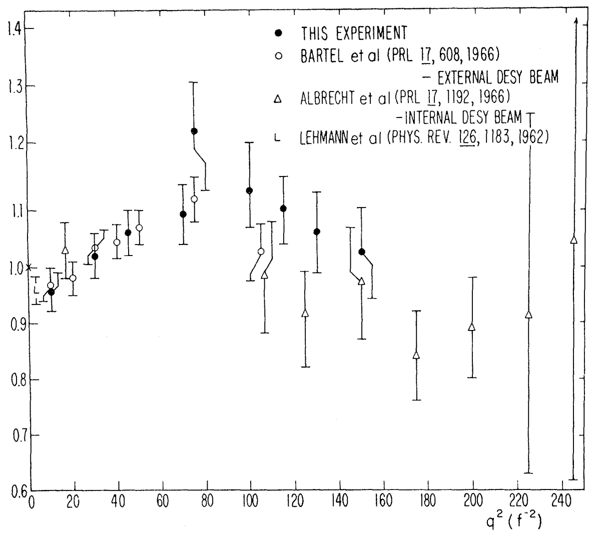

FIG. 2. Ratio of experimental data to the one-parameter fit. The value of 1 at $q^2=0$ F^{-2} is imposed by the static values of the form factors.

The agreement between the present data and those of other laboratories is excellent below 100 F^{-2}; above this value it is adequate, but there is an indication of a systematic discrepancy of approximately 10%. We feel that these data represent an improvement over previous forward-angle measurements from this laboratory[7] and should supersede them.

A discussion of the comparison of these data with the available theoretical predictions appears in an accompanying Letter.[8]

The help of Professor Norman Ramsey, M. Wanagel, J. McElaney, R. Wharton, W. Dunn, and their staffs; of the entire Cambridge-Electron-Accelerator staff under the guidance of M. Stanley Livingston; and in particular of G. Voss and J. Cerino is gratefully acknowledged.

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COMPARISON OF ELASTIC ELECTRON-PROTON SCATTERING CROSS SECTIONS WITH SOME THEORETICAL PREDICTIONS*

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New data on elastic electron-proton scattering have recently become available.[1-3] We wish to point out that the best present theoretical predictions are not adequate to describe the detailed functional dependence of the cross sections on the four-momentum transfer.

We will directly compare the theoretically predicted cross sections with the experimental data. It is customary to remove the trivial but rapidly varying dependence of cross sections on energy and angle by presenting them as ratios to the point (Mott) cross sections. We remove the major remaining dependence by using instead an approximate fit to the form factors in conjunction with the Rosenbluth formula. We use the form-factor fit

$$G_E = \frac{G_M}{\mu} = \left[1 + \frac{q^2}{0.71(\mathrm{BeV}/c)^2}\right]^{-2} \qquad (1)$$

and refer to cross sections evaluated with this fit as the "Hofstadter-Wilson cross sections." This fit has no theoretical basis. However, this simple formula describes data to within

15% over the entire range for which measurements presently exist.

It is widely believed that the proton form factor should be dominated by a sum of terms $m^2/(q^2+m^2)$, where m is the mass of each of the known vector mesons ρ, ω, and φ. Fits to these three alone will not work. One way out is to guess the existence of a fourth meson whose mass is a variable of the fit. We have fitted the new data together with that treated by Chan et al.,[4] excluding the previous forward-angle Harvard data, to a four-pole fit with no cores (Fit 4 of Ref. 4). The results are shown in Fig. 1 in which both the data and the predictions of our fit for the data points are shown as ratios to the Hofstadter-Wilson cross sections. Note that the initial dip around 7 F^{-2} is a significant feature of the data. The width of the rho meson is expected to result in an effective downward shift of its mass. We have, therefore, tried fitting with effective rho masses of 700 and 650 MeV. These fits are worse. Figure 1 also shows the 650-MeV fit. It is apparent that fits of this kind are unable to account for cross sections at high momentum transfers. Three-pole fits, with or without cores, are worse.

Massam and Zichichi[5] have suggested that the coupling of the vector mesons to the nucleon may be multiplied by a factor

$$[1+q^2/\Lambda^2]^{-1}, \tag{2}$$

where Λ is an adjustable mass. Such a factor might alternatively, or in addition, be present at the electron-photon vertex or, indeed, at the photon–vector meson vertex. They fit the low-momentum-transfer data with a mass Λ of 980 MeV with approximate agreement. We have fitted all the proton data (as above) with their expressions, finding a mass Λ of 1.015 BeV to give the best fit. Figure 2 shows the predictions of this fit for three masses. It is clear that the data are not reproduced in detail by this theory. We have refrained from quoting chi-squared values for these and the following fits in the belief that they are too poor to allow any meaning to be given to that number.

Cocho et al.[6] have proposed that the electric form factor be given by a series of pole terms

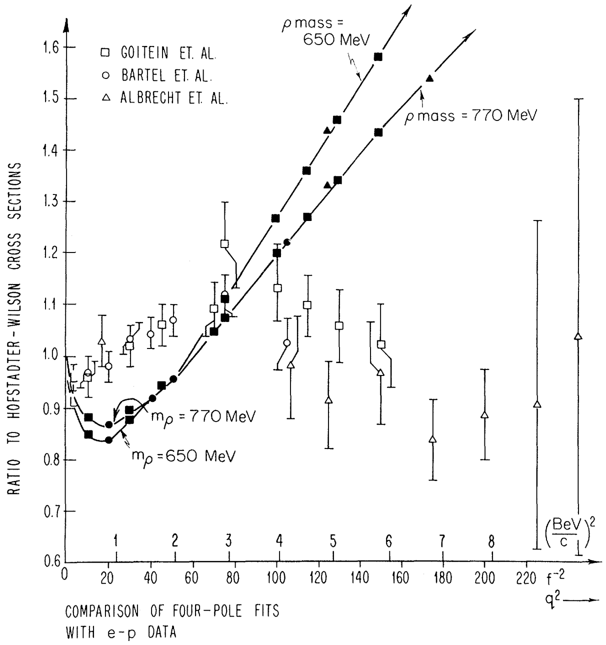

FIG. 1. Comparison of cross sections derived from four-pole fits (using ρ masses of 770 and 650 MeV) with the e-p data, both being given as ratios to the Hofstadter-Wilson cross sections [Eq. (1)]. The solid points are the theoretical predictions for the associated experimental (open) points. The lines are merely to guide the eye through the theoretical predictions. A fit with a ρ mass of 700 MeV is not shown, but lies between the fits using 650 and 770 MeV.

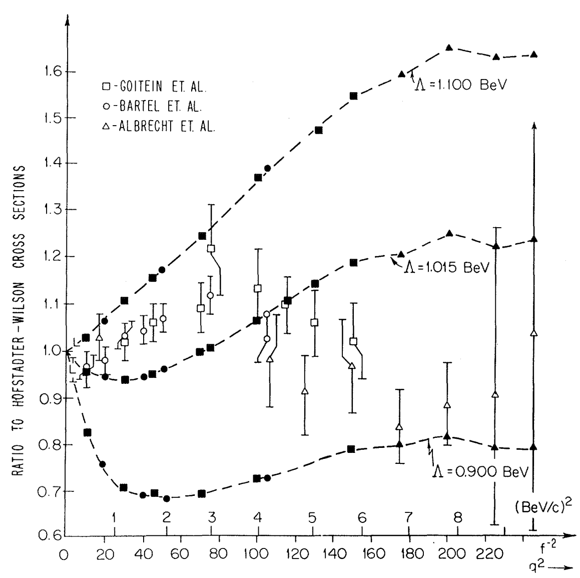

FIG. 2. Comparison of Massam and Zichichi fit (Ref. 5) with experimental data. The solid points are the theoretical predictions for the associated experimental (open) points. The lines are merely to guide the eye through the theoretical predictions. A value of 1.015 BeV for the fitted parameter Λ gave the minimum chi-squared.

for ω, ρ, and φ mesons, multiplied by a factor

$$[1+q^2/4M^2]^{-7/2} \qquad (3)$$

(where M is the mass of the proton). They get adequate agreement with the low-momentum-transfer data. Unfortunately the knowledge of G_E at high momentum transfers is still very limited and cannot provide a critical test of this hypothesis. Multiplication of both electric and magnetic form factors by the above factor gives a very poor fit to the high-momentum-transfer data [a factor of 3 discrepancy at $q^2=3$ (BeV/c)^2].

Signell and Durso[7] have recently fitted the isovector form factor using a ρ meson, some small terms, and a core. Their fit to F_{2V} uses a large core and is completely unacceptable for momentum transfers greater than 1 BeV/c. We have inadequate information to extend the fit to F_{1V} in detail but it clearly does not fall off fast enough with increasing momentum transfer.

The preceding theories represent efforts to modify simple dispersion-theoretical calculations of the contributions of the known vector mesons. Another line of approach is to relate electron-proton (e-p) and proton-proton (p-p) scattering. If we consider the electromagnetic scattering between two particles with the same structure—such as two protons—the cross section is equal to a point cross section multiplied by the fourth power of a form factor. It is tempting to make the following two further assumptions: (A) that the strong interaction between two protons is basically a point interaction whose source is spread out in exactly the same way as the charge (and magnetic moment) and (B) that there is little absorption of the scattering from some regions of the proton by other regions. These assumptions are among those always made in using a quark model.[8] These two assumptions lead to

$$X=\frac{(d\sigma/d\Omega)_{\text{c.m.}}}{(d\sigma/d\Omega)_{\text{c.m.},0^\circ}}=\frac{(d\sigma/dt)}{(d\sigma/dt)_{0^\circ}}=G^4(q^2) \qquad (4)$$

(where the cross sections are evaluated at the same incident energies). We now discuss how well this relation holds.

At small t, the relation tells us that the rms radius found from small-angle p-p scattering is $\sqrt{2}$ times the rms radius from e-p scattering. This has been known for a long time.[9] The latest data[10] on p-p scattering from 10 to 20 BeV give

$$\frac{(d\sigma/d\Omega)}{(d\sigma/d\Omega)_{0^\circ}}\simeq(1+10.5t),$$

implying an rms radius 1.4 times the radius from e-p scattering and falling a little below this at lower energies, which is attributed to a Regge-type shrinkage. A simple optical-model calculation shows that at small angles this estimate of the radius does not depend on assumption (B), and that absorption may reduce the cross section by a factor of 2 and still not alter the radius.[11]

At high momentum transfers the p-p scattering is not a unique function of t, and depends in general on two variables. Orear[12] has shown that at high momentum transfers the data are approximately fitted by a relation

$$X=A\exp[-P_\perp/(0.15\text{ BeV})],\quad P_\perp=P_0\sin\theta, \qquad (5)$$

where only one variable is required; Krisch[13] finds a better fit by writing

$$X=\exp(+4\sin\theta)\{A\exp(-aP_\perp^2)+B\exp(-bP_\perp^2)+C\exp(-cP_\perp^2)\}. \qquad (6)$$

Krisch proposes that the curly bracket (= Y) represents the proton structure. The factor $\exp(+4\sin\theta)$ is found phenomenologically but it could be, for example, the basic quark-quark angular distribution (which would also have an imaginary phase). Recent data on 90° p-p scattering[14] have established a break in the wide-angle high-energy data implied by relation (6) and have somewhat modified the constants of Ref. 13. We use the new fit to the data in representing the p-p scattering.

Wu and Yang[15] interpret Eq. (4) in the asymptotic limit and, prompted by Orear, prescribe a correspondence between $P_\perp^2$ (p-p data) and q^2 (e-p data). Although they wrote relation (4) specifically for 90° c.m. scattering, it would then hold for a large range of angles. At small angles $P_\perp^2=-t$ and the correspondence of the small-angle data discussed above still holds. Using this prescription we investigate the predictions of relation (4) in Fig. 3.

The following conclusions can be drawn: Neither of the curves X or Y is a particularly good fit to the e-p data. Scaling Y by an

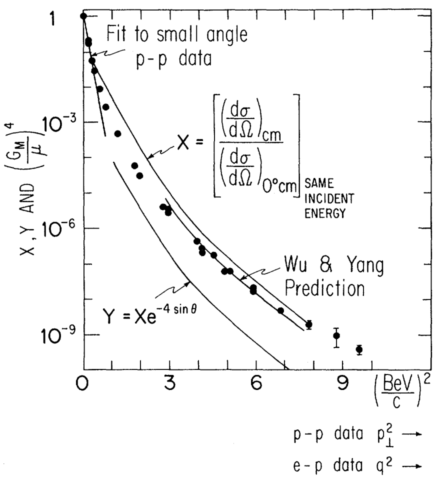

FIG. 3. Comparison of p-p and e-p data. The curves are fits to the p-p data of Refs. 10 and 14. The points are values of $(G_M/\mu)^4$ deduced from e-p data. Where not shown, the errors are within the points. The Wu and Yang prediction is to scale X by an arbitrary constant. The p-p fits are plotted against $P_\perp{}^2$, the e-p data against q^2.

adjusted constant (Wu and Yang's prediction) gives moderate agreement above $3(\mathrm{BeV}/c)^2$ although the high-q^2 e-p data fall slower than the present p-p data extrapolated to higher $P_\perp$. The agreement will be more impressive if future p-p data show a further break as Akerlof et al.[14] believe it may. The curve Y falls below the e-p data. We could only explain this by the presence of absorption effects (failure of assumption B) which, in addition, exhibit unusual cancellations. Serber[16] has suggested an extreme of such a model. Thus Krisch's prescription (to represent proton structure by Y) is unlikely.

Absorption effects can give rise to diffraction maxima and minima. This may be the explanation of the break so evident in the p-p data.[14] Such breaks are not prominent in the e-p data. If they are found to be absent, it would reinforce the interpretation of the p-p break as due to absorption effects.

We also present in Fig. 4 the same comparison as in Fig. 3 but equating q^2 (e-p scattering) with $-t$ (p-p scattering) rather than $P_\perp{}^2$. This is not unique, because of the energy dependence of p-p scattering discussed above. The p-p fits are even higher compared to the e-p data using this prescription. This comparison has also been made by others.[17]

Drell et al.[18] have proposed a model leading to a multiplicative sinusoidal factor in the ex-

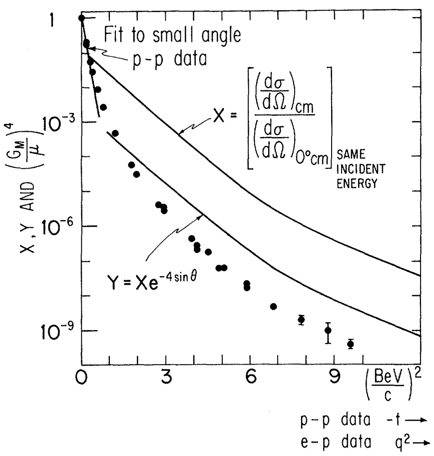

FIG. 4. Comparison of p-p and e-p data. This plot differs from Fig. 3 in that the p-p fits are here plotted against $-t$ while the e-p data are still plotted against q^2.

pression for the form factor. There are oscillations of the data about the Hofstadter-Wilson cross sections evident in our plots. Since there are no zeros in the cross section, however, there would have to be quite large contributions from second-order terms ignored in the calculation for these oscillations to be the phenomenon predicted.

We conclude that there is still no adequate theory to describe the electromagnetic structure of the nucleons, which is one of the more elementary phenomena involving strong interactions.

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SEARCH FOR FRACTIONALLY CHARGED PARTICLES IN COSMIC RAYS NEAR SEA LEVEL*

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An array of spark chambers and scintillation-counter trays has been used to search for fractionally charged particles in cosmic rays near sea level. No acceptable events have been found with energy losses by ionization between 0.04 and 0.7 that of singly charged minimum-ionizing particles. This experiment sets new upper limits for the fluxes of fractionally charged particles in cosmic rays, namely, 1.7×10^{-10} and 3.4×10^{-10} $\text{cm}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}$ (90% confidence) for minimum-ionizing particles with charges $\frac{1}{3}$ and $\frac{2}{3}$, respectively.

Since Gell-Mann[1] and Zweig[2] proposed that all strongly interacting particles are composed of fractionally charged objects, several authors[3-9] have reported on their searches in cosmic rays for these particles (quarks) using scintillation-counter arrays. An experiment is now running at the California Institute of Technology using an array of spark chambers and plastic scintillation counters to look for particles in cosmic rays near sea level which have energy losses by ionization anywhere between 0.04 and 0.7 that of singly charged minimum-ionizing particles. The system has an acceptance of 0.15 m^2 sr and has been operated for 3300 h. During this time, 1.5×10^8 cosmic-ray particles have traversed the array and no acceptable events have been found.

The arrangement of the two four-gap spark chambers and the 12 plastic scintillation counters paired into six counter trays is illustrated in Fig. 1. The resolution of the counters is 25% full width at half-maximum in all but two counters for which it is 45%. A trigger was generated when pulses between 0.03 and 0.7 that for minimum-ionizing particles occurred in all counter trays. The spark chambers have 1-cm gaps filled with a mixture of 75% argon, 24% helium, and 1% ethanol at atmospheric pressure.

Since it was imperative in this experiment that the pulse heights recorded from the counters corresponded to the particle whose track was observed in the spark chambers, a system of two lights was used to indicate the passage of another particle within the sensitive time of the chambers. For each trigger, oscilloscope

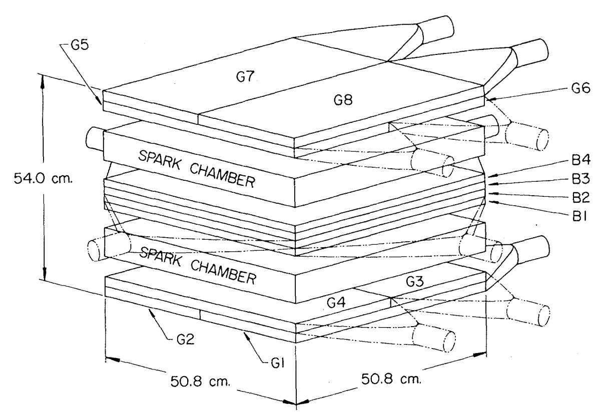

FIG. 1. The arrangement of the two spark chambers and the 12 plastic scintillators paired into six counter trays. G scintillators, 2.5 cm thick; B scintillators, 1.9 cm thick.