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UPPER LIMITS OF THE PROTON MAGNETIC FORM FACTOR IN THE TIME-LIKE
REGION FROM $\bar{p}p \rightarrow e^+e^-$ AT THE CERN-ISR

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ABSTRACT

From the measurement of e^+e^- pairs from the reaction $\bar{p}p \rightarrow e^+e^-$ at the CERN-ISR, using an antiproton beam and a hydrogen jet target, we derived upper limits for the proton magnetic form factor in the time-like region at $Q^2 \simeq 8.9 \text{ (GeV/c)}^2$ and $Q^2 \simeq 12.5 \text{ (GeV/c)}^2$.

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The study of the proton electromagnetic form factors $F_{1,2}(Q^2)$ is of great importance for the understanding of the structure of this particle. Since the pioneer work of Hofstadter and co-workers in 1955 on the e-p elastic scattering [1], many experiments have produced data [2] on the electromagnetic form factors in the space-like region. On the other hand, in the time-like region, the existing measurements are relatively poor. Antiproton annihilation experiments performed at CERN [3] and BNL [4] gave only upper limits at $Q^2 = + 6.8, + 6.6$ and $+ 5.1$ (GeV/c)². The first positive results were obtained in 1972 for an e^+e^- colliding beam experiment at Frascati [5] at $Q^2 = + 4.3$ (GeV/c)² and was confirmed later by four points in the same energy region, measured at DCI in 1978 [6]. In the inverse channel $\bar{p}p \rightarrow e^+e^-$, the first result was obtained at CERN [7] in 1976. Two points were measured: one at threshold ($Q^2 = 4$ Mp²) and the other at $Q^2 = + 3.61$ (GeV/c)². Finally, a recent measurement at CERN using the LEAR facility [8], confirms the previous threshold measurement.

The data in the time-like region are essential for determining the analytic function $F(Q^2)$ in the whole complex Q^2 -plane. Although the data at/and near the threshold are fundamental, the asymptotic behaviour of the form factors is also very important. For this reason, we have extracted from $\bar{p}p \rightarrow e^+e^-$ data at the CERN-ISR, upper limits of the magnetic form factor G_M (assuming $G_E = 0$) at $Q^2 \simeq 8.86$ (GeV/c)² and $Q^2 \simeq 12.48$ (GeV/c)².

The experiment was primarily devoted to Charmonium spectroscopy through the formation channel $\bar{p}p$ [9]. Electromagnetic final states (e^+e^- , e^+e^-x , $\gamma\gamma$) were chosen in order to have the best signal/noise ratio. The ψ , χ_1 (³P₁), χ_2 (³P₂) and η_c resonances were studied. An attempt to see the singlet ¹P₁ state was made. For the whole study, an inclusive e^+e^- trigger was set during the energy scans and gave data ON and OFF the resonances.

The experiment was performed at the ISR using the CERN $\bar{p}$ complex. The intense $\bar{p}$ beam (few mA) circulating in the ring 2 of the ISR, permanently cooled and interacting with a hydrogen jet-target, allowed to reach a luminosity of 3.10^{30} cm⁻² s⁻¹. With such a luminosity, cross-sections of the order of a few pb, can be measured, corresponding to form factors in the

(0.01 - 0.10) range. The detector [10] is a two-arm non-magnetic spectrometer complemented by a large-acceptance veto system and a silicon detector telescope to monitor the source luminosity. Each of the two identical arms consists of an upstream section for tracking charged particles followed by an electromagnetic calorimeter. Its e^+e^- geometrical acceptance is of the order of 0.10 (of 4π).

At the trigger level, events were selected by requiring an ARM1 * ARM2 coincidence, where ARM1 is a coincidence of a four scintillator hodoscopes and an atmospheric pressure FREON 13 Cherenkov counter to tag electrons.

Data at the J/ψ formation energy through the channel $\bar{p}p \rightarrow e^+e^-$ were accumulated in various runs. In principle these data could allow the relative determination of $|G_E|$ and $|G_M|$ by fitting the center of mass angular distribution, and therefore to test the magnetic form factor dominance predicted by perturbative QCD [11], and observed at the J/ψ by the MARK II Coll. [12]. Unfortunately this dominance, which corresponds asymptotically to a $1 + \cos^2\theta$ distribution, cannot be clearly observed in our data due to the poor angular acceptance [$-0.57 \leq \cos\theta \leq 0.57$]. Nevertheless, we keep this G_M dominance hypothesis and from now on, we assume $G_E = 0$ in the interpretation of the results.

Data near the η_c ($Q^2 = 8.81$ to 8.92 (GeV/c) 2) corresponding to scanning steps ON and OFF the resonance were added for a total integrated luminosity of 653 nb^{-1} (sample I). Since η_c has no direct or high mass (e^+e^-) inclusive decay, taking data on the resonance is completely unambiguous. On the contrary, for the data in the P states region ($Q^2 = 12.32$ to 12.65 (GeV/c) 2), we encounter the problem to distinguish with the apparatus, direct (e^+e^-) pairs from (e^+e^-) pairs coming from the resonance decay, $\bar{p}p \rightarrow P \rightarrow e^+e^- X$ when we are on the resonance. (For example $\chi \rightarrow \psi \gamma$, $\psi \rightarrow e^+e^-$ with an unseen γ). Since in this case we cannot separate the direct $\bar{p}p \rightarrow e^+e^-$ events we have to take into account such events for the upper limits of G_M . Data ON and OFF the P resonances constitute therefore the sample II amounting for a total integrated luminosity of 2276 nb^{-1} .

The analysis chain is described elsewhere [13]. Basically, we request for an e^+e^- candidate, only one well behaved electromagnetic shower in each arm : one charged track in the charged telescope, Cherenkov signal, shower in the calorimeter. In addition, the two-body kinematics will give severe constraints.

At the end, no event from sample I passed through the analysis chain and only one event from sample II is retained. This event, sitting at the χ_1 mass, is also compatible with the hypothesis $\bar{p}p \rightarrow \psi$ (unseen γ), $\psi \rightarrow e^+e^-$.

The results of the analysis are summarized in table I. Assuming G_M dominance, the differential cross-section for $\bar{p}p \rightarrow e^+e^-$ is given by the following relation [14]

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{16} \frac{\alpha^2}{EP} (1 + \cos^2\theta) |G_M|^2$$

where E,P are the antiproton CM energy and momentum and θ the CM angle between electron and $\bar{p}$.

For a given integrated luminosity L, the number of events is

$$N = L \int_{\phi_1}^{\phi_2} d\phi \int_{\cos\theta_1}^{\cos\theta_2} \frac{d\sigma}{d\cos\theta} E(\cos\theta) d\cos\theta$$

where $E(\cos\theta)$ is the total efficiency. The angular dependence of this efficiency can be factorized out: $E = \bar{E} f(\cos\theta)$ where $f(\cos\theta)$ is the acceptance correction function and is due mainly to the edge effects in the Cherenkov counter.

For the estimation of the upper limit of $|G_M|$ we ignore this $f(\cos\theta)$ function and take for E its average value $\bar{E} = 0.94$.

$$N = L \bar{E} \int_{\phi_1}^{\phi} d\phi \int_{\cos\theta_1}^{\cos\theta} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

$$= 0,389 \cdot 10^6 L \bar{E} \Delta\phi \frac{1}{16} \frac{\alpha^2}{EP} |G_M|^2 \left[\cos\theta + \frac{\cos\theta^3}{3} \right]_{\cos\theta_1}^{\cos\theta_2}$$

With E and P in GeV or GeV/c, L in nb⁻¹, $\Delta\phi = \pi/2$.

For the "sample I":

$$\langle Q^2 \rangle = 8.86 (\text{GeV}/c)^2, \cos\theta_2 = -\cos\theta_1 = 0.54$$

$$L = 653 \text{ nb}^{-1}.$$

The $\cos\theta$ values are also averaged values corresponding to $\langle Q^2 \rangle$. If we take $N \leq 2.36$ evts (90% confidence level)

$$|G_M| \leq 0.052 \quad \text{at 90\% CL}$$

$$\text{and} \quad \sigma_T (\bar{p}p \rightarrow e^+e^-) \leq 34.5 \text{ pb}$$

For the "sample II"

$$\langle Q^2 \rangle = 12.48 (\text{GeV}/c)^2, \cos\theta_2 = -\cos\theta_1 = 0.58$$

$$L = 2276 \text{ nb}^{-1}.$$

We observed at best one event i.e. $N \leq 3.89$ at 90% CL

$$\text{Thus} \quad |G_M| \leq 0.042 \text{ at 90\% CL}$$

$$\text{and} \quad \sigma_T (\bar{p}p \rightarrow e^+e^-) \leq 15.0 \text{ pb.}$$

The results are shown in Fig. 1 where the previous results in $|G_M|$ [3,4,5,6,7,8] in this time-like region are also reported.

It is interesting to compare with the QCD prediction for which the asymptotic behaviour, derived on the basis of the general arguments of the quark counting rule [15], is of the form $|G_M| \propto 1/Q^4$.

The solid curve on the figure represents this $1/Q^4$ dependence arbitrarily normalized to the experimental value of $|G_M|$ at $Q^2 = 5 \text{ (GeV/c)}^2$

In conclusion, if we believe in the perturbative QCD and make $1/Q^4$ extrapolations from the actual values of $|G_M|$, we can observe that we are not very far from recording real events corresponding to $\bar{p}p \rightarrow e^+e^-$ and contributing to the proton magnetic form factor in the time-like region. The experimental method we used, seems very promising for this kind of physics.

We would like to mention that we obtained in our experiment, as a by-product of a few weeks of data-taking, lower limits than previous dedicated experiments standing for a long time in classical $\bar{p}$ beams.

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Table I

Sample	I	II
Q^2 range (GeV/c) ²	8.81 - 8.92	12.32 - 12.65
Integrated Luminosity (nb ⁻¹)	653	2276
Number of events	0	1*
σ_T ($\bar{p}p \rightarrow e^+e^-$) (pb)	34.5	15.0
$ G_M $	0.052	0.042

* This event could be a χ_1 event. (see text)

REFERENCES

- [1] R. Hofstadter and R.W. Mc Allister, Phys. Rev. 98 (1955) 217.
- [2] See for example: J.J. Drickey and L. Hand, Phys. Rev. Lett. 9 (1962) 521.
D. Benaksas et al. Phys. Rev. 148 (1966) 1327
T. Janssen et al. Phys. Rev. 142 (1966) 922
K.W. Chen et al. Phys. Rev. 141 (1966) 1267
W. Bartel et al. Phys. Rev. Lett. 17 (1966) 608
W. Albrecht et al. Phys. Rev. Lett. 17 (1966) 1192
M. Goitein et al. Phys. Rev. Lett. 18 (1967) 1016
D.H. Coward et al. Phys. Rev. Lett. 20 (1968) 292
W. Albrecht et al. Phys. Rev. 18 (1967) 1014
H.J. Behrend et al. Nuovo Cimento 48A (1967) 140
D. Yount and J. Pine, Phys. Rev. 128 (1963) 1842.
- [3] M. Conversi et al. Nuovo Cimento 40 (1965) 690.
- [4] D.L. Hartill et al. Phys. Rev. 184 (1969) 1415.
- [5] M. Castellano et al. Nuovo Cimento 14A (1973) 1.
- [6] B. Delcourt et al. Phys. Lett. 86B (1979) 395.
D. Bisello et al. Nucl. Phys. B224 (1983) 379.
- [7] G. Bassompierre et al. Phys. Lett. 68B (1977) 477
G. Bassompierre et al. Nuovo Cimento 73A (1983) 347.
- [8] LEAR Workshop - Tignes 1985.
- [9] C. Baglin et al. CERN-EP/84-145 ; contribution to Leipzig Durham and Santa-Cruz conferences.
- [10] C. Baglin et al. CERN-EP Internal Report 85-01.
- [11] S.J. Brodsky and G.P. Lepage, Phys. Rev. D24 (1981) 2848
M. Claudson et al. Phys. Rev. D25 (1982) 1345.
- [12] M.W. Eaton et al., Phys. Rev. D29 (1984) 804.
- [13] C. Baglin et al. Submitted to Phys. Lett.
J.M. Brom; Thesis to be published at the University of Strasbourg, France.
S. Stapnes; Thesis, Inst. of Physics, University of Oslo, June 1985.
- [14] A. Zichichi et al. Nuovo Cimento 24 (1962) 170.
- [15] D.H. Mueller, Physics. Reports 73 (1981).

FIGURE CAPTION

The proton magnetic form factor $|G_M|$ plotted vs. Q^2 . ∇ ADONE [ref. 5], $\circ$ DCI [ref. 6], $\bullet$ Mulhouse-Strasbourg-Torino [ref. 7], $\blacksquare$ LEAR [ref. 8]. The experimental points and the CERN [ref 3] and BNL [ref 4] upper limits correspond to $|G_M| = |G_E|$. The solid curve is the $1/Q^4$ prediction of $|G_M|$ normalized to the experimental value at 5 (GeV/c)^2 .