mission, and by the U. S. Air Force, through the Office of Scientific Research of the Air Research and Development Command.

†Visitor from University of Strasbourg, Strasbourg, France.

[1]E. E. Chambers and R. Hofstadter, Phys. Rev. 103, 1454 (1956).

[2]R. Herman and R. Hofstadter, High-Energy Electron Scattering Tables (Stanford University Press, Stanford, California, 1960), and the work of F. Bumiller and R. Hofstadter shown in Fig. 8 of this reference.

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SPLITTING OF THE PROTON FORM FACTORS AND DIFFRACTION IN THE PROTON*

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Electron-scattering studies of the proton obtained in the last few years have been summarized recently.[1] The measurements showed that the proton form factors (F_1, F_2) were less than unity, implying a finite structure, and lay in a region in which they were approximately equal to each other at momentum transfers (q) as high as $q^2=9.3$ in units of squared inverse fermis. At this value of the momentum transfer the measured ratio was $F_1/F_2=1.23\pm0.20$.[2] The experiments were confined to angles larger than 60° at the highest energies then obtainable (650 Mev) because of the limitation imposed by the energy-handling ability of the 36-in. spectrometer. It was therefore not possible to solve for F_1 and F_2 separately at values of $q^2 \geq 9.3$. Several independent experiments[2,3] indicated that the F_1 values were slightly greater than the F_2 values at the same momentum transfer, but for simplicity and ease of calculation, in the past, the ratio of form factors was usually taken to be unity.

We have now succeeded in splitting apart the two proton form factors. Because of the great interest in the proton form factors and because our data appear to be internally consistent, we wish to present in this paper some conclusions drawn from the experimental results given in the accompanying paper.[4]

Our procedure has been to solve for the separate form factors (F_1, F_2) at conditions lying between $7.7 \leq q^2 \leq 25$ by choosing a pair of experimentally measured cross sections at the same value of q^2 but at different correlated values of energy and angle. We have used the method of intersecting ellipses[5] to find the form factors.

Table I shows the values selected and the form factors found by combining the results. In a few cases, indicated by asterisks, we have used older data and combined the older values with the newly-measured cross section at the same value of q^2. In two cases (866 Mev, 75°; 675

Table I. Form factors F_1 and F_2.

q^2 (f^{-2})	E_1 (Mev)	θ_1 (deg)	$(d\sigma/d\Omega)_1$ (cm²/sr)	E_2 (Mev)	θ_2 (deg)	$(d\sigma/d\Omega)_2$ (cm²/sr)	F_1	F_2
7.70	800	45°	1.04×10^{-31}	400	124°	*1.06×10^{-32}	0.520	0.490
9.16	700	60°	3.80×10^{-32}	464	135°	*6.26×10^{-33}	0.500	0.420
11.50	800	60°	2.35×10^{-32}	500	135°	*4.18×10^{-33}	0.451	0.341
14.06	900	60°	1.43×10^{-32}	597	120°	2.65×10^{-33}	0.423	0.214
16.97	866	75°	5.56×10^{-33}	650	135°	1.51×10^{-33}	0.430	0.160
18.03	900	75°	5.35×10^{-33}	675	135°	1.23×10^{-33}	0.451	0.108
21.24	900	90°	2.09×10^{-33}	750	141.5°	7.35×10^{-34}	0.405	0.087

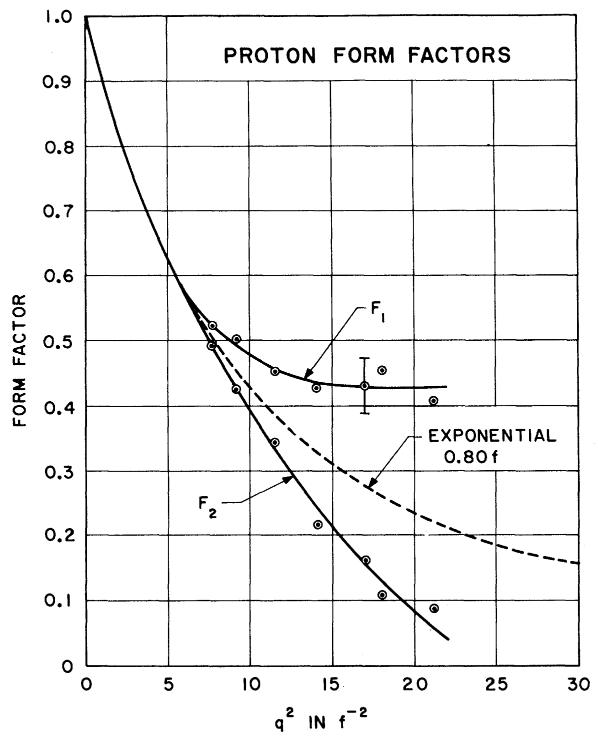

FIG. 1. The proton form factors obtained in Table I, plotted against q^2. F_2 may be approaching a diffraction zero.

Mev, 135°) we have interpolated between two newly-measured results in order to obtain properly matched pairs of cross sections.

The form factor results now show the behavior plotted in Fig. 1. The dashed line is the form factor corresponding to the exponential model and $F_1 = F_2$. Apparently our new F_2, which is seen to approach zero, indicates qualitatively that the Pauli magnetic moment cloud is a "soft," spread-out distribution. On the other hand, the constancy of F_1 suggests qualitatively that the Dirac electric/magnetic cloud has a small, perhaps point-like, core.

The form factors found in the above manner were then put back into the well-known Rosenbluth Eq. (40) of reference 1:

$$d\sigma/d\Omega = \sigma_{NS}\{a_{11}F_1{}^2 + a_{12}F_1F_2 + a_{22}F_2{}^2\}, \quad (1)$$

where the values of the coefficients a_{11}, a_{12}, and a_{22} are taken from the tables[1] at the appropriate energies and angles. When this is done we obtain the results shown in Fig. 2. Notice that in Fig. 2(c) the cross section appears to be going through a diffraction dip, so characteristic of electron-scattering studies on heavier nuclei. The experimental data indeed show this diffraction dip and we believe that this is the first time diffraction has been observed in the proton.

Within experimental error the new experimental results appear to be in agreement with the split form factor curves. It is very interesting to observe that the new form factors account for an increase of the cross section above the exponential case at small angles, merge approximately with the exponential case at 120°, and drift below the exponential case at the large angles 135° and 145°. This is what the experiments appear to indicate and the result is a rather complicated pattern of cross sections which the form factors must satisfy. The experimental data appear to fit the calculated curves for separate form factors absolutely as well as relatively.

The data are in excellent agreement with the earlier experimental results.[1] The measurements of a proton root-mean-square radius appear to remain undisturbed because those measurements were made at low q values. However, we are aware that at higher values of q^2 the conclusions about the neutron's form factors may be influenced slightly.[1,6] This question is now under investigation by R. Herman and the authors. It may be pointed out that the inelastic electron-scattering studies on the deuteron should perhaps yield new information on the F_1 iorm factor of the neutron when combined with these results. It is interesting to speculate on whether the proton's F_2 factor rises again after approaching zero at about $q^2 \cong 24$ or whether it becomes negative at that point. In our analysis we assumed $F_2 \cong 0$ at $q^2 > 24$.

By use of these results new information on F_2 of the neutron should result from a study of the deuteron's elastic scattering at large angles.

We wish to thank Mr. Francis Lewis for his help in making some of the calculations with intersecting ellipses.

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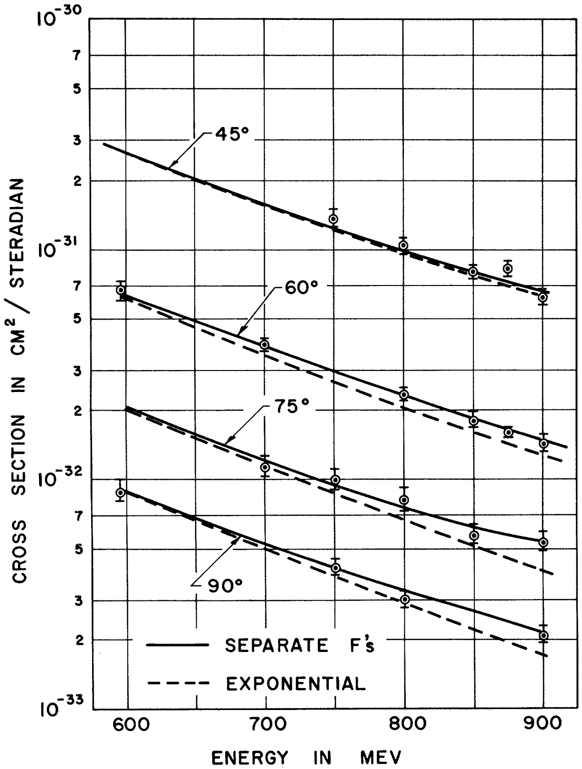
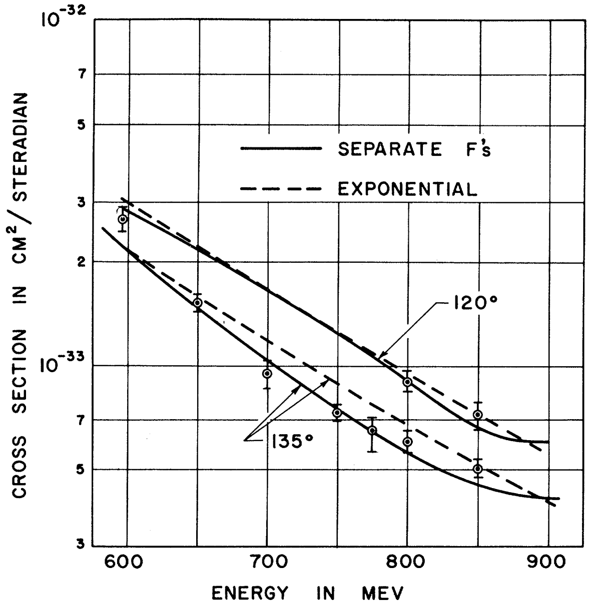
[1]R. Herman and R. Hofstadter, High-Energy Electron Scattering Tables (Stanford University Press, Stanford, California, 1960).

[2]F. Bumiller and R. Hofstadter; see Fig. 8, p. 28,





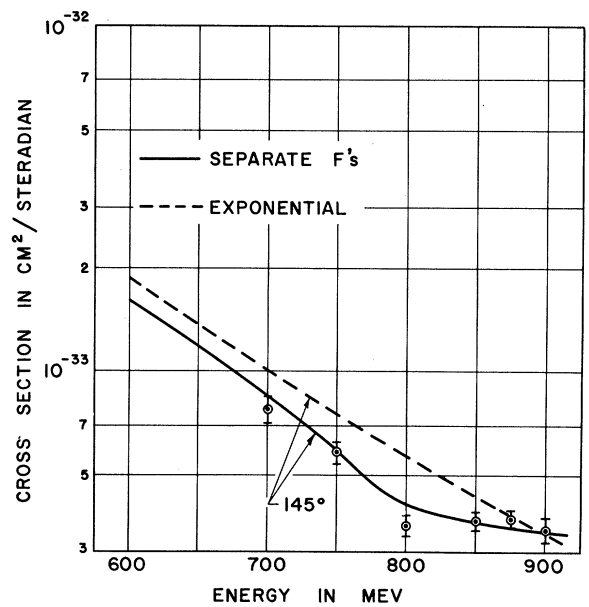


FIG. 2. Comparison of observed and calculated cross sections. The experimental points are shown by hollow circles. The dashed line refers to the case $F_1 = F_2$ and corresponds to the form factors deduced from the old exponential model.[1] The solid line is obtained from Eq. (1) and the newly-obtained form factors of Table I and Fig. 1.

of reference 1.

[3]E. E. Chambers and R. Hofstadter, Phys. Rev. 103, 454 (1956).

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

[5]R. Hofstadter, Ninth Annual International Conference on High-Energy Physics, Kiev, July, 1959 (unpublished). See also reference 1, pp. 30-32.

[6]R. Hofstadter, F. Bumiller, and M. R. Yearian, Revs. Modern Phys. 30, 482 (1958).