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Elastic Electron-Deuteron Scattering at High Momentum Transfer*

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We show that a careful conventional treatment of exchange currents in the calculation of the deuteron form factor $[0 \leq q^2 \leq 8\ (\mathrm{GeV}/c)^2]$ is not in contradiction with experiment. It rather shows an overall good agreement. We propose measurements of the deuteron form factor at momentum transfer much higher than $q^2 \cong 100\ \mathrm{fm}^{-2}$ in order to obtain valuable information on the neutron form factor.

Very recently the elastic electron-deuteron scattering cross section has been measured at high momentum transfer with a very surprising result.[1] The comparison with the few available calculations in this momentum range seems to indicate that a conventional meson-exchange treatment of the deuteron form factor (FF) at high momentum q is orders of magnitude off. Obviously the "flattening out" of the deuteron FF as has been predicted[2-4] does not occur, at least not in the region of present experiments. The manifestation of these results would be very surprising as we know that the discrepancies between experiment and impulse approximation in thermal n-p capture[5,6] as well as in electrodisintegration of the deuteron at threshold[7] can be removed completely by inclusion of meson-exchange currents.

Regarding the present theoretical investigations[2,3] the authors of Ref. 1 were led to the conclusion that at high momentum transfer there should be no exchange currents. They pointed out that the present experimental findings could be rather interpreted as evidence of the deuteron being a six-quark bound state.

In the present note we report on our calculations of the deuteron FF which show that such conclusions are premature. It actually turns out that the resolution of the apparent discrepancy of orders of magnitude is a rather simple one. As already noted in Ref. 1 the $\rho\pi\gamma$ coupling is now measured[8] to be about a factor 3 smaller than the one used by Chemtob, Moniz, and Rho.[2] This leads to an overall decrease of the $\rho\pi\gamma$ contribution as compared to that in Ref. 2. Another more crucial point is the neglect of meson-nucleon FF's in all previous works. We realize that the electron transfers a high momentum to the mesons or the nucleon-antinucleon pair (Figs. 1 and 2). From this it is obvious that one has to use momentum-dependent photon-nucleon and photon-meson couplings. This is well known and has also been considered in the standard meson-exchange calculations of the deuteron FF. However, throughout it has been disregarded that the mesons couple with a high momentum to the nucleons too, so one has to consider momentum-

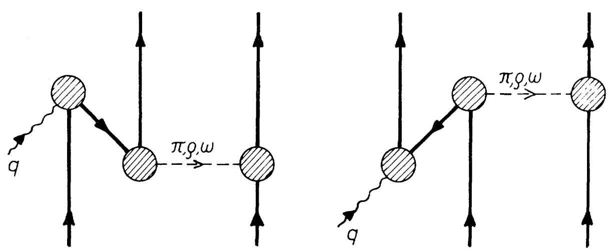

FIG. 1. Nucleon-antinucleon pair contributions to π, ρ, ω exchange effects. The shaded circles indicate the form factors to be included in the calculation.

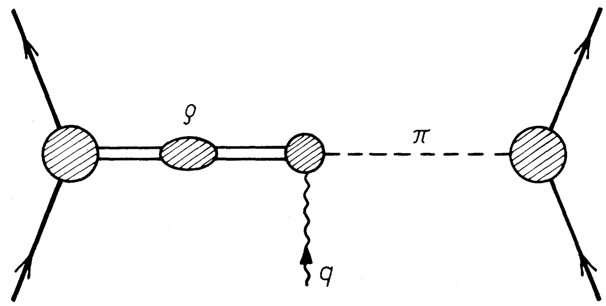

FIG. 2. Diagrammatic representation of the $\rho\pi\gamma$ exchange contributions. The shaded circles indicate the form factors to be included. The finite width of the ρ meson is indicated. The effect of the nonvanishing decay width is given in Fig. 4.

dependent meson-nucleon couplings. The use of form factors for the meson-nucleon vertices as well should decrease the contribution of the exchange currents at high momentum transfer and should forbid a flattening out of the deuteron FF. Another important fact in discussing meson-exchange contributions is related to the choice of the neutron FF since it is not known. There are several possibilities. Moreover in previous calculations the exchange currents have been calculated only partially. While Jackson, Landé, and Riska[9] have taken into account only pion-exchange processes for $q^2 < 35\ \mathrm{fm}^{-2}$, Chemtob, Moniz, and Rho[3] consider only $\rho\pi\gamma$ and $\sigma\omega\gamma$ contributions and Blankenbecler and Gunion[2] only ρ exchange. A complete analysis including all established processes has not been done. In the present note we give our results of a conventional exchange-current calculation for the deuteron FF where we include all established exchange currents (Figs. 1 and 2). The treatment is conventional insofar as we do not consider relativistic effects[10] or baryon-resonance[11] admixtures to the deuteron. In any case it will be interesting to see how well such a treatment compares with experiment.

The main points of our calculation can be summarized as follows: (i) Exchange currents of π, ρ, ω, $\rho\pi\gamma$ (Figs. 1 and 2) are included (finite decay width of ρ meson is also taken into account). (ii) Two types of photon-nucleon FF are used: (a) empirical dipole fit and (b) Iachello, Jackson, and Landé FF.[12] The $\rho\pi\gamma$ vertex FF is taken from Ref. 3 but corrected for the now-measured decay width.[8] (iii) The pion-nucleon FF is taken from Schmit[13] in the monopole form. The ρ and ω meson-nucleon FF's are taken from Ref. 12 in the dipole form. For zero decay width of the ρ meson a simple monopole form is assumed.

In our notation the elastic electron-scattering cross section is given by

$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}}\left[F_E^2(q^2)+\left(1+2\tan\frac{\theta}{2}\right)\frac{q^2}{6M^2}F_M^2(q^2)\right],$$

with

$$F_E^2(q^2)=F_C^2(q^2)+\frac{q^4}{18}F_Q^2(q^2).$$

F_C, F_Q, and F_M denote the charge, quadrupole, and magnetic form factors, respectively. To compare with experiment[1] F_M can be neglected.

Our results for the form factor F_E^2 are given for two ranges of momentum transfer: in Fig. 3 for $0 \le q^2 \le 60\ \mathrm{fm}^{-2}$ and in Fig. 4 for $50\ \mathrm{fm}^{-2} \le q^2 \le 200\ \mathrm{fm}^{-2}$. The results presented in both diagrams are obtained by the use of deuteron wave functions derived from the Reid soft-core potential. We calculated $F_E^2(q^2)$ also for Hamada-Johnston and supersoft-core wave functions. The results are very similar. For high momentum transfer (Fig. 4) we show also the effect of a nonvanishing ρ-meson decay width. We realize that this is a non-negligible effect.

Already at low momentum transfer we realize the limits of the calculations due to the freedom in the choice of the photon-nucleon FF. Although the meson-exchange contributions are almost the same for both photon-nucleon FF's we note that in the momentum range $q^2 \simeq 40-50\ \mathrm{fm}^{-2}$ it is already difficult to disentangle the two effects. The only region where meson-exchange contributions are not masked by the freedom in the choice of the FF's is for $20\ \mathrm{fm}^{-2} \le q^2 \le 40\ \mathrm{fm}^{-2}$. The apparent discrepancy between experiment and theory at $q^2 \sim 20\ \mathrm{fm}^{-2}$ arises probably from the charge FF $|F_C|$ which has a minimum there. Here the baryon-resonance admixtures might be

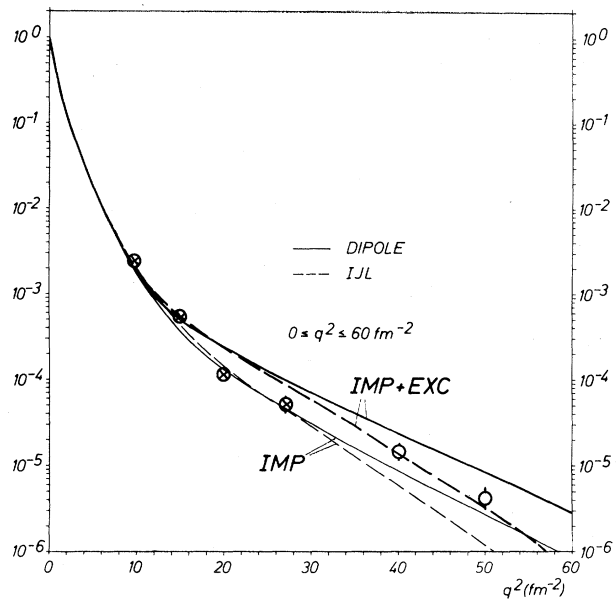

FIG. 3. Electron-deuteron form factor for low momentum transfer. The deuteron is decribed by a Reid soft-core wave function. Curves are given for two types of nucleon form factors: empirical-dipole fit and form-factor fit by Iachello, Jackson, and Landé (IJL). The unmodified impulse approximation gives the curves labeled IMP; inclusion of exchange gives those labeled IMP + EXC. The low-momentum data (crossed circles) are taken from Elias *et al.*, Ref. 14.

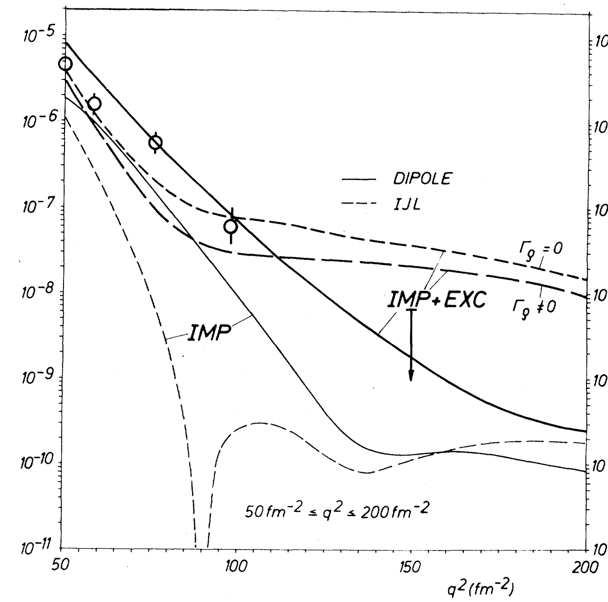

FIG. 4. Electron-deuteron form factor for high momentum transfer. The deuteron is described by a Reid soft-core wave function. Labeling of curves is as in Fig. 3.

important as they will shift the minimum.[11]

For high momentum transfer the situation changes considerably (Fig. 4). Here already the impulse approximations show considerable differences. This is mostly due to the minimum in the FF of Iachello, Jackson, and Landé (IJL). The IJL impulse approximation is in strong disagreement with the present experiment. The empirical dipole fit is very close to the experimental result as noted also in Ref. 1. Looking at the form factor $F_E^2(q^2)$ with exchange-current contributions, we realize that F_E^2 calculated with the IJL form factor is very close to the impulse approximation calculated with the empirical dipole FF. F_E^2 with exchange currents for the empirical dipole FF gives results a bit larger than the one obtained with IJL up to momentum transfer $q^2 \sim 100$ fm^{-2}. It seems to us that this range of momentum transfer is not very promising for obtaining information on the neutron FF since different effects mask each other. The comparison of our results with experimental data shows interesting features. We emphasize that a more realistic treatment of exchange currents is well able to agree with experiment. From the present comparison one would rather expect to obtain some information on the neutron FF at higher momentum transfer. For this purpose we calculated the deuteron FF up to $q^2 = 200$ fm^{-2}. Here we realize a dramatic change in the deuteron FF. A very interesting point, however, is that the total deuteron form factor $F_E^2(q^2)$ is very different for different neutron FF's. In the present case the large difference arises from the fact that the IJL form factor has a minimum at about $q^2 \sim 80$ fm^{-2} while the dipole FF does not. So the IJL form factor changes sign and thus leads to very different results for the total form factor $F_E^2(q^2)$, as compared to the dipole case. This actually results from the fact that not all exchange contributions depend on the isoscalar nucleon FF, so while some contributions add in the IJL case, they subtract in the dipole case. For this reason it seems to us that the range of interest for the deuteron FF is above $q^2 \sim 100$ fm^{-2}. In this region one can hope to obtain valuable information on the neutron FF.

In conclusion we note an overall good agreement of our deuteron FF (including exchange currents) with present experiments.

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Experimental Measurement of $K_L{}^0 \to \mu^+\mu^-$*

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Using a spark-chamber magnet spectrometer and applying very stringent requirements to eliminate background contamination, we find three events of the rare process $K_L{}^0 \to \mu^+\mu^-$ corresponding to a branching ratio relative to $K_L{}^0 \to \pi^+\pi^-$ of $4.2^{+5.1}_{-2.6} \times 10^{-6}$. Using the branching ratio $(K_L{}^0 \to \pi^+\pi^-)/(K_L{}^0 \to \text{all}) = 0.21\%$, we calculate the branching ratio to be $8.8^{+10.7}_{-5.5} \times 10^{-9}$ (90% confidence level) for the $K_L{}^0 \to \mu^+\mu^-$ decay.

The rate for the decay $K_L{}^0 \to \mu^+\mu^-$ has been in question for several years. Since the rate for $K_L{}^0 \to \gamma\gamma$ is known,[1] a straightforward calculation results in a lower bound of 4.3×10^{-9} for the branching ratio for the 2μ process.[2,3] Clark *et al.*[4,5] searched for the 2μ decay and reported[6] at a 90% confidence level an experimental upper bound of 3.3×10^{-9}, significantly below this lower limit. Carithers *et al.*[7,8] found nine events corresponding to a branching ratio of $12^{+8}_{-4} \times 10^{-9}$ in clear disagreement with the first experiment. A third experiment is necessary to resolve this experimental discrepancy

This experiment was performed in a 250-μsr solid angle neutral beam at the Brookhaven National Laboratory alternating-gradient synchrotron (see Fig. 1). The external proton beam ($\sim 10^{11}$ protons/pulse) incident upon an Ir target yielded $\sim 10^4$ $K_L{}^0$ decays per pulse in the decay region. Charged particles and γ rays were removed by a sweeping magnet preceded by 10 radiation lengths of Pb. The spectrometer consisted of 22 spark chamber planes (eight planes had magnetostrictive readout; all others used capacitive readout[9]); a magnet (46 cm$\times$46 cm$\times$183 cm wide gap; field integral 209 MeV/c); and trigger counters (UHL, UHR, and the downstream hodoscope banks). The downstream banks, separated by 173 cm, were used to impose the "picket-fence" requirements (PFR, PFL) that only downstream tracks with projected angles in the x-z plane less than $\pm$ 44 mrad with respect to the beam line be accepted.

To suppress potential neutron-related backgrounds the neutral beam was in vacuum from the sweeping collimator to the downstream end of the decay region and was dumped into a re-entrant cavity downstream of the muon detector. All counters and absorbers were placed outside the beam.

There were two types of triggers: (1) a sixfold coincidence, two-track trigger from which the normalization $K_{\pi\pi}$ events were obtained (2T$\equiv$ UHR $\cdot$ UHL $\cdot$ PFR $\cdot$ PFL), and (2) a tenfold coincidence