ELECTROMAGNETIC FORM FACTORS OF THE DEUTERON

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We have measured electric and magnetic elastic scattering from the deuteron at $q^2 = 3$, 4, and $5F^{-2}$ by observing the momentum-analyzed recoil deuteron. At 45° laboratory angle we have measured the ratio of deuteron and proton scattering cross sections, the errors being significantly smaller in the ratio, and have analyzed the data to determine the electric form factor of the neutron G_{En} using the Hamada deuteron form factor.[1] At 0° we have measured directly the magnetic form factor of the deuteron G_{Md} and have analyzed to determine the value of G_{Mn}.

Experimental methods.—(1) 45° laboratory angle: Energy-analyzed incident electrons from the Orsay linear accelerator were incident on a 0.7-cm liquid target containing either deuterium or hydrogen. After passing through the target, the electrons were monitored in a secondary emission monitor (SEM) which was calibrated against a Faraday cup. Elastically scattered deuterons or protons were momentum analyzed with a double-focusing spectrometer and counted with two thin plastic scintillators in coincidence. The spectrometer had been calibrated in momentum with an accuracy of 0.5% by a floating wire measurement, and the solid angle was defined by slits between the target and the spectrometer. The pulse-height spectra led us to conclude that the counter efficiencies were identical for deuterons and protons and consistent with 100%, the assigned error varying between 1% and 3% depending on the point. Target thickness and liquid deuterium density are assigned a larger error for absolute cross sections than for the ratio.

(2) 0° laboratory angle: The solid angle for measurements at 0° was defined with baffles placed at 45° inside the spectrometer vacuum chamber, and calibrated by the ratio of two measurements made by observing elastic electron-proton scattering, the first measurement using our baffles inside the spectrometer, and the second using a geometrically defined solid angle.

Elastic deuteron peaks were observed at 0°, corresponding to complete magnetic scattering. The electron beam was monitored in a two-foil SEM (3 μ aluminum) placed 0.5 meter before the target, and calibrated to better than 1% by frequent comparison with a Faraday cup. The incident electrons passed into the magnetic field of the spectrometer and left the magnet through a specially designed hole in the spectrometer, greatly reducing backgrounds. Deuterons were counted as previously. At both 0° and 45° the incident energy was defined with a nmr probe placed in the energy-analyzing system and previously calibrated by observing elastically scattered electrons in two well-calibrated spectrometers. We have assigned 0.6% error to the absolute value of the energy and find agreement between the incident energy, angles, and observed elastic peak position.

Absolute cross sections.—Table I lists our measured absolute cross sections with accompanying error. Our absolute proton measurements appear to be higher than, though consistent with, the latest Dudelzak measurements.[2]

The accuracy of our measurements was limited by the small cross sections at 0°, while at 45° the use of a thin flat target made an accurate determination of the target length difficult even though this error cancels in the deuteron and proton cross-section ratio. In spite of the use of a thin target the elastic peaks were too widened by energy loss in the target to permit use of the "flat-top" method to take data, further reducing the final accuracy.

Magnetic scattering.—Magnetic scattering from the deuteron is difficult to measure at angles

Table I. Measured absolute cross sections.

q^2	θ^a	$d\sigma/d\Omega$ (10^{-32} cm^2/sr)	Absolute error (%)
Proton			
3.00	45°	46.47	3.5
3.98	45°	31.75	3.75
5.015	45°	22.37	4.0
Deuteron			
3.00	45°	3.611	5.4
2.97	0°	0.138	12.7
4.023	45°	1.266	6.3
3.96	0°	0.0900	9.4
5.02	45°	0.573	5.8
4.93	0°	0.0403	12.5

[a] θ is here the laboratory angle of the recoil heavy particle.

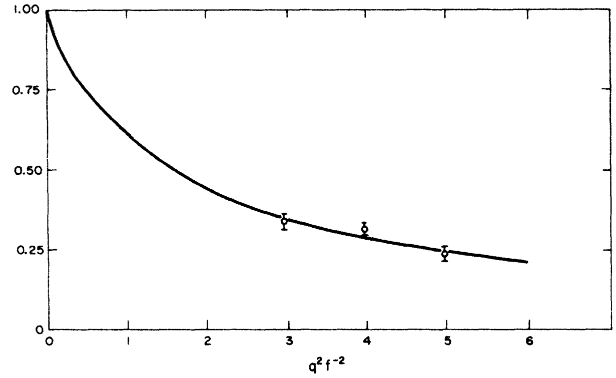

FIG. 1. Experimental points represent the ratio $G_{Md}/\mu_d(G_{En}+G_{Ep})$. The curve represents $G_{Md}/\mu_d \times (G_{Ep}+G_{En})$ determined from the equations of Jankus with the Hamada form factor and assuming "scaling" of the nucleon form factors.

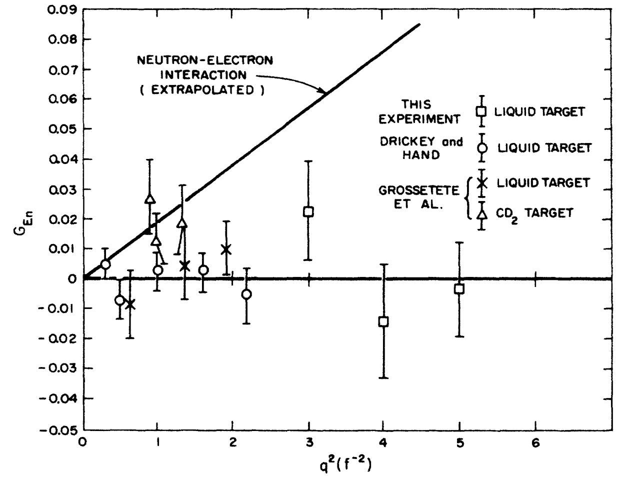

FIG. 2. Electric form factor of the neutron. All points have been calculated using the Hamada form factor.

other than 180° electron angle because of the contaminating electric scattering. 180° measurements at low q^2 have been recently reported by Schaerf and Goldemberg,[3] but no direct measurements have been taken in our q^2 region where more significant deviations from the throry are expected. Figure 1 shows our measured results for the deuteron magnetic scattering. Here our experimental points are presented in the form

$$G_{Md}/\mu_d(G_{Ep}+G_{En}),$$

G_{Md} being determined at 0° and $(G_{En}+G_{Ep})$ at 45°.

The curve shows a calculation of $G_{Md}/\mu_d(G_{Ep}+G_{En})$ following the Jankus theory with the assumption of "scaling" for the nucleon form factors, i.e., $G_{Mn}+G_{Mp}=(\mu_p+\mu_n)(G_{Ep}+G_{En})$. Our experimental points are just on this curve.[4] We conclude that if the nonrelativistic model of the deuteron is accurate, the hypothesis of "scaling" is correct. The values of G_{Mn} calculated in this manner are given in Table II, together with a summary of our other form factor results. In our analysis we assume $G_{Mp}=\mu_p G_{Ep}$, well verified in this q^2 region.[2] We conclude that all form factors of nucleons are equal, except G_{En} which is zero in the region $3 \leq q^2 \leq 5$.

Electric scattering.—Our measurements of G_{En} are shown in Fig. 2. We show the curve of G_{En} as determined from a linear extrapolation of the neutron-electron interaction. We find disagreement with the extrapolated curve and agreement with the results at lower q^2 found by Drickey and Hand[5] and with the more recent Orsay measurements.[6]

Deuteron theory.—It may be inaccurate to use a nonrelativistic theory of the deuteron for comparison with our results. However, recent[7] measurements of coherent π^0 photoproduction on the deuteron show the deuteron form factor to be well determined by the Hamada potential even at $q^2=14$. In addition, the results of Glendenning and Kramer[8] show that F_d at low q^2 is insensitive to the inner form of the potential and is primarily a function of the triplet scattering length. Relativistic effects have been often estimated with various and sometimes contradictory results so that the theoretical picture is at present not clear.

To summarize, we have found, in the region

Table II. Form factors.

q^2	G_{Ed}	G_{Ep}	G_{En}/G_{Ep} [a]	G_{Md}/μ_d	G_{Mn}/μ_n
3.0	0.255 ± 0.007	0.754 ± 0.013	0.027 ± 0.023	0.263 ± 0.017	0.74 ± 0.08
4.0	0.171 ± 0.005	0.685 ± 0.013	−0.022 ± 0.028	0.210 ± 0.009	0.63 ± 0.06
5.0	0.125 ± 0.0035	0.618 ± 0.012	−0.003 ± 0.025	0.138 ± 0.009	0.62 ± 0.06

[a]This column contains the errors pertinent to the ratio measurements.

$3 \leq q^2 \leq 5$,

$$G_{Mn}/\mu_n \approx G_{Mp}/\mu_p \approx G_{Ep}, \qquad (1)$$

$$G_{En} \approx 0. \qquad (2)$$

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[1]We thank E. Erickson of Stanford for performing the calculations of the Hamada form factor using wave functions supplied by F. Partovi from the Massachusetts Institute of Technology.

[2]B. Dudelzak and P. Lehmann, Proceedings of the Sienna International Conference on Elementary Particles (Società Italiana di Fisica, Bologna, Italy, 1963).

[3]J. Goldemberg and C. Schaerf, Phys. Rev. Letters 12, 298 (1964).

[4]Models of the deuteron with 7 % D state are known to be inaccurate at $q^2=0$, predicting $\mu_d=0.840$, instead of $\mu_d=0.857$, the known deuteron magnetic moment.

[5]D. J. Drickey and L. N. Hand, Phys. Rev. Letters 9, 12, 521 (1962).

[6]D. J. Drickey, B. Grossetête, and P. Lehmann, Proceedings of the Sienna International Conference on Elementary Particles (Società Italiana di Fisica, Bologna, Italy, 1963).

[7]E. Erickson and C. Schaerf, Phys. Rev. Letters 11, 401 (1963).

[8]N. K. Glendenning and G. Kramer, Phys. Rev. 126, 2159 (1962).

BROKEN SYMMETRIES AND WEAK INTERACTIONS*

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The observed dominance of $\Delta T=\frac{1}{2}$ processes in nonleptonic decays has been related[1] to the massive nature of the particles associated with the Z field, the charged vector field of weak interactions. The dynamical mechanism can be represented by the nonvanishing vacuum expectation value (vacuon) of the $T=\frac{1}{2}$, $Q=0$, $CP=1$ component of the phenomenological fields attached to 0^- particles (Φ), and to 0^+ particles (S). The pseudoscalar and scalar vacuons produce, respectively, parity-violating and parity-preserving $\Delta T=\frac{1}{2}$, $|\Delta Y|=1$ mixing of baryon fields and of meson fields, which initiates the decays. Thus the pseudoscalar vacuon ($\langle\Phi_{23}\rangle=-\langle\Phi_{32}\rangle$) couples the vector field of K^* with the pseudovector field of π. This implies $K_1{}^0 \to \pi+\pi$ and also the s-wave part of hyperon pion decay. An analogous λ_5 mixing of baryon fields will not exist if the baryon coupling to 0^- mesons is pseudovector in form rather than pseudoscalar.

The p-wave part of hyperon pion decay and $K \to 3\pi$ should be explained analogously by scalar vacuon ($\langle S_{23}\rangle=\langle S_{32}\rangle$) mixing of K and π, K^* and ρ, and various baryons. For example, the decay $\Lambda \to N+\pi$ can occur either through the strong π coupling, $\Lambda \to \Sigma+\pi$, followed by the vacuon baryon mixing $\Sigma \to N$ and by the baryon mixing $\Lambda \to N$ followed by the strong interaction $N \to N+\pi$, or through the strong K coupling, $\Lambda \to N+\bar{K}$, followed by the vacuon meson mixing $\bar{K} \to \pi$. If, however, the breakdown of SU(3) symmetry is limited to the mass displacement described by the vacuon $\langle S_{33}\rangle$, no such decays occur, since the complete effect of $\langle S_{23}\rangle$ can be eliminated by a unitary transformation.[2] In the example of $\Lambda \to N+\pi$ the two contributions cancel in virtue of the coupling-constant equality, for π and K coupling with baryons, that expresses SU(3) symmetry. It is the failure of that equality, $f_K \neq f_\pi$, and of similar coupling-constant equalities that permits the scalar-vacuon mechanism to operate and to cause $\Delta T=\frac{1}{2}$ parity-conserving decays.

The idea of partially suppressed parity-conserving decays receives some support from the analysis of pionic hyperon decays. An essential aspect of the phenomena, which is omitted by the processes we have described, can be attributed to an effect that would be negligible were not the principal mechanism largely self-cancelling. This effect is the mixing of different SU(3) representations associated with the broken W_3 scheme. The baryon decays act to increase hy-