DETERMINATION OF THE NEUTRON-NEUTRON SCATTERING LENGTH IN *nd* BREAKUP REACTION AT 40-60 MEV

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We report the first results of a kinematically complete experiment on measurement of *nd* breakup reaction yield at neutron beam RADEX of Institute for Nuclear Research. In the experiment two neutrons are detected in geometry of neutron-neutron final-state interaction which allow one to determine the $^1S_0$ neutron-neutron scattering length a_{nn}. Experimental dependence of the reaction yield on relative energy of two secondary neutrons was compared with predictions of Watson-Migdal theory. For $\Delta\Theta=6^o$ and E_n=40 MeV the value of neutron-neutron scattering length a_{nn} = −17.9 ± 1.0 fm is obtained. The further improving of experimental uncertainty will allow one to remove the existing difference of results obtained in various experiments.

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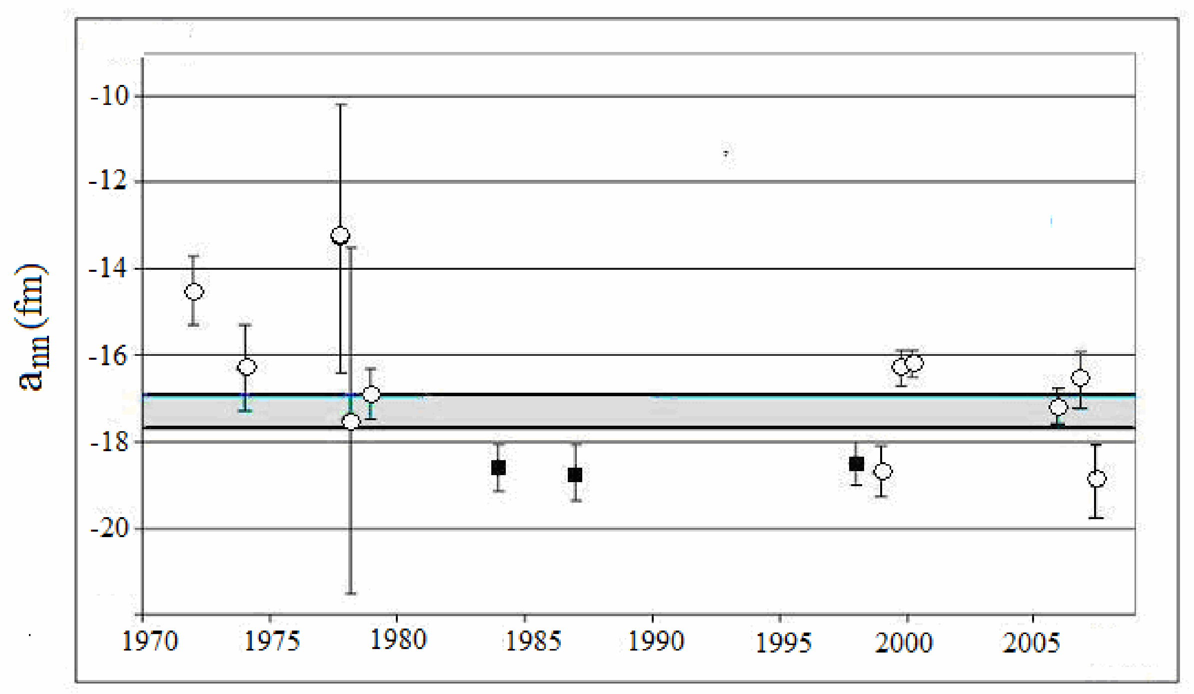
1. INTRODUCTION

Our work is related to the problem of charge symmetry of nuclear forces. It is known that the charge symmetry breaking (CSB), i.e. the difference in nuclear *nn* and *pp* interactions, is a small effect, which, according to the modern concepts, is related to the mass difference between *up* and *down* quarks and electromagnetic energy differences caused by their different electric charges and magnetic moments [1].

Due to the presence of a virtual level with a close to zero energy in the singlet state of two nucleons, the corresponding scattering length is very sensitive to small changes in the *NN* potential. The authors of [2] wrote that "the nucleon-nucleon scattering length is a powerful magnifying glass to study the *NN* interaction." A ~1% change in the nuclear potential leads to a ~30% change of the value for the scattering length. 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 value of proton-proton scattering length a_{pp} = −17.3 ± 0.3 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.

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



2. THE STATEMENT OF THE EXPERIMENT

The most of works determining a_{nn} in the *nd* breakup reaction were performed whether in recoil geometry, detecting proton and neutron flying on the opposite sides in respect to the beam of primary neutrons (Φ=180º geometry), or in the FSI geometry detecting two neutrons flying together (opening angle close to 0º) with small relative momentum (Φ=0º geometry). Difference of our work consists in the possibility of obtaining data on *nd* breakup reaction in FSI geometry for various opening angles and various energies of incident neutrons. In this geometry neutron–neutron FSI manifests itself in the form of a maximum in the distribution of the reaction yield over the relative energy of two neutrons

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

Rigorous theoretical calculations showed that the shape of this distribution is sensitive to the *nn*-scattering length and that experiments in this region are ideal for determining a_{nn}. To describe the dependence of the reaction yield on the relative energy of two neutrons, simple Watson–Migdal formula is often used:

$$F_{MB} \sim \frac{\sqrt{\varepsilon}}{\varepsilon + \varepsilon_0}, \quad (2)$$

where the parameter ε_0 and scattering length a_{nn} are connected as

$$\varepsilon_0 = \frac{\hbar^2}{m_N a_{nn}^2} \approx \frac{41.5}{a_{nn}^2} . \quad (3)$$

So, to determine a_{nn} 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 dependence obtained.

3. EXPERIMENTAL DETAILS

The $n + d \to p + n + n$ reaction is investigated at the neutron beam of the RADEX channel of the Moscow meson factory of the Institute for Nuclear Research, Russian Academy of Sciences. A schematic of the setup is shown in Fig. 1. The proton beamstop of the INR linear accelerator is used as a neutron source. The neutrons produced by 200 MeV protons in the tungsten target (60 mm W) are collimated at zero angle at a length of 12 m to form a beam of ~60 mm in diameter at the scattering target. A deuterated polyethylene disk with a thickness of 100 mg cm^{-2} and a diameter of 50 mm is used as the scattering target.

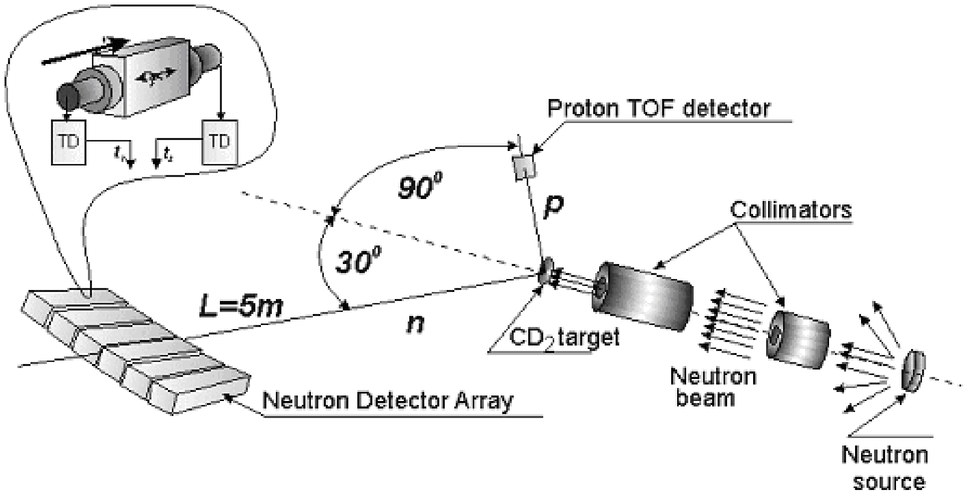


Fig.1. Schematic of the experimental setup for determining the *nn*-scattering length in the $n+d \to n+n+p$ reaction.

Protons are detected by a fast scintillating plastic detector 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. Detection of protons at a certain angle is needed 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. For six neutron detectors, there are 15 such combinations with different opening angles: 2°, 4°, 6°, 8°, and 10° (five, four, three, two, and one, respectively). So during the experiment data on reaction yield may be simultaneously obtained for various opening angles of secondary neutrons. The time resolution of all detectors was about of 0.6 ns. The angular resolution of about ±0.5° was defined by the detector cross section size and the time-of-flight distance.

Based on the information about the time-of-flights (and accordingly energies) of two neutrons and the numbers of triggered detector (opening angle) the relative energy ε of two neutrons is calculated. Then the distribution of the number of *nd* breakup events on ε is constructed.

The energy spectrum of the neutrons incident on the deuterium target is continuous and includes all energies, up to the limiting one, 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 $n + d \to p + n + n$ reaction and obtain data on the reaction yield in a wide range of neutron energies, determined only by the statistics of the experiment. In Fig.2 we can see the reconstructed spectrum of neutrons incident on the deuterium target and causing correlated events in the detectors located at opening angle 6°. It is seen that data on reaction yield may be obtained in broad energy region 30-70 MeV. Data at greater energies, because of low flux of primary neutrons, require bigger run time. Experiment at lower energies leads to big uncertainties connected with registration of low energy protons. So the energy range of 30-70 MeV is optimal for obtaining data on the *nd* breakup reaction at our setup.

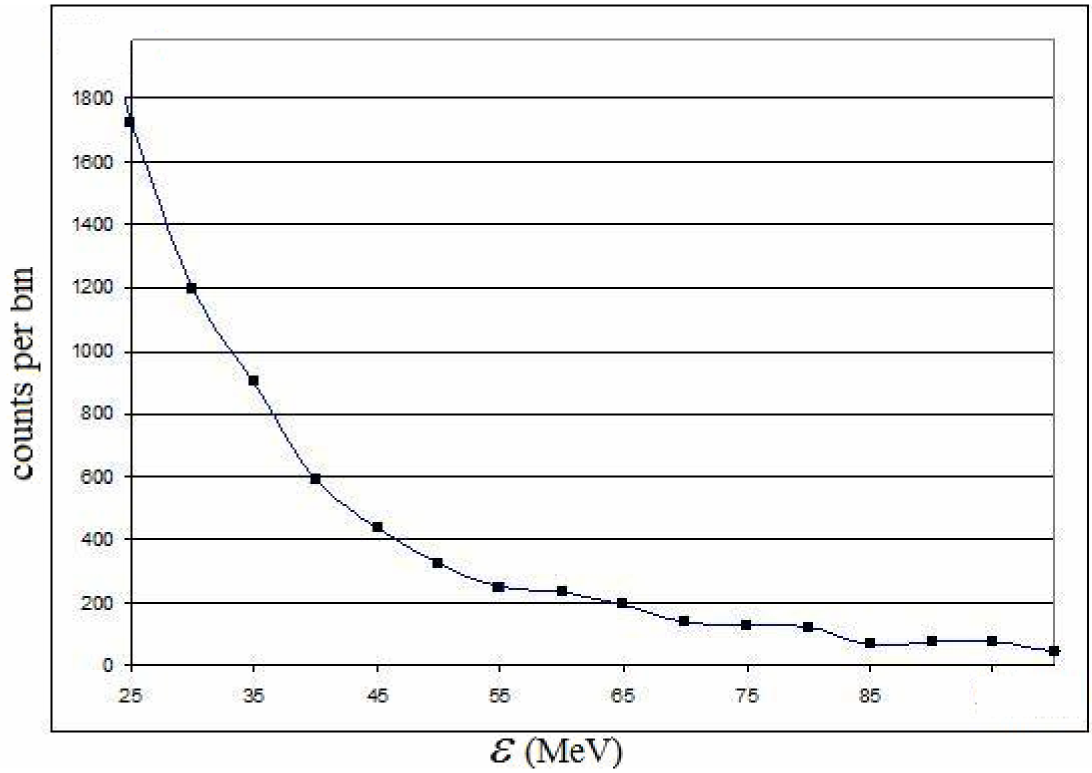


Fig.2. Reconstructed spectrum of neutrons incident on the deuterium target and causing correlated events in the detectors located at opening angle 6°.

4. *nd* BREAKUP SIMULATION

To extract the value of neutron-neutron scattering length the experimental dependence of the reaction yield on ε should be compared with the simulation results. In this case, the three body kinematics of the $n + d \rightarrow p + n + n$ reaction is modeled in two stages: $n + d \rightarrow p + (nn)$ and $(nn) \rightarrow n_1 + n_2$. At the first stage $n+d \rightarrow p+(nn)$ the formation of two-neutron system (nn) with effective mass $M_{nn}c^2=2m_nc^2+\varepsilon$ is considered. Thus, the dependence of the reaction yield on ε is taken into account by the number of simulated events with different relative energies of the *nn*-system, according to the curves calculated from the simplified Watson-Migdal formula (2). So in such a way, the dependence of the shape of the distribution on scattering length is introduced. The energy of primary neutrons are simulated in the energy range related to the experimental one. Then the emitting angles and energies of the proton Θ_p, E_p and center of mass of *nn*-pair in laboratory frame are calculated. At the second stage we consider the decay of the (nn)-pair $(nn) \rightarrow n_1+n_2$ and calculate the emitting angles and energies of the two breakup neutrons Θ_1, Θ_2, E_1 , E_2. Then the experimental geometry and conditions are taken into account: energies of incident neutrons, the position and number of the detectors and their energy and angular resolution.

So, the simulation results as well as the experimental data may be obtained for different energies of incident neutrons and for various opening angles. In Fig.3 are shown the experimental and simulated dependences of the reaction yield on the relative energy of two neutrons for various opening angles - 4, 6 and 8 degrees at equal energy of primary neutrons - 40±5 MeV. One can see that the significant difference in the shape of the experimental distributions is well reproduced by the simulation.

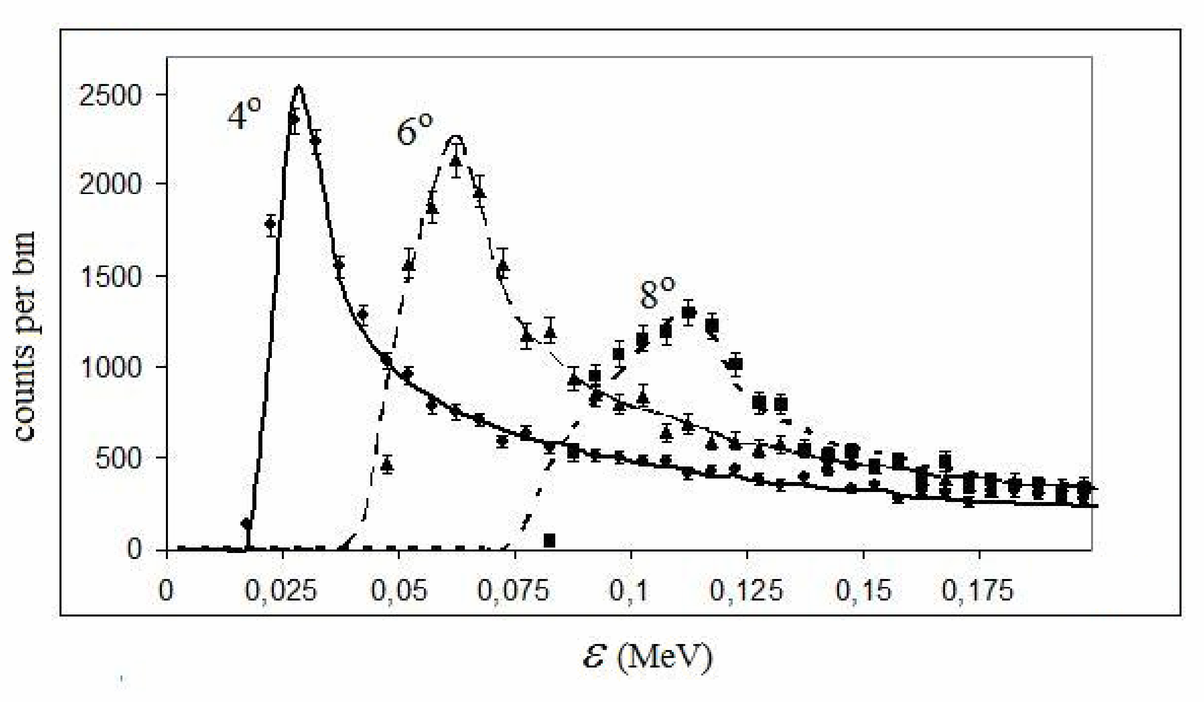


Fig.3. Experimental and simulated dependences of the reaction yield on the relative energy of two neutrons for various opening angles - 4, 6 and 8 degrees at equal energy of primary neutrons E_n=40±5 MeV.

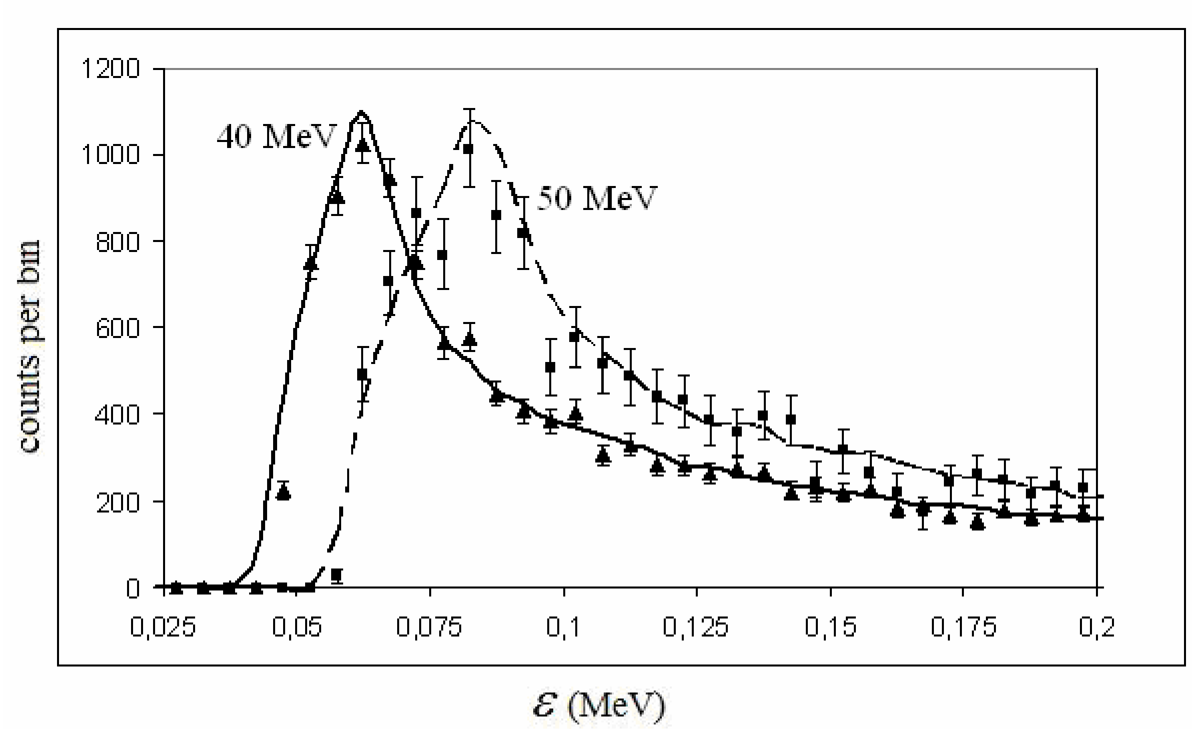


Fig.4. Experimental and simulated curves for the opening angle of 6 deg. but for different energies of primary neutrons 40 and 50 MeV

In Fig.4 the experimental and simulated curves for the opening angle of 6 degrees but for different energies of primary neutrons 40 and 50 MeV are presented. One can see that the dependence on energy of primary neutrons is also well reproduced by simple calculations using Watson-Migdal formula. It should be noted that all simulated distribution are obtained for a_{nn} =–18 fm.

5. DETERMINATION OF a_{nn}

To extract a_{nn} the experimental data were compared with simulation results. The best statistics in the experiment was obtained for incident energy of 40 MeV and opening angle of secondary neutrons 6 deg., In Fig.5 these experimental data are compared with the simulation results for three *nn* scattering lengths (–15.5, –17.9, and –21.5 fm). The total statistical error is shown for experimental points, including the statistical uncertainty of background subtraction.

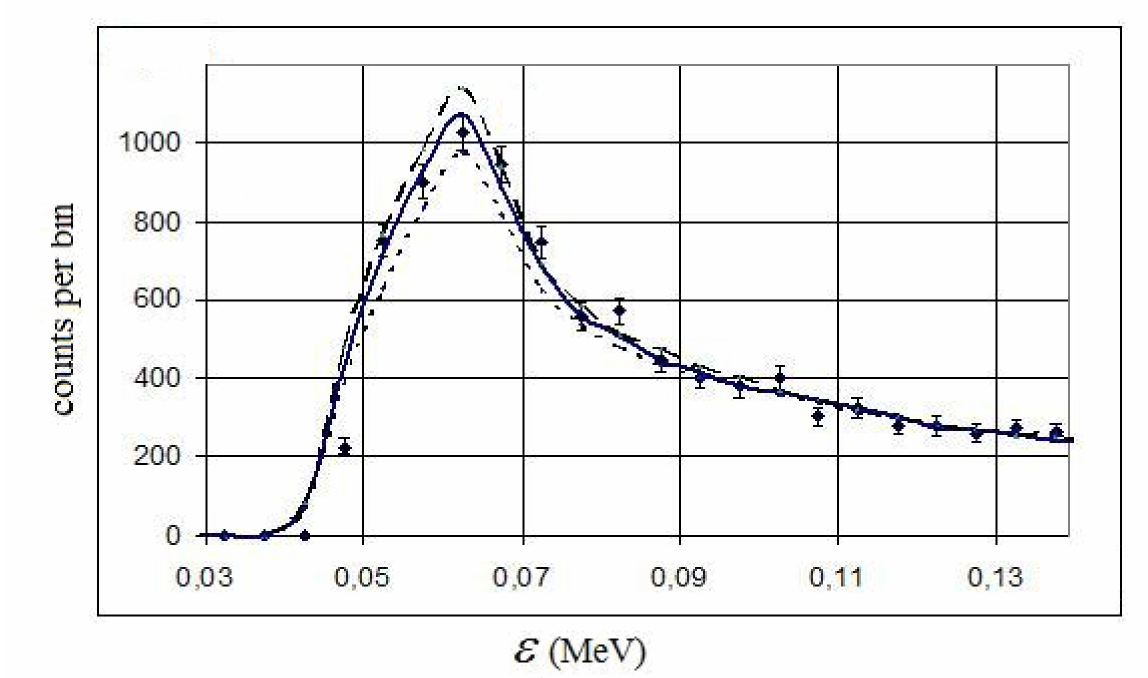


Fig.5. Comparison of the experimental dependence of reaction yield on ε (ΔΘ=6º, E_n=40±5 MeV) and the simulation curves for different a_{nn}. The curves with maximum and minimum yields correspond to a_{nn} =–21.5 and –15.5 fm, respectively. The intermediate curve corresponds to the best fitting a_{nn}=–17.9 fm.

The best fitting is obtained for a_{nn} = –17.9 ± 0.9 fm. During fitting, we calculated the χ2 value for experimental and theoretical (simulated for different scattering lengths) points, which is given by the expression:

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

where A is the normalization coefficient, determined as the ratio of the integrals of the experimental and theoretical spectra over a wide range of ε (0– 0.8 MeV), and $\Delta \frac{dN^{эксп}(\Delta\Theta)}{d\varepsilon}$ is the statistical error of experimental points.

To determine the scattering length and its statistical uncertainty, the values of $\chi^2(a_{nn})$ are approximated by a quadratic polynomial (Fig.6). In this case, the minimum value of χ^2_{min} determines the scattering length, and the statistical error in determining a_{nn} is given by (5):

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

i. e. is defined by values of a_{nn} at χ^2_{min} and χ^2_{min}+1.

The values $\chi^2(a_{nn})$ in Fig. 6 were obtained by summation over 14 points in the range of ε from 0.052 to 0.117 MeV; however, a change in the fitting range to 8 (0.052–0.087 MeV) or 20 (0.052–0.147 MeV) points barely changes both the scattering length and the statistical error in its determination (the average value for three fittings is a_{nn} = –17.9 ± 1.0 fm). Thus, the result obtained is stable with respect to a change in the fitting range.

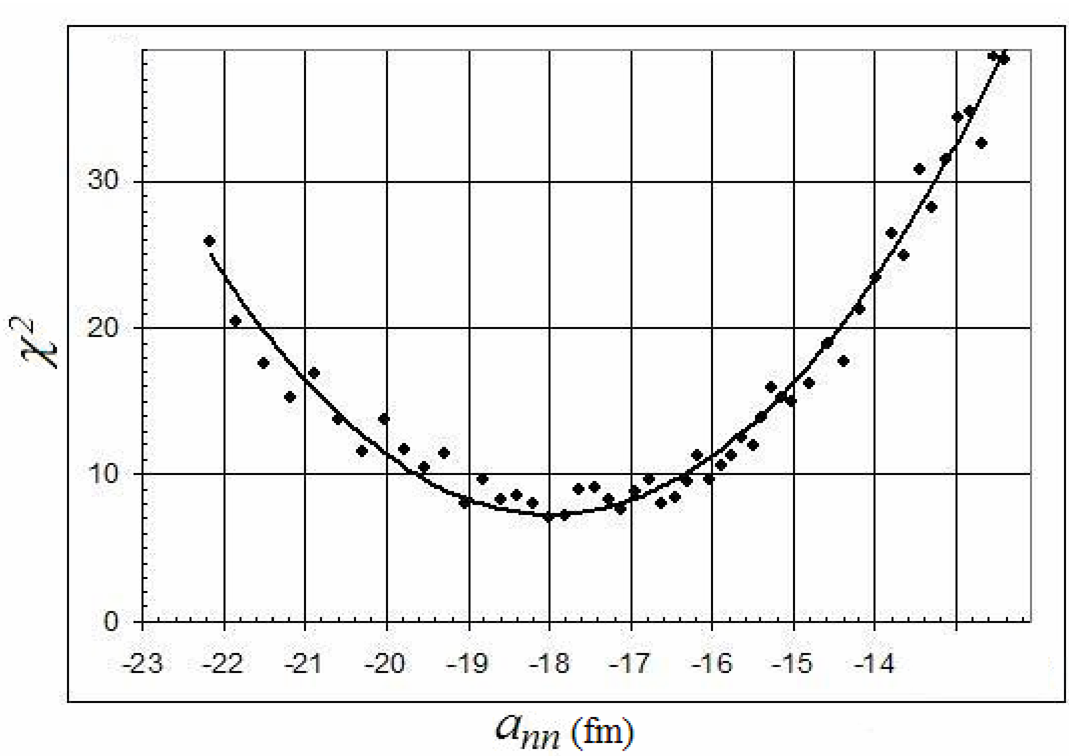


Fig.6. χ^2 vs a_{nn} from the shape analysis of data on reaction yield for $\Delta\Theta$=6° and E_n=40±5 MeV. The curve is the approximation by a quadratic polynomial.

6. SUMMARY

The neutron-neutron $^1S_0$ scattering length a_{nn} has been determined from a kinematically complete *nd* breakup experiment at E_n =40-60 MeV and four opening angles of the *nn* pair between 4 and 10 deg. We performed the shape analysis of the FSI dependence of reaction yield on relative energy of *nn* pair. The value of $a_{nn} = -17.9 \pm 1.0$ fm was obtained at energy of incident neutrons of 40±5 MeV and opening angle of 6 deg. We also obtained data for other opening angles: ΔΘ= 4°, 8° and 10°; however, these data have poorer statistics and cannot be used at this stage to determine the *nn* scattering length. Note that the accuracy of the data for the opening angle ΔΘ= 6° is also insufficient for eliminating the existing discrepancy in the *nn*-scattering length obtained at TUNL and Bonn. Additional statistics should be collected in our experiment.

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