Direct Measurement of Neutron-Neutron Scattering


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Abstract. To resolve long-standing discrepancies in indirect measurements of the neutron-neutron scattering length $a_{nn}$ and to contribute to solving the problem of the charge symmetry of the nuclear force, the collaboration DIANNA (Direct Investigation of $a_{nn}$ Association) plans to measure the neutron-neutron scattering cross section $\sigma_{nn}$. The key issue of our approach is the use of the through-channel in the Russia reactor YAGUAR with a peak neutron flux of $10^{18}$/cm$^2$/s. The proposed experimental setup is described. Results of calculations are presented to connect $\sigma_{nn}$ with the $nn$-collision detector count rate and the neutron flux density in the reactor channel. Measurements of the thermal neutron fields inside polyethylene converters show excellent prospects for the realization of the direct nn-experiment.

INTRODUCTION

An attractive way to solve the fundamental problem of charge symmetry of the nuclear force is comparison of the values for the neutron-neutron $a_{nn}$ and proton-proton $a_{pp}$ scattering lengths. While the length $a_{pp}$ has the well established value of $-17.3 \pm 0.005$ (stat) $\pm 0.4$ (syst) fm obtained in the pp-scattering experiments, determination of the length $a_{nn}$ has encountered difficulties. Recent $\sim 10\%$ discrepancies [1, 2] in the results of indirect measurements of $a_{nn}$, which prevent comparison with the quark approach [3] to the symmetry breaking, provide an additional motivation for direct measurements of $a_{nn}$.

Direct measurements have been proposed for pulsed reactors [4, 5, 6], for accelerators [7], for steady-state reactors [8], and even for underground nuclear explosions [9]. However, no experiment has been performed. The main idea was to use neutron collisions in a powerful beam and to detect the scattered neutrons externally. The “target” and the “beam” then are neutrons produced by the same neutron source, and therefore the nn-scattering intensity is proportional to the square of the neutron flux density, while the background due to scattering on walls or on residual gas depends linearly on the flux density.

The densities of such neutron targets are extremely small, e.g., $10^{10}$/cm$^3$ for a flux density of $2.5 \times 10^{15}$/cm$^2$/s at the best steady-state reactors. The situation can be much better at pulsed neutron sources, where the thermal neutron flux density is $\geq 1 \times 10^{17}$/cm$^2$/s or higher. Increasing the flux improves dramatically the ratio of the nn-effect to background, and nn-measurements become feasible.

Here we describe the DIANNA approach to the direct nn-scattering measurement which is proposed [10] to be performed at the Russian pulsed reactor YAGUAR.

DIRECT MEASUREMENT OF THE NN-SCATTERING LENGTH

The nn-cross section and scattering length

In effective-range theory, the singlet spin scattering cross section $\sigma_s$ is defined by the scattering length $a_{nn}$, the effective range $r_0$, and the neutron wave number $k$ as

$$\sigma_s = \frac{4\pi}{(1/a_{nn} - k^2r_0/2)^2 + k^2} = 4\pi a_{nn}^2 k^2 \quad \text{at} \quad k \to 0. \quad (1)$$
For thermal neutrons (with typical energy of 0.025 eV), the $r_0 = 0$ approximation works well. The cross section $\sigma_{nn}$ measured with unpolarized neutrons is a statistical sum of the singlet $\sigma_s$ and triplet $\sigma_t$ cross sections:

$$\sigma_{nn} = \frac{1}{4}\sigma_s + \frac{3}{4}\sigma_t = \frac{1}{4}\sigma_s = \pi a_{nn}^2.$$  \hspace{1cm} (2)

Since the Pauli exclusion principle for identical particles forbids the interaction of two neutrons in the triplet state, $\sigma_t$ is expected to be zero, and the measured cross section $\sigma_{nn}$ is equal to one fourth of the “theoretical” singlet cross section $\sigma_s$. Eq. (2) determines directly the scattering length $a_{nn}$ from the measured $\sigma_{nn}$. The relative uncertainty for $a_{nn}$ is one half of that for $\sigma_{nn}$.

### Scheme of the $nn$-experiment at YAGUAR

The reactor YAGUAR (VNIITF, Snezhinsk, Russia) [11], can produce two bursts per day with an energy release of up to 33 MJ per burst. During the pulse duration $T = 0.90$ ms (FWHM for the case of an inserted thermal neutron converter), about $10^{18}$ fast neutrons with an average energy of 0.9 MeV are generated in a $V = 40$-liter volume of the liquid active core. The solute contains 465 g per liter of Uranium (90% $^{235}$U) and 5 g per liter of cadmium. The critical height is about 39 cm. The body of the reactor has a cylindrical space of 12-cm diameter for the experimental channel.

After collisions in the reactor channel, neutrons will reach the detector placed at about 12 m from the channel central plane, and will be measured by the time-of-flight (TOF) method. At this flight path the detector effective solid angle $\Omega_{eff}$ is about $5 \times 10^{-6}$. The detector counts $N_D$ per pulse (integrated over the thermal part of the TOF spectrum) are related to $\sigma_{nn}$ and neutron flux density $\Phi_{av}$ by

$$N_D = 2c_{av}\frac{\Phi_{av}^2}{v_0} \sigma_{nn} TV \Omega_{eff} \text{ (counts/pulse).}$$  \hspace{1cm} (3)

This relation is discussed in the next subsection.

One possible arrangement for the experiment is shown schematically in Fig. 1. The reactor active core 3 is placed at 2 m above the floor level. The polyethylene moderator 4 is inserted in the reactor channel. An evacuated tube contains a collimation system 5 that is designed to screen the neutron source from the detector and to eliminate background due to neutrons scattered from the walls. The neutron detector 6 is placed at about 12 m from the above the center of the moderator. An absorber 1 reduces the neutron scattering from the back wall into the detector, while the time-of-flight measurement additionally separates (due to the difference in flight paths) the remaining back-wall background from the $nn$ signal. The shields 2 serve to screen the detector from epithermal and fast neutrons.

### Analytical and Monte Carlo calculations

If the geometry of the $nn$-cavity is fixed and the neutron field and velocities are known at each point of the cavity, then the Eq. (3) constants $c_{av}$ and $v_0$ can be calculated. We consider the cylindrical $nn$-cavity surface as a source of thermal neutrons with characteristics provided by Monte-Carlo modeling of the reactor and moderator. We assume that the neutron speeds are purely Maxwellian, then $v_0$ is the most probable velocity. Since the YAGUAR pulse is much longer than the neutron moderation time, we neglect a possible small correction due to a non-stationary stage of the neutron moderation process.

The $nn$-cavity is an evacuated volume inside the neutron moderator in the through-channel. Fig. 2 shows the geometry of the $nn$-cavity with two source points $Q_1$ and $Q_2$ at distances $d_1$ and $d_2$ from the cavity point $P$, respectively, where two neutrons collide. Due to the cylindrical symmetry of the problem, it is sufficient to consider the cavity points on the $y$-axis. The density of neutrons at the point $P$ produced by the surface element at $Q_1$ is proportional to the surface element $ds_1 = R d\phi_1 dz_1$, to the density of neutrons at the surface, and to the probability of neutron emission from the moderator surface with an angle $\delta_1$ to the normal. The source density varies with

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1 To the best of our knowledge, this distinction between $\sigma_{nn}$ and $\sigma_s$ was not made in all earlier proposals, where $\sigma_{nn} = 4\pi a_{nn}^2$ was used.
height and radius of the \( nn \) cavity for different \( A \) values. The characteristic \( \cos^2(\pi z/L') \) of the \( nn \)-production has less than 10% dependence on \( A \) in the range of \( A \) values considered. For the YAGUAR case of \( A = 0 \), the calculated value is \( c_{av} = 0.83 \pm 0.01 \) and \( N_D = 170 \) counts per pulse.

**FIRST EXPERIMENTAL RESULTS**

Neutron activation measurements were performed [14] to study the neutron fluxes formed by polyethylene converters inside the through-channel. The converters were fabricated as hollow cylinders of 40-cm length and 12.0-cm outer diameter, while the thickness was varied. The activation detectors for the absolute flux measurements were Au- and Cu-foils placed at the central plane.

![FIGURE 3. Experimental and calculated flux results.](image)

Fig. 3 [14] shows the thermal neutron fluency \( F (10^{13}/\text{cm}^2/\text{MJ}) \) versus the polyethylene converter thickness \( t \) (cm). The fluency is defined as the number of neutrons per \( \text{cm}^2 \), per \( 1\text{-MJ} \) pulse. The points with error bars are the experimental results, while the circles represent our Monte-Carlo calculations. We conclude that the 3-cm thick converter provides for the 30-MJ pulse an instantaneous value of \( 1.1 \times 10^{18}/\text{cm}^2 \text{s} \) for the thermal neutron flux density in the central plane. The measured height distribution of the activation behaves as \( \cos(\pi z/L') \), and yields \( L' = 48.0 \) cm, which agrees with the calculations.

From the Monte Carlo modeling, the neutron velocity spectrum is expected to be predominantly Maxwellian.
with an $1/E^n$ epithermal tail, where the slope parameter $n$ has a value about unity for moderator thicknesses greater than 3 cm. Activation data with an extended set of detectors were measured and analyzed to obtain such parameters as the effective Maxwellian temperature, and the relative size and slope of the epithermal tail. The neutron spectrum generated with these parameters is shown in Fig. 4 for the 2.2-cm thick polyethylene converter.

**CONCLUSION**

The goal of the planned experiment is a study of the charge symmetry of nuclear forces by performing a direct measurement of the $nn$-scattering length using the pulsed reactor YAGUAR. Analytical calculations and Monte-Carlo modeling show that $a_{nn}$ can be measured with a total accuracy of $\leq 3\%$. This first $nn$-experiment will be crucial for evaluating the prospects of obtaining even better accuracy in direct measurements of $a_{nn}$.

In the preliminary experiments at YAGUAR aimed at optimizing the thermal neutron field inside the through-channel, an instantaneous value of $1.1 \times 10^{15}$/cm²s was obtained for the thermal neutron flux density. This suggests excellent prospects for the realization of the first direct measurement of $a_{nn}$.

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