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

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23.09.2015
VEPP-2000 complex

Center-of-mass energy (E) 0.3-2.0 GeV
Beam energy spread 0.6 МэВ (at E=1.8 GeV)
Luminosity (L) $0.7 \cdot 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ (at E=1.8 ГэВ)
## Data 2010-2012

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Integrated luminosity</th>
<th>$\sqrt{s} &gt; 1.88$ GeV</th>
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</thead>
<tbody>
<tr>
<td><strong>(1.05 – 2.0 GeV)</strong></td>
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<tr>
<td>02.2010 – 06.2010</td>
<td>5 pb$^{-1}$</td>
<td>71 nb$^{-1}$</td>
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<tr>
<td>12.2010 – 06.2011</td>
<td>25 pb$^{-1}$</td>
<td>3.8 pb$^{-1}$</td>
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<tr>
<td>01.2012 – 04.2012</td>
<td>17 pb$^{-1}$</td>
<td>4.9 pb$^{-1}$</td>
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<tr>
<td><strong>Total</strong></td>
<td>47 pb$^{-1}$</td>
<td>8.8 pb$^{-1}$</td>
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</tbody>
</table>

![Graph showing data distribution](image-url)
\[ e^+e^- \rightarrow \text{nucleon anti-nucleon} \]

Total cross section:
\[ \sigma(s) = \frac{4\pi \alpha^2 \beta C}{3s} \left(|G_M(s)|^2 + \frac{2M_N^2}{s} |G_E(s)|^2 \right) \]

where C is the Coulomb factor
\[ C \approx \frac{\pi \alpha}{\beta s} \]

for proton
\[ C = 1 \]

for neutron

\( G_E \) and \( G_M \) are the electric and magnetic form factors.

Differential cross section:
\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s} \left(|G_M(s)|^2 (1+\cos^2\theta) + \frac{4M_N^2}{s} |G_E(s)|^2 \sin^2\theta \right) \]

Angular distributions is used to extract \( |G_E/G_M| \)

“Effective form factor”:
\[ F(s) = \frac{|G_M(s)|^2 + \frac{2M_N^2}{s} |G_E(s)|^2}{1 + \frac{2M_N^2}{s}} \]
CMD-3

1 – vacuum chamber
2 – drift chamber
3 – electromagnetic calorimeter, BGO
4 – Z – chamber
5 – CMD SC solenoid
6 – electromagnetic calorimeter, LXe
7 – electromagnetic calorimeter, CsI
8 – yoke
9 – VEPP-2000 solenoid
\( e^+ e^- \rightarrow p\bar{p} \) events

- \( E_{\text{beam}} = 945 \text{ MeV} \)
- \( p \) stops and annihilates in the beam pipe
- produces secondary particles

- \( E_{\text{beam}} = 970 \text{ MeV} \)
- \( p \) is absorbed in the Z-chamber
- \( \bar{p} \) annihilates
- some secondary particles came back
\[ \bar{p}p: \text{Signal selection} \]

\[ E_{\text{beam}} \leq 950 \text{ MeV}: \]
- 4 or more tracks common vertex found in the beam pipe material;
- no tracks with energy deposition in calorimeter higher than 400 MeV.

\[ E_{\text{beam}} > 950 \text{ MeV}: \]
- two opposite-charge collinear central tracks in DC;
- \[ |p_1 - p_2|/(p_1 + p_2) < 0.15 \] (< 0.2 for \( E_{\text{beam}} < 955 \text{ MeV} \));
- total energy deposition in the calorimeter >200 MeV.
pp: CMD-3 Results

arXiv:1507.08013

Cross section

systematic uncertainty $\sim 6\%$

Fit

$|G_E/G_M| = 1.49 \pm 0.23 \pm 0.3$
SND

NIM A449 (2000) 125-139

1 – beam pipe
2 – tracking system,
3 – aerogel cherenkov counter
4 – NaI(Tl) crystals
5 – phototriodes
6 – iron muon absorber
7–9 – muon detector
10 – focusing solenoids
$e^+e^- \rightarrow \bar{p}p$ events

960 MeV

> 960 MeV
pp: Signal events selection

\( E_{\text{beam}} < 960 \text{ MeV} \):

- exactly 3 tracks with a common vertex located in the beam pipe material;
- no other tracks (proton is not registered).

\( E_{\text{beam}} \geq 960 \text{ MeV} \):

- two collinear central tracks in DC with large dE/dx;
- total energy deposition in the calorimeter > 650 MeV;
- one of tracks is not associated with calorimeter cluster.
pp: SND Results

Preliminary!

Cross section

systematic uncertainty ~ 7%

Fit:

$|G_E/G_M| = 1.64 \pm 0.26$
e^+e^- \rightarrow n\overline{n} \text{ events}

- no signal from neutron
- “star” from anti-neutron
śn: Signal events selection and background substraction

Selection:

- Muon system veto;
- At least 2 clusters in EMC

Cosmic background substraction using

\[ N_i = x \cdot T_i + \sigma_{vis}(E_{beam}) \cdot L \]

Other processes controlled with

- \( 950\text{MeV} < E_{emc} < 1500\text{MeV} \)
- \( P_{emc} > 0.5 \cdot E_{beam} \)
- \( 25 < \theta_{PEMC} < 155 \)
- no e+e-, γγ events

\[ \sigma_{nn} = 0 \]
$ar{n}n$: Cross section

Cross section
systematic uncertainty
$\sim 17\%$
Discussion on proton results

- The cross section is constant, through it is natural to expect its decrease as $\beta = (1-4m_p^2/s)^{1/2}$ when approaching the threshold.

- Both SND and CMD-3 results confirm the BABAR result, that $|G_E/G_M|$ near threshold strongly differs from unity. This was somewhat unexpected, because $G_E = G_M$ at threshold.
Nucleon form factors

- The $e^+e^- \rightarrow n\bar{n}$ cross section is constant and coincides within the errors with that for proton anti-proton (asymptotics pQCD $\sigma_p/\sigma_n = 4$).

- $\sigma_p = \sigma_n \Rightarrow$ either isoscalar or isovector amplitude dominates in $e^+e^- \rightarrow n\bar{n}$

I. Subthreshold resonance
II. Final state interaction

V. F. Dmitriev, A. I. Milstein, S. G. Salnikov
Phys. Atom. Nucl. 77 (2014) 1173:
Paris N anti-N optical potential:
$I=0$ – attraction, $I=1$ – repulsion $\Rightarrow$
the isoscalar form factor dominates.
Relation with $e^+e^- \rightarrow 6\pi$

A.E. Obrazovsky, S.I. Serednyakov
JETP Lett. 99 (2014) 363

In the total $e^+e^- \rightarrow \text{hadrons}$ cross section, the appearance of the $e^+e^- \rightarrow n\bar{n}$ processes is fully compensated by the dip in the cross section for the isovector processes $e^+e^- \rightarrow 3(\pi^+\pi^-)+2(\pi^+\pi^-\pi^0)$.

In other cross sections near $n\bar{n}$ threshold, any features, comparable in magnitude with that for $e^+e^- \rightarrow 6\pi$, are not observed.
Plans

• VEPP-2000: upgrade to increase a luminosity by the order of magnitude;

• Use of the laser Compton backscattering method for beam energy measurement;

• SND: the time measurement in the calorimeter electronics, will allow to separate signal from the cosmic background;

• CMD-3: using the new TOF system for the events selection;
Conclusion

● Cross section of the $\text{e}^+\text{e}^- \rightarrow \bar{\text{p}}\text{p}$ process and the timelike form factor of the proton are measured;
● Cross section of the $\text{e}^+\text{e}^- \rightarrow \bar{\text{n}}\text{n}$ process and the timelike form factor of the neutron are measured;
● Results for both the neutron and the proton form factor near the pair birth threshold raise some interpretation questions;