STUDY OF $nn$-INTERACTION IN $nd$- AND $dd$-REACTIONS

E.Konobeevski$^1$, A.Kasparov$^1$, V.Lebedev$^2$, M.Mordovskoy$^1$, A.Spassky$^2$, S.Zuyev$^1$

$^1$Institute for Nuclear Research, Russian Academy of Sciences
$^2$Skobeltsyn Institute of Nuclear Physics, Moscow State University
**NN-Interaction**

---

**pp and np Interaction**

A huge amount of data on pp and np interactions has been accumulated. Careful analysis of these data led to constructing NN interaction potentials describing vast majority of experimental data.

**nn Interaction**

The situation around neutron–neutron interaction is more ambiguous. Because of the absence of neutron target, data on this interaction are obtained primarily from reactions with two neutrons in the final state. But in many cases, there are serious discrepancies between available experimental data and the results of the current precise calculations on the basis of Faddeev equations.
Unresolved Problems in \(Nd\)-breakup

\textit{nd-} and \textit{pd-}breakup in SS-configuration \quad \textit{nn-}quasifree scattering

Experimental CS for \textit{pd-} and \textit{nd-}breakup differ greatly while the theoretical CS are almost identical and do not agree with the experimental data.

Experimental CS for \textit{nn-}QFS exceed theoretical estimates by about 18%. At the same time, the theory describes well the CS obtained for \textit{np} QFS.

The analysis performed by several authors showed that theoretical results remain quite stable using different standard NN-potentials and introducing modern three-nucleon forces.
Data on proton-proton and neutron-neutron scattering lengths

The results obtained by now testify significant uncertainty of \( a_{nn} \) values, which are clustered around \(-16.3 \pm 0.4\) fm (Bonn) and \(-18.5 \pm 0.4\) fm (TUNL, LAMPE), so there is even uncertainty about the sign of the difference \( a_{nn} - a_{pp} \). This is a measure of CSR all relative energy with nucleon-dependent corrections or odd-parity effects.
Two protons in $^3$He are mainly in opposite spin states

Two neutrons in $^3$H are also in a spin-singlet state

Strong discrepancies observed in Nd-breakup can be explained by a significant strengthening of $nn$- and $pp$-correlations of attractive character in the third nucleon field.
Dibaryon Model (Kukulin et al)

New mechanism arising in the Dibaryon Model: New force – meson exchange between the nucleon and dibaryon

\[ Nd \text{ or } t (^3\text{He}) \]

\[ dd \rightarrow D + D \rightarrow n+n+p+p \]

Our plans: study of \( nd \rightarrow p+nn \), \( nt \rightarrow d+nn \) and \( dd \rightarrow pp+nn \) and \( \ldots \)

In these reactions \( nn \)-correlated pair can be produced dynamically in the intermediate state. Thus, measured \( nn \)-correlation, in particular energy of \( nn \) virtual singlet state, may be different from those inherent for the free \( NN \)-systems.
Determination of 
nn-Virtual-State Energy 
and Scattering Length 
in $n + ^2H \rightarrow n + n + p$ Reaction
$^nd$ Breakup Reaction

Setup for Determination $nn$-Scattering Length

- Neutron beam is produced in the beam stop of INR proton accelerator
- A CD$_2$ disk (~ 100 mg cm$^{-2}$) is used as the scattering target.
- Registration in coincidence of one proton and two neutrons
- Protons are detected by a plastic detector located at 75°±6°
- Neutrons are detected by a six-detector hodoscope at 30°-42°
- Energies of secondary neutrons are determined by a TOF technique
- Incident neutron energy and $\Theta_p$ are reconstructed from kinematics

FSI

$$\varepsilon = \frac{(E_{n1} + E_{n2} - 2(E_{n1}E_{n2})^{1/2}\cos\Delta\Theta)}{2}$$

$$\frac{dN}{d\varepsilon}_{WM} = \frac{\sqrt{\varepsilon}}{\varepsilon + E_{nn}}$$
Experimental and simulated dependences $N(\varepsilon)$ for various values of $E_{nn}$; $\Delta \Theta = 6^\circ$, $E_0 = 40 \pm 5$ MeV

$E_{nn} = 170$ keV
$E_{nn} = 130$ keV
$E_{nn} = 80$ keV

$$\frac{1}{a_{nn}} = -\left(\frac{m_n E_{nn}}{\hbar^2}\right)^{1/2} - \frac{1}{2} r_{nn} \frac{m_n E_{nn}}{\hbar^2} + ...$$

The best fit is obtained for $E_{nn} = 129 \pm 14$ keV.
Determination of $E_{nn}$ from $\chi^2$ versus $E_{nn}$ curve

$\Delta \Theta = 6^\circ$; $E_0 = 40 \pm 5$ MeV

The values of $\chi^2(E_{nn})$ are approximated by a quadratic polynomial. The minimum of the curve determines $E_{nn}$.

Statistical uncertainty $\Delta E_{nn}$ is given as

$$\Delta E_{nn} = |E_{nn}(\chi^2_{min}) - E_{nn}(\chi^2_{min} + 1)|$$

$E_{nn} = 129 \pm 14$ keV $\rightarrow a_{nn} = -16.6 \pm 0.9$ fm
Determination of

$nn$-Virtual-State Energy

and Scattering Length

in $d + ^2H \rightarrow (nn)^S + (pp)^S \rightarrow n+n+p+p$

Reaction
Simulation of \[ d + ^2\text{H} \rightarrow ^2\text{n} + ^2\text{p} \] Reaction; 
\[ E_d = 15 \text{ MeV} \]

Output parameters: \[ \Theta_{p1} = \Theta_{p2} = 27^\circ; \Theta_n = 36^\circ \] (red areas)

Corresponding energies: \[ E(^2\text{p}) \sim 6 \text{ MeV}; E(^2\text{n}) \sim 4 \text{ MeV} \]
Simulation of $d + {^2}H \rightarrow n + n + p + p$ Reaction:

$E_d = 15$ MeV, $\Theta_{p1} = 27^\circ$, $\Theta_{p2} = 27^\circ$, $\Theta_{n1} = 36^\circ$

$E_{n1}$ vs $E_{n2}$

$E_{nn}$ Spectrum

$E_{nn} = \left[ E_1 + E_2 - 2(E_1 \times E_2)^{1/2} \times \cos \Delta \Theta \right] / 2$

For democratic breakup two neutrons can have a relative energy in the range 0 - 1.8 MeV
Simulation of \[ d + {}^2\text{H} \rightarrow n + n + p + p \] Reaction:

\[ E_{n1} \text{ vs } E_{n2} \quad E_{nn} \text{ Spectrum} \]

- Democratic breakup
- \( E_{nn} = 120 \text{ keV}, \quad \Gamma_{nn} = 50 \text{ keV} \)

This structure in spectrum is due to the fact that to reach detector, installed at angle of emitting \( nn \)-system in two-body reaction, may only breakup particles emitted in c.m. system in forward or in backward direction.
Simulation of $d + ^2H \rightarrow n + n + p + p$ Reaction: Different Energies of Singlet State

The distance between peaks depends on the excitation energy (excess mass of two-nucleon system over the sum of masses of its constituents)
Simulation of $d + ^2\text{H} \rightarrow n + n + p + p$ Reaction:
Different Widths of Singlet State; $E_{nn} = 120$ keV

![Graph showing time spectra with different state widths](image)

On the shape of the spectra, sensitive to the state energy and width, that will allow us to determine the state width and shift of the peaks with experimental data.

- $\Gamma_{nn} = 110$ keV
- $\Gamma_{nn} = 70$ keV
- $\Gamma_{nn} = 20$ keV

The shape of time spectra is sensitive to values of the state energy and width, that will allow us to determine these quantities from a comparison of experimental data and simulation results.
**Experimental:** Setup for Study

\[ d + ^2H \rightarrow p + p + n + n \]  Reaction @ \( E_d = 15 \text{ MeV} \)

Conditions: 15 MeV deuteron beam of U120 cyclotron of SINP MSU

- CD\(_2\)-target
- p- and n-detectors are set at angles of 2p and 2n emitting both protons are detected in one \( \Delta E-E \) telescope
- n-detector at 83° was used for timing calibration in dd → \(^3\text{He}+n\) reaction
Selecting events on $p+p$ region and determining the neutron time of flight for these events we obtained neutron timing spectrum.
Experimental: Neutron Time-of-flight Spectrum vs Simulated
$\chi^2$-Fitting on $\Gamma_{nn}$ for Different $E_{nn}$

\[
\chi^2(E_{nn}, \Gamma_{nn}) = \sum_t \frac{(N_{E_{nn}}^{th}(t) - A N_{\text{exp}}(t))^2}{(\Delta N_{\text{exp}}(t))^2}
\]
To determine $E_{nn}$ the dependence of minimum value on $E_{nn}$ was fitted by a quadratic polynomial. The minimum value of $\chi^2$ determines the most probable value of the quasibound state energy.

Error in determining $E_{nn}$ is given as

$$\Delta E_{nn} = \left| E_{nn}(\chi^2_{\text{min}}) - E_{nn}(\chi^2_{\text{min}} + 1) \right|$$

The minimum value of the polynomial is achieved at $E_{nn} = 76$ keV, $\Delta E_{nn} = \pm 6$ keV.
Analysis of $a_{nn}$ data obtained in nd- and dd-breakup

For each experiment we introduced parameter $R$ which corresponds to distance between $nn$ pair and proton (or diproton in dd experiment) for arbitrary time interval.

$$\frac{1}{a_{nn}} = -\left(\frac{m_n E_{nn}}{\hbar^2}\right)^{1/2} - \frac{1}{2} r_{nn} \frac{m_n E_{nn}}{\hbar^2} + \ldots$$
The neutron-neutron $^1S_0$ scattering length $a_{nn}$ has been determined from a kinematically complete $nd$ breakup experiment at $E_n = 40\text{ MeV}$.

The values of $a_{nn} = -16.6^{+0.9}_{-0.6}\text{ fm}$ and $E_{nn} = 129 \pm 14\text{ keV}$ were obtained performing the shape analysis of the FSI dependence of reaction yield on relative energy of $nn$ pair.

- For the first time, in $d + ^2\text{H} \rightarrow ^2nS + ^2pS \rightarrow n+n+p+p$ reaction the energy of virtual state of $^2n$-system and $nn$-scattering length were determined - $E_{nn} = 76 \pm 6\text{ keV}$; $a_{nn} = -22.2 \pm 0.6\text{ fm}$.

- The obtained values of scattering lengths were compared with experimental values of $^1S_0$ $nn$-scattering length obtained in $nd$-breakup reaction.

- One can conclude that the difference in the scattering lengths obtained under different kinematic conditions can be explained by the influence of $3N$-forces depending on the relative velocity between the $nn$-pair and the charged fragment.
Thank you!
Experimental 2D-plot $\Delta E - E$
Summary

- We investigated $d + ^2\text{H} \rightarrow ^2n^S + ^2p^S \rightarrow n + n + p + p$ reaction, passing through a formation in the intermediate state of dineutron and diproton singlet pairs.
- For the first time, in a kinematically complete experiment the energy virtual state of $2n$-system is determined.
- The energy of the state is determined by comparing the experimental TOF spectrum of neutrons from breakup of this state with simulated spectra depending on this energy.
- The obtained value $E_{nn} = 76 \pm 6$ keV was compared with experimental values of $^1S_0$ $nn$-scattering length obtained in $nd$-breakup reaction.
- One can conclude that the difference in the scattering lengths obtained under different kinematic conditions can be explained by the influence of 3N-forces depending on the relative velocity between the $nn$-pair and the charged fragment.
Experimental 2D-plot E-Ef (400 μm)
1-2 – полное поглощение, 2-3 - пролет
Experimental 2D-plot $E$-$E_f$ (400 μm)

1-2 – полное поглощение, 2-3 - пролет
$\Delta E - E$: пролетный локус (2-3)
Experimental 2D-plot E-E_{f} (400 \mu m)

1-2 – полное поглощение, 2-3 - пролет
dE-E: полное поглощение (1-2)
PSD: n-γ разделение (EJ-301)
PSD - Spectrum

![PSD Spectrum Graph](image-url)
Предварительные результаты по эксперименту $dp \rightarrow ppn$

- Проведено моделирование реакции $dp \rightarrow ppn$
- Отлажена детектирующая система ($\Delta E$-E и n-детекторы)
- Отлажена методика выделения p+n событий
- Начат набор статистики
Experimental Spectrum vs Simulated

- $E_{mn} = 40$ keV, $\chi^2 = 3.6$
- $E_{mn} = 80$ keV, $\chi^2 = 1.06$
- $E_{mn} = 160$ keV, $\chi^2 = 5.8$
- Dem. breakup, $\chi^2 = 12.3$
Analysis: Fitting Procedure
Simulation of $d + ^2H \rightarrow n + n + p + p$ Reaction: Democratic vs Quasibound state

Simulated time-of-flight spectra of neutrons: 1 – for events of democratic breakup, 2 – for events with $E_{nn} = 120$ keV, $\Gamma_{nn} = 50$ keV. Neutron time-of-flight base 0.79 m.
Space Star (SS) Anomaly

- SS Anomaly was first found in 1989 in \textit{nd} breakup reaction at 13 MeV.

\begin{itemize}
  \item In Star configuration, outgoing 3 nucleons have the same energy and form an equilateral triangle.
  \item In Space Star (SS), the star plane is perpendicular to the beam axis in c.m. system.
\end{itemize}

The Search for *NN*-Correlations in 3*N*-Systems

In $^3$He neutron causes a correlation of two protons leading to an appearance of quasibound $^1S_0$ diproton state.

In $^3$H proton causes a correlation of two neutrons leading to an appearance of quasibound $^1S_0$ dineutron state.

Removal of proton from $^3H$ and/or neutron from $^3He$ provide conditions advantageous for *NN*-correlations to search.
Space Star (SS) Anomaly in \textit{pd} breakup

- \textit{pd calc.} were made by Deltuva \textit{et al}. and by Ishikawa.

\textit{pd calc.} by Deltuva \textit{et al.} (2005)

\begin{itemize}
  \item At \textit{pd} SS, exp. cross section is \textbf{smaller} than \textit{pd calc.}
  \item At \textit{nd} SS, exp. cross section is \textbf{larger} than \textit{nd calc.}
\end{itemize}

A.Deltuva et al., PRC72,054004 (2005)
Our Preliminary Results of $d+D\rightarrow ^2\text{He}+2n$

Neutron TOF Spectrum @ TOF Base 1 m

Experiment: $\Theta_{2\text{He}} = 27^\circ$; $\Theta_n = 36^\circ$
Simulation: $E_{nn} = 80$ keV

$T_n$ Spectrum
The Search for NN-Correlations

Результаты кинематического моделирования реакции $d + 2H \rightarrow ^2n_s + ^2p_s$ – двумерные диаграммы $\Theta_{2n}-\Theta_{2p}$ (а) и $E_{2n}-E_{2p}$ (б), где $\Theta_{2n}$ и $\Theta_{2p}$ – углы вылета, а $E_{2n}$ и $E_{2p}$ – энергии двухнейтронной и двухпротонной систем. Красные области соответствуют вылету системы $^2p_s$ под углом $27^\circ \pm 1.5^\circ$
nd-breakup configurations and unresolved problems
Modification of $^1S_0$ nn force

H. Witala & W. Gloeckle suggested

$$V_{nn}(^1S_0) = \lambda \times V_{\text{CDBonn}}(^1S_0)$$


- $\lambda = 1.08$

No arguments for this modification

Kinematical curves for FSI geometry in \( nd \)-breakup

\[ E_0 = 40 \pm 5 \text{ MeV}, \ \Theta_n 1 = -36^\circ, \ \Theta_p = 75^\circ \]

**1-neutron, 2-proton**

**1-neutron 3-neutron**

FSI

\[ E_{13} = \varepsilon = (E_1 + E_2 - 2(E_1 E_2)^{1/2}\cos\Delta\Theta)/2 \]

\( 0, \ \Theta_1 \approx \Theta_2 \)

3N Faddeev equation

\[
\frac{d\sigma}{d\Omega_1 d\Omega_3 dS} = \frac{dN}{d\varepsilon} \quad \text{WM-approximation}
\]

\[
\frac{dN}{d\varepsilon}_{WM} = \frac{\sqrt{\varepsilon}}{\varepsilon + \varepsilon_0}
\]

INR RAS 2012
nn- и pp-длины рассеяния
Charge Independence and Charge Symmetry of Nuclear Forces

**pp and np Interaction**

A huge amount of data on pp and np interactions has been accumulated. Careful analysis of these data led to constructing NN interaction potentials describing vast majority of experimental data.

**nn Interaction**

The situation around neutron–neutron interaction is more ambiguous. Because of the absence of neutron target, data on this interaction are obtained primarily from reactions with two neutrons in the final state. But in many cases, there are serious discrepancies between available experimental data and the results of the current precise calculations on the basis of Faddeev equations.