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Measurement of the $e^+e^- \to n\bar{n}$ cross section with the SND detector at the VEPP-2000 collider

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Abstract. New measurement of the $e^+e^- \to n\bar{n}$ cross section based on the data set recorded in 2017 with the SND detector at the VEPP-2000 e^+e^- collider is presented. In the energy range from the threshold up to 2 GeV the cross section is almost flat. Its average value is 0.5 nb. The polar angle distribution indicates dominance of the magnetic form factor G_M.

1 Introduction

Measurement of e^+e^- annihilation into nucleon-antinucleon pairs allows to study the nucleons internal structure described by the timelike electromagnetic form factors, electric G_E and magnetic G_M. The $n\bar{n}$ production cross section is given by the following equation:

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

where α is the fine structure constant, $s = 4E_b^2 = E^2$, E_b is the beam energy, E is the center-of-mass (c.m.) energy, $\beta = \sqrt{1-4m_n^2/s}$, m_n is neutron mass, $\tau = s/4m_n^2$, and θ is the neutron polar angle. The $|G_E/G_M|$ ratio can be extracted using this expression from the measured $\cos\theta$ distribution.

The $e^+e^- \to n\bar{n}$ cross section was measured previously in the FENICE [1] and SND [2] experiments. The value of the cross section obtained in these experiments below 2 GeV is about 1 nb. In this work we present the results from the new SND [3] measurement at VEPP-2000 collider [4] . Data have been taken in 9 energy points in the e^+e^- c.m. energy range from the nucleon threshold up to 2 GeV with an integrated luminosity of 19 pb^{-1}.

2 Backgrounds and events selection

The $n\bar{n}$ events are very different from events of other e^+e^- annihilation processes. Below 2 GeV the produced neutron has low energy and therefore gives low energy deposition in the SND electromagnetic calorimeter (EMC). The antineutron annihilates inside the EMC and produces pions with the total energy up to $2m_n$. In this analysis, the position of the calorimeter crystal with maximal energy deposition is taken as an estimate of the position of antineutron annihilation and used to determine the antineutron production angles, θ and φ.

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Using the described specifics of $n\bar{n}$ events to suppress the physical background from other e^+e^- annihilation processes, we select events containing no charged tracks originated from the interaction region with a large unbalanced total event momentum measured in the calorimeter ($P_{EMC} > 0.5E_b$). To reject the beam-induced background the condition on the total energy deposition in the EMC is applied ($E_{EMC} > 1.05E_b$).

Under these conditions, we have significant cosmic background. For its suppression, we reject events with cosmic track in EMC and use the veto from the SND muon system. In addition, the energy deposition in the third layer of the calorimeter should be not large ($E_3 < 0.7E_b$).

As a result of all applied conditions, we manage to make physical background negligibly small and reduce the beam background to the level of $\sim$ 10% of the $n\bar{n}$ signal. The rate of residual cosmic background is about 5 events/hour.

3 Detection efficiency

The detection efficiency ε is calculated using Monte Carlo simulation. The simulation includes emission of an additional photon by initial electron and positron and takes into account c.m. energy spread, which is about 1 MeV. The distribution over $\cos\theta$ in Eq. (1) is taken to be uniform in the simulation. We also take into account spurious photons and charged tracks generated by beam background. They are simulated by using special background events recorded during data taking with a random trigger. These events are superimposed on simulated $n\bar{n}$ events.

The detection efficiency as a function of the c.m. energy is shown in Fig. 1. It varies from 13% to 18%. A drop in the efficiency close to the threshold is due to the radiative corrections and the rise of the antineutron annihilation rate in the central part of the SND detector and subsequent suppression of such events by our selection criteria. A slow decrease of the efficiency above 1.9 GeV is explained by the increase of the antineutron annihilation length in the EMC with the energy increase.

4 Determination of the number of $n\bar{n}$ events

The most of selected data events originate from the two sources, $e^+e^- \to n\bar{n}$ signal and cosmic background, in approximately equal amounts. To separate signal and background, we analyze the distribution of the event trigger time with respect to the beam collision time. The data time distribution for the energy points from the range $E_b = 940.3 - 942.0$ MeV is shown in Fig. 2. It consists of the uniform cosmic distribution and a peaked distribution, which contains signal $n\bar{n}$ events with a small contamination of beam background events. The latter is shown by the filled histogram. The vertical line in Fig. 2 indicates the position of zero delay time between the trigger and the beam collision. This position and the shape of the background distribution are determined using $e^+e^- \to \gamma\gamma$ events. The effective cross section for the beam background events is determined using data recorded below the $n\bar{n}$ threshold. The special study shows that the number of beam background events is approximately proportional to the integrated luminosity.

One can see from the Fig. 2 that for the energy range $E_b = 940.3 - 942.0$ MeV the average delay of $n\bar{n}$ events with respect the beam collision time is approximately 20 ns. The data distribution in Fig. 2 is fitted by a sum of the $n\bar{n}$ simulated distribution, cosmic and beam background time spectra. The result is shown by the solid histogram. The number of $n\bar{n}$ events is obtained using the same fit in each energy point. In total, about 800 $n\bar{n}$ data events are found.

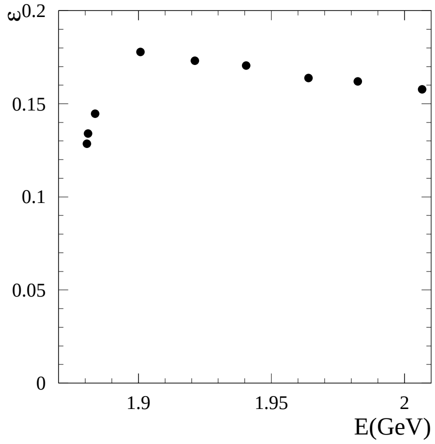

Figure 1. The detection efficiency ε determined using MC simulation.

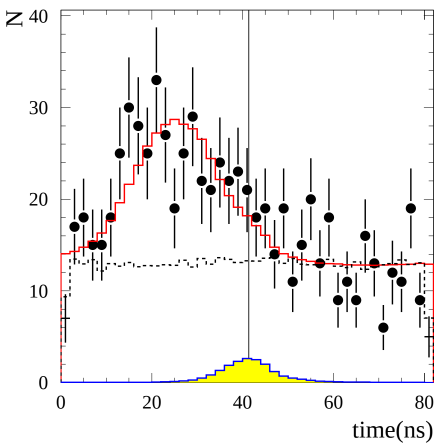

Figure 2. The data distribution of the event trigger time with respect to the beam collision time (point with error bars). The dashed histogram represents cosmic background. The filled histogram shows the expected beam background distribution. The solid histogram is the result of the fit described in the text. The vertical line indicates the position of zero delay between the trigger and the beam collision.

The recoiled neutron can be also observed in EMC in the direction opposite to the antineutron direction as a photon or several photons. We construct the distribution of the angle between the photon direction and the expected neutron direction $\Delta\theta_n$ for photons with energy greater than 20 MeV. The $\Delta\theta_n$ distribution for the energy range $E_b = 970 - 1000$ MeV is shown in Fig. 3. The peak in the distribution near zero is clearly seen. The data and simulated $\Delta\theta_n$ distributions are in good agreement. The efficiency of the recoiled neutron detection is about 30%.

5 The $e^+e^- \to n\bar{n}$ cross section

The Born cross section σ_0 for the process $e^+e^- \to n\bar{n}$ is related to the experimental data by the following expression:

$$\sigma_0(1 + \delta) = N/(\varepsilon L) \tag{2}$$

where $1+\delta$ is the radiative correction factor (Fig. 4), calculated based on work [5], taking into account beam energy spread, N, ε, and L are the number of $n\bar{n}$ events, detection efficiency and luminosity in each energy point.

The obtained Born cross section σ_0 is presented in Fig. 5 in comparison with the measurements by FENICE [1] and SND [2]. In average, σ_0 is about 0.5 nb, what is significantly lower than both previous measurements. In our previous work [2], the detection efficiency, and beam and physical background were not properly evaluated.

In Fig. 6 the data cosθ distribution for the energy range $E_b = 980 - 1000$ MeV is shown. This distribution is fitted by the angular function from Eq. (1) with three fixed $|G_E/G_M|$ values. The four histogram bins in Fig. 6 at cos$\theta = \pm 0.65, \pm 0.75$, the most sensitive to $|G_E/G_M|$,

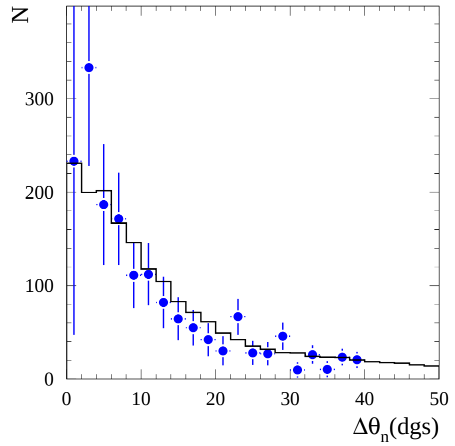

Figure 3. The distribution of the angle between the neutron-candidate direction and the reverse antineutron direction for data (points with error bars) and simulated (histogram) events.

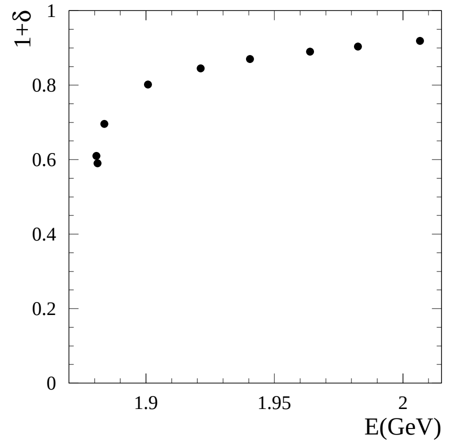

Figure 4. The radiative correction factor for the process $e^+e^- \to n\bar{n}$ in the nine experimental energy points.

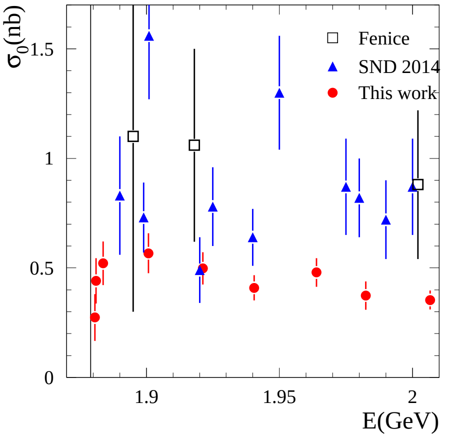

Figure 5. The $e^+e^- \to n\bar{n}$ cross section measured in this work compared with the previous measurements [1, 2]. The vertical line shows the $n\bar{n}$ threshold.

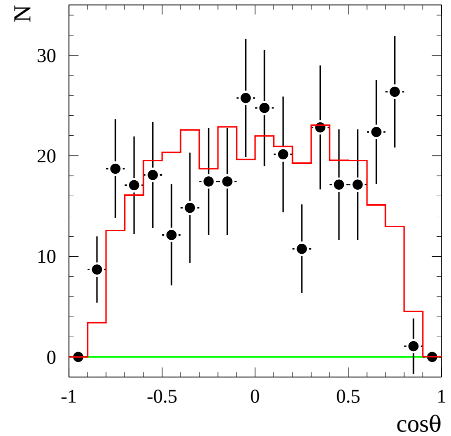

Figure 6. The cosθ distribution for data $e^+e^- \to n\bar{n}$ events at the energies 1960, 1980, 2000 MeV. The histogram is the result of the fit with $|G_E| = 0$.

are used in the fit. We obtained χ^2/ND=3.9/3 for $|G_E|$=0, χ^2/ND=9.5/3 for the uniform cosθ distribution and χ^2/ND=19.5/3 for $|G_M|$=0, where ND=3 is the number of degrees of freedom. We conclude that the data strongly prefer dominant contribution of the $|G_M|$ term. The hypothesis of $|G_M|$=0 is excluded at the level of 3.5σ.

6 Systematic uncertainties on the cross section

The summary of corrections and uncertainties:

- uncertainty in $|G_E/G_M|$ ratio: $(-2.2 \pm 2.2)\%$,
- data/MC difference in cosmic background suppression: $\pm 3.0\%$,
- uncertainty in the signal integration time in EMC simulation: $(-5.0 \pm 2.5)\%$,
- uncertainty in determination of the beam background: $\pm 10\%$,
- accuracy in radiative corrections and luminosity: $\pm 3.0\%$,
- data/MC difference in the energy deposition in the EMC: $\pm 15.0\%$.

The total systematic is 18%. In Fig. 5 only the statistical uncertainty is shown.

7 Conclusions

The experiment to measure $e^+e^- \to n\bar{n}$ cross section has been carried out with the SND detector at the VEPP-2000 e^+e^- collider in the vicinity of nucleon-antinucleon threshold. The measured cross section is almost flat in the energy range from the threshold up to 2 GeV. Its average value of 0.5 nb is lower than in the previous measurements by FENICE [1] and SND [2]. The measured cosθ distribution prefers domination of the $|G_M|$ term in the differential $e^+e^- \to n\bar{n}$ cross section.

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