Experimental Status Report on Time-Like Baryon Form Factors

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In this paper I report on the experimental situation of baryon form factors in the time-like region. Some unexpected features have been found, such as a steep behaviour near threshold for the proton form factor and a value for $\sigma(e^+e^- \to n\overline{n})$ greater than the one for $\sigma(e^+e^- \to p\overline{p})$. High statistics measurements are called for in order to highlight in this field.

1. INTRODUCTION

Knowledge of the electromagnetic structure of hadrons is still far from complete. In this context the experimental study of the electromagnetic form factors (FF) of nucleons is of great importance. At small q^2 we get information on charge distribution and magnetization current within the nucleon, while at high q^2 form factors probe the valence quark distribution functions. Measurements of form factors are important to test the validity of QCD predictions, from the non-perturbative regime, near threshold, to the perturbative one at large q^2. The time-like region is studied through the reactions

$$p\overline{p} \;\to\; e^+e^- \tag{1}$$

$$e^+e^- \;\to\; N\overline{N} \tag{2}$$

and the experimental situation will be described in this paper. In this region the q^2 is positive and it is equal to the square of the c.m. energy, $q^2 = s$. The differential cross section of reaction (2), expressed in terms of the FF, is given by the formula

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta C}{4s}\left[|G_M|^2\,(1+cos^2\theta) + \frac{4M_N^2}{s}\,|G_E|^2\,sin^2\theta\right] \tag{3}$$

where θ is the c.m. production angle of the nucleon, G_E and G_M the electric and magnetic form factors of the nucleon, α the fine structure constant, β the nucleon velocity in the c.m. system and C the a Coulomb correction factor, which makes the cross section at threshold non-zero. In the time-like region the FF are complex and one obtains $|G_E|$ and $|G_M|$ through equation (3) by measuring the angular distribution of the reaction. At threshold ($q^2 = 4{M_N}^2$) the electric and magnetic form factors are equal, and the angular distribution is isotropic. On the contrary, for very high q^2, the electric contribution is negligible and one can measure only the magnetic FF, with a distribution (1+cos$^2\theta$). Between threshold and high q^2, if one is able to make good measurements of the angular distributions, one can disentangle the two contributions and measure the two FF separately.

On the theoretical side, analyticity relates time-like and space-like FF asymptotically, predicting a continuous transition. Therefore time-like FF at high $|q^2|$ are expected to approach space-like FF and are expected to be real. The same predictions are done by QCD, which predicts also that for large momentum transfer $q^4|G_M|$ should be nearly proportional to the square of the running coupling constant for strong interactions $\alpha_s^2(q^2)$ [1]. The square of the ratio between neutron and proton FF is predicted by QCD to be 0.25, i.e. the square of the ratio between the charge of down and up quarks. This prediction is expected to hold also near the threshold region, based on QCD and dispersion relations. In general any prediction where the nucleon is mostly represented in terms of valence quarks should hardly foresee a value for the neutron FF bigger than the one for the proton. Data near threshold are usually compared with predictions of phenomenological models, in particular the Vector Meson Dominance (VMD) models which assume the photon to be coupled to hadrons through intermediate vector meson. The FF are then sensitive, particularly near threshold, to the existence of any hadron with the photon quantum numbers ($J^{PC} = 1^{--}$), like vector meson in non physical region ($q^2 < 4{M_N}^2$) or nuclear states generated by $N\overline{N}$ potential.

2. PROTON TIME-LIKE FORM FACTORS

In this section I will report results on the proton time-like FF. First I will describe measurements done near threshold, then measurements at higher values of q^2.

2.1. Near threshold region

The most precise data about proton FF near threshold, through reaction (1), come from the PS170 experiment [2] done at Low Energy Antiproton Ring (LEAR) at CERN. It used the antiproton beam from LEAR (with a momentum ranging from 300 MeV/c to 900 MeV/c) and a liquid hydrogen target. The apparatus mainly consisted of the target surrounded by multiwire proportional chambers (immersed in a magnetic field of 1.2 T), a Čerenkov counter, two layers of drift tubes, two

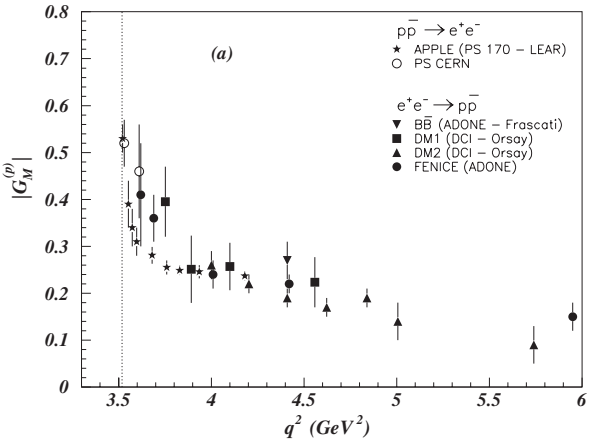

Figure 1: The proton magnetic form factor versus q^2: the low energy region.

scintillator hodoscopes and a shower detector. The number of collected e^+e^- events (more than three thousand) is more than one order of magnitude bigger than the ones collected by other experiments. The proton FF values, measured in the hypothesis $|G_E^p|$=$|G_M^p|$, are shown in Figure 1, together with the results of other experiments [3–7].

At each energy results of all experiments are compatible, but due to the good accuracy of PS170 data, a steep dependence of $|G_M^p|$ with the energy is clearly outlined close to the threshold, whereas in the region 3.8 GeV^2 $< s <$4.2 GeV^2 one can recognize an almost flat behaviour.

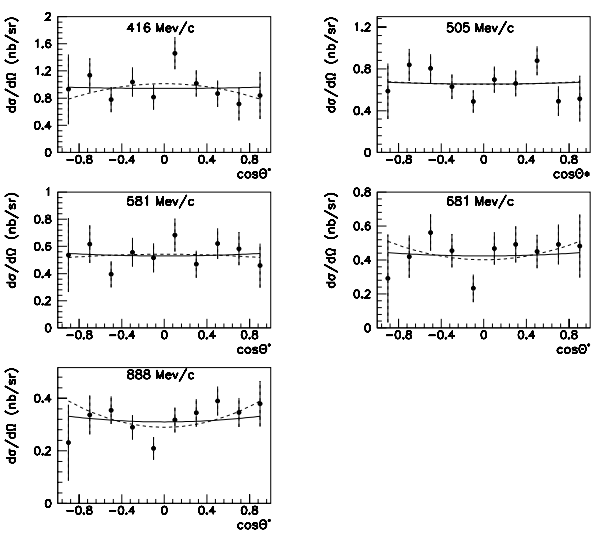

Figure 2: Differential cross sections for $p\overline{p} \to e^+e^-$ events from PS170 experiment. The full line is the fit of data with $|G_E^p|$=$|G_M^p|$. The dashed line fits the data with indipendent $|G_M^p|$ and $|G_E^p|/|G_M^p|$.

The experiment provided for the first time a measurement of the differential cross section of the reaction, to observe possible differences between $|G_E^p|$ and $|G_M^p|$. Figure 2 shows the differential cross sections for $p\overline{p} \to e^+e^-$ events at each of the five higher beam momenta. The full line corresponds to $|G_E^p| = |G_M^p|$, the dashed line to a fit with $|G_M^p|$ and $|G_E^p|/|G_M^p|$ both indipendent. The values of $|G_E^p|$ and $|G_M^p|$ are very similar, within the quoted errors. Then in this energy range the $|G_E^p|/|G_M^p|$ ratio is compatible with 1, even if there is an indication of its decrease with energy. But to be more conclusive, higher statistics are needed.

2.2. High Energy Region

Measurements of the proton time-like FF at large momentum transfers have been done by the Fermilab experiment E760 [8]. New, improved measurements of the cross section for the reaction (1) have been reported by experiment E835 [9], which used an upgraded version of the E760 apparatus. The experiment, dedicated to the study of charmonium by resonant formation in $p\overline{p}$ annihilations, has been carried out at the antiproton accumulator at Fermilab, with the antiproton beam which intersects an internal hydrogen gas jet target. The E835 apparatus has been designed to detect electromagnetic final states. It is a non-magnetic spectrometer with cylindrical symmetry around the beam axis. Its main components are a lead glass calorimeter, a threshold Čerenkov counter, an inner tracking system and a luminosity monitor.

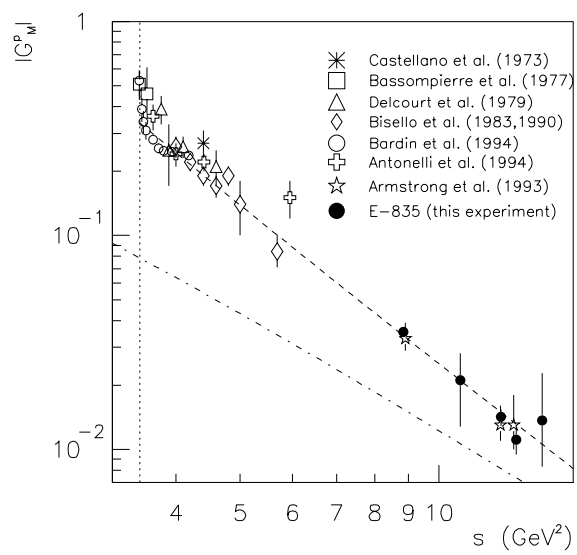

Figure 3: The proton magnetic form factor versus q^2. The dashed and dot-dashed curves are explained in the text.

The values of $|G_M^p|$, obtained under the assumption $|G_E^p| = |G_M^p|$, are plotted in Figure 3, where they are compared with E760 results and with earlier measurements. The dashed line in Figure 3 shows a fit to the data in the form

$$|G_M| = \frac{A}{s^2 ln^2(s/\Lambda^2)} \tag{4}$$

where Λ=0.3 GeV is the QCD scale parameter and A is a free parameter. This functional form comes from the already discussed perturbative QCD prediction. It can be seen that

the fit reproduces the main q^2 dependence of the data over the entire range explored so far. The dipole behaviour of the FF in the space-like region is also plotted in Figure 3 (dot-dashed line). It is to be noted that the numerical values of $|G_M^p|$ in the region explored by E835 experiment are approximately twice as large as those in the corresponding space-like region.

3. NEUTRON TIME-LIKE FORM FACTORS

Neutron form factors in the time-like region have been measured only by FENICE experiment [10] at the ADONE e^+e^- storage ring in Frascati. They were measured through the reaction $e^+e^- \to n\overline{n}$, with the identification of the $\overline{n}$ annihilation. The FENICE apparatus was a non-magnetic detector, whose main components were limited streamer tubes as tracking devices, scintillation counters as timing and triggering devices and thin iron plates as distributed converters where antineutrons annihilate. The many charged prongs topology of annihilations and the relatively long time of flight between production and annihilation were the signatures that allowed for the identification of candidate events. No neutron signature was required, because of the rather low neutron detection efficiency.

Figure 4 shows the neutron magnetic form factor, extracted from the data in the hypothesis $|G_E^n|$=0, which seems to be preferred by the data, as will be discussed later. The result is based on 74 events for a total integrated luminosity of 0.4 pb^{-1}. The lowest q^2 result is shown as a shaded area between two points corresponding to two different hypotheses on the c.m. energy: for $\sqrt{s}$=1.90 GeV there is no signal and only an upper limit on FF is given. Assuming a positive shift in the c.m. energy of a few MeV, as suggested by data, a significant signal is present (see [10] for details). The dotted line shown in Figure 4 corresponds to a parameterization of the proton magnetic FF. Then in this energy region $|G_M^n|/|G_M^p|$ is greater than 1, whereas perturbative QCD [11,12], analyticity [13] and dispersive approaches [14,15] expect a ratio less than 1. On the contrary, in most of the VMD models the neutron FF turns out to be larger or equal to the proton one.

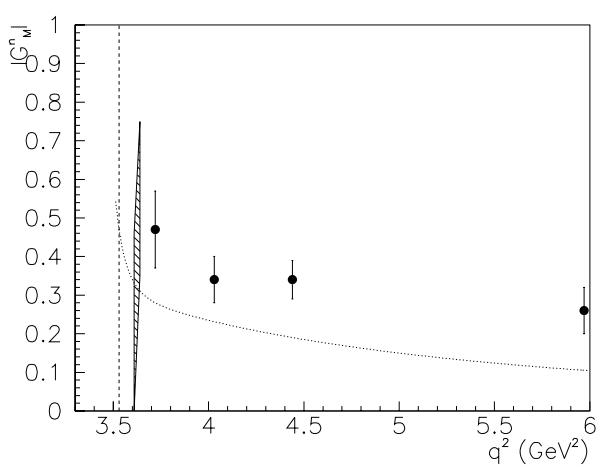

Figure 4: The neutron magnetic form factor versus q^2. The dotted line is a parameterization of the proton FF.

Figure 5 shows the $|\cos(\theta)|$ distribution summed over all energies for the $n\overline{n}$ events (Figure 5a) and for background events (Figure 5b). The two distributions show that $|\cos(\theta)| < 0.7$ is approximately the cut imposed by the acceptance of the detector. Moreover Figure 5a shows an indication of a dip around $\cos(\theta)$=0, which is not present in Figure 5b. Fitting the distribution of Figure 5a with the function A(1+$\cos^2\theta$) + B $\sin^2\theta$, where A and B are positive free parameters, the best fit is obtained for B=0 (see Figure 5a). This means that the $|\cos(\theta)|$ distribution indicates $|G_E^n|/|G_M^n|$ to be close to 0. On the contrary, the background has a flat distribution. Also distribution for $e^+e^- \to p\overline{p}$ events is flat, in agreement with the hypothesis $|G_E^p| = |G_M^p|$

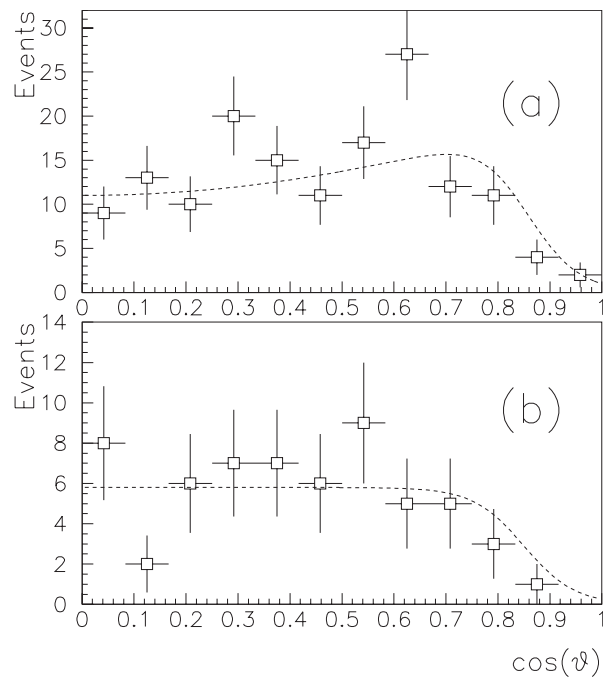

Figure 5: Angular distributions of (a) $n\overline{n}$ events; (b) background events. The dotted lines are the result of the fits.

4. THE TOTAL MULTIHADRONIC CROSS SECTION NEAR THE NUCLEON-ANTINUCLEON THRESHOLD

Figure 6a shows the total multihadronic cross section from the FENICE experiment, together with the average of data from previous experiments. A narrow resonance interfering with the background given by broad resonances can generate the observed dip in the multihadronic cross section just below the nucleon-antinucleon threshold as well as the steep behaviour of the time-like proton FF near threshold (Figure 6b). The parameters of this state, that could be interpreted as a $N\overline{N}$ bound state, are M=(1.87 $\pm$ 0.01) GeV, Γ=(10 $\pm$ 5) MeV.

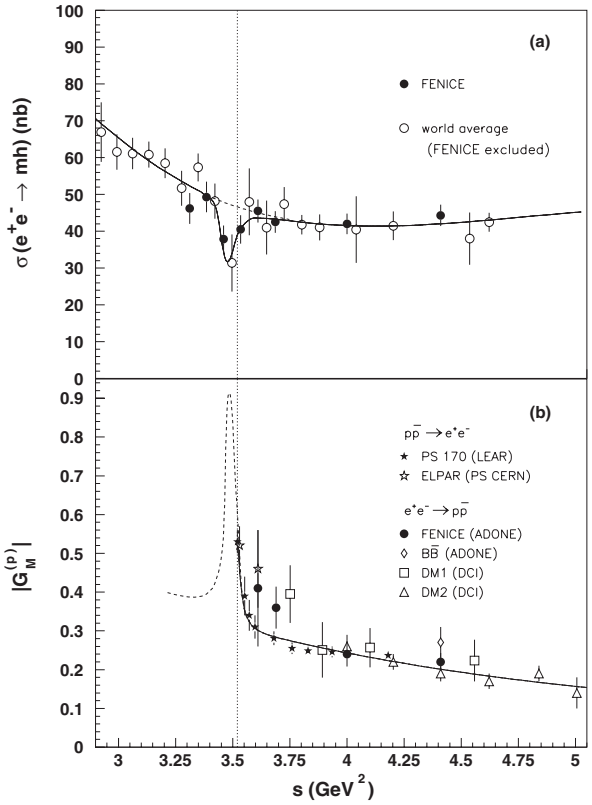

Figure 6: (a) Total multihadronic cross section (FENICE data and the average over previous experiments) with superimposed the result of the fit to a narrow resonance close to the $N\overline{N}$ threshold; (b) comparison of the proton FF data to the expected behaviour for the presence of such a resonance.

A similar structure has been detected by the DM2 experiment [16], as shown in Figure 7, in the $e^+e^- \to 6\pi$ channel, which is the multihadronic channel with the largest cross section at these c.m. energies. It has also been observed by E687 at FNAL in diffractive photoproduction of $3\pi^+3\pi^-$ [17].

5. OTHER BARYON TIME-LIKE FORM FACTOR MEASUREMENTS

There are essentially no measurements about other baryon form factors in the time-like region. Only Λ form factor has been measured by the DM2 experiment with poor statistical accuracy. The anomalies in the space-like Δ data could be clarified by time-like measurements. Hyperon form factors are related to the nucleons one by flavour symmetry, and accurate predictions of flavour-symmetry breaking is another important test of QCD.

6. NEW MEASUREMENTS AT PEP-N

A new measurement of nucleon form factors in the time-like region, through the reaction (2), is being proposed. Also

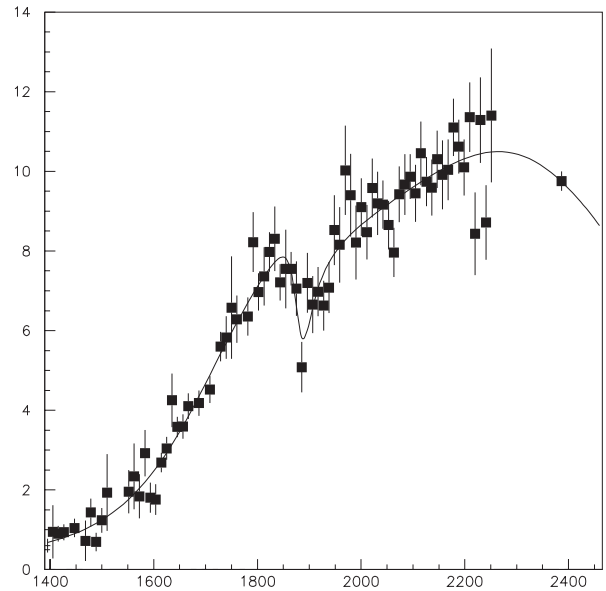

Figure 7: Cross section for the reaction $e^+e^- \to 6\pi$ measured by the DM2 experiment.

baryon FF, with the annihilation of e^+e^- into a baryon-antibaryon pair, and transition FF will be measured. The configuration which we are studying is the one with asymmetric e^+e^- collisions. The advantage of such a configuration is that the neutron should have sufficient energy, through Lorentz boost, to produce an hadronic shower. This, in addition to the many charged prongs topology of antineutron annihilations, will identify the reaction (2) against the background. The PEP-N experiment will have an excellent capability in the time-like form factor field [18]: as an example, for the neutron FF, all the existent statistics will be collected in less than one day of data taking.

7. CONCLUSIONS

Unexpected experimental features have been observed in the time-like region; some of them are summarized in the following.

- A value for $\sigma(e^+e^- \to n\overline{n})$ greater than the one for $\sigma(e^+e^- \to p\overline{p})$ has been found.
- The proton magnetic FF shows a steep behaviour near threshold.
- There are indications that the electric contribution for the neutron is negligible.This should imply a steep $|G_E^n|$ decrease after threshold, where $|G_E^n|$ and $|G_M^n|$ are equal.
- The steep FF behaviour suggests a relatively narrow structure at the boundary of the unphysical region, which should be also seen in multihadronic e^+e^- annihilation across the $N\overline{N}$ threshold. Anomalies are indeed seen in some multihadronic e^+e^- cross sections.

All these features needs to be confirmed and understood. PEP-N experiment will have an excellent capability in this field.

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