curves because of conversion to center-of-mass energy.

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MEASUREMENT OF THE DEUTERON MAGNETIC FORM FACTOR AT LOW MOMENTUM TRANSFER*

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We have measured at 180° the ratio of the elastic electron-proton and electron-deuteron scattering. We have made the measurement at two values of the primary electron energy: 54 and 68 MeV. These correspond, respectively, to momentum transfers of 0.26 and 0.41 F^{-2}. At our highest momentum transfer point the electric form factor of the proton differs from unity by only 4%. Therefore we have assumed that in the energy range of interest to us, all the nucleon form factors have the same dependence as functions of momentum transfer. Under this assumption we have obtained from our data information on the magnetic form factor of the deuteron. The electron beam from the Mark II Stanford Linear Accelerator was momentum analyzed in a two-magnet achromatic translation system and then brought into the experimental area. There the beam was monitored by a three-foil secondary emission monitor and deflected ~10° by a small magnet. After deflection it entered a liquid deuterium (or hydrogen) target and continued in a large vacuum pipe for five more feet before striking a concrete wall.

The target was 1/2 inch long and the target walls were made of stainless steel foil 0.0005 inch thick. Alternatively hydrogen and deuterium were condensed under pressure in the target which was cooled by a reservior full of liquid hydrogen. The electrons emitted at 180° in the target passed again through the small deflecting magnet and entered a 120° double-focusing magnetic spectrometer. A system of two scintillation counters in coincidence, placed in the focal plane of the spectrometer, was used as detector. A more detailed description of the apparatus is contained in the paper of Peterson and Barber.[1] The total amount of material traversed by the beam before entering the target was 0.003 inch of aluminum.

In the relativistic limit the scattering at 180° should be entirely magnetic. However, because of the smallness of the magnetic moment of the deuteron, the cross section for magnetic scattering from the deuteron is small, and the contribution to this cross section from electric (Coulomb) scattering is not completely negligible.

This was mainly produced by two causes. First, the usual approximation in which the velocity of the electron is equal to the velocity of light was not true in our case and a small contribution from terms of the order $1-\beta^2$ had to be taken into account. Second, multiple Coulomb scattering in the target introduced some angular dispersion in our beam. For this reason particles undergoing scattering at angles very close to 180° could enter our spectrometer. This effect was larger than the one introduced by the finite solid angle of the spectrometer which was therefore neglected. The contributions from electric transitions were calculated at 54 and 68 MeV to be, respectively, 0.62 and 0.02 of the magnetic scattering. Radiative corrections have been calculated according to Meister and Yennie and found to be practically equal for the proton and deuteron case.[2]

The result of our experiment is indicated in Fig. 1. The experimental value of the form factor normalized to one at $q^2=0$ is defined as follows[3]:

$$[F(q^2)]^2 = \tfrac{3}{2}(\sigma_d/\sigma_p)[\mu_p/\mu_D]^2 \times [1+2E/M_d][1+2E/M_p]^{-1}, \tag{1}$$

where E is the initial electron energy, M_p and M_d are the proton and deuteron masses, σ_d/σ_p is the experimental value for the ratio of the cross sections, and

$$\mu_p/\mu_d = 3.2572 \tag{2}$$

is the experimental measured value.[4]

The static magnetic moment of the deuteron

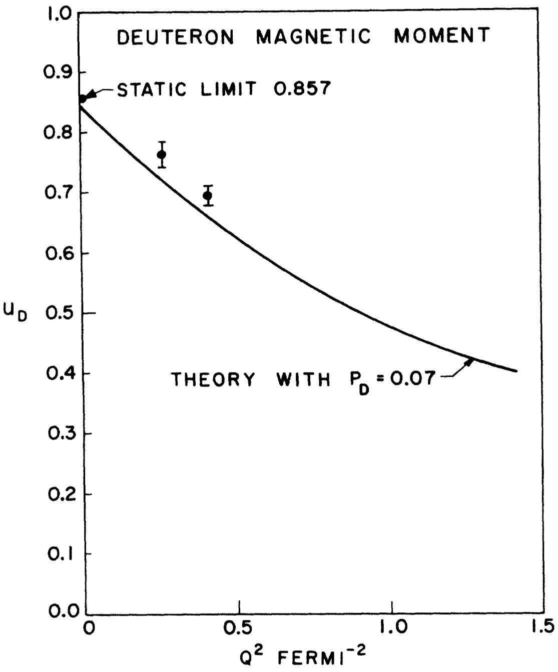

FIG. 1. Available data on the deuteron magnetic moment. The theoretical curve has been calculated as explained in the text with $P_D = 0.07$. The static limit ($q^2 = 0$) of the deuteron magnetic moment has been measured to extremely high accuracy using nuclear magnetic resonance techniques and has been found to be 0.857. The corresponding theoretical value at $q^2 = 0$ is 0.84.

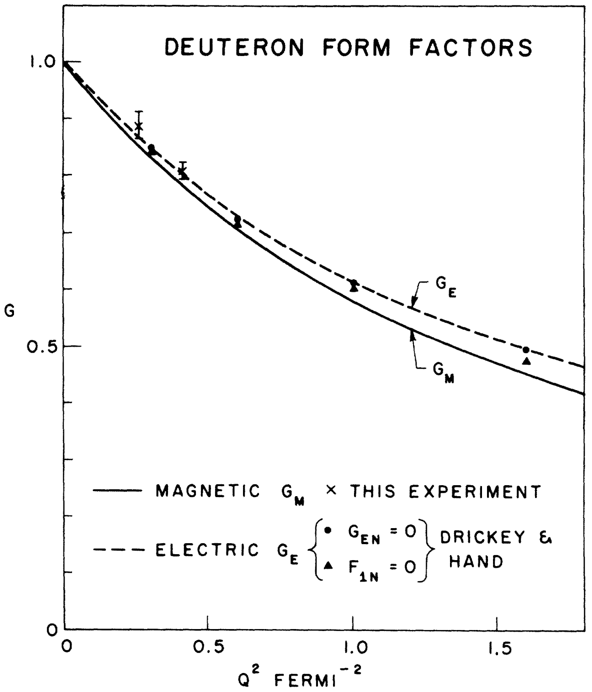

FIG. 2. The result of this experiment together with the results of Drickey and Hand for the electric deuteron form factor. The values of G_E have been calculated from the experimental numbers under two different assumptions for the neutron charge form factor: $F_{1n} = 0$ and $G_{En} = 0$. The theoretical curves have been calculated as explained in the text; the calculations and the data are normalized independently to unity at zero momentum transfer.

can be expressed in a nonrelativistic theory as

$$\mu_d = \mu_S - \tfrac{3}{2}(\mu_S - \tfrac{1}{2})P_D, \qquad (3)$$

where $\mu_S = \mu_p + \mu_n$ and P_D is the D-state probability in the deuteron ground state. This expression has the advantage of being independent of the spatial structure of the wave functions. The fact that the deuteron is an isocalar makes all contributions from pion exchange currents identically zero. Relativistic corrections, as calculated by Jones,[5] do not introduce any variation to the static magnetic moment. For this reason the value

$$P_D = 0.039$$

obtained from Formula (3) has been considered for a long time a very close estimate. However, recent analyses of the photodisintegration of the deuteron[6] have shown that a somewhat larger percentage of D state is necessary to fit the experimental data. A very similar result has been obtained for the coherent photoproduction of neutral pions in deuterium.[7] Both types of experiments seem to require a D-wave contamination of approximately 0.07. With this value of P_D the theoretical value of the static deuteron magnetic moment becomes 0.84 against the measured value of 0.857.

We have calculated the theoretical values of the magnetic form factor of the deuteron from the nonrelativistic expression of Gourdin,[8] using the deuteron wave functions calculated by Brandt, Breit, and Ruppel[9] with $P_D = 0.07$. A discussion of the approximations involved is included in the article by Gourdin. In Fig. 1 we have plotted the deuteron magnetic moment as a function of the momentum transfer.

The theoretical calculations indicate also that the magnetic form factor is slightly smaller than the electric one, while our experimental result combined with that of Drickey and Hand[10] leads to the opposite conclusion (Fig. 2). In this graph we normalized the form factors to unity at zero momentum transfer. More specifically, we can say that the ratio of the magnetic to the electric radius of the deuteron is

$$r_m/r_e = 0.93 \pm 0.038.$$

In conclusion we can say that, both from the static magnetic moment and from our measurements, there is some evidence that other contributions besides the impulse approximation have to be taken into account to understand the magnetic structure of the deuteron. We also have some evidence that the form factor connected with this anomalous contribution decreases less rapidly, as the momentum transfer increases, than the form factor obtained from the impulse approximation.

It is a pleasure to thank Professor W. C. Barber for his continuous support and many useful discussions. Our understanding of the problems connected with the deuteron form factors has greatly improved through discussion with various people, in particular, Professor S. Drell, Professor L. I. Schiff, Mr. R. Adler, and Mr. E. Erickson. Dr. G. Vanpraet and Mr. G. Gosta have been of great help in the data taking period. Mr. W. Ewings is responsible for the manufacturing of the particular hydrogen cell that made this experiment possible.

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SOLAR NEUTRINOS. I. THEORETICAL*

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The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence ${}^{1}\mathrm{H}(p, e^{+}\nu){}^{2}\mathrm{H}(p,\gamma){}^{3}\mathrm{He}$ and terminated by the following sequences: (i) ${}^{3}\mathrm{He}({}^{3}\mathrm{He}, 2p){}^{4}\mathrm{He}$; (ii) ${}^{3}\mathrm{He}(\alpha,\gamma){}^{7}\mathrm{Be}(e^{-}\nu){}^{7}\mathrm{Li}(p,\alpha){}^{4}\mathrm{He}$; and (iii) ${}^{3}\mathrm{He}(\alpha,\gamma){}^{7}\mathrm{Be}(p,\gamma){}^{8}\mathrm{B}(e^{+}\nu){}^{8}\mathrm{Be}^{*}(\alpha){}^{4}\mathrm{He}$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) ${}^{37}\mathrm{Cl}(\nu_{\mathrm{solar}}, e^{-}){}^{37}\mathrm{Ar}$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo[3] and Alvarez.[4] In this note, we predict the number of absorptions of