

Measurement of the timelike neutron and proton form factors at VEPP-2000

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Abstract: Results are presented of the study of the $e^+e^- \rightarrow n\bar{n}$ and $e^+e^- \rightarrow p\bar{p}$ reactions in the energy range from the nucleons production threshold up to 2 GeV. The measurements have been performed at the VEPP-2000 e^+e^- collider with the SND and CMD-3 detectors using the events collected during the data taking runs of 2011 and 2012. Also discussed here are the obtained electromagnetic form factors of nucleons and future plans of these results improvement.

Key words: proton; neutron; electromagnetic form factor; e^+e^- annihilation; SND; CMD-3

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VEPP-2000 上类时中子和质子形状因子的测量

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摘要: 利用正负电子对撞机 VEPP-2000 上 SND 和 CMD-3 探测器从 2011 至 2012 年获取的对撞数据, 给出了从产生阈值到 2 GeV 能区 $e^+e^- \rightarrow n\bar{n}$ 和 $e^+e^- \rightarrow p\bar{p}$ 的实验结果. 同时, 讨论了核子的电磁形状因子, 并对结果的改进进行了展望.

关键词: 质子; 中子; 电磁形状因子; 正负电子淹没; SND; CMD-3

0 Introduction

Electromagnetic interaction of the nucleons (neutrons and protons) can be described with two complex functions of transferred momentum, the electric form factor $G_E(s)$ and the magnetic form factor $G_M(s)$. In the timelike region above nucleons production threshold ($s > 4M_N^2$) this

functions can be partially extracted from the total cross section and the angle distribution in the annihilation processes $e^+e^- \rightarrow p\bar{p}$ and $e^+e^- \rightarrow n\bar{n}$.

The early results were obtained by the BaBar^[1] and PS170^[2] experiments for protons and in the FENICE^[3] experiment for neutrons. In this paper we review the results from the CMD-3 and SND detectors for the process $e^+e^- \rightarrow p\bar{p}$, and the

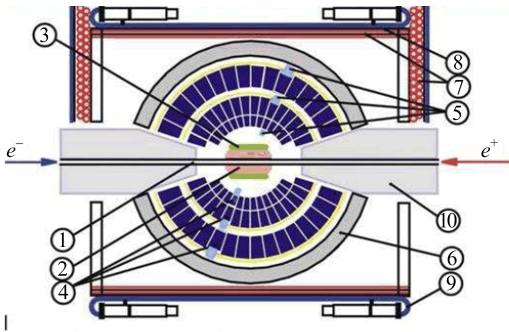
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result from the SND detector for process $e^+e^- \rightarrow n\bar{n}$. The data were collected at the VEPP-2000 collider^[4] during the data taking runs in 2011 and 2012 at the center of mass energy range 1.8~2.0 GeV. The collider allows to study e^+e^- collisions at the center of mass energy range 0.3~2.0 GeV with the luminosity in the studied region (~ 1.8 GeV) $L \approx 0.7 \times 10^{31} \text{ cm}^{-2} \cdot \text{sec}^{-1}$ and the energy spread $\delta E \approx 0.6$ MeV. The detectors are located in the opposite sides of the VEPP-2000 collider. The data are being collected in parallel.

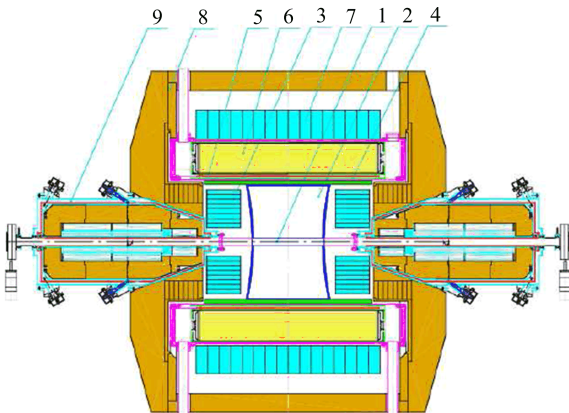
The SND^[5-9] (Fig. 1) detector includes the drift chamber (DC), the three layer electromagnetic (EMC) NaI(Tl) calorimeter and the muon system.



1 - beam pipe, 2 - tracking system, 3 - aerogel cherenkov counter,
4 - NaI(Tl) crystals, 5 - phototriodes, 6 - iron muon absorber,
7~9 - muon system, 10 - VEPP-2000 solenoids

Fig. 1 The SND layout

The CMD-3 detector^[10-11] (Fig. 2) includes the drift chamber in the 1.3 T magnetic field, EMC



1 - vacuum chamber, 2 - drift chamber, 3 - BGO calorimeter,
4 - Z-chamber, 5 - SC solenoid, 6 - LXe calorimeter,
7 - CsI calorimeter, 8 - yoke, 9 - VEPP-2000 solenoids

Fig. 2 CMD-3 layout

calorimeter consisting of BGO endcap and two barrel layers, LXe and CsI. It also includes the muon system.

The integrated luminosity collected in the region of interest is $\sim 8.7 \text{ pb}^{-1}$ and summarized in Tab. 1.

Tab. 1 The integrated luminosity

experiment	IL/pb ⁻¹	IL($\sqrt{s} > 1.88$ GeV)/pb ⁻¹
12. 2010~06. 2011	25	3.8
01. 2012~04. 2012	17	4.9
total	43	8.7

The differential cross section of the process $e^+e^- \rightarrow N\bar{N}$ can be expressed as a function of transferred momentum squared (s) and polar angle (θ):

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

where C is the Coulomb factor^[12] taking values $C=1$ for neutron and $C \approx \frac{\pi\alpha}{\beta} (1 - e^{-\frac{\pi\alpha}{\beta}})$ for proton, M_N is the nucleon mass, $G_M(s)$ and $G_E(s)$ are electric and magnetic form factors.

The full cross section then can be written as:

$$\sigma(s) = \frac{4\pi\alpha^2 \beta C}{3s} \left(|G_M(s)|^2 + \frac{2M_N^2}{s} |G_E(s)|^2 \right) \quad (2)$$

It is convenient to use also “effective form factor” for comparison of the results from the different experiments:

$$F(s) = \frac{|G_M(s)|^2 + \frac{2M_N^2}{s} |G_E(s)|^2}{1 + \frac{2M_N^2}{s}} \quad (3)$$

The measured event distribution from $\cos\theta$ can be used to obtain the ratio of electrical and magnetic form factors $\frac{G_E(s)}{G_M(s)}$.

1 CMD3 and SND $p\bar{p}$ measurements

The selection procedure of $p\bar{p}$ events depends on the proton energy. Close to the kinematic threshold both protons and antiprotons stop in the beam pipe material with loss of the proton,

while the antiproton gives an annihilation star. For the higher proton energy both the proton and the antiproton cross drift chamber, giving high dE/dX tracks. Then antiproton gives an annihilation star in the outer wall of the drift chamber.

The main criteria for selecting $p\bar{p}$ events at CMD-3 and $E_{\text{beam}} < 950$ MeV (near the threshold), are the following^[13]: 4 or more tracks with a common vertex found in the beam pipe material; no tracks with energy deposition in calorimeter higher than 400 MeV. At $E_{\text{beam}} \geq 950$ MeV two opposite-charge collinear central tracks in DC are required; the track momentum values are limited as $\frac{|p_1 - p_2|}{|p_1 + p_2|} < 0.15$ (< 0.2 for $E_{\text{beam}} < 955$ MeV), and the total energy deposition in the calorimeter is > 200 MeV.

The criteria at SND and $E_{\text{beam}} < 960$ MeV are the following (preliminary): exactly 3 tracks with a common vertex located in the beam pipe material, and no other tracks (proton is not registered). At $E_{\text{beam}} \geq 960$ MeV two collinear central tracks in DC with large dE/dx are required, the total energy deposition in the calorimeter is > 650 MeV, one of the tracks should not have any associated calorimeter cluster.

The $p\bar{p}$ cross sections ($\sigma_{p\bar{p}}$) were obtained from the well known expression:

$$N = \epsilon \delta \sigma_{p\bar{p}} \cdot L \quad (4)$$

where N is the number of events, L is the integrated luminosity, ϵ is the detection efficiency, and δ is the radiative correction. The systematic uncertainty is estimated to be 6% for CMD-3 and 7% for SND.

Fit of the $\cos \theta$ distribution to extract $\frac{G_E}{G_M}$ is also made for both experiments. The results are $\frac{G_E}{G_M} = 1.49 \pm 0.23 \pm 0.3$ at CMD-3^[13] and $\frac{G_E}{G_M} = 1.64 \pm 0.26$ at SND (preliminary result).

The cross sections for the CMD-3^[13] and the SND (preliminary) are shown in Fig. 3 and Fig. 4.

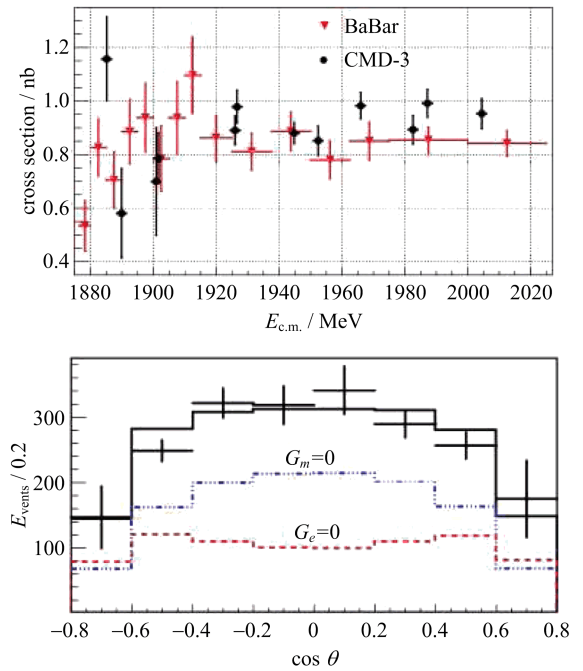


Fig. 3 The CMD-3 $p\bar{p}$ cross section and angle distribution

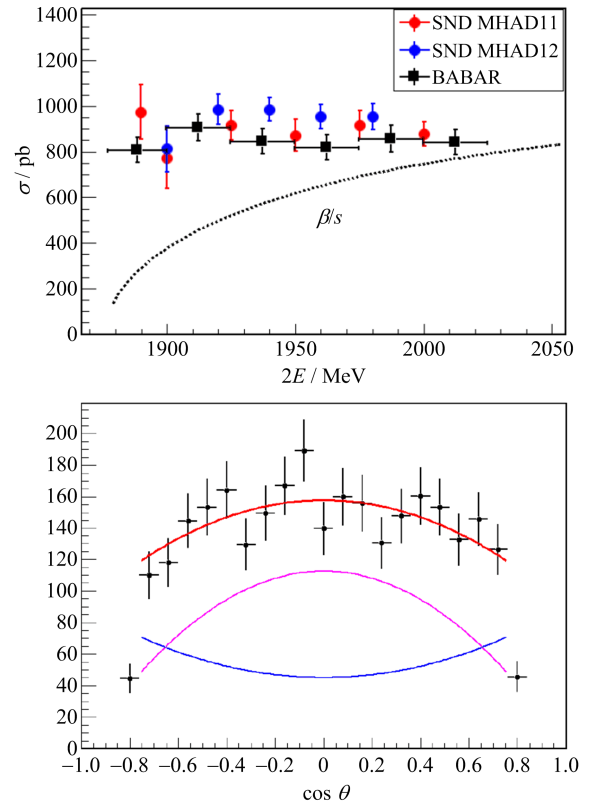


Fig. 4 The SND $p\bar{p}$ cross section and angle distribution (preliminary results)

2 SND \bar{m} measurement

To select events from the $e^+ e^- \rightarrow \bar{m}$ process^[14], all events that meet the criteria for $e^+ e^- \rightarrow e^+ e^-$ and $e^+ e^- \rightarrow 2\gamma$ are removed explicitly, cosmic background is suppressed with the muon system veto. At least two clusters in the EMC calorimeter are required in the event. Other criteria utilize the energy: $950 \text{ MeV} < E_{\text{EMC}} < 1\,500 \text{ MeV}$ and the total event momentum registered in calorimeter: $P_{\text{EMC}} > 0.5 \cdot E_{\text{beam}}$, $25^\circ < \theta_{P_{\text{EMC}}} < 155^\circ$.

To extract the cross section ($\sigma_{\bar{m}}$) from the number of events (N) the following expression taking into account cosmic background is used:

$$N = \sigma_{\text{TH}} \cdot L + \sigma_{p\bar{p}, \text{VIS}} \cdot L + x \cdot T + \epsilon \delta \sigma_{\bar{m}} \cdot L$$

where $\sigma_{p\bar{p}, \text{VIS}}$ is a visible $p\bar{p}$ cross section satisfying \bar{m} selection criteria, σ_{TH} is a visible cross section of processes with smooth behavior near \bar{m} pair production threshold, x is the visible cosmic events rate, T is the time of data taking for particular energy, L is the integrated luminosity, ϵ is the detection efficiency, and δ is the radiative correction. The visible cosmic event rate is obtained with a common fit in all energy points and found to be $(1.40 \pm 0.07) \times 10^{-3} \text{ Hz}$. For σ_{TH} its direct measurement below \bar{m} threshold is used, but it is also estimated from possible physical background process contributions and found to be in a good agreement. The obtained cross section separately for two seasons and early data from FENICE^[3] are shown in Fig. 5^[14].

3 Discussion

The $e^+ e^- \rightarrow p\bar{p}$ cross section is almost constant, though it is natural to expect its decrease

as $\beta/s = \frac{\sqrt{1 - \frac{4M^2}{s}}}{s}$ when approaching the threshold

(Fig. 4). Both SND and CMD-3 results (Fig. 6) confirm the BaBar result, that $\frac{G_E}{G_M}$ near

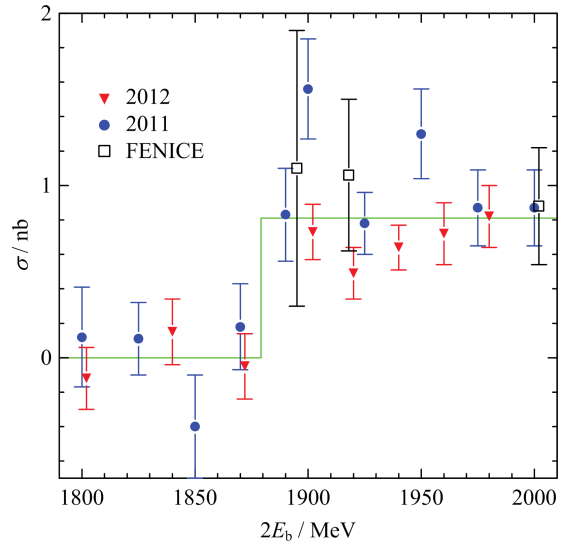


Fig. 5 The SND \bar{m} cross section

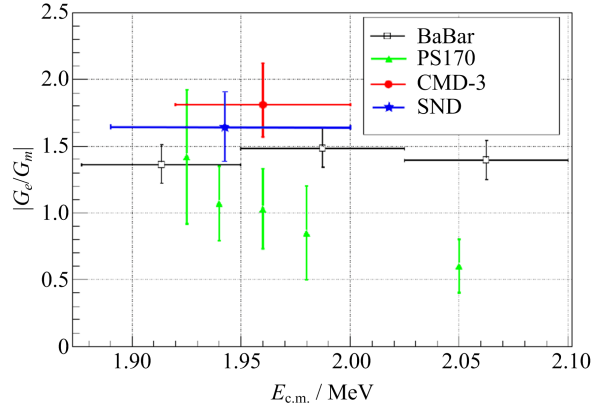


Fig. 6 The p EM form factors ratio

threshold strongly differs from unity. This was somewhat unexpected, because of $G_E = G_M$ at threshold.

The $e^+ e^- \rightarrow \bar{m}$ cross section is also constant (Fig. 5) and coincides within the errors with for $e^+ e^- \rightarrow p\bar{p}$ (Fig. 7). The $\sigma_p = \sigma_n$ relation suggests that either the isoscalar or isovector amplitude dominates in the $e^+ e^- \rightarrow \bar{m}$ process near the threshold. The pQCD asymptotics is $\frac{\sigma_p}{\sigma_n} = 4$.

Possible explanations of this observation could be:

- ① sub-threshold resonance;
- ② final state interaction between nucleons.

The theoretical discussion of the phenomenon on the base of Paris nucleon-antinucleon optical

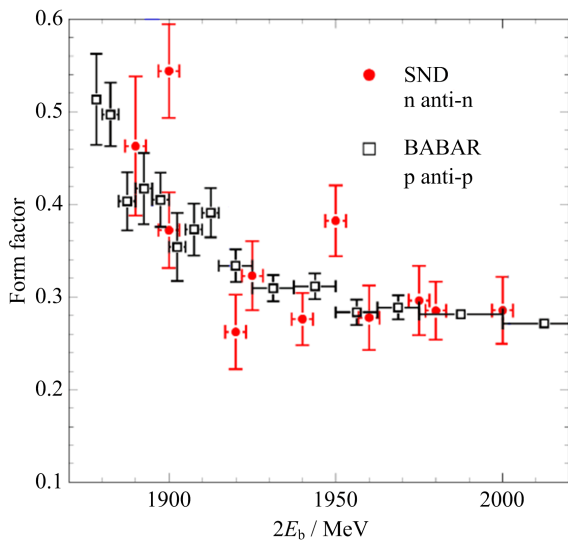


Fig. 7 Nucleon effective form factor

potential^[15] suggests that isoscalar channel dominance should lead to attraction while isovector to repulsion. However, it is noted^[16] that $e^+e^- \rightarrow n\bar{n}$ threshold jump has almost equal value and opposite sign with isovector part of $e^+e^- \rightarrow 3(\pi^+\pi^-) + 2(\pi^+\pi^-\pi^0)$ processes (Fig. 8). In other multipion channels any features compatible in magnitude are not observed near the nucleon pair production threshold.

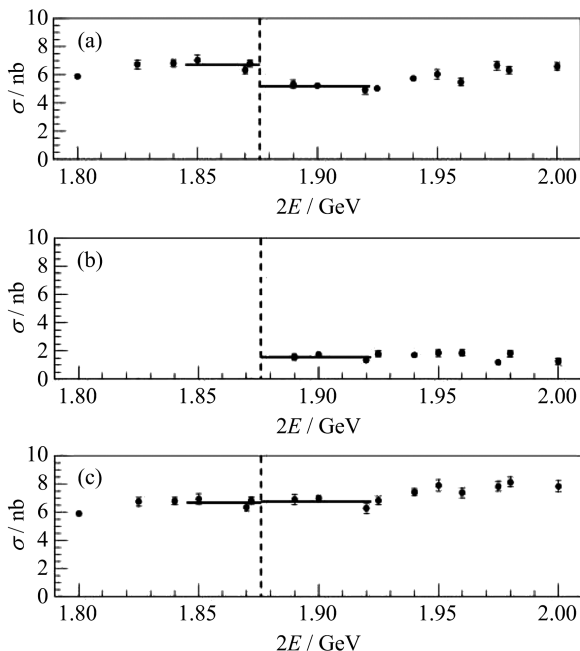


Fig. 8 $e^+e^- \rightarrow n\bar{n}$ and isovector $e^+e^- \rightarrow 6\pi$ jump compensation

4 Conclusion and plan

The cross section of the $e^+e^- \rightarrow p\bar{p}$ is measured independently with the CMD-3 detector and with the SND detector at VEPP-2000 collider. The timelike effective electromagnetic form factor of protons, ratio of electric and magnetic form factors are extracted.

The cross section of the $e^+e^- \rightarrow n\bar{n}$ is measured with the SND detector, timelike effective electromagnetic form factor of neutron, ratio of electric and magnetic form factors are extracted.

Results for both the neutron and the proton form factor near the pair production threshold agree well with previous measurements (BaBar, FENICE), but raise some interpretation questions.

Future modernization of collider and both detectors would allow to improve these results. VEPP-2000 is undergoing an upgrade of the electron and positron sources which will allow to increase its luminosity by the order of magnitude. For the new runs the laser Compton backscattering method will be used for the beam energy measurement. An electronics upgrade of the SND detector will allow the time measurement in the calorimeter to better separate antineutron signal from the cosmic background. The new time of flight (TOF) system on the CMD-3 detector will also improve the power of antineutron selection.

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