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PROTON FORM FACTORS

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All published experimental data, as of May, 1970, on the differential cross section for scattering of electrons by protons in the momentum transfer range $0.3\ F^{-2} \le q^2 \le 225\ F^{-2}$ are processed with the aim of determining the form factors and radius of the proton. Various types of dependence of the form factors on q^2 are considered and parameter values which yield the best fit to the experimental data are obtained for different ranges of q^2. It is shown that a statistically satisfactory fit to all the data in the range $0.3\ F^{-2} \le q^2 \le 225\ F^{-2}$, for the types of parametrization of the form factors considered, is impossible to obtain. The data of the various groups can be made consistent with each other only if renormalization, which takes into account all possible systematic errors, is carried out; and a satisfactory fit to them is possible only for $q^2 \le 30\ F^{-2}$.

As a result of a systematic study of the elastic scattering of high-energy electrons by protons, extensive data on proton form factors in a wide range of transferred momenta have been amassed. However, since information about the proton form factors has, in the past, been extracted from separate individual groups of experimental data, these form factors are not always in good agreement with each other. An evidence of this is the large dispersion among the values for the proton mean square radius obtained in different papers[1].

It is possible that this, to some extent, is also due to the fact that the determination of the dependence of the form factors on the square of the transferred momentum $G_{E,M}(q^2)$ has hitherto been carried out in two stages. The values of $G_{E,M}(q^2)$ for fixed values of q^2 were first determined from the Rosenbluth plot and, after that, from these values of $G_{E,M}(q^2)$, an analytical expression for this dependence was found.

Furthermore, attention has recently been drawn to the necessity for obtaining more accurate information about small momentum transfer scattering of electrons by protons. Barrett, Brodsky, Erickson and Goldhaber[1] have introduced the idea of the so-called "proton halo." Arbuzov[2] has related the possibility of investigation into non-linear effects in electrodynamics with more accurate data in the small momentum transfer region. Interest in data on form factors has also grown in connection with the verification of the scaling law and the application of the Veneziano model to the treatment of the dependence of the proton form factors on q^2[3].

It has been necessary, in connection with the attempts at a more profound analysis of the data on form factors, to compare the results of the various experimental groups so as to obtain sounder indications as to what the accuracy of future investigations should be. These circumstances led us to think of the necessity for carrying out a statistical processing of all the published data on elastic electron-proton scattering. The results of this analysis are presented below.

FORMULATION OF THE PROBLEM

As is well known, the differential cross section for elastic e-p scattering in the one photon approximation is given by the Rosenbluth formula

$$\frac{d\sigma}{d\Omega} = \sigma_{NS}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \operatorname{tg}^2\frac{\theta}{2}\right], \tag{1}$$

where

$$\sigma_{NS} = \left(\frac{e^2}{2E_0}\right)^2 \frac{\cos^2(\theta/2)}{\sin^4(\theta/2)}\left(1 + \frac{2E}{M}\sin^2\frac{\theta}{2}\right)^{-1}, \quad \tau = \frac{q^2}{4M^2},$$

Here, M is the proton mass; q^2—the square of the four-momentum transfer—is equal to

$$q^2 = 4E_0^2 \sin^2\frac{\theta}{2}\left(1 + \frac{2E_0}{M}\sin^2\frac{\theta}{2}\right)^{-1} = 2MT,$$

while E_0 and θ are the initial energy and the scattering angle of the electron in the laboratory system, T is the kinetic energy of the recoil proton, and e is the electron charge.

Formula (1) is used to extract information about the form factors from the results of experiments in which the scattered electrons were recorded. For the case in which the recoiling protons were detected, Rosenbluth's formula may be written in the form[4]:

$$\left(\frac{d\sigma}{d\Omega}\right)_p = \left(\frac{e^2}{M}\right)^2 \frac{1}{\cos\gamma}\left(1 + \frac{T}{2M}\right)\left\{\frac{2M}{T}G_E \sin^2\gamma + G_M^2\left[\left(1 + \frac{T}{M}\right)\left(1 + \cos^2\gamma\right) - \frac{2P}{M}\cos\gamma\right]\right\}, \tag{2}$$

where γ and P are the angle and momentum of the recoiling proton in the laboratory system.

As is customary, the form factors G_E and G_M are normalized such that

$$G_E(0) = 1, \quad G_M(0) = \mu_p,$$

where μ_p is the total proton magnetic moment in nuclear magnetons.

For small q^2, the expansion of $G(q^2)/G(0)$ has the form

$$G_{E,M}(q^2)/G_{E,M}(0) = 1 - {}^1/_6\, q^2 \langle r_{E,M}^2\rangle,$$

where $\langle r_E^2\rangle^{1/2}$ and $\langle r_M^2\rangle^{1/2}$ are the root mean square electric and magnetic radii of the proton which are determined by the differential coefficients of the form factors at $q^2 = 0$:

$$\langle r_{E,M}^2\rangle = -6\frac{dG_{E,M}(q^2)}{dq^2}\bigg|_{q^2=0}.$$

It has been hitherto assumed that the greater part of the experimental data on the form factors are compatible with the so-called dipole formula

$$G(q^2)/G(0) = [1 + q^2/0{,}71(\mathrm{GeV}^2/c^2)]^{-2} \tag{3}$$

and the scaling law

$$G_E(q^2) = G_M(q^2)/\mu_p. \tag{4}$$

However, indications of deviations from these laws have recently been obtained[5].

In our case, the method of least squares was used in the processing of the experimental data. We minimized the functional

$$\chi^2 = \Big[\sum_k \sum_i \frac{1}{(\Delta_i^k)^2}\Big(\frac{d\sigma^k}{d\Omega_i} - N_k \frac{d\sigma^k}{d\Omega_i}(\text{theor})\Big)^2\Big], \tag{5}$$

where N_k is the normalizing factor (norm) which is introduced for the k-th experiment so as to take into account possible systematic errors; $d\sigma^k/d\Omega_i$ and Δ_i^k are the values for the differential cross sections and the corresponding errors for the i-th point of the k-th experiment; $d\sigma^k/d\Omega_i$ (theor) is the differential cross-section computed from the Rosenbluth formula.

The dependence on q^2 of the form factors in $d\sigma^k/d\Omega_i$ expressed as

$$G_E(q^2) = (1 + a_1 q^2 + a_2 q^4)/(1 + a_3 q^2)^2, \tag{6}$$

$$G_M(q^2) = G_E(q^2)\mu_p/(1 - a_4 q^2 - a_5 q^4). \tag{7}$$

The coefficients a_1, a_2 are introduced to take into account a possible deviation from the dipole formula while a_4 and a_5 take into account a possible deviation from the scaling law.

Apart from the formulas (6) and (7), we considered the parametrization of the form factors in accordance with the form of the Veneziano model given in[3]:

$$\frac{G_{E,M}(t)}{G_{E,M}(0)} = \delta_0^{E,M}\frac{\Gamma(1-\rho(t))\Gamma(^5/_2+1-\rho(0))}{\Gamma(1-\rho(0))\Gamma(^5/_2+1-\rho(t))} + \delta_1^{E,M}\frac{\Gamma(2-\rho(t))\Gamma(^5/_2+2-\rho(0))}{\Gamma(2-\rho(0))\Gamma(^5/_2+2-\rho(t))} + (1-\delta_0^{E,M}-\delta_1^{E,M})\frac{\Gamma(3-\rho(t))\Gamma(^5/_2+3-\rho(0))}{\Gamma(3-\rho(0))\Gamma(^5/_2+3-\rho(t))}. \tag{8}$$

Here, $t = -q^2$, $\Gamma(x)$ is the gamma function, and the ρ trajectory parameters $\rho(t) = 0.483 + 0.885t$ are assumed to be fixed. In this case there are two free parameters, namely, $\delta_0^{E,M}$ and $\delta_1^{E,M}$, for each form factor (G_E and G_M). The requirements of the scaling law are not imposed.

The minimization of the functional was done using the linearization method[6] in accordance with the FUMILI program. The experimental data, which were processed, are given in Table I. Only points that agreed with the rest within three standard errors (the contribution to the minimized functional $\Delta\chi^2 \leq 9$), were processed. The total number of experimental points in the range $0.3\ \mathrm{F}^{-2} \leq q^2 \leq 225\ \mathrm{F}^{-2}$ equals 279. Experimental data for large q^2 were excluded from the processing after the very first trial runs as a result of a bad fit.

Table I

Number of experiment	Laboratory	Number of points processed	Number of points discarded
1	Stanford [7]	78	15
2	Stanford [8]	8	0
3	Cornell [9]	24	4
4	Cornell [10]	9	0
5	CEA [11–14]	43	3
6	ORSAY [4]	9	1
7	DESY [15–17, 25]	25	12
8	Cornell [18]	12	13
9	DESY [15, 16]	8	3
10	ORSAY [19–21]	10	2
11	SLAC [22, 23]	32	7
12	Bonn [24]	21	3

Table II

	$q^2 \leqslant 11$	$q^2 \leqslant 11$	$q^2 \leqslant 16$	$q^2 \leqslant 30$
a_1	0	0	0	0,390±0.180
a_2	0	0	0,149±0,040	−0.081±0,062
a_3	1.408	1,383±0,016	1.41±0.03	1,66±0.13
a_4	0	0	−0.063±0.026	−0.032±0.020
N_1	0.933±0.004	0,915±0.013	0,935±0.016	0,950±0,018
N_2	1.002±0.005	0.998±0.006	1.003±0.007	1.011±0.009
N_3	1.019±0.019	1.004±0.021	1,016±0.024	1,014±0.023
N_4	0.892±0.046	0.878±0.047	0.887±0.041	0.836±0.032
N_5	0.969±0.011	0.699±0.017	0.955±0.020	0.972±0.021
N_6	0,960±0.008	0,961±0.009	0.969±0.010	0.977±0.011
N_7	1.036±0.052	1.001±0.055	0.915±0.038	0.932±0.033
N_8	0.859±0.014	0.843±0.018	0,849±0.019	0.854±0.020
N_9	0.919±0.030	0,896±0.033	0.905±0.031	0.941±0.026
N_{10}	0.971±0.008	0,957±0.012	0,975±0,015	0.986±0.017
N_{11}	—	—	0	0.926±0.021
N_{12}	—	—	0.932±0.018	0.951±0.019
χ^2	102,7	99,9	141.5	231
$\overline{\chi^2}$	86.0	85.0	115.0	173
$\chi^2/\overline{\chi^2}$	1.19	1.17	1.23	1.33
R_E	0.811	0.804±0.005	0,812±0.009	0.829±0.012
R_M	0.811	0.804±0,005	0.821±0,008	0.833±0.012

Note. For $q^2 \leqslant 11\ \mathrm{F}^{-2}$ and for norms which are assumed fixed and equal to unity, $\chi^2 = 550.2$ while the ratio $\chi^2/\overline{\chi^2} = 5.73$.

RESULTS

The dipole formulas (6) and (7). The values obtained for χ^2 when the data in the complete range of values of the square of the transferred momentum $0.3\ \mathrm{F}^{-2} \leq q^2 \leq 225\ \mathrm{F}^{-2}$ were processed—even when deviations from the dipole formula and the scaling law were taken into account—were so large that for the given number of degrees of freedom ($\overline{\chi}^2 \sim 200$) the confidence level was extremely low and the fit to the experimental data could not be considered acceptable (see Table IV below). A similar situation was also observed when the range of q^2 was shortened and the data processing was carried out for values of $q^2 \leq 30\ \mathrm{F}^{-2}$.

The results of the treatment of the data for $q^2 \leq 16\ \mathrm{F}^{-2}$ and $q^2 \leq 30\ \mathrm{F}^{-2}$ are given in Table 2. It can be seen from Table II that only by the introduction of variable parameters characterizing deviations from the dipole formula (a_1 and a_2) and the scaling law (a_4 and a_5), is it possible to obtain fits with $\chi^2/\overline{\chi^2} = 1.23$ and 1.33 for $q^2 \leq 16\ \mathrm{F}^{-2}$ and $q^2 \leq 30\ \mathrm{F}^{-2}$ respectively. The corresponding confidence levels are then respectively equal to 4.6 and 0.2%.

A good fit ($\chi^2/\overline{\chi^2} \approx 1$) was obtained only in the region $q^2 \leq 11\ \mathrm{F}^{-2}$. In this region of q^2, the dipole formula and the scaling law enable us to obtain by varying the norm a good fit to the experimental data (Table II). In the case when the norms are assumed fixed and equal to unity, a satisfactory fit to an experiment is impossible to achieve. If the parameter a_3 in formula (6) is varied, then the best fit leads to the value $a_3 = 1.383 \pm 0.016$, which, in the limit of two standard errors, is equal to the value usually used in the dipole formula (column 1, Table II).

Table III

	$q^2 \leqslant 11$	$q^2 \leqslant 16$	$q^2 \leqslant 30$	$q^2 \leqslant 225$
$\delta_0{}^E$	1,80±0.22	1.47±0.14	1,24±0.07	1.30±0.04
$\delta_1{}^E$	−2.50±0.79	−1.31±0.45	−0.561±0.223	−0.563±0.112
$\delta_0{}^M$	1.68±0,15	1.43±0.08	1.30±0.03	1,12±0,01
$\delta_1{}^M$	−1.89±0.51	−1.09±0.23	−0,714±0.071	−0.246±0.013
N_1	0.961±0.020	0,934±0,016	0.909±0.011	0.862±0.007
N_2	1,016±0.009	1,004±0,007	0,994±0.006	0.990±0.006
N_3	1,047±0.027	1,017±0,024	0.966±0.018	0.937±0,015
N_4	0.918±0,050	0,887±0,041	0,802±0.029	0.755±0.026
N_5	0.980±0,022	0,954±0,019	0,929±0.014	0,903±0.012
N_6	0,982±0.011	0.969±0,010	0,959±0,009	0,950±0.009
N_7	0,910±0.053	0.912±0,037	0.897±0,030	0.848±0.016
N_8	0,890±0.023	0,848±0,019	0,817±0,015	0,778±0,012
N_9	0,915±0,036	0.904±0,030	0.902±0,022	0,877±0,019
N_{10}	1,001±0.018	0,974±0,015	0.948±0,011	0,918±0.009
N_{11}	—	—	0.892±0.015	0.861±0,019
N_{12}	—	0.930±0,017	0,913±0,013	0.870±0,011
χ^2	83,9	141,8	237,9	451,0
$\overline{\chi^2}$	82,0	115,0	173,0	263
$\chi^2/\overline{\chi^2}$	1.02	1,23	1,37	1,72
R_E	0,839±0,016	0,815±0,012	0.796±0,008	0.793±0,005

Table IV

	$q^2 \leqslant 11$	$q^2 \leqslant 16$	$q^2 \leqslant 30$	$q^2 \leqslant 225$
a_1	0	0	0.053±0,023	0,098±0.018
a_2	0	0.149±0.040	0.033±0.016	−0.009±0.007
a_3	1,38±0.02	1,41±0.03	1.408	1.408
a_4	0	−0.063±0.026	−0,031±0,020	−0,035±0.015
N_1	0,915±0.013	0,935±0.016	0,916±0,009	0,903±0.005
N_2	0,998±0.006	1.003±0,007	0.998±0.005	0.995±0.005
N_3	1.004±0,021	1.016±0.024	0,979±0.016	0,970±0.014
N_4	0,878±0.047	0,887±0.041	0.809±0.029	0.793±0.026
N_5	0,949±0.017	0,955±0,020	0,938±0,013	0,934±0.011
N_6	0,961±0.009	0.969±0.010	0.962±0.009	0.959±0.009
N_7	1,001±0,055	0.915±0.038	0,903±0,030	0.873±0.016
N_8	0,843±0.018	0.849±0,019	0,823±0,014	0.812±0.012
N_9	0,896±0.033	0.905±0,031	0,909±0.021	0.911±0,019
N_{10}	0,957±0,012	0.975±0,015	0,956±0,010	0.944±0.008
N_{11}	—	—	0,895±0.015	0.887±0.013
N_{12}	—	0.932±0.018	0,920±0.012	0,914±0.009
χ^2	99,9	141,56	236,3	410,12
$\overline{\chi^2}$	85,0	115,0	174,0	264,0
$\chi^2/\overline{\chi^2}$	1,17	1,23	1,36	1,55
R_E	0.804±0,005	0,819±0.009	0.803±0,003	0.797±0.003
R_M	0,804±0,005	0.821±0.008	0.808±0.003	0.802±0.001

For data in the region $q^2 \leq 2$ F^{-2}, a satisfactory fit is obtained with the aid of the dipole formula without the introduction of the norm and the variable parameters $a_1 - a_4$. It can be seen from Table II that the values for the proton radii obtained on the basis of the various assumptions about the dependence of the proton form factor on q^2, differ from each other by not more than one standard error (~4%) and agree with the value 0.8 F.

Veneziano type model (formula (8)). The results of the treatment are given in Table III. It follows from the obtained results that, for a fixed index of the asymptotic form factors, the fit based on the Veneziano approach is not worse than the conventional "dipole" fit. However, if, in this case, as in the previous one, the experimental data in the range 0.3 $F^{-2} \leq q^2 \leq 225$ F^{-2} are considered, then the confidence level is found to be appreciably lower than the acceptable level. Notice also that the radius found from the data in the range $q^2 \leq 2$ F^{-2} by means of the parametrization (8), differs by two standard deviations from the radius obtained on the basis of the dipole description of the same data.

Thus, a satisfactory fit to the experimental data for all the considered forms of dependence on q^2 of the proton form factor is possible only in the range $q^2 < 30$ F^{-2} and, then, only when these data are renormalized. The norms thus introduced differ from unity in half the cases by 5–12%. The errors in the norms are, as a rule, less than 5%.

In introducing the norms in the cases considered hitherto, we tacitly assumed that the differential cross section is a smooth function of the scattering angle, that systematic errors (more correctly, normalization errors) are present only in the data of the individual experiments and that on averaging over the whole experimental material, these errors vanish. The normalization of the differential cross sections, however, may be readily verified if we use the fact that as $q^2 \to 0$, the differential cross-section tends to σ_{NS}. The magnitude of and the error in the differential cross section for e-p scattering are then determined by only the value of the fine structure constant α ($\alpha^{-1} = 137.0359 \pm 0.0004$[26]) and the scattering angle θ. It is assumed here that the contribution from the two-photon diagram in the region of small q^2 can be neglected. The error introduced by neglecting the nucleon structure may be made as small as we wish by a judicious choice of the scattering angle. Consequently, extrapolation of the dependence $d\sigma/d\Omega$ obtained from the fit to the experimental data should yield in the region $q^2 \ll 1$ F^{-2} quite a definite value for σ_{NS}, which is known to a high degree of accuracy.

To verify the normalization of the cross sections by the method described above, we added to the bulk of experimental data, which was being processed, two theoretical values for the differential cross section for $q^2 = 8 \times 10^{-6}$ and 1.8×10^{-5} $(GeV/c)^2$, and $\gamma = 89.9°$ and $89.85°$, computed on the assumption that, for these values of q^2, the scattering cross section $d\sigma/d\Omega = \sigma_{NS}$. The norm for these points were assumed fixed and equal to unity. The remaining norms were varied. The results of the treatment carried out with the aid of the dipole formula with normalization to σ_{NS} are given in Table IV. The data given in the table show that, within the limits of the errors in the first stage of the processing, the norms were correctly determined.

Our inability to obtain a satisfactory fit to the experimental data from the various forms of parametrization of the form factors considered, may be the result of two circumstances, namely:

a) the non-applicability of the one-photon approximation for $q^2 > 30$ F^{-2},

b) deviation of the true dependence of the form factors from the functions considered in (6)–(8).

It is, apparently, not possible at present to say which of these causes plays the dominant role and in which region of q^2. One may think, however, that for $q^2 < 100$ F^{-2}, the "unsuccessful" description is the consequence of the deviation of the dependence $G_{E,M}(q^2)$ from the different forms considered. The result of the verification of the "one-photon behavior"—see the review[27]—may serve as the basis of this thinking. Also evident, is the necessity for further experimental verification of the "one-photon behavior" of e-p scattering.

In conclusion, it is necessary to point out that the dependence of $d\sigma/d\Omega$ in the region of very small momentum transfers ($q^2 < 1$ F^{-2}) is not, at present, known to a relatively high degree of accuracy. The corridor of errors for the curve $d\sigma/d\Omega$ obtained by processing the data without normalizing them on σ_{NS} is, in this region of q^2, ~10%.

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