ELECTRON SCATTERING FROM THE DEUTERON AT $\theta = 180°$[*]

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We have measured cross sections for elastic and inelastic electron scattering from the deuteron at a scattering angle of 180° and incident electron energies up to 370 MeV. Our elastic scattering results are in agreement with those of Buchanan and Yearian[1] showing disagreement with simple impulse-approximation theory, and for the first time we demonstrate a similar effect in the inelastic scattering. At a scattering angle of 180°, the inelastic cross section near threshold is dominated by the $M1$ transition from the ground state to the virtual ^1S state of the deuteron. Our experimental values of the inelastic cross section near threshold are appreciably larger, at high electron energies, than the values derived from impulse-approximation theory.[2,3]

The apparatus used was essentially similar to that described previously by Rand.[4] The liquid-deuterium target was about 1 cm thick and was confined by 0.001-in. aluminum-alloy foils. Electrons from the Stanford Mark-III linear accelerator were passed through a circular deflecting magnet and through the target. Electrons scattered at 180° traversed the deflecting magnet a second time, bending away from the incident beam, and entered the Mark-III double-focusing 180° spectrometer. There they were detected by an array of scintillators in a ladder configuration. The momentum acceptance of the spectrometer was 4 % and the over-all momentum resolution was approximately 0.4 %. The incident beam was integrated by a secondary emission monitor which was calibrated frequently by passing the beam into a Faraday cup.[4]

Table I. Systematic errors.

Quantity	Error (%)
Target density	4
Target thickness	<1
Beam-monitor efficiency	3
Incident-energy calibration	1
Normalization statistics	2
Proton cross section	3
Rms total	6.3

Background scattering was measured with an empty target. At the highest energy used, as many as 50 % of the counts at the top of the elastic peak of the scattered-electron spectrum were background events. To determine the absolute efficiency of the counting system we measured the elastic scattering from a liquid-hydrogen target and used the best-fit proton form factors given by Hughes et al.[5] Estimated systematic errors, totaling 6.3 %, are listed in Table I.

The spectrum of electrons scattered from deuterium at an incident energy of 325 MeV is shown in Fig. 1. Background events have been subtracted. The elastic peak is seen at an electron momentum of 241.3 MeV/c along with the peak due to the excitation of the virtual ^1S state at 239 MeV/c. The results of a preliminary analysis are also indicated.

The theoretical elastic cross section was calculated[1] from impulse-approximation theory using the Partovi model of the deuteron[6] with 7% D state. No meson-exchange diagrams were included. The elastic peak was predicted from the theoretical cross section by folding a δ function at the proper electron momentum with the momentum resolution function cal-

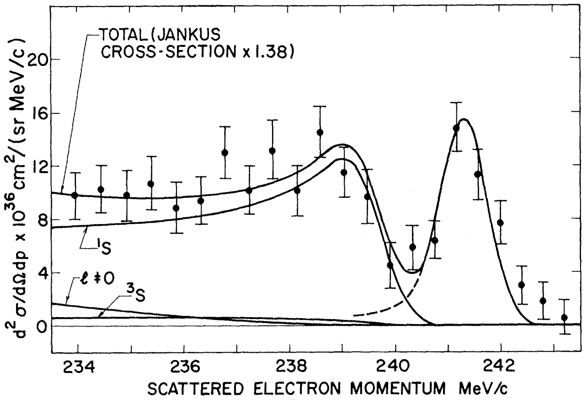

FIG. 1. Differential cross section for 325-MeV electrons scattered at 180° from the deuteron. The modified Jankus (see text) calculations for the separate ^1S, ^3S, and $l > 0$ final states are shown with experimental resolution and radiation effects folded in. These cross sections and the folded elastic peak are normalized to the data.

culated from the experimental parameters, and then with the radiative-tail-shape function determined using the method described by Tsai.[7] Both Schwinger radiation and bremsstrahlung effects[8] were taken into account.

The inelastic spectrum was predicted using the nonrelativistic impulse-approximation theory of Jankus[2] with the following three modifications:

(1) For the electron energies of our experiment, Jankus's calculation led to substantially incorrect values of the inelastic threshold momentum. We found, however, that by replacing in Jankus's formalism the absolute value of the three-momentum transfer by that of the four-momentum transfer, we obtained very accurate threshold momenta. The corresponding change of the height of the theoretical spectrum, as a function of $(p_T - p)$, where p is the scattered electron momentum and p_T the threshold momentum, was typically about 3% and not significant for our purposes.

(2) The cross sections were multiplied by the square of the magnetic isovector nucleon form factor $G_{MV}(q^2)$ obtained from the three-pole fit given by Hughes et al.[5] q^2 is the four-momentum transfer at the momentum of the scattered electron. The form factor was normalized to unity at $q^2 = 0$. While the introduction of the nucleon form factor has a sizable effect on the calculation at the energies of our experiment, the choice of the particular algebraic fit is not critical; replacement of the fit of Hughes et al.[5] by that of Chan et al.[9] would change the cross section by only 7% at the highest q^2 of our experiment.

(3) The wave functions used by Jankus[2] were modified to allow for the presence of a hard core in the ^3S ground state and in the excited state of the deuteron. The wave functions derived from the Eckart potential were modified as outlined in Jankus's thesis.[10] The S-wave functions vanish at the hard-core radius r_0 instead of $r = 0$ and become analytic functions of $r - r_0$ instead of r. The two free parameters are refitted, in the case of ^1S to the effective range and scattering length and in case of ^3S to binding energy and scattering length. In all cases a value of 0.42 F was assumed for r_0.

As in the elastic case, the total theoretical spectrum was corrected for the experimental momentum resolution and for radiative effects.[7,8] This procedure had the effect of broadening the ^1S final-state peak and of reducing the height of the spectrum by a small amount, typically ~10%. The inelastic and the elastic spectrum were then each multiplied by variable factors until a best fit of the total spectrum to the experimental points was obtained. In the case shown in Fig. 1, the best fit was obtained by multiplying the inelastic spectrum by 1.38 and the elastic peak by 2.68. The corresponding factors for all our data are shown in Fig. 2. In this figure, q^2 is the four-momentum transfer squared for elastic scattering. The error bars were obtained by changing the respective factor until χ^2 was higher by 1.0 than the best value. A summary of our experimental results is given in Table II. For the first spectrum taken, at $q^2 = 7.0\ \mathrm{F}^{-2}$, the absolute efficiency of the counting system was not determined. We therefore used the elastic magnetic deuteron form factor measured by Buchanan[11] to normalize the cross section.

The points due to earlier inelastic scatter-

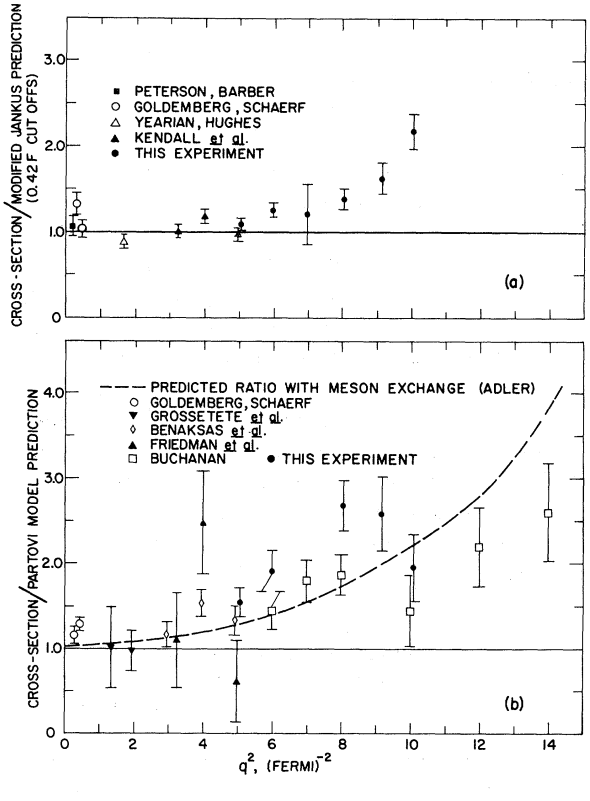

FIG 2. (a) Inelastic (mainly $M1$) e-D experimental cross section normalized to the modified Jankus theory (see text) using 0.42-F hard cores in initial and final states. (b) Magnetic elastic e-D experimental cross sections normalized to the Partovi-model predictions. Also shown is the calculation of Adler and Drell including the $\rho\pi$ exchange current.

Table II. Results of e-D scattering at 180°. E_0 is the incident electron energy; q^2 is the square of the four-momentum transfer to the deuteron for elastic scattering; σ/σ_J is the ratio of inelastic cross section to that predicted by modified Jankus theory near threshold, where the ${}^1S$ state dominates (see text); $d\sigma_J/dp$ is the differential inelastic cross section at $p=0.98p_{\text{threshold}}$ (i.e., at a flat part of the spectrum) as predicted from modified Jankus theory; σ_{el} is the experimental e-D elastic cross section.

E_0 (MeV)	q^2 (F^{-2})	σ/σ_J	$d\sigma_J/dp$ [10^{-36} cm^2 sr^{-1} (MeV/c)$^{-1}$]	σ_{el} (10^{-36} cm^2/sr)
250	5.07	1.08 ± 0.07	50.4	83 ± 9
275	6.01	1.25 ± 0.08	25.9	56 ± 7
300	7.01	1.20 ± 0.35	13.4	...
325	8.06	1.38 ± 0.12	6.86	24.5 ± 2.6
350	9.17	1.62 ± 0.18	3.49	13.9 ± 2.4
370	10.09	2.17 ± 0.20	2.01	6.9 ± 1.4

ing experiments shown in Fig. 2(a) were calculated using the same portion of the spectrum as in our experiment, i.e., the data at electron momenta $p \geq 0.98p_T$ (p_T is the threshold momentum). The data are those of Peteron and Barber,[12] Goldemberg and Scharf,[13] Yearian and Hughes,[14] and Kendall et al.[15] The latter two experiments were not performed at $\theta = 180°$ but at scattering angles sufficiently large for the ${}^1S$ contribution to be dominant. Elastic magnetic cross sections were measured by Goldemberg and Scharf,[16] Grossetête, Drickey, and Lehmann,[17] Benaksas, Drickey, and Frèrejacque,[18] Friedman, Kendall, and Gram,[19] and Buchanan.[11] The elastic magnetic cross sections divided by the values derived from the Partovi model of the deuteron are plotted in Fig. 2(b). Cross sections from the earlier experiments were not taken from the original papers, but have been reanalyzed by Buchanan[11] taking into account that the proton cross sections, which were used to normalize the deuteron cross sections, are now known more accurately than at the time of these experiments.

It appears from Fig. 2(b) that our points are systematically higher than those of Buchanan. However, as a large part of the error is systematic in both experiments, we do not consider the discrepancy to be significant.

It is evident from Fig. 2 that both the elastic and inelastic magnetic cross sections are considerably larger at high electron energies than the theoretical predictions. The effect in the elastic cross section has been discussed previously.[17] Adler and Drell[20] proposed scattering from meson-exchange currents to explain both the observed elastic magnetic form factor and the discrepancy between the observed magnetic moment of the deuteron and the value calculated from a 7% D-state probability. For elastic e-D scattering the lowest mass state available corresponds to the π-ρ exchange.[20] Adler and Drell have calculated this contribution; the prediction is shown in Fig. 2(b). However, a recent analysis of photoproduction data by Donnachie and Shaw[21] requires that the ρ-π-γ coupling constant be at least an order of magnitude smaller than that assumed by Adler and Drell.

Adler and Littig[3] are recalculating the inelastic cross section using the impulse approximation with relativistic corrections and including the D state in the bound deuteron. Hamada-Johnston[22] wave functions are used for the ${}^3S$ and ${}^3D$ bound states as well as for the ${}^1S$ virtual state. The contributions of meson-exchange diagrams to the cross section are being calculated. The following preliminary conclusions can be drawn from this calculation:

(1) If the cross section were due to a pure ${}^3S$ to ${}^1S$ transition, introduction of relativistic corrections and a better deuteron model would lower the expected cross section by ~25% at the highest energy $E_0 = 370$ MeV.

(2) Including the ${}^3D$ to ${}^1S$ transition lowers the the predicted cross section still further to ~50% of the Jankus prediction with a 0.42-F hard core and increases the discrepancy with experiment.

(3) If the meson-exchange diagram involving the π-π-γ vertex, which is the lowest mass diagram available in this case,[3] is taken into account the predicted cross sections at large energies increase. However, the upper limit of this contribution is only enough to cancel the inclusion of the D state.

(4) The higher mass meson exchange diagrams, i.e., those involving the ω-π-γ vertex, the ρ-η-γ vertex, etc.,[3] are not likely to account for the remaining discrepancy with coupling constants estimated from photoproduction data[21,23] and SU(3) relations.

In conclusion, we have found that similar discrepancies between experiment and impulse-approximation theory occur for both elastic and inelastic $M1$ electron scattering from the deuteron. It appears at present that the introduction of meson-exchange diagrams into the calculation changes the theoretical predictions in the right direction but does not remove the whole deviation. The assumption made in our analysis that the magnetic form factor (normalized to unity at $q^2=0$) of the nucleons bound in the deuteron is the same as that of the free proton is being tested by Budnitz and co-workers at the Cambridge Electron Accelerator in a coincidence experiment on the electrodisintegration of the deuteron.[24] Preliminary results indicate agreement for the proton form factors G_{EP} and G_{MP} but a possible deviation for the neutron form factor G_{MN}. The deviation has the same sign as that observed in our experiment.

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