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EXTRACTION OF NEUTRON-NEUTRON SCATTERING LENGTH FROM nn COINCIDENCE-GEOMETRY nd BREAKUP DATA

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We report preliminary results of a kinematically complete experiment on measurement of *nd* breakup reaction yield at neutron beam RADEX of Institute for Nuclear Research (Moscow, Russia). In the experiment two secondary neutrons are detected in geometry of neutron-neutron final-state interaction. Data are obtained at energy of incident neutrons E_n = 40 - 60 MeV for various divergence angles of two neutrons ΔΘ = 4, 6, 8º. $^1S_0$ neutron-neutron scattering length a_{nn} were determined by comparison of the experimental dependence of reaction yield on the relative energy of two secondary neutrons with results of simulation depending on a_{nn}. For E_n = 40 MeV and ΔΘ = 6º (the highest statistics in the experiment) the value a_{nn} = -17.9 ± 1.0 fm is obtained. The further improving of accuracy of the experiment and more rigorous theoretical analysis will allow one to remove the existing difference in a_{nn} values obtained in different experiments.

Keywords: breakup reaction, neutron, deuteron, neutron-neutron scattering length.

Introduction

The aim of this work – determination of singlet length of *nn*-scattering – is associated with the problem of charge symmetry of nuclear forces suggested in 1932 by Heisenberg. It is known that the charge symmetry breaking (CSB) of nuclear forces, i.e. a difference in nuclear *nn*- and *pp*-interactions, according to the modern representations is associated with difference in masses of **up** and **down** quarks, their charges and magnetic moments [1].

Due to existence of the virtual singlet state of two nucleons with close to zero energy, the corresponding scattering lengths a_{nn} and a_{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). The authors [2] wrote that "the nucleon-nucleon scattering length is a powerful magnifying glass to study the *NN* interaction". Thus, precise determination of singlet scattering lengths and their difference a_{nn} - a_{pp} from experimental data is a convenient way for determining the measure of CSB of nuclear forces.

The proton-proton scattering length is determined in experiments on free *pp* scattering (a_{pp} = -17.3 ± ± 0.4 fm), and its uncertainty is related mainly to the model dependent procedure of exclusion of electromagnetic component of the *pp* interaction.

As the results on direct measurement of neutron-neutron scattering length are not obtained yet, this value is determined mostly using $n + d \rightarrow p + n + n$ and $\pi^- + d \rightarrow \gamma + n + n$ reactions and investigating the region of the *n-n* FSI where two neutrons fly together with small relative energy [2 - 5]. In Fig. 1 the basic recent experimental data on neutron-neutron scattering length are shown. One can see, that results obtained by now testify significant uncertainty of a_{nn} values which are clustered near -16.3 ± 0.4 [2, 3] (Bonn) and -18.5 ± 0.4 fm [4 - 7] (TUNL, LAMPF), so there is even uncertainty about the sign of the difference a_{nn}-a_{pp} which is a measure of CSB. One can note the only known result obtained by TUNL–Bonn collaboration and published in TUNL Annual Report-2005-2006, a_{nn} = = -17.6 ± 0.2, which differs from results of both groups and is consisted with a_{pp} value. But later the both experimental groups presented data close to those they obtained earlier.

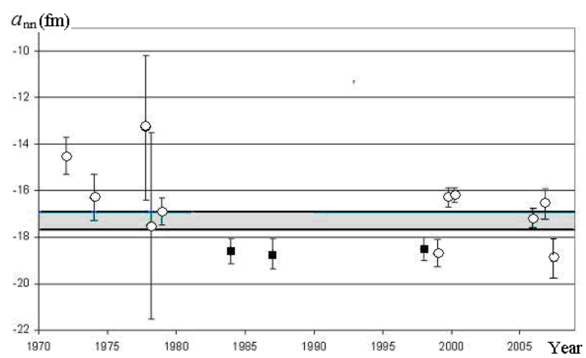

Fig. 1. The recent experimental data on neutron-neutron scattering length. Squares – data extracted from $\pi^- + d \rightarrow \gamma + n + n$ reaction, circles – from $n + d \rightarrow p + n + n$ reaction. The gray region corresponds to a_{pp} values.

In order to remove the existing uncertainty in the value of *nn* scattering length the new precise experiments are needed.

Experiment

In this experiment, the neutron-neutron final state interaction (FSI) is investigated in the $n + d \rightarrow p + n + n$ reaction at an incident neutron energy of 40 ± 5 MeV. Two-neutron events in the output channel, having a very small relative momentum, correspond to the FSI kinematical region. In this case, the neutron-neutron FSI manifests itself as a peak in the dependence of the reaction yield on the relative energy of two neutrons:

$$\varepsilon = \frac{1}{2}(E_1 + E_2 - 2\sqrt{E_1 E_2}\cos\Delta\Theta), \qquad (1)$$

whose shape is sensitive to a_{nn}.

To obtain an experimental dependence of the reaction yield and determine a_{nn}, it is necessary to detect in coincidence two neutrons, emitted in a narrow cone of angles with respect to the direction of motion of their center of mass, and measure the energies of both neutrons (E_1 and E_2) and angle $\Delta\Theta$ between their exit directions.

The $n + d \rightarrow p + n + n$ reaction is investigated on the neutron beam of the RADEX channel of the Moscow meson factory at the Institute for Nuclear Research [8]. A schematic of the facility is shown in Fig. 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 to form a beam ~60 mm in diameter at the reaction target. At the first stage of the experiment, data for primary neutrons with an energy of 40 ± 5 MeV were obtained and processed. In this case, the secondary particles (neutrons and protons) have energies in the range of 10–20 MeV. The range of primary neutron energies studied here is optimal, because it produces simultaneously a sufficiently high neutron flux and fairly good time resolution of secondary neutrons.

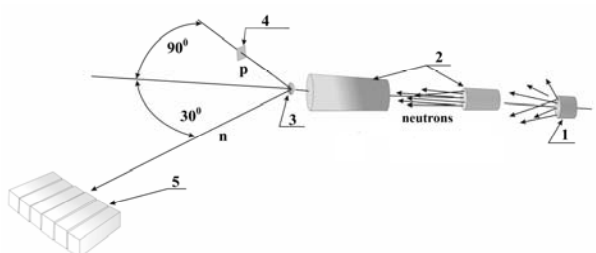

Fig. 2. Schematic of the experimental setup for determining the nn scattering length in the n + d → p + n + n reaction: *1* – neutron-producing target; *2* - neutron beam collimators; *3* - deuterium (CD_2) target; *4* - proton detector; *5* - neutron hodoscope.

A deuterated polyethylene disk with a thickness of 100 mg cm^{-2} and a diameter of 50 mm is used as the measurement target. To subtract the background, measurements with a carbon target were performed. To decrease the proton energy loss, the targets were oriented at an angle of 20° with respect to the proton detector and, correspondingly, at angles of about 50° to the neutron detectors. In this case, the emitted protons have minimum ionization loss in the target and at the same time the multiple neutron scattering in the target remains minimal.

Protons are detected by a fast scintillating plastic detector with a diameter of 40 mm and a thickness of 5 mm. The detector is located at a distance of 30 cm on the right from the CD_2 target at an angle of 90° with respect to the incident neutron beam axis. It is necessary to detect protons at a certain angle both to form a starting signal for the time-of-flight spectrometer and to additionally select events with low relative neutron energies.

The neutron time-of-flight hodoscope consists of six detectors, located at angles of 24 - 34° with respect to the primary neutron direction, with a step of 2° at a flight distance of 5 m from the CD_2 target, on the left from the incident neutron beam axis. The detectors are made of scintillating plastic in the form of rectangular prisms with a cross section of 100·140 mm^2 and a length of 300 mm. The angular spread of neutron detection is defined by the detector cross section size and the time-of-flight distance; it was found to be ±0.5° in our experiment. The time resolution of the scintillation detectors was measured using light emitting diodes as light sources. The lower amplitude detection threshold corresponds to the Compton edge of the ^{137}Cs γ-line: 488 keV (~1 MeV for neutrons).

Having obtained information on the time-of-flight, the energies of two neutrons are calculated while the neutron opening angle is determined from the numbers of the triggered detectors. The relative energy ε of two neutrons is calculated using formula (1) from the measured energies of two neutrons and their opening angle, after which the distribution of the number of *nd*-breakup events on ε is constructed.

Simulation of the nd breakup reaction yield

The procedure for extracting information on the singlet *nn* scattering length from the data on the *nd* breakup reaction yield consists in comparing the shape of the FSI peak in the experimental dependence of the reaction yield on the relative energy of two neutrons **ε** with the results of the reaction simulation using various theoretical models. This dependence, the shape of which is sensitive to a_{nn}, can be described using the Watson - Migdal (WM) formula in the simplified form (zero range nuclear force approximation) with a particular value of the parameter a_{nn}

$$F_{WM} \sim \frac{\sqrt{\varepsilon}}{\varepsilon + \varepsilon_0}. \qquad (2)$$

The relation between the parameter ε_0 and the scattering length a_{nn} is expressed by the formula

$$\varepsilon_0 = \frac{\hbar^2}{m_n \alpha_{nn}^2} \approx \frac{41.5}{\alpha_{nn}^2}, \qquad (3)$$

where m_n is the neutron mass, a_{nn} is in fm, and ε_0 is in MeV. The three-body kinematics of the *nd* breakup reaction was simulated in two stages. At the first stage, the formation of a neutron pair with effective invariant mass $M_{nn} = 2m_n + \varepsilon$ in the two-particle reaction $nd \rightarrow p + (nn)$ was considered and the emission angles and kinetic energies of the proton Θ_p and E_p and the *nn*-pair center of mass Θ_{nn} and E_{nn} were calculated in the laboratory coordinate system. The ε dependence of the reaction yield was taken into account by the number of simulated events with different ε, in accordance with curves calculated by the WM formula (2) with a particular value of ε_0 or a_{nn} (3).

At the second stage, the (*nn*) breakup $(nn) \rightarrow n_1 + n_2$ was considered and the emission angles and kinetic energies of two neutrons Θ_1, Θ_2 and E_1, E_2 were calculated in the laboratory coordinate system. The experimental conditions (the arrangement and number of detectors, their energy and angular resolution) were then taken into account. Events corresponding to the simultaneous arrival of the proton at the proton detector and of the pair of neutrons separated by the angle ΔΘ at the hodoscope's neutron detectors were selected from the total number of simulated events.

Determination of a_{nn}

To determine scattering lengths a_{nn} the experimental dependence of the yield of *nd*-breakup reaction $\frac{dN^{\exp}(\Delta\Theta)}{d\varepsilon}$ is compared with results of simulation $\frac{dN^{sim}(\Delta\Theta)}{d\varepsilon}$. In Fig. 3 experimental data for ΔΘ = 4, 6, 8º and energy of incident neutrons 40 ± 5 MeV are compared with simulation results for three values of *of nn*-scattering length (-15.5 fm, -17.9 fm, -21.5 fm). For the experimental points total statistical error, including the statistical uncertainty of background subtraction, is shown. One can see that the best conditions for comparison with results of simulation are for data at ΔΘ = 6º. Data for 8º are obtained with worse statistics, while for 4º the FSI peak is very narrow, that impedes the comparison. Therefore at the given stage of data collection extraction of value of neutron-neutron scattering length was performed for the data obtained at ΔΘ = 6º.

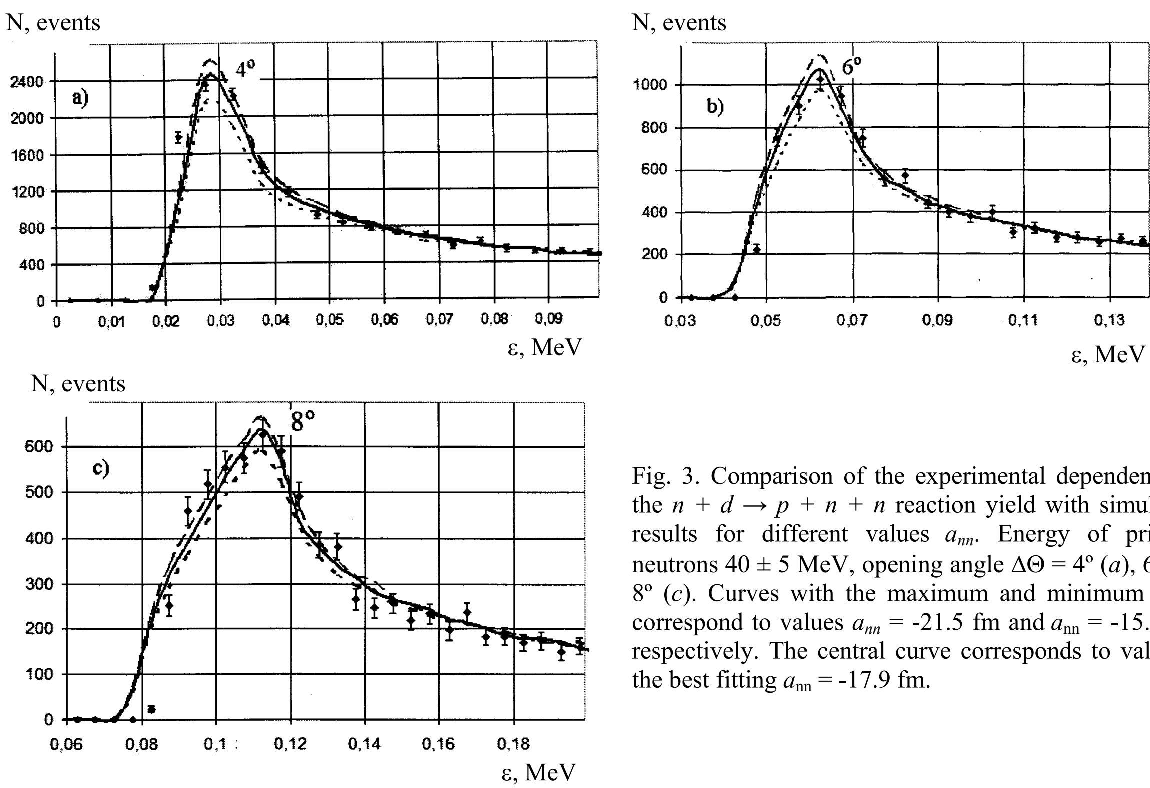

Fig. 3. Comparison of the experimental dependence of the $n + d \rightarrow p + n + n$ reaction yield with simulation results for different values a_{nn}. Energy of primary neutrons 40 ± 5 MeV, opening angle ΔΘ = 4º (*a*), 6º (*b*), 8º (*c*). Curves with the maximum and minimum yield correspond to values a_{nn} = -21.5 fm and a_{nn} = -15.5 fm, respectively. The central curve corresponds to value of the best fitting a_{nn} = -17.9 fm.

To determine scattering length the simulation was performed in a wide range of a_{nn} values from -13 up to -23 fm. Further we have minimized value χ^2 for the experimental and theoretical (simulated) points, given by expression:

$$\chi^2(a_{nn}) = \sum_{\varepsilon} \frac{\left(\frac{dN^{\exp}(\Delta\Theta)}{d\varepsilon} - A\frac{dN^{sim}(\Delta\Theta)}{d\varepsilon} \right)^2}{\left(\Delta \frac{dN^{\exp}(\Delta\Theta)}{d\varepsilon} \right)^2}, \qquad (4)$$

where *A is* the normalizing coefficient determined as the ratio of integrals of experimental and theoretical spectra in a wide range of ε (0 - 0.8 MeV), and $\Delta \frac{dN^{\exp}(\Delta\Theta)}{d\varepsilon}$ is a statistical error of the experimental points. To extract the value of scattering length and its statistical uncertainty, the dependence $\chi^2(a_{nn})$ was approximated by a quadratic polynomial (Fig. 4).

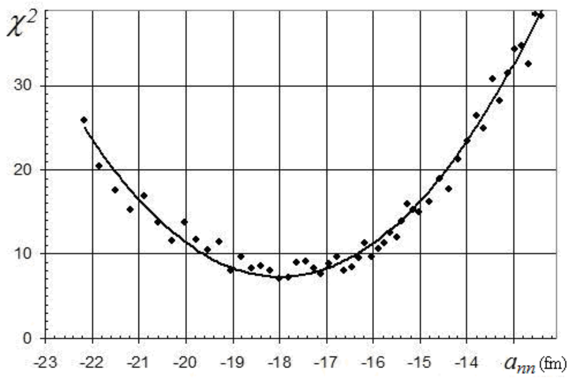

Fig. 4. χ^2 versus a_{nn} dependence for E_n = 40 5 MeV, ΔΘ = 6º. Values χ^2 *(a_{nn})* are obtained using Eq. (4) by summation over 8 points on ε (0.052 - 0.087 MeV). Curve is approximation by a quadratic polynomial.

In this case, the minimum value $\chi^2_{\min}$ determines the scattering length, and the statistical error in determining a_{nn} is given by the formula

$$\Delta a_{nn} = \left| a_{nn}(\chi^2_{\min}) - a_{nn}(\chi^2_{\min} + 1) \right|. \qquad (5)$$

Conclusion

Neutron-neutron FSI was studied in the $n + d \to p + n + n$ reaction in the kinematically complete experiment at neutron energy 40- 60 MeV. In the experiment two neutrons outgoing in a narrow cone of opening angles ΔΘ = 2 - 10º were detected. $^1S_0$ neutron-neutron scattering length a_{nn} was determined by comparison of the experimental dependence of reaction yield on the relative energy of two secondary neutrons with results of simulation depending on a_{nn}. For E_n=40 MeV and ΔΘ = 6º (the highest statistics in the experiment) the value a_{nn} = = -17.9 ± 1.0 fm is obtained. The further improving of accuracy of the experiment and more rigorous theoretical analysis will allow one to remove the existing discrepancy in a_{nn} values obtained in different experiments.

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ВИЗНАЧЕННЯ НЕЙТРОН-НЕЙТРОННОЇ ДОВЖИНИ РОЗСІЯННЯ З ДАНИХ ПРО ВИХОДИ РЕАКЦІЇ nd РОЗВАЛУ В ГЕОМЕТРІЇ РЕЄСТРАЦІЇ ДВОХ НЕЙТРОНІВ У КІНЦЕВОМУ СТАНІ

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Одержано попередні дані вимірювання виходу реакції *nd* розвалу в кінематично повному експерименті, що виконувався на нейтронному каналі РАДЕКС Інституту ядерних досліджень (Москва, Росія). В експерименті реєструються два вторинних нейтрони в конфігурації нейтрон-нейтронної взаємодії в кінцевому стані. Дані одержано при енергії первинних нейтронів E_n = 40 - 60 МеВ для різних кутів розльоту двох нейтронів ΔΘ = 4, 6, 8º. $^1S_0$ нейтрон-нейтронна довжина розсіяння a_{nn} визначається шляхом порівняння експериментальної залежності виходу реакції від відносної енергії вторинних нейтронів з результатами моделювання, що залежать від величини a_{nn}. Для E_n = 40 МеВ и ΔΘ = 6º (найкраща статистика в експерименті) одержано значення a_{nn} = = -17,9 ± 1,0 Фм. Подальше покращання точності експерименту та більш строгий теоретичний аналіз одержаних даних дасть змогу усунути існуюче розходження результатів для a_{nn}, одержаних у різних експериментах.

Ключові слова: реакція розвалу, нейтрон, дейтрон, нейтрон-нейтронна довжина розсіяння.

ОПРЕДЕЛЕНИЕ НЕЙТРОН-НЕЙТРОННОЙ ДЛИНЫ РАССЕЯНИЯ ИЗ ДАННЫХ О ВЫХОДЕ РЕАКЦИИ nd РАЗВАЛА В ГЕОМЕТРИИ РЕГИСТРАЦИИ ДВУХ НЕЙТРОНОВ В КОНЕЧНОМ СОСТОЯНИИ

Е. С. Конобеевский, М. В. Мордовской, И. М. Шарапов, С. И. Поташев, С. В. Зуев

Получены предварительные данные измерения выхода реакции *nd* развала в кинематически полном эксперименте, проводимом на нейтронном канале РАДЭКС Института ядерных исследований (Москва, Россия). В эксперименте детектируются два вторичных нейтрона в конфигурации нейтрон-нейтронного взаимодействия в конечном состоянии. Данные получены при энергии первичных нейтронов E_n = 40 - 60 МэВ для различных углов разлета двух нейтронов $\Delta\Theta$ = 4, 6, 8º. $^1S_0$ нейтрон-нейтронная длина рассеяния a_{nn} определяется сравнением экспериментальной зависимости выхода реакции от относительной энергии вторичных нейтронов с результатами моделирования, зависящими от величины a_{nn}. Для E_n = 40 МэВ и $\Delta\Theta$ = 6º (наилучшая статистика в эксперименте) получено значение a_{nn} = -17,9 ± 1,0 Фм. Дальнейшее улучшение точности эксперимента и более строгий теоретический анализ полученных данных позволит устранить существующее расхождение результатов для a_{nn}, полученных в разных экспериментах.

Ключевые слова: реакция развала, нейтрон, дейтрон, нейтрон-нейтронная длина рассеяния.

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