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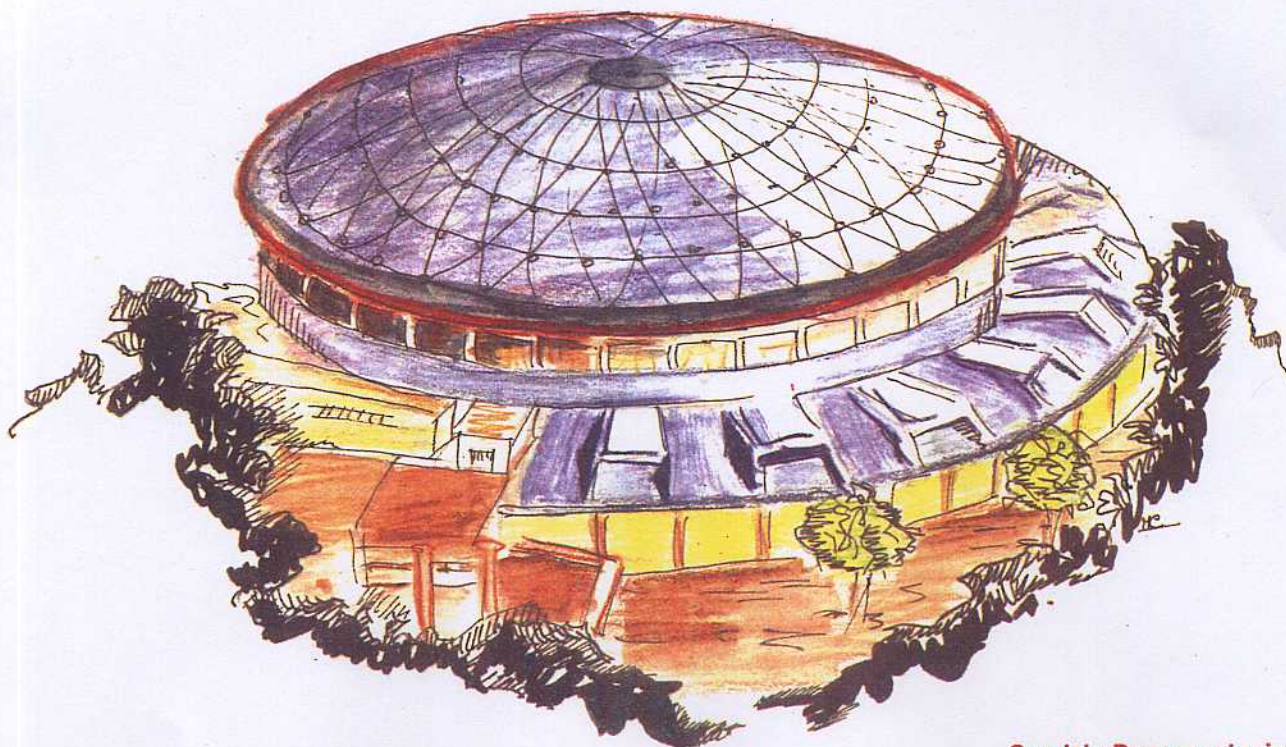
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FIRST MEASUREMENT OF THE NEUTRON ELECTROMAGNETIC FORM FACTOR IN THE TIME-LIKE REGION

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First measurement of the neutron electromagnetic form factor in the time-like region

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Abstract

The first measurement of the neutron form factor in the time-like region has been performed by the FENICE experiment at the ADONE e^+e^- storage ring. Results at $q^2 = 4.0$ and $4.4 (GeV/c)^2$, together with a new measurement of the proton form factor are presented here.

The understanding of the nucleon structure is still an open and fundamental problem [1]. In spite of the large amount of data collected on proton space-like form factors, only recently high precision data on the neutron space-like form factors became available up to $q^2 \sim -4M_n^2$ [2]. Likewise in the time-like region the proton form factor has been measured at low q^2 [3], but only recently results [4] were obtained at high q^2 and before this experiment there was no experimental information at all on the neutron time-like form factors.

Through the cross section measurement of the annihilation process

$$e^+e^- \rightarrow N\bar{N}$$

the nucleon time-like electromagnetic form factors G_E^N and G_M^N can be extracted [5]:

$$\left(\frac{d\sigma}{d\Omega}\right)_{CM} = \frac{\alpha^2\beta}{4q^2} \left[|G_M^N|^2(1 + \cos^2\theta) + \frac{4M_N^2}{q^2} |G_E^N|^2 \sin^2\theta \right].$$

They are supposed to be the analytic continuation of the corresponding space-like form factors and it is expected that $G_E(4M_N^2) = G_M(4M_N^2)$, according to S-wave dominance at threshold.

Very different predictions on the behaviour of the neutron form factor in the time-like region are given by Perturbative QCD (PQCD), Extended Vector Meson Dominance Models (EVMD) and other theoretical models. For instance according to PQCD in the nucleon there is a leading quark carrying nearly 60% of the total momentum, like a quark-diquark system. Therefore PQCD expects [6]: $r = \sigma(e^+e^- \rightarrow n\bar{n})/\sigma(e^+e^- \rightarrow p\bar{p}) \simeq 0.25$ and, as a matter of fact, PQCD is considered reliable at $q^2 \sim -4M_N^2$. EVMD inspired fits [7] to the space-like data predict $r = 1 \div 100$ depending on the location of the vector meson recurrences, which are not yet well established. Moreover, Skyrme models [8] predict $r \sim 1$.

The FENICE experiment has been settled in Frascati at the ADONE storage ring, restored as e^+e^- collider, in order to perform for the first time the measurement of the neutron form factor in the time-like region via reaction

$$e^+e^- \rightarrow n\bar{n}. \quad (1)$$

FENICE results have already been published [13], concerning a significant improvement in the measurement of the $J/\psi \rightarrow n\bar{n}$ branching ratio.

The detector is fully described elsewhere [9]. In short, it is a non magnetic detector consisting of layers of limited streamer tubes, scintillation counters and iron plates. The antineutrons are detected in the limited streamer tubes by means of their annihilation on nuclei, characterized by a typical 'star' topology. Their velocity can be determined from the scintillation counters by the time of flight (TOF) [10] with respect to the beam crossing time. Only in a fraction of events the neutron is detected by thick scintillation counters, with an efficiency ranging from 10 to 40% [11] for neutron kinetic energy ranging from 50 to 500 MeV.

In order to reduce the rate of cosmic ray events interacting in the detector, the whole apparatus is surrounded by a 100-cm thick concrete shield equipped with a double layer of Resistive Plate Counters (RPC) [12] used as a veto in the trigger for reaction (1). The trigger signals are provided by scintillation counters and RPC; other logic triggers have also been implemented for $\mu^+\mu^-$ and multi-hadronic final states. The trigger rate was about 10 Hz and the dead time due to data acquisition was 3%.

Data have been taken below the $n\bar{n}$ threshold, at 1900, 1920, 2000, 2100, 2440 MeV/c in the center of mass, and at the formation energy of the J/ψ . The average luminosity was $\sim 10^{29} \text{cm}^{-2} \text{s}^{-1}$, with one bunch and a mean lifetime of about 4 hours and it was continuously monitored by a single bremsstrahlung detector located in the interaction region. Bhabha events collected in the detector agree with this luminosity measurement within 5%.

The analysis described in the following refers to a first sample corresponding to an integrated luminosity of 31.9nb^{-1} at $q^2 = 4.0 (\text{GeV}/c)^2$ and 37.3nb^{-1} at $q^2 = 4.4 (\text{GeV}/c)^2$, that is about 30% of the total statistics collected at these energies.

A filter [15] of the data has been performed in order to reject cosmic ray events escaping the veto system and beam-beam, beam-pipe background events. This is done

using the tracking information given by the limited streamer tubes and the TOF from the scintillation counters. Besides $n\bar{n}$, other channels (e^+e^- , $\mu^+\mu^-$, $\gamma\gamma$, $p\bar{p}$ and multi-hadronic events) have been selected for monitoring purposes or for their physical interest. Events from reaction (1) have been selected through the identification and reconstruction of the charged prongs of the antineutron annihilation star and its corresponding TOF, following the same procedure used in the selection of $J/\psi \rightarrow n\bar{n}$ events [13].

From a final visual inspection two samples of 32 and 37 $n\bar{n}$ candidate events have been selected at $q^2 = 4.0 (GeV/c)^2$ and $q^2 = 4.4 (GeV/c)^2$ respectively. The velocity $\beta_{\bar{n}}$ of each event is determined from the position of the annihilation vertex and from its time of flight with respect to the beam crossing time. The $1/\beta_{\bar{n}}$ distributions of the candidate events at $q^2 = 4.0 (GeV/c)^2$ (fig.1a) and at $q^2 = 4.4 (GeV/c)^2$ (fig.1b) show a peak corresponding to the expected values of the \bar{n} signal at these energies.

At $q^2 = 4.0 (GeV/c)^2$ the only background source comes from very energetic cosmic neutrons which interact in the detector simulating an antineutron star. The shape of this background component is obtained from cosmic ray events that passed the same selection criteria. At $q^2 = 4.4 (GeV/c)^2$ together with this cosmic ray background a further background is allowed, due to events from the reaction $e^+e^- \rightarrow n\bar{n}\pi^0$ where the photons from the π^0 decay either escape detection or are hidden in the annihilation star. In these events the antineutrons are less energetic hence their $1/\beta_{\bar{n}}$ distribution is displaced with respect to events from reaction (1). Both the distributions are therefore fitted with a gaussian for the signal added to a function describing these background events. From the fit the number of $n\bar{n}$ events $N_{n\bar{n}}$ is obtained, as reported in table (1).

The numbers of cosmic ray events found in the $1/\beta_{\bar{n}}$ distributions at the different energies are consistent with the corresponding running times.

As a further check of the background subtraction procedure, data have been collected below the $n\bar{n}$ production threshold, at a center of mass energy range from 1820 MeV to 1880 MeV. A sample of 15 nb^{-1} has been analysed using the $n\bar{n}$ selection criteria described above. A total number of 12 candidate events has been selected: as expected, their $1/\beta_{\bar{n}}$ distribution, shown in fig.1c, does not show any significant structure and is consistent in shape and number with the estimated cosmic ray background events.

In order to measure the proton form factor and make a comparison with the neutron form factor, also events from reaction

$$e^+e^- \rightarrow p\bar{p} \quad (2)$$

have been selected. At $q^2 = 4.4 (GeV/c)^2$ the whole collected data has been analysed and preliminary results are reported here. At this energy events from reaction (2) are identified by two back to back charged tracks pointing to the interaction region, one of them ending with an antiproton annihilation star, which is identified using the same criteria used for the antineutron star. The number $N_{p\bar{p}}$ of $p\bar{p}$ events is obtained from the $1/\beta_{\bar{p}}$ distribution, shown in fig. 2, which is consistent with Montecarlo expectation. The cosmic rays background turns out to be negligible.

The detection efficiencies $\epsilon_{n\bar{n}}$ and $\epsilon_{p\bar{p}}$ for events from reaction (1) and (2) respectively have been obtained from Montecarlo events and are reported in table (1). Using the assumption $G_E = G_M = G$ which is consistent with the angular distributions and with $p\bar{p} \rightarrow e^+e^-$ data [14], the value of the form factors $|G^n|$ and $|G^p|$ can be extracted from the measured cross sections. The results obtained, for the neutron at $q^2 = 4.0 (GeV/c)^2$ and

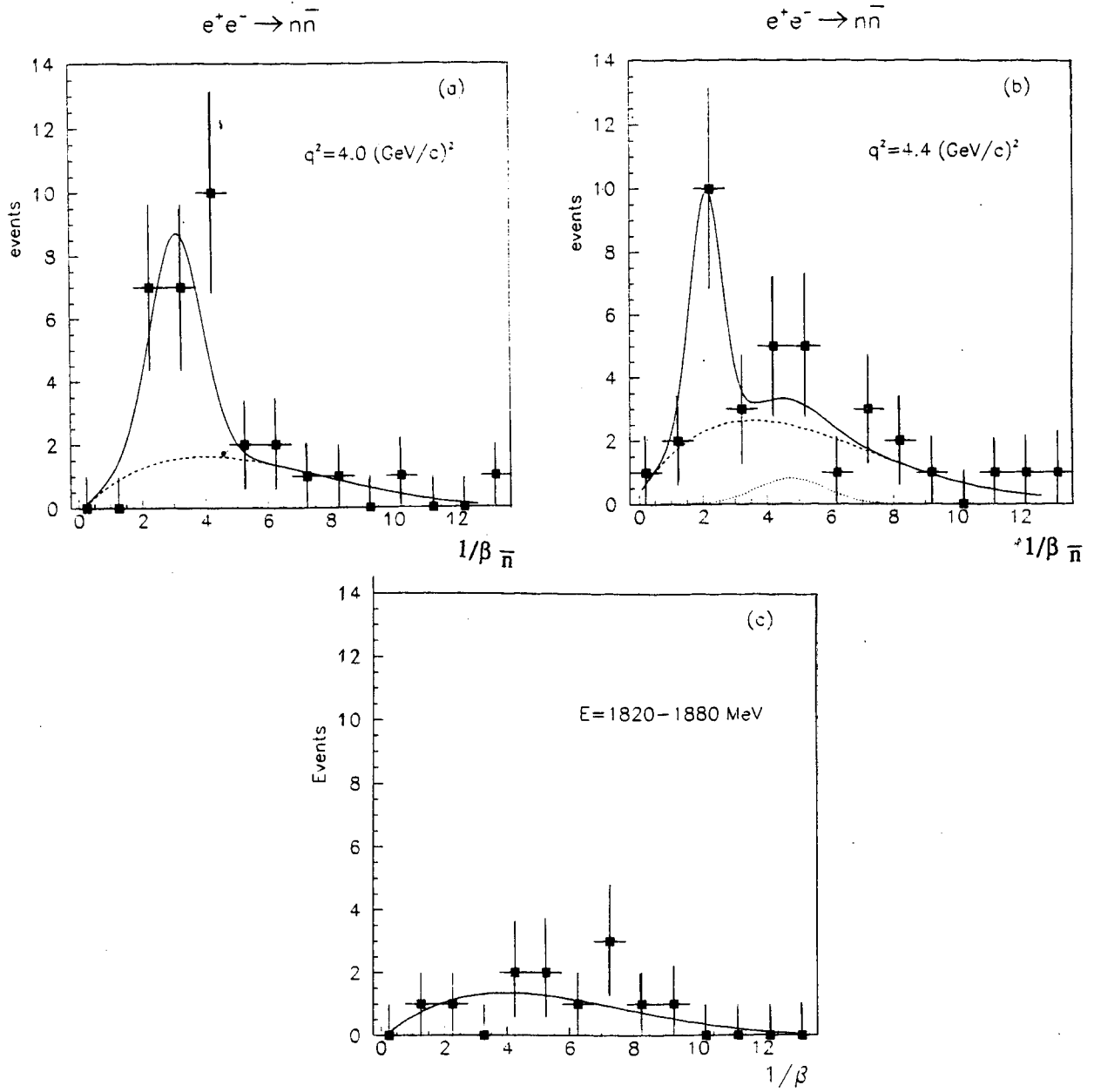


FIG. 1 – The $1/\beta_{\bar{n}}$ distribution of the candidate events for reaction (1) at $q^2 = 4.0 \text{ (GeV/c)}^2$ (a), $q^2 = 4.4 \text{ (GeV/c)}^2$ (b), and at a center of mass energy range below the $n\bar{n}$ production threshold (from 1820 MeV to 1880 MeV) (c). The continuous line is the overall fit to the data, the dashed line is the cosmic ray background, the dotted line is the prediction for events coming from $e^+e^- \rightarrow n\bar{n}\pi^0$ at $q^2 = 4.4 \text{ (GeV/c)}^2$.

TABLE 1

$q^2(\text{GeV}/c)^2$	4.0	4.4
	neutron	
$\mathcal{L}_{\text{analysed}} (nb^{-1})$	31.9 ± 1.6	37.3 ± 1.9
$N_{n\bar{n}}$	14 ± 5	13 ± 6
$\epsilon_{n\bar{n}}$	0.31 ± 0.03	0.41 ± 0.04
$\sigma(e^+e^- \rightarrow n\bar{n}) (nb)$	$1.42 \pm 0.51 \pm 0.15$	$0.85 \pm 0.39 \pm 0.10$
$ G^n $	$0.37 \pm 0.07 \pm 0.02$	$0.26 \pm 0.06 \pm 0.01$
	proton	
$\mathcal{L}_{\text{analysed}} (nb^{-1})$		100.3 ± 5.0
$N_{p\bar{p}}$		28 ± 5
$\epsilon_{p\bar{p}}$		0.42 ± 0.04
$\sigma(e^+e^- \rightarrow p\bar{p}) (nb)$		$0.66 \pm 0.11 \pm 0.07$
$ G^p $		$0.23 \pm 0.02 \pm 0.01$

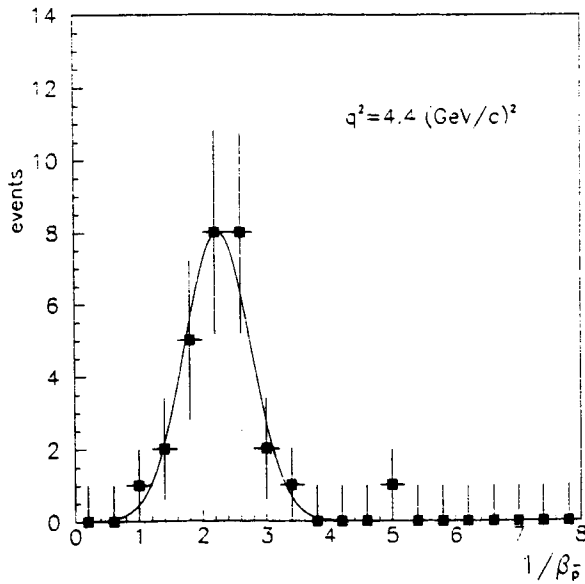


FIG. 2 - The $1/\beta_p$ distribution for candidate events of reaction (2). The continuous line is the gaussian fit to the data.

$q^2 = 4.4 (GeV/c)^2$ and for the proton at $q^2 = 4.4 (GeV/c)^2$, are summarized in table (1), where the first quoted error is statistical and the second one is due to systematics.

The first results on neutron and proton form factors, obtained by the FENICE collaboration, are reported as a function of q^2 in fig. 3, where they are compared to the previously measured values of the proton form factor at low q^2 .

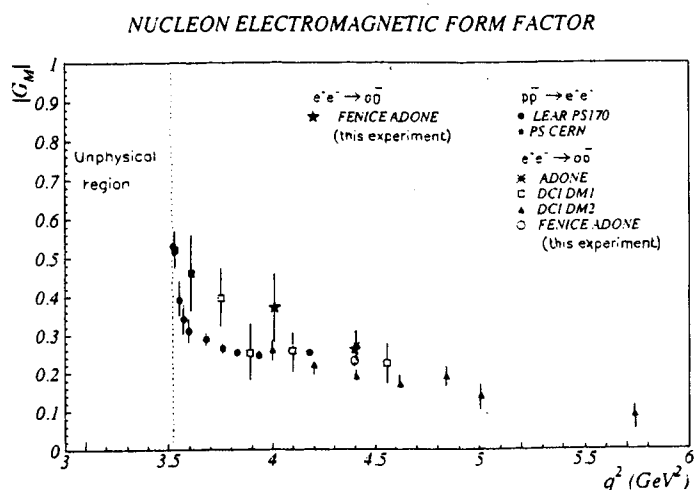


FIG. 3 - The first results on the neutron form factor and the new measurement of the proton form factor in the time like region are compared with previously measured values of the proton form factor at low q^2 .

The measured value of $|G^p|$ is in good agreement with the earlier experimental data [16]. From the comparison of the two measured values of $\sigma(e^+e^- \rightarrow n\bar{n})$ with the overall $\sigma(e^+e^- \rightarrow p\bar{p})$, it is possible to conclude that $r \geq 1$. When the analysis of all the data collected at the different c.m. energies will be completed, it will be possible to see whether r is energy dependent or consistent with 1, in agreement with some EVMD and Skyrme-inspired predictions, but considerably different from simple PQCD expectations.

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