

The polarization of the negative muons was consistent with zero, as expected. A detailed analysis of the longitudinal polarization in terms of the form factors is in progress.

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⁸The pion background of about 17% is due to positive pions which either decay in flight or come to rest without interacting. These pions come from the alternate decay modes: $K_L^0 \rightarrow \pi^+ + \mu^- + \nu$, $K_L^0 \rightarrow \pi^+ + \pi^- + \pi^0$, $K_L^0 \rightarrow \pi^+ + e^- + \nu$.

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SMALL-ANGLE ELECTRON-PROTON ELASTIC-SCATTERING CROSS SECTIONS FOR SQUARED MOMENTUM TRANSFERS BETWEEN 10 AND 105 F⁻²

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We report on the result of an electron-proton scattering experiment in which the elastic-scattering cross section for squared momentum transfers between 10 and 105 F⁻² was measured with a precision of about 5%. The measurements were performed at the scattering angles $\theta_{\text{lab}} \leq 25^\circ$, where charge scattering contributes noticeably to the cross section. When combined with existing large-angle data,¹⁻⁶ separation of the electric and the magnetic form factors is possible over the whole range of squared momentum transfers.

In the experiment, the slowly ejected electron beam of the 6-GeV synchrotron was momentum analyzed and focused onto a liquid-hydrogen target. A Faraday cup,⁷ placed in a concrete house 32 m behind the target, acted as an intensity monitor and beam stopper. A secondary emission chamber,⁷ located in the beam between target and Faraday cup, served as an additional monitor. Elastically scattered electrons were identified by means of the magnetic spectrometer shown in Fig. 1(a). The

spectrometer was composed of six quadrupole magnets and three bending magnets mounted on a turntable, which can be pivoted around the target center. Electrons which approximately satisfied the elastic-scattering kinematics were brought to a horizontal angular focus by quadrupoles Q_1 and Q_2 . The horizontal angular acceptance ($\Delta\theta_x = \pm 12.00$ mrad) was defined by a collimator, H , at this focus and was therefore independent of the target size. Under this action of quadrupoles Q_3 and Q_4 and the bending magnets M_1 , M_2 , and M_3 , a dispersed horizontal image of H was produced at counters S_1 and S_2 . The electrons were then identified in a 5.5-m-long ethylene-filled threshold Čerenkov counter and registered in counters S_3 , S_4 , S_5 , and S_6 . In the vertical plane, the target was imaged onto counters S_1 and S_2 , and the angular acceptance ($\Delta\theta_y = \pm 9.11$ mrad) was defined by collimator V behind Q_3 . Optics and counter dimensions were chosen such that full transmission through the entire system was assured for all particles having passed colli-

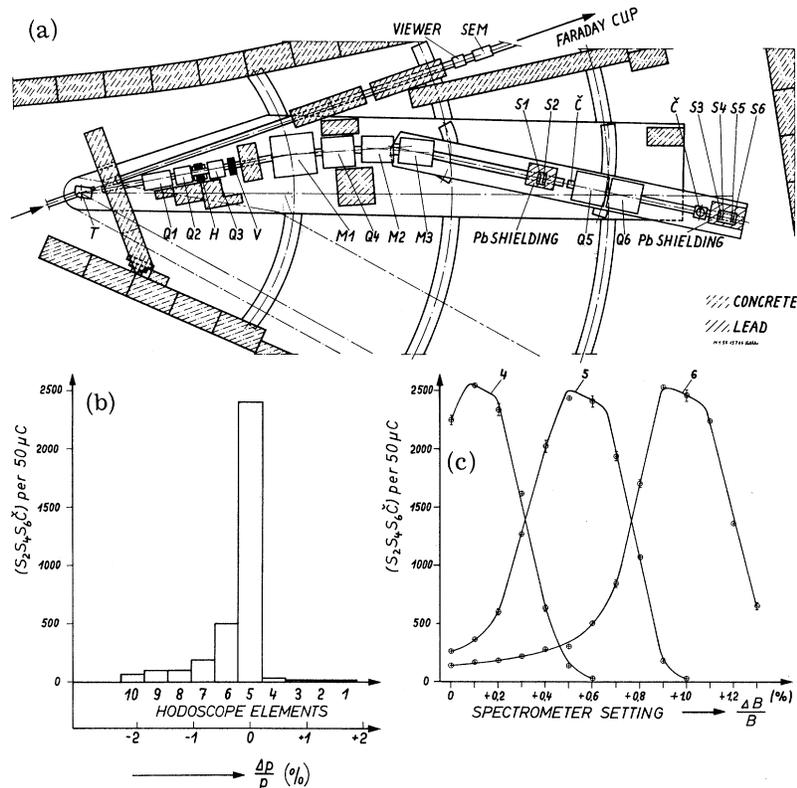


FIG. 1. The magnetic spectrometer. (a) Drawing of the arrangement. The target T had a length of 5 cm for measurements at $q^2 = 10, 20, 30, 40, 50$, and 75 F^{-2} , and a length of 10 cm for $q^2 = 45$ and 105 F^{-2} and for test runs at $q^2 = 30 \text{ F}^{-2}$. (b) Elastic peak with radiative tail registered by the hodoscope at $q^2 = 30 \text{ F}^{-2}$, using a 10 cm long target. (c) The elastic peak recorded by hodoscope elements 4, 5, and 6, with spectrometer setting varied in steps of 0.1%.

meters H and V . The momentum band was limited by the horizontal width of counters S_1 and S_2 . The spectral shape of the elastic peak was registered by the ten counter elements of 0.8-cm horizontal width which constituted S_1 . An example for $q^2 = 30 \text{ F}^{-2}$, where q^2 is the squared momentum transfer, is shown in Fig. 1(b). Optimum resolution was obtained at any scattering angle and energy by adjusting the slope of the acceptance window in the p - θ plane to that of the kinematic curve for electron-proton scattering. This was achieved by pivoting the rear part of the spectrometer around a turning point at the exit of M_2 , i.e., by changing the bending in magnets M_2 and M_3 . A line spectrum obtained at $q^2 = 30 \text{ F}^{-2}$ by changing the spectrometer setting in steps of 0.1% is shown in Fig. 1(c). The Čerenkov counter had an efficiency of $(99.7 \pm 0.3)\%$ for counting electrons, but it was insensitive to muons and heavier particles. On the basis of kinematics, negative particles having a momentum within

2% of the elastic-peak value had to be electrons. Electron identification was done in five different coincidence channels: $(S_1 S_3 S_5)$, $(S_2 S_4 S_6)$, $(S_1 \check{C} S_3 S_5)$, $(S_2 \check{C} S_4 S_6)$, $(S_1 S_2 S_3 S_4 S_5 S_6)$, where S_4 and S_6 were about 20% larger than S_3 and S_5 . The comparison of the five channels served as a continuous check of the spectrometer optics, background rejection, and the functioning of the counters and electronics.

For cross-section evaluation a hydrogen density of $(0.0706 \pm 0.0003) \text{ g/cm}^2$ was assumed and various corrections applied. The most important were the radiative⁸ and bremsstrahlung corrections. When finite horizontal angular acceptance, dead time, counter efficiency, and other smaller corrections were added, the correction to the cross section amounted to between 25 and 30%. The 3% total error in the cross sections for $q^2 \leq 50 \text{ F}^{-2}$ was essentially systematic. For $q^2 = 75$ and 105 F^{-2} , counting statistics contributed 2 and 3.5%, respectively.

The cross sections obtained are listed in

Table I. Proton form factors derived by assuming⁹ $G_E = G_M/\mu$, using only data of Table I, are shown in the second column of Table II. Separation of the form factors was achieved by combining the cross sections of Table I with large-angle-scattering data of other authors.

Table I. Cross sections.

q^2 (F ⁻²)	θ (deg)	E_{inc} (GeV)	$\frac{d\sigma}{d\Omega} \times 10^{32}$ (cm ² /sr)	$\frac{d\sigma}{d\Omega} / \left(\frac{d\sigma}{d\Omega} \right)_{Mott}$
10	10.0	3.685	176.0	0.284 ($\pm 3\%$)
20	10.0	5.274	33.9	0.115 ($\pm 3\%$)
20	12.0	4.433	22.76	0.115 ($\pm 3\%$)
20	14.8	3.640	14.62	0.118 ($\pm 3\%$)
30	11.1	5.907	8.75	0.0582 ($\pm 3\%$)
30	15.1	4.436	4.37	0.0585 ($\pm 3\%$)
40	14.8	5.278	1.800	0.0321 ($\pm 3\%$)
45	16.0	5.245	1.024	0.0253 ($\pm 3\%$)
50	15.0	5.888	0.813	0.0195 ($\pm 3\%$)
75	19.5	5.883	0.0952	0.00732 ($\pm 4\%$)
105	25.0	5.886	0.0113	0.00272 ($\pm 5\%$)

Table II. Form factors. Values in column 2 were obtained assuming $G_E = G_M/\mu$. The form factors in columns 3 and 4 were evaluated from the data of Table I and large-angle data.

q^2 F ⁻²	$G_E = G_M/\mu$	Separated form factors		Ref.
		G_E	G_M/μ	
10	0.410 $\pm 2\%$	0.421	0.400	a
		$\pm 2.8\%$	$\pm 1.8\%$	b
20	0.226 $\pm 2\%$	0.411	0.409	b
		$\pm 3.5\%$	$\pm 2.5\%$	a
30	0.145 $\pm 2\%$	0.210	0.234	a
		$\pm 5\%$	$\pm 1.5\%$	a
40	0.100 $\pm 2\%$	0.146	0.145	a
		$\pm 12\%$	$\pm 4.2\%$	c
45	0.0861 $\pm 2\%$	0.0891	0.103	c
		$\pm 16\%$	$\pm 2.6\%$	c
50	0.0739 $\pm 2\%$	0.0955	0.0834	c
		$\pm 15\%$	$\pm 4.3\%$	c
75	0.0405 $\pm 2.5\%$	0.0721	0.0743	c
		$\pm 45\%$	$\pm 9.2\%$	d
105	0.0222 $\pm 3\%$	$G_E^2 < 0$	0.0487	d
			$\pm 7.3\%$	e
		0.0826	0.0304	e
		$\pm 23\%$	$\pm 14\%$	d
		$G_E^2 < 0$	0.0307	d
			$\pm 10\%$	f
		0.0532	0.0167	f
		$\pm 30\%$	$\pm 26\%$	

^aRef. 1.^bRef. 2.^cRef. 3.^dRef. 4.^eRef. 5.^fRef. 6.

The results are shown in columns 3 and 4 of Table II.

At $q^2 = 10$ F⁻², our measurement is in excellent agreement with those from Stanford and Orsay [Fig. 2(a)]. Rosenbluth plots for $q^2 = 20$ and 30 F⁻² displaying the results of this experiment and the Stanford measurements are shown in Figs. 2(b) and 2(c). There is no indication of a failure of the one-photon-exchange approximation.

For $q^2 = 40$ and 45 F⁻², the Cornell cross sections³ measured at very large angles, together with the results of this experiment, allow a good separation of the form factors (Table II). The Rosenbluth plot for $q^2 = 45$ F⁻² is shown in Fig. 2(d). At $q^2 = 50$ F⁻² the charge form factor was derived by extrapolating the magnetic form factor found at Cornell³ for $q^2 = 45$ F⁻². The extrapolation was made with the Orsay fit.¹⁰ For $q^2 \leq 50$ F⁻² the data of the Harvard group⁴ have not been used in the analysis, since they were taken at angles only slightly larger than the ones covered in the present experiment.

The magnetic form factors measured by the Harvard group⁴ at $q^2 = 75$ F⁻² and at $q^2 = 100$ F⁻², the latter one extrapolated to $q^2 = 105$ F⁻², were used in the analysis. For both 75 and 105 F⁻² one finds $G_E^2 < 0$. The Harvard data⁴ alone also give $G_E^2 < 0$ for $q^2 \geq 75$ F⁻². On the other hand, positive values for G_E^2 are obtained when the data of the DESY internal-beam-scattering group^{5,6} are used.

We summarize our results as follows:

(1) The cross sections, combined with published large-angle data, can be well described by the Rosenbluth formula for squared momentum transfers up to 50 F⁻². (2) For $q^2 = 20, 30, 40, 45,$ and 50 F⁻², the precision in G_E has been improved. (3) The relation $G_E = G_M/\mu$ is valid within the experimental limits for $q^2 \leq 50$ F⁻². (4) Precise measurements at large angles are needed to derive G_E and G_M for $q^2 > 50$ F⁻².

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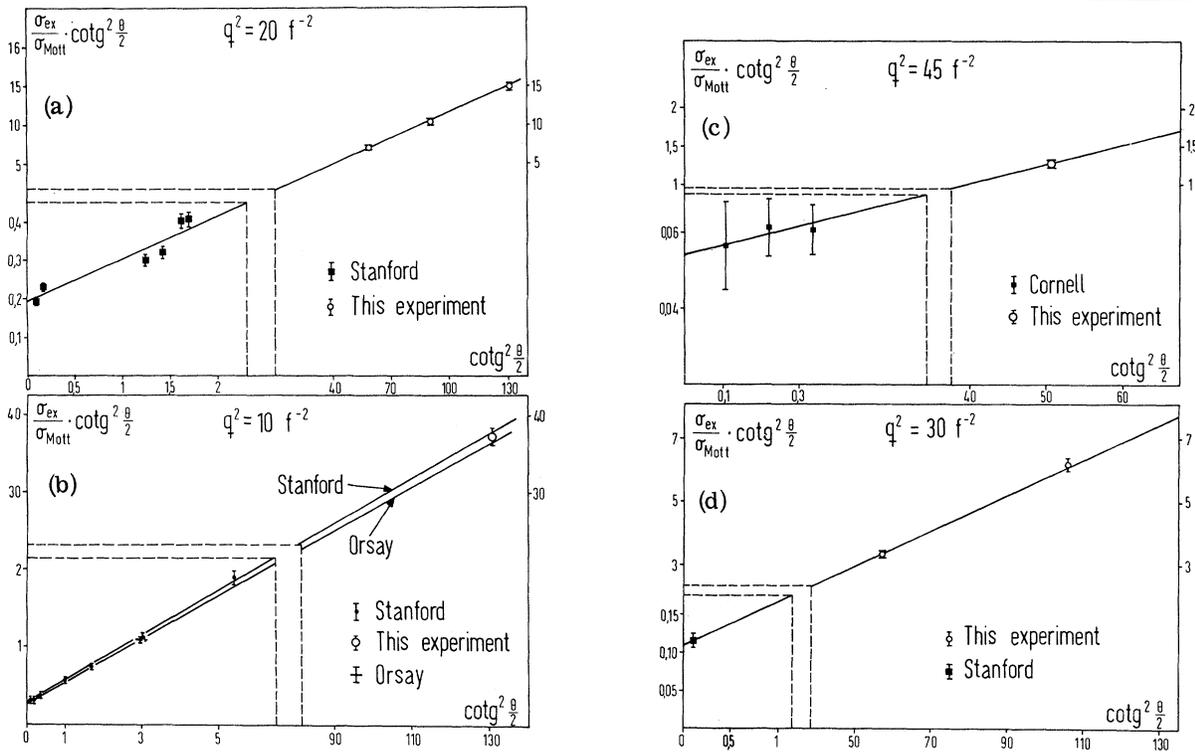


FIG. 2. Rosenbluth plots. (a) for $q^2 = 10 \text{ F}^{-2}$ the two straight-line fits to the Orsay² and Stanford¹ data and our point at $\theta = 10^\circ$. (b) Straight-line fit to our points and the Stanford¹ data at $q^2 = 20 \text{ F}^{-2}$. (c) The same as (b) for $q^2 = 30 \text{ F}^{-2}$. (d) A fit to the large-angle points of the Cornell³ group and our 16° point for $q^2 = 45 \text{ F}^{-2}$.

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