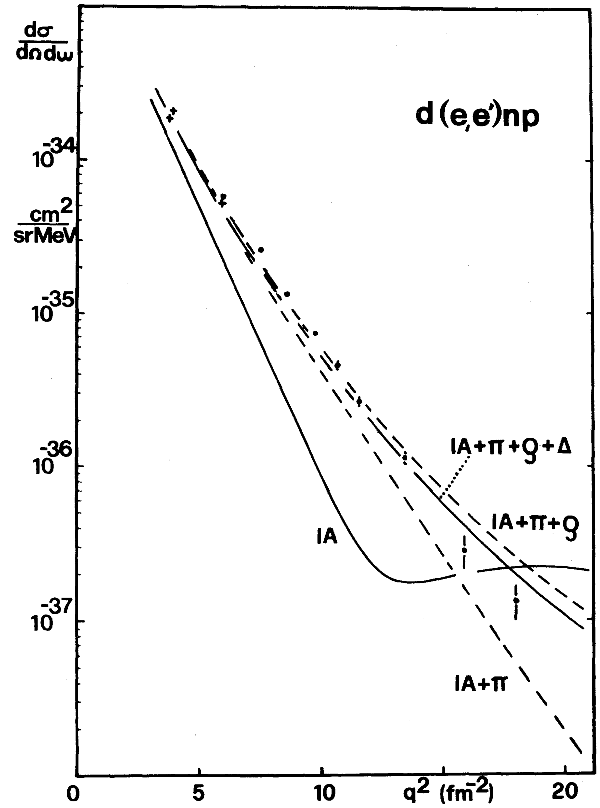

FIG. 3. Same as for Fig. 2. The curves have been calculated by Sommer (Ref. 5).

The calculations of Fabian and Arenhövel are shown in Fig. 2. The impulse-approximation cross section, calculated by using the Reid soft-core nucleon-nucleon interaction, exhibits a minimum at $q^2 \simeq 12\ \mathrm{fm}^{-2}$, and a maximum at $q^2 \simeq 20\ \mathrm{fm}^{-2}$. Both of these features are eliminated by the meson-exchange current contributions. The bulk of the MEC is due to the pair and pionic current diagrams; the effect of the Δ isobar component is comparatively minor in the threshold region. The calculation of Sommer[5] is displayed in Fig. 3. This calculation shows, in addition, that the contribution of the $\rho\pi\gamma$ diagram is quite small,[5] while the ρ exchange is important to bring the calculated values up to the experimentally observed ones (Fig. 3). The calculations of Fabian and Arenhövel yield cross sections too low at large q, while the cross sections of Sommer are somewhat too large.[12] Overall, both calculations of meson-exchange current contributions account quite well for the new experimental results at large momentum transfer.

TABLE I. Inelastic cross sections for $d(e,e')$ at $\theta = 155°$ averaged over threshold region (E_{np} = 0–3 MeV) as a function of electron energy E_0.

E_0 (MeV)	$q_4{}^2$ (fm^{-2})	$d\sigma/d\Omega_e d\omega_{\mathrm{lab}}$ (cm^2/sr MeV)
280	5.89	$(0.602 \pm 0.008) \times 10^{-34}$
320	7.47	$(0.266 \pm 0.007) \times 10^{-34}$
350	8.74	$(0.136 \pm 0.004) \times 10^{-34}$
370	9.63	$(0.751 \pm 0.030) \times 10^{-35}$
390	10.55	$(0.445 \pm 0.030) \times 10^{-35}$
410	11.50	$(0.261 \pm 0.020) \times 10^{-35}$
450	13.47	$(0.115 \pm 0.009) \times 10^{-35}$
495	15.82	$(0.286 \pm 0.072) \times 10^{-36}$
535	18.00	$(0.134 \pm 0.037) \times 10^{-36}$

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[12]The difference between the IA results of Refs. 4 and 5 is presently not understood.

Multiplicity of the Statistical γ Rays following (^{16}O,xn) Reactions

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The multiplicity $\bar{M}_S$ of the statistical γ rays following several (^{16}O,xn) reactions has been measured. A correlation between the total γ multiplicity $\bar{M}_T$ and $\bar{M}_S$ was found. This effect is attributed to an increase in the mean excitation energy above the yrast line with increasing angular momentum input.

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In recent years there has been considerable interest in the study of continuum γ rays following heavy-ion reactions. The continuum spectrum consists of statistical γ rays carrying little angular momentum, and the yrast cascade, a prominent bump for $E_\gamma \lesssim 1.5$ MeV arising from mainly stretched γ rays which carry off most of the angular momentum. In deformed nuclei the yrast cascade is normally composed of strongly enhanced $E2$ transitions[1] within rotational bands roughly parallel to the yrast line.

Our knowledge about statistical γ rays is currently minimal. The exponential shape of the statistical spectrum for $E_\gamma \gtrsim 1.5$ MeV is easily recognized, but not well fitted by any calculation. However, below this energy the shape is generally obscured by the yrast cascade and the discrete γ rays. Trautmann *et al.*[2] showed, for reactions with low input angular momentum, that the average multiplicity $\bar{M}_S$ of the statistical γ rays did vary with bombarding energy. However, in recent years it has been generally assumed that for higher angular momentum reactions $\bar{M}_S$ is approximately constant[3,4] with a value of ~4. Our present measurements with ^{16}O-induced reactions on a number of nuclei are at variance with this conclusion.

The reactions studied were ^{110}Pd(^{16}O,$4n$)^{122}Xe and ^{122}Sn(^{16}O,$4n$)^{134}Ce at 65 and 83 MeV, and ^{149}Sm(^{16}O,$3n$)^{162}Yb, ^{150}Sm(^{16}O,$4n$)^{162}Yb, and ^{154}Sm(^{16}O,$4n$)^{166}Yb at 73 and 85 MeV. We also made measurements on the reaction ^{166}Er(α,$2n$)^{168}Yb at 21, 27, and 36 MeV. Here the angular momentum input is low and consequently the yrast cascade has low intensity and low E_γ. The beams were provided by the Australian National University 14UD Pelletron. The continuum γ rays were detected in a 7.6-cm×7.6-cm NaI (Tl) detector at 40 cm from the target, in coincidence with γ rays detected in a 50-cm^3 Ge(Li) detector set at 8.5 cm and at 125° to the beam. The discrete spectrum was measured with a second 50-cm^3 Ge(Li) at 10.5 cm, set alternately with the NaI at 90° and at 0° [32° for the (α,$2n$) experi-