Study of Neutron-Neutron Scattering in \( nd \) Breakup Reaction

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Abstract. To study the \( n+d \rightarrow p+n+n \) breakup reaction the experimental setup allowing registration of all secondary particles in different kinematical arrangements was installed at the neutron channel of the Moscow Meson Factory of the Institute for Nuclear Research. The experiment is performed in broad energy range of neutrons (20-100 MeV) incident on deuterium target. The first preliminary data on neutron-neutron scattering length \( a_{nn} \) obtained in the final state interaction (FSI) geometry are presented. For \( E_n = 40 \) MeV and \( \Delta \Theta = 6^\circ \) the value \( a_{nn} = -17.9 \pm 1.0 \) fm is obtained. Test measurements in the \( np \) quasi-free scattering (QFS) arrangement showed that we are able to obtain data on \( nn \) QFS in a broad range of neutron energy.

1. Introduction
In 1932, Heisenberg established the so–called charge independence, which implies that if electromagnetic effects are eliminated the scattering of protons on protons, protons on neutrons and neutrons on neutrons yields nearly the same results. A weaker condition is the so–called charge symmetry, which states that the \( pp \) and \( nn \) force should be equal. Now it is known that the charge independence is broken, for example by the small difference between the proton and neutron mass. The exact form of the \( NN \) potential can be obtained most strictly by studying the simplest systems, for example, the deuteron and nucleon-nucleon scattering experiments. But the absence of free neutron target prevents study of direct neutron-neutron scattering and direct comparison of \( nn \) and \( pp \) interaction. Thus investigation of \( nn \) scattering is performed only by studying the final state interaction (FSI) of two neutrons or quasi-free neutron-neutron scattering in reactions with few-body systems.

Among the few-body reactions the \( nd \) breakup is the most powerful tool for studying \( nn \) interaction. In view of absence of a free neutron target the use of deuterium target and neutron beam is as a matter of fact a unique and effective way of studying \( nn \) interaction. The rather small number of nucleons in the system allows the accurate strict solution of the three-body problem. Despite the simplicity of final \( pnn \) system the experiments can be performed in different kinematical arrangements of the outgoing three nucleons and their results can be compared with rigorous theoretical predictions.

2. Discrepancies in \( nn \) quasi-free scattering and \( nd \) Space Star configuration
Important arguments for continuation both experimental and theoretical works in this area are the clear discrepancies between the theory and existing data. The strongest discrepancies occur in the \( nn \) quasi-free scattering (QFS). In this geometry the two neutrons are detected at angles close to those of \( nn \)
elastic scattering while the outgoing proton is at rest in the laboratory system. In \( nd \) breakup also the \( np \) QFS is possible.

The experimental \( nn \) QFS cross sections data were obtained at \( E_n = 26 \text{ MeV} \) [1] and \( E_n = 25 \text{ MeV} \) [2]. These data overestimate the \( nd \) theory by \( \sim 18\% \). It is contrasted with the fact that the theory described nicely the \( np \) QFS cross section data obtained in \( nd \) breakup reaction at \( E_n = 26 \text{ MeV} \) [1]. Theoretical analysis performed by H.Witala and W.Glökle [3] shows that the theoretical results are quite stable under exchange of the standard nuclear potentials. Also the modern \( 3N \) forces have negligible effect on the QFS configurations. Authors proposed that the disagreement is connected with the unsettled properties of the \( nn \) force [3]. Thus, by simply multiplying the \( nn \) \( ^1S_0 \) force matrix element by a factor \( \lambda = 1.08 \) one can perfectly well reconcile theory and data. Thereby it turned out that the \( nn \) QFS peak height is very sensitive to effective range parameter \( r_{\text{eff}} \) and hardly sensitive to \( a_{\text{nn}} \). The outcome for an agreement with the data is the requirement that \( r_{\text{eff}} \) decreases from the value \( r_{\text{eff}} = 2.75 \text{ fm} \) to a significantly smaller one: \( r_{\text{eff}} = 2.41 \text{ fm} \). That strongly breaks charge symmetry and charge independence and is not supported by the present day chiral potential theory.

In the space star (SST) configuration, three nucleons are flying away in the plane perpendicular to the incoming beam in the center of mass system with momenta of equal magnitude. The low-energy \( nd \) SST cross sections are clearly underestimated by rigorous \( nd \) theoretical predictions. The theoretical cross sections practically do not depend on the \( NN \) potential used in the calculations and do not change significantly if any of the present day \( 3NF \) models is included [4]. Even such a large increase of the \( nn \) \( ^1S_0 \) force strength by a factor \( \lambda \approx 1.08 \) [3] will not remove the discrepancy for the \( nd \) SST configuration.

3. Discrepancies in \( nn \) scattering length data
The final state interaction (FSI) geometry, where two neutrons fly together with small relative energy, is widely used for determination of singlet \( nn \) scattering length characterizing the \( nn \) scattering at zero energy. Replacing one of the neutrons by a proton we may determine the neutron-proton scattering length in the same \( nd \) breakup reaction.

Due to existence of the virtual singlet state of two nucleons with close to zero energy, the corresponding scattering lengths \( a_{\text{nn}} \) and \( a_{\text{pp}} \) have large negative values and are rather sensitive to small differences in \( nn \) and \( pp \)-potentials (a \( 1\% \) change in the potential strength results in 20-30\% shift in the scattering length). Thus, precise determination of singlet scattering lengths and their difference \( a_{\text{nn}} - a_{\text{pp}} \) from experimental data is a convenient way for determining the measure of charge symmetry breaking (CSB) of nuclear forces.

![Figure 1](image-url)  
**Figure 1.** The recent experimental data on neutron-neutron scattering length. The gray region corresponds to \( a_{\text{pp}} \) values. Circles – data from \( \pi^+d\rightarrow\gamma+n+n \) reaction, squares – from \( n+d\rightarrow p+n+n \) reaction.
In Figure 1 the recent results of determination of $nn$ scattering length are shown. As one can see, the results for neutron-neutron scattering length obtained by now testify significant uncertainty of $a_{nn}$ values which are clustered near ($16.3\pm0.4$) fm [5,6] and ($18.5\pm0.4$) fm [7,8]. The value $a_{pp} = (–17.3\pm0.3)$ fm is determined in experiments on free $pp$ scattering, and its uncertainty is related mainly to the model dependent procedure of exclusion of electromagnetic component of the $pp$ interaction. So there is even uncertainty about the sign of the difference $a_{nn}–a_{pp}$, which in turn is a measure of charge symmetry breaking (CSB). In order to remove the existing uncertainty in the value of $nn$ scattering length the new precise experiments are needed.

4. The experimental setup for studying $nd$ breakup reaction

To study the $nd$ breakup reaction the experimental setup allowing registration of all secondary particles was installed at the neutron channel of the Moscow Meson Factory of the Institute for Nuclear Research (INR) [9]. The setup allows us to obtain data in different kinematical arrangements in a broad energy region of neutrons (20–100 MeV).

![Figure 2. Schematic of the experimental setup for determining the $a_{nn}$ scattering length in the $nd$ breakup reaction: 1 – neutron-producing target; 2 - neutron beam collimators; 3 - deuterium (CD$_2$) target; 4 - proton detector; 5 - neutron hodoscope. For details see [10].](image)

A schematic of the facility is shown in Figure 2. The beam stop of 200 MeV protons of the INR linear accelerator is used as a neutron source. The neutrons produced in the tungsten target (60 mm W) are collimated at zero angle at a length of 12 m in order to form a beam with a diameter of about 60 mm at the reaction CD$_2$ target. We plan to exchange the passive deuterium target by the active scintillation one. In this case the proton detection will occur in the target and accordingly the proton signal will serve as a starting signal for the time of flight neutron spectrometer.

In the case of passive target, protons are detected by a $\Delta E-E$ telescope consisting of two fast plastic scintillation detectors. Thus the proton telescope determines the proton energy and gives the start signal for TOF spectrometer. The angle of proton detector (placed on the right from the incident neutron beam axis) and its distance from the CD$_2$ target may be changed depending on the geometry used (FSI, QFS, SST). The neutron time-of-flight hodoscope consists of several (5-6 at the moment) detectors, located at different angles with respect to the primary neutron direction at a flight distance of 4-5 m from the CD$_2$ target, on the left from the incident neutron beam axis. The time resolution of all detectors was of about 0.6 ns. The angular resolution was defined by the detector cross section size and the time-of-flight distance; it was about ±0.5°.

The neutrons incident on the deuterium target have a continuous energy spectrum, with an endpoint energy equal to the proton beam energy. However, detection of three particles in coincidence (proton
and two neutrons) makes it possible to reconstruct the primary neutron energy in the \( n+d \rightarrow p+n+n \) reaction and obtain data on the reaction yield in a wide range of neutron energies, determined only by the statistics of the experiment.

5. Preliminary data on \( a_{nn} \)

The first experiments at our setup have been performed in the FSI geometry with the goal obtaining data on neutron-neutron scattering length. In our study we can obtain data on nd breakup reaction yield for various neutron opening angles and various energies of incident neutrons. In an experiment like this, the neutron–neutron FSI manifests itself as a peak in the reaction yield distribution versus the relative energy of two neutrons

\[
\varepsilon = \frac{1}{2} (E_1 + E_2 - 2 \sqrt{E_1 E_2 \cos \Delta \theta}),
\]

whose shape is very sensitive to \( a_{nn} \).

To obtain this distribution it is necessary to detect in coincidence two neutrons flying in a narrow cone of angles with respect to the direction of motion of their center of mass, then measure the energies of both neutrons \( E_1 \) and \( E_2 \) and the angle between them, and finally analyze the shape of the dependence obtained. To extract the value of the neutron-neutron scattering length, the experimental dependence of the reaction yield on \( \varepsilon \) has to be compared with the simulation results based on the Watson-Migdal approximation [11].

![Figure 3. Comparison of the experimental dependence of reaction yield (\( E_n=40 \) MeV, \( \Delta \Theta=6^\circ \)) with simulation results for different values \( a_{nn} \). Curves with the maximum (dotted line) and minimum yield (dashed line) correspond to \( a_{nn} = -21.5 \) fm and -15.5 fm, respectively, central curve (solid line) corresponds to the value of the best fitting: -17.9 fm.](image)

The best statistics in the experiment was obtained for an incident energy of 40 MeV and an opening angle of secondary neutrons of 6º. In Figure 3 these experimental data are compared with the simulation results for three \( nn \) scattering lengths (–15.5, –17.9, and –21.5 fm). During fitting, we calculated the \( \chi^2 \) value for experimental and theoretical (simulated for different scattering lengths) points. To determine the scattering length and its statistical uncertainty, the values of \( \chi^2(a_{nn}) \) were approximated by a quadratic polynomial (see Figure 4). In this case, the minimum value \( \chi^2_{\text{min}} \) determines the scattering length, and the statistical error in determining \( a_{nn} \) is given by

\[
\Delta a_{nn} = \left| a_{nn} \left( \chi^2_{\text{min}} \right) - a_{nn} \left( \chi^2_{\text{min}} + 1 \right) \right|,
\]

i.e., is defined by values of \( a_{nn} \) at \( \chi^2_{\text{min}} \) and \( \chi^2_{\text{min}+1} \). So the value
of neutron-neutron scattering length and its statistical error determined from the data shown in Figure 4 are \( a_{nn} = (-17.9 \pm 0.9) \) fm.

![Figure 4. Dependence of \( \chi^2 \) on \( a_{nn} \) for \( E_n = 40 \pm 5 \) MeV, \( \Delta \Theta = 6^\circ \). The curve is an approximation of the \( \chi^2 \)-dependence by a quadratic polynomial. The minimum of the curve corresponds to the best fitting - \( a_{nn} = -17.9 \) fm.](image)

6. Conclusion

The \( nd \) breakup reaction is a powerful tool to study \( nn \) interaction. Despite the simplicity of final \( pnn \) system the experiments can be performed in different kinematical arrangements of the three outgoing nucleons and their results can be compared with rigorous theoretical predictions. Important arguments for continuation both experimental and theoretical works in this area are the clear discrepancies between the theory and existing data. The strongest discrepancies occur in the \( nn \) quasi-free scattering (QFS) and in the \( nd \) space star geometries. Also the results for neutron-neutron scattering length obtained by now testify significant uncertainty of \( a_{nn} \) values.

The \( nd \) breakup reaction has been investigated at the neutron channel of the Moscow Meson Factory of the Institute for Nuclear Research. We presented the preliminary data on neutron-neutron scattering length, obtained in FSI geometry. Also, the test experiment in the np QFS geometry was performed. The results of the study show that we are able to perform measurements of \( n+p \to p+n+n \) reaction in various kinematical geometries – FSI, QFS and SST.. The data obtained will give new valuable information on the neutron-neutron interaction in a broad range of neutron energies.

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