Measurement of the neutron timelike electromagnetic form factor at the VEPP-2000 e+e- collider with the SND detector

On the behalf of SND Collaboration
Sergey Serednyakov
Novosibirsk State University
Budker Institute of Nuclear Physics
OUTLINE

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Measurement of the neutron TL form factor ...

\[ e^- N \rightarrow e^- N \]
Scattering

\[ e^+e^- \rightarrow N \bar{N} \]
Annihilation

Spacelike form factor

Timelike form factor

From Yu. Nefedov
e^+e^- → NN cross section

Differential cross section:
\[
\sigma(e^+e^- \rightarrow B\bar{B}) = \frac{\alpha^2 \beta C^2}{4m^2} \left( |G_M|^2 (1 + \cos^2 \theta) + \frac{4m_B^2}{m^2} |G_E|^2 (1 - \cos^2 \theta) \right)
\]

Total cross section:
\[
\sigma(e^+e^- \rightarrow B\bar{B}) = \frac{4\pi \alpha^2 \beta C}{3m^2} \left( |G_M|^2 + \frac{2m_B^2}{m^2} |G_E|^2 \right)
\]

Effective form factor
\[
|F|^2 = \frac{|G_M|^2 + |G_E|^2}{1 + 1/2\tau}, \quad \tau = \frac{m^2}{4m_B^2}
\]

At threshold: \( s=4m_B^2 \rightarrow |G_E| = |G_M| = |F| \)

\( F_n = - F_p / 2 \)

Asymptotic prediction: \( F(+\infty) = -F(-\infty) \sim 1/s^2 \)

Two measurable values:
1 - effective FF,
2 - \( G_E/G_M \)
C=1 for neutrons
Existing data on the $e^+e^- \rightarrow n + \text{anti-n}$ cross section

**Graphs:**
- Plot of Born Cross Section (pb) vs. $\sqrt{s}$ (GeV)
- Plot of Effective Form Factor $|G^e_{\text{eff}}|$ vs. $\sqrt{s}$ (GeV)

**References:**
- PhiPsiConf2019
- Nucleus-2020
- Nefedov, Sess. March, 2020
Existing data on the neutron timelike form factor

BESIII preliminary

B. Zhang

Measurement of the neutron TL form factor …
Existing data on the neutron timelike form factor

BESIII preliminary

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12.10.2020
VEPP-2000 parameters:
- c.m. energy E=0.3-2.0 GeV
- round beam optics
- Luminosity at E=1.8 GeV:
  - $1 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$ (project),
  - $5 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$ (achieved)

In operation since 2010
Total integrated luminosity
at CMD-3 and SND ~300 inv.pb.
Planned luminosity ~ 2 inv.fb

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SND detector (since 1995)

1 – vacuum chamber,
2 – tracking DC,
3 – aerogel n=1.13, 1.05
4 – NaI(Tl) crystals,
5 – phototriodes,
6 – absorber,
7–9 – muon detector,
10 – SC solenoids

Attenuation length
SND – good antineutron detector

Solid angle - 90% 4\pi

rad.length -2.6 cm
<table>
<thead>
<tr>
<th>Data taking run 2017</th>
<th>Data taking run 2019</th>
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<tbody>
<tr>
<td>$E_{\text{beam}} = 900 – 1004$ MeV, 9 energy points (above threshold)</td>
<td>$E_{\text{beam}} = 900 – 987.5$ MeV, 7 energy points (above threshold)</td>
</tr>
<tr>
<td>Integr. luminosity = 16.5 pb$^{-1}$</td>
<td>Integr. luminosity = 18 pb$^{-1}$</td>
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<tr>
<td>Reconstructed $nn$ candidate events $\sim 1000$</td>
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**Selection of n+anti-n events**

**Key features**

\( \text{(No tracks\(^*\), no photons\(^*\), no kinematic } \chi^2 \)\)

1. veto \( \mu \) system
2. no cosmic muon track in EMC
3. event momentum: \( P > 0.3E_{\text{beam}} \)
4. EMC energy: \( E_{\text{tot}} > 1.05E_{\text{beam}} \)
5. 3-d EMC layer energy: \( E_3 < 0.7E_{\text{beam}} \)

**Selection results:**

1. total events recorded \( \sim 2 \times 10^7 \) events/pb\(^{-1} \)
2. after applying cuts \( \sim 100 \) events/pb\(^{-1} \), including
   physical, beam and cosmic background and n anti-n events

**Selection efficiency:**

\( \varepsilon_{\text{MC}} \approx 18 \% \) (951,955 MeV)
Measurement of the neutron TL form factor ...
Physical, beam and cosmic backgrounds

Three types of background for $\text{e}^+\text{e}^- \rightarrow \text{n}+\text{anti-n}$:

1. **Physical background** - from processes $\text{e}^+\text{e}^- \rightarrow \gamma\gamma(\gamma)$,
   $\text{K}_S\text{K}_L+\text{n}\pi^0(\gamma)$, ppbar etc, suppressed to $\sim 1 \text{ pb}$ of detection cross section.

2. **Cosmic background** - trigger rate $\sim 150 \text{ Hz}$, suppressed to $\sim 10^{-3} \text{ Hz}$.

3. **Beam background** - suppressed to $\sim 1\text{ pb}$ by the condition on the total EMC energy $E_{\text{cal}} > E_{\text{beam}}$. 

Spectrometric channel in 2019 run. The measured parameters are pulse time and pulse height.

The EMC spectrometric channel

Nal(Tl) & VPT → CSA x12 → F12 module (Shaper) x2 → Z24 module (FADCs) x160 → FLT → Clock (3 x $F_{\gamma}$)

Typical signal waveform from an EMC channel.

Event time spectra in 2019 run

Ideal MC time picture

Exp. data time picture

σ=0.8 ns time resolution

Suppressed beam background
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Time spectra in 2017 run
Calculation of $e^+e^- \rightarrow n+\text{anti-n}$ cross section

$$\sigma_B = \frac{N}{\varepsilon \delta L}$$

$N$ – detected events number, $\sim 100$
$L$ – integrated luminosity, $\sim 1 \text{ pb}^{-1}$,
$\varepsilon$ – MC detection efficiency, $\sim 0.15$
$\delta$ – radiative correction, $\sim 0.8$
$\sigma_B$ – total cross section $\sim 0.4-0.8 \text{ nb}$
**e^+e^- → n+anti-n cross section**

SND data of 2017 and 2019 runs comparison

![Graphs showing e^+e^- → n+anti-n cross section comparison for Run 2017 and Run 2019.](image_url)
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e^+e^- \rightarrow n+\text{anti-n cross section}

Comparison of the new SND results with the previous data

![Graph showing comparison of cross sections](image-url)

**BESIII preliminary**

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Systematic uncertainties in $e^\pm e^- \rightarrow n + \text{anti-n}$ cross section

1. Detection efficiency uncertainty $\sim 10\text{-}15\%$
   $\sim 20\text{-}30\%$ close to threshold
2. Physical and beam background uncertainty $\sim 5\text{-}10\%$
3. Energy calibration and bg MC mixing uncertainty $\sim 5\%$
4. Luminosity and radiative corrections $\sim 3\%$
5. Total systematics $\sim 15\text{-}20\%$, ($\sim 20\text{-}30\%$ at threshold)

Statistical error $\Delta\sigma/\sigma$ at one energy point if from 10% to 30%. 
The neutron timelike form factor compared with the proton form factor

The neutron FF is found to be close to the proton FF near the threshold, but becomes lower with the rise of energy.

The asymptotic prediction is $F_n = -\frac{F_p}{2}$

Comparison with BESIII: $F_n \sim 0.2$

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The neutron timelike form factor compared with the proton form factor

The neutron FF is found to be close to the proton FF near the threshold, but becomes lower with the rise of energy. The asymptotic prediction is $F_n = - F_p/2$.

Comparison with BESIII: $F_n \sim 0.2$
Measurement of the neutron TL form factor …

Linear fit to the neutron timelike form factor vs neutron momentum

SND 2017–2019 data
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Extraction of the \(|GE|/|GM|\) ratio from the \(\cos \theta\) distribution

\[ |GM|^2 \approx 1 + \cos^2 \theta, \]
\[ |GE|^2 \approx 1 - \cos^2 \theta, \]

Fit results:
\[ |GE|/|GM| = 1.35 \pm 0.35, \]
\[ \chi^2/\nu = 1.1 \]

Conclusion: the measured \(|GE|/|GM|\) is with \(1\sigma\) significance above the \(|GM|=|GE|\) model

Comparison with BESIII: \(G_E/G_M \approx 1\)

Nucleus-2020

12.10.2020

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Conclusions and perspectives

1. Experiment have been carried out with the SND detector at the VEPP-2000 e+e- collider to measure the $e^+e^- \rightarrow n + \text{anti-} n$ process cross section and the neutron timelike e.m. form factor.
2. The SND electromagnetic calorimeter based on 1680 NaI(Tl) crystals is used as an effective antineutron detector.
3. Due to the selection conditions and delay time measurements the events of $e^+e^- \rightarrow n + \text{anti-} n$ process are selected.
4. The $e^+e^- \rightarrow n + \text{anti-} n$ cross section is measured from the threshold up to 2 GeV of c.m. energy, its value is $\sim 0.6-0.3$ nb.
5. The measured neutron timelike e.m. form factor varies from 0.5 to 0.2. the data are mostly consistent with the $|G_E| \approx |G_M|$ model.

6. Now we continue data taking above the threshold of the $e^+e^- \rightarrow n + \text{anti-} n$ process with the goal to collect the 300 inv.ppb data. The analysis of recorded data is going on.
Measurement of the neutron TL form factor …

Thank you for listening