mately the nucleon Compton wavelength. The proton core is surrounded by a positive cloud, the neutron by a negative one. The neutron has in addition a positive shell at its outside that contains a few percent of the elementary charge. The distributions of the anomalous magnetic moments are spread out with rms radii of about 0.8 f and it is not necessary, with present accuracy, to assign a magnetic core.[8]

*Supported by joint contract of the Office of Naval Research and the U. S. Atomic Energy Commission.

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[1]R. Wilson, K. Berkelman, J. Cassels, and D. Olson, Nature 188, 94 (1960).

[2]F. Bumiller, M. Croissiaux, and R. Hofstadter, Phys. Rev. Letters 5, 261 (1960).

[3]L. L. Foldy, Revs. Modern Phys. 30, 471 (1958).

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[5]P. Federbush, M. Goldberger, and S. Treiman, Phys. Rev. 112, 642 (1958). They point out that $F_{2S}(0)/F_{2V}(0)=(\mu_p-\mu_n)/(\mu_p+\mu_n)=0.03$.

[6]Unfortunately, there is not much information on the shape of the form factors from meson theory. From dispersion relations one can derive a Yukawa or Clementel-Villi type form factor according to whether one uses unsubtracted or subtracted dispersion relations [J. Bowcock, W. N. Cottingham, and D. Lurié, Phys. Rev. Letters 5, 386 (1960)]. In these calculations the $\pi$-$\pi$ resonance was approximated by a $\delta$ function. A. Stanghellini [Nuovo cimento 18, 1258 (1960)] implies that a wider resonance allows for quite different shapes of form factors.

[7]F. Ernst, R. Sachs, and K. Wali, Phys. Rev. 119, 1105 (1960). They suggest that the charge and magnetic moments are determined by $F_{\mathrm{ch}}=F_1-(q^2/2M)F_2$ and $F_{\mathrm{mag}}=(1/2M)F_1+F_2$.

[8]Our results were presented at the New York meeting of the American Physical Society: R. R. Wilson, Bull. Am. Phys. Soc. 6, 35 (1961); D. N. Olson, H. F. Schopper, and R. R. Wilson, Bull. Am. Phys. Soc. 6, 63 (1961). At the same meeting the Stanford group also presented new measurements of electron-deuteron scattering that allowed the determination of $F_{1n}$ and $F_{2n}$ at $q^2<20$. As nearly as we could determine, their results were quite consistent with our curves of $F_{1n}$ and $F_{2n}$, but perhaps our interpretations in terms of isoscalar and isovector form factors differed.

# DIRAC AND PAULI FORM FACTORS OF THE NEUTRON*

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Recent work on electron scattering at Stanford[1-3] has shown that the electromagnetic form factors of the proton were split apart at large values of the momentum transfer ($q$) and the detailed behavior of the Dirac ($F_{1p}$) and Pauli ($F_{2p}$) form factors was reported. These studies showed also that $F_{2p}$ is approaching zero and that the electron-proton scattering cross section exhibits a diffraction dip at $q^2 \cong 25$ f$^{-2}$ which is associated with the behavior of $F_{2p}$ at that value of the momentum transfer. Some information concerning the proton form factors has also been reported by the Cornell group.[4] The information in references 1-3 was used by Herman and Hofstadter,[5] who deduced values of the Dirac and Pauli form factors of the neutron ($F_{1n}$ and $F_{2n}$, respectively) from the above data by making the assumption that $F_{2n}=F_{2p}$ which was known from earlier measurements[6,7] to be roughly true at low values of $q^2$. In this way the work of reference 5 showed that $F_{1n}\neq 0$. Although there is an ambiguity in the sign of $F_{1n}$, Herman and Hofstadter chose the negative sign because it has been commonly accepted that the charge cloud of the neutron is due primarily to the presence of negative mesons. The chief result of the present communication is the independent experimental determination of the two form factors of the neutron ($F_{1n}, F_{2n}$) and a verification that $F_{1n}\neq 0$. In another communication[8] we attempt to resolve the ambiguity of sign in $F_{1n}$.

The above results were obtained by combining measurements of the inelastic electron scattering cross section of the deuteron at two sets of values of energy ($E$) and angle ($\theta$) of the scattered electron for the same value of $q^2$. In essence this method is the same as the method of intersecting ellipses used in determining $F_{1p}$ and $F_{2p}$ of the proton.[9,10] The application of this method to the neutron was given in reference 9. This method of determining $F_{1n}$ and $F_{2n}$ eliminates many errors. In the present work the modified Jankus theory of electrodisintegration of the deuteron was used to evaluate $F_{1n}$ and $F_{2n}$ from the value of the cross section at the peak of the inelastic continuum.[6,11,12] The modified Jankus theory was employed in an extended form provided by Goldberg[13] which takes account of finite nonzero values of $F_{1n}$. Calculations made by Durand[14] show that the modified Jankus theory[10] is quite accurate at the peak of the inelastic continuum.

In all cases the measurement of the deuteron peak was accompanied by a corresponding measurement of the cross section of the proton peak. This procedure minimizes many possible experimental errors. Thus, an absolute cross section of the deuteron peak could be obtained by using the absolute data in references 1-3. Radiative corrections were calculated for the deuteron and proton peaks by Sobottka's method[7] and the magnitude of the radiative correction applied in finding the final value of the deuteron cross section was nearly always small and constant: ~10%. Furthermore, the differences in the corrections for the interaction in the final state[12] were estimated and found to be <~4% when calculated for the two members of the deuteron cross-section pair. The final-state corrections were not applied in the above evaluation of the deuteron cross sections since they are small (<~4%) and not particularly well known at the present time. Improved calculations of these interactions are now in progress.[15]

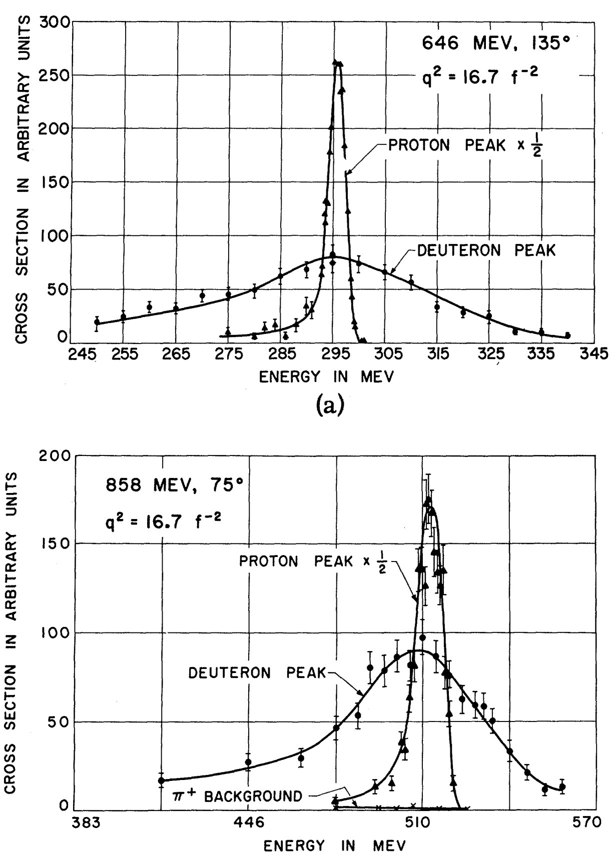


FIG. 1. A pair of deuteron inelastic continua is shown for $q^2 \cong 16.7$ f$^{-2}$, along with the comparison proton peaks used for absolute calibration. The very small $\pi^+$ background at 858 Mev and 75° was measured in order to estimate the $\pi^-$ background under the deuteron peak (see references 7 and 11).

In Fig. 1 we show a pair of deuteron inelastic peaks at a value of $q^2 = 16.7$ f$^{-2}$ with the accompanying proton peaks. The data were taken with targets of liquid hydrogen and liquid deuterium with the new 72-in. magnetic spectrometer.[1-3] We present in Table I the values of the deuteron

Table I. Experimental electron-deuteron scattering cross sections.[a]

| $q^2$ (f$^{-2}$) | $E_0$ (Mev) | $\theta^0$ | $(d^2\sigma/d\Omega dE)_{\max}\times10^{34}$ (cm$^2$/sr Mev) |
|---|---|---|---|
| 5.1 | 300 | 135 | 8.32* |
| | 500 | 60 | 35.9* |
| 7.0 | 362 | 135 | 4.6** |
| | 600 | 60 | 17.8* |
| 8.6 | 414 | 135 | 3.07** |
| | 675 | 60 | 11.1 |
| 9.1 | 429 | 135 | 2.65** |
| | 700 | 60 | 8.9 |
| 11.5 | 500 | 136 | 1.59 |
| | 800 | 60 | 5.44 |
| 14.7 | 590 | 135 | 0.82 |
| | 850 | 67.5 | 2.6 |
| 16.7 | 646 | 135 | 0.51 |
| | 858 | 75 | 1.31 |
| 18.0 | 675 | 135 | 0.46 |
| | 900 | 75 | 1.32 |
| 21.0 | 750 | 141.5 | 0.25 |
| | 900 | 90 | 0.53 |

[a]The experimental cross-section values with one asterisk have been taken from Sobottka, reference 7. Those with two asterisks have been interpolated by using Sobottka's values for $\theta = 135°$.

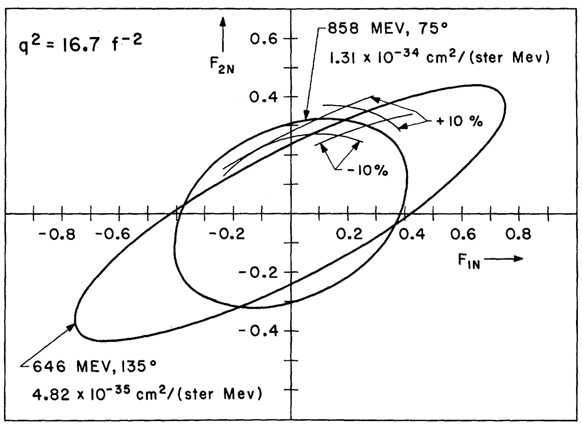


FIG. 2. An example of intersecting ellipses according to the modified Jankus theory for the pair 858 Mev, 75° and 646 Mev, 135° at $q^2 \cong 16.7\ f^{-2}$. Note the effect that would be caused by ±10% experimental errors in the deuteron cross section. The value of the cross section at 646 Mev and 135° used in the text is slightly different from the value used in this example and is $5.1 \times 10^{-35}\ cm^2/(sr\ Mev)$.

cross sections obtained in the above manner.

The convenient method of intersecting ellipses used in obtaining the form factors of the neutron is illustrated in Fig. 2 at $q^2 = 16.7\ f^{-2}$. The effect of possible errors in the measurement of the deuteron cross sections is also shown in the figure. The errors in the neutron form factors arising from all sources other than possible systematic errors are believed to be approximately of the order of the spread in the final values. The errors in the deuteron cross section are believed to be less than about ±10%.

In studying the neutron problem, one finds four possible intersections of ellipses for a given value of $q^2$ which determine the $F_{1n}, F_{2n}$ pair. Of these we have chosen the one set which seems to be physically reasonable. This set is given in Table II together with the known proton form factors.[1-3] Further details concerning the other possible solutions will be described subsequently. It should be noted that in all cases $F_{2n} \neq F_{2p}$ although at small values of $q^2$ the assumption of equality used in reference 5 is satisfied approximately.

From the chosen set of values of $F_{1p}$, $F_{1n}$, $F_{2p}$, $F_{2n}$, we may now form the corresponding set of values of the isotopic form factors which are defined as follows:

$$F_{1S} = F_{1p} + F_{1n}, \quad (1)$$

$$F_{1V} = F_{1p} - F_{1n}, \quad (2)$$

$$F_{2S} = [1.79 F_{2p} - 1.91 F_{2n}]/(-0.12), \quad (3)$$

$$F_{2V} = [1.79 F_{2p} + 1.91 F_{2n}]/(3.70). \quad (4)$$

The experimental values of the isotopic form factors as defined above are given in Table II. We observe that $F_{1V}$ and $F_{2V}$ are quite similar to each other while $F_{1S}$ has a different behavior. $F_{2S}$ is the least well-known isotopic form factor since it is associated with the small difference between the absolute values of $F_{2p}$ and $F_{2n}$. We are investigating the possible errors in the values of the isotopic form factors but believe that the errors are not large enough to change the basic pattern of behavior exhibited in Table II.

We wish to thank C. Buchanan, F. W. Bunker, B. Chambers, H. Collard, and E. Dally for their help in this experiment. Our special appreciation is due Donald W. Aitken who helped us considerably during the early stages of this work. Finally we wish to acknowledge a number of valuable discussions with Dr. A. Goldberg and

Table II. Proton, neutron, and isotopic form factors.[a]

| $q^2$ ($f^{-2}$) | (1) $F_{1p}$ | (2) $F_{2p}$ | (3) $F_{1n}$ | (4) $F_{2n}$ | (5) $F_{1S}$ | (6) $F_{2S}$ | (7) $F_{1V}$ | (8) $F_{2V}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 5 | 0.62 | 0.62 | 0.04 | 0.70 | 0.66 | 1.9 | 0.58 | 0.66 |
| 10 | 0.48 | 0.39 | 0.11 | 0.51 | 0.59 | 2.2 | 0.37 | 0.45 |
| 15 | 0.43 | 0.21 | 0.17 | 0.38 | 0.60 | 3.0 | 0.26 | 0.30 |
| 20 | 0.42 | 0.08 | 0.19 | 0.32 | 0.61 | 3.9 | 0.23 | 0.20 |

[a]The entries in columns (3)-(4) represent smoothed values taken from curves through the experimental data of this communication. Columns (5)-(8) are the result of calculations using Eqs. (1)-(4). The results for the other sets of intersections will be discussed in a forthcoming paper.

Dr. M. R. Yearian.

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*This material was presented as a post-deadline paper at the New York Meeting of the American Physical Society, February 1-4, 1961. This work was supported in part by the Office of Naval Research and the U. S. Atomic Energy Commission and by the U. S. Air Force, through the Office of Scientific Research of the Air Research and Development Command.

†On leave from Institute of Nuclear Research, Amsterdam, The Netherlands.

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[3]R. Hofstadter, F. Bumiller, and M. Croissiaux, Phys. Rev. Letters 5, 263 (1960).

[4]K. Berkelman, J. M. Cassels, D. N. Olson, and R. R. Wilson, reference 1, p. 757. See also R. R. Wilson, K. Berkelman, J. M. Cassels, and D. N. Olson, Nature 188, 94 (1960).

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## ELECTRIC AND MAGNETIC STRUCTURE OF THE PROTON AND NEUTRON*

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We attempt to present in this paper a unified interpretation of the presently known experimental data on the electromagnetic form factors of two fundamental particles: the proton and the neutron. As we shall show, this interpretation is fully consistent with the idea that the two particles are two different aspects of a single entity—the nucleon. The third component of the isotopic spin of the nucleon is then used to distinguish between the two fundamental particles. The new experimental material on the neutron form factors,[1] which now completes a block of information on the proton[2] and neutron, has served as the stimulus for the attempted explanation.

We would like to explain the main features of the experimental behavior of the Dirac form factors ($F_{1p}, F_{1n}$) and Pauli form factors ($F_{2p}, F_{2n}$) of the proton ($p$) and neutron ($n$) as functions of the momentum-transfer invariant ($q^2$). We propose to do this in a well-known way[3] by expressing each proton and neutron form factor as a sum of a scalar and vector contribution. This decomposition is rooted in the idea that the scalar and vector form factors are simpler and more basic than those of either the proton or neutron. Accordingly we make the following definitions, which are standard except perhaps for the normalizing constants:

$$F_{1S}=F_{1p}+F_{1n}, \tag{1}$$

$$F_{1V}=F_{1p}-F_{1n}, \tag{2}$$

$$F_{2S}=[1.79F_{2p}+(-1.91)F_{2n}]/(-0.12), \tag{3}$$

$$F_{2V}=[1.79F_{2p}-(-1.91)F_{2n}]/(3.70). \tag{4}$$

This choice of normalization has the advantage that at $q=0$ all four isotopic form factors take on the value of unity.

We shall now attempt to find the four isotopic form factors from the experimental information given in Hofstadter et al.[1,2] for the values of