CURRENT STATUS OF THE EXPERIMENT ON DIRECT MEASUREMENT OF NEUTRON – NEUTRON SCATTERING LENGTH AT THE REACTOR YAGUAR

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Abstract. It is proposed in 2002 the new experiment on the first direct measurement of neutron-neutron scattering on the powerful pulsed reactor YAGUAR placed at Snezhinsk, Ural region, Russia. After that an extensive work has been done for modeling of background conditions and an optimization of the set-up design. To make the experiment feasible it was necessary to suppress the background of various origins for more than 16 (for thermal neutrons) and 14 (for fast neutrons) orders of magnitude. In 2003 it had been drilled under reactor and equipped a channel for time-of-flight measurements. During next two years at this channel there were carried out a series of test experiments aimed at checking out an accuracy of background condition modeling. A good agreement of the measured results with the calculated values allowed us to realize the final design of full scale set-up. During 2005-2006 it has been manufactured and after vacuum tests at JINR the set-up has been mounted at YAGUAR reactor hall. In 2006-2007 the calibration measurements with noble gases have been carried out. The obtained results confirmed a validity of the full scale experiment modeling and allowed to verify necessary calibration. The first preliminary experiments for nn-scattering were performed at April 2008. The results are discussed.

Keywords: Nuclear physics, charge invariance of nuclear forces, nucleon-nucleon scattering lengths.

INTRODUCTION

A main motivation for performing the direct neutron-neutron scattering (*nn)* measurements is the issue of charge symmetry violation in the nuclear force; the size of this symmetry breaking remains an open fundamental problem in nuclear physics. One way to study this problem is the comparison of the neutron–neutron, a_{nn}, and proton–proton, a_{pp}, scattering lengths. Although the *pp*-scattering length is well measured, existing indirect *nn*-data (from nuclear reactions with two neutrons and a third particle in the final state) for many years contradicted each other [1-4] in both the magnitude and sign of the difference between the *nn*- and *pp*-scattering lengths. This value is rather essential for verification of QCD at low energy.

An idea how to measure *nn*-scattering directly is discussed in detail in ref. [5]. There it is shown that a direct measurement of the neutron scattering length with 3% accuracy (0.5 fm) may resolve the above mentioned contradictions.

STRATEGY OF EXPERIMENT

As it is shown in ref. [5] only possibility at present to measure *nn*-scattering directly is to use the pulsed reactor YAGUAR, VNIITF, Snezhinsk. The main parameters of the respective experiment are: energy of YAGUAR pulse is up to ~30 MJ, a repetition rate is one per day, number of neutrons, flied out from the reactor per pulse ~10^{18} , duration of the pulse is ~1 *m*s, the thermal neutron flux density in central cavity of the reactor reaches ~10^{18} n/cm^2/s. Effective density of "neutron target" could be ~ 10^{13} n/cm^3 , number of n-n collision per pulse estimates as ~10^7 and an expected number of n-n scattered neutrons, counted by the detector (100÷300) per pulse. The basic idea of the experiment is to use time-of-flight (TOF) method for separating of *nn*-scattering events from all other false effects. For such limited statistics a providing of appropriate background conditions is crucial for realization of the experiment.

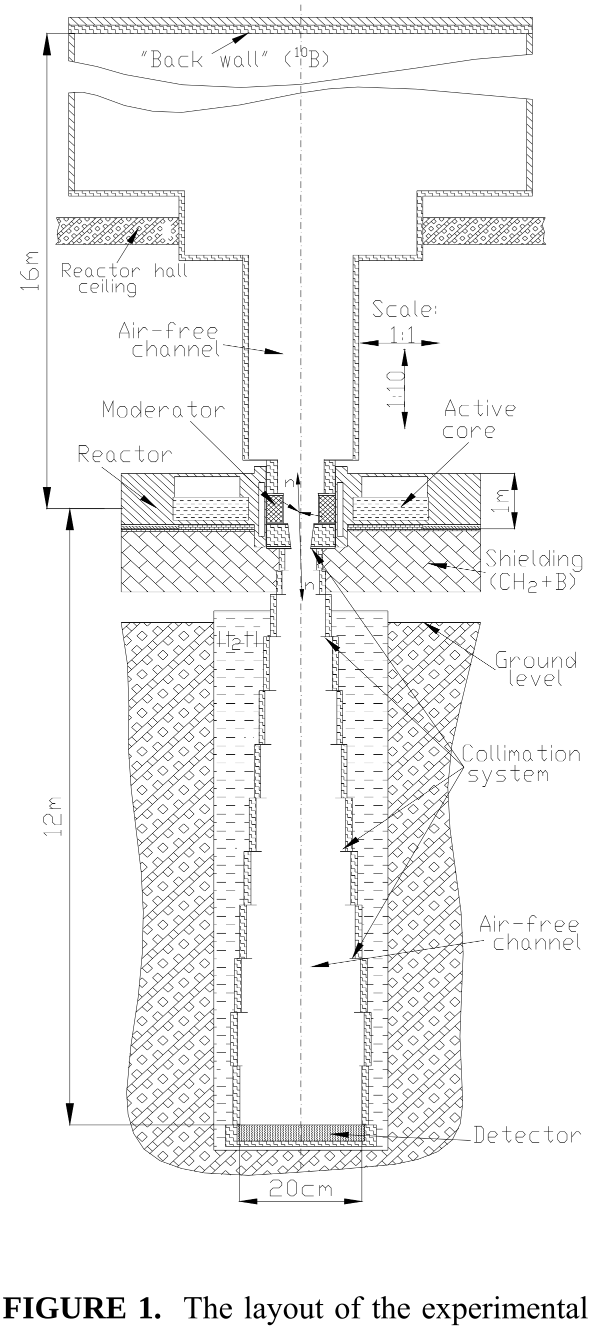

FIGURE 1. The layout of the experimental setup.

For realization of the *nn*-experiment was chosen the following strategy: its preparation and an execution were broken for some stages. In doing so each next stage started to implement only after a successful completion of the previous one.

First of all the detailed calculations of neutron fields within the reactor through channel have been done. The results of these calculations coincided well with the spatial, energy and time distributions of neutron measured in special precise experiments [5]. After that it was formulated full mathematic model of the set-up and as result it was obtained the quantitative estimation of numbers of n-n scattered neutrons, counted by the detector.

If we wish to reach the 5% accuracy in the *nn*-cross-section (2.5% in a_{nn}) so the effect/background ratio should be not more than 40-50%. It results immediately that a thermal neutron background must be suppressed for sixteen orders of magnitude. Due to the fact that the YAGUAR pulse has long tail related to delayed neutrons with flux ~10^{14} n/cm^2/s it needs to take special measures for elimination of a very high background of fast neutrons. The modeling with such level of background suppression did not carried out up to now. But necessary calculations have been successfully done [6] in parallel by two independent groups from JINR and RRITP, Snezhinsk using MCNP and PRIZMA codes respectively.

In fig.1 the lay-out of the set-up is shown. Thermal neutrons escaped from the inner surface of the reactor cavity covered by moderator in thin aluminum case scatter on other neutrons placed there and move after collision up and down by the respective evacuated flight passes. In chosen design of set-up first scattered thermal neutrons reach the detector ~ 2ms after the reactor pulse whereas the thermal neutrons reflected by “the back wall” (the lid of upper flight pass) after collision in reactor cavity have time delay about 10 ms. It allows one to detect *nn*-scattering events in the time window (2 – 12) ms. In this situation TOF method could diminish the background from fast neutrons emitted during YAGUAR pulse at least for four order of magnitude.

The first conic collimator just under reactor core serves for exclusion of a direct visibility of the moderator surface by the detector. Beside that the collimation system has to prevent neutrons reach the detector after first scattering on walls of the lower flight pass. To diminish effect of multiple scattering of thermal neutron on the walls the inner surfaces of both flight passes these were covered by cadmium sheets of 1mm thick. To decrease a number of neutrons scattered on the back wall and hit the detector the surface of this wall is covered by ^{10}B.

A thick borated polyethylene shield under the reactor core and water surrounding the lower flight pass serve for suppression of fast neutron background.

Part of the fast delayed neutrons can penetrate the shielding and induce background during the time interval allocated for detecting thermal neutron collision during the reactor pulse. A suppression of this background could be achieved by used shielding and specially designed detector with low sensitivity to fast neutrons.

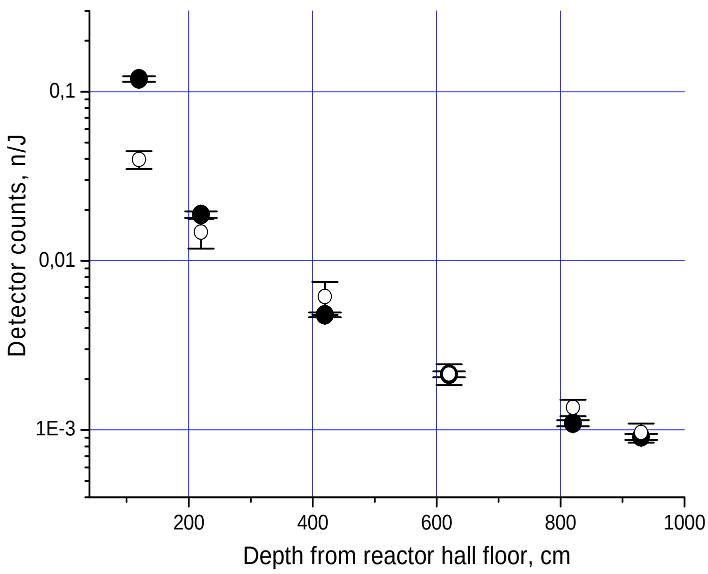

FIGURE 2. The count of the fast neutron detector normalized for one Joule of the reactor energy is presented in dependence of the shaft depth. The black and open cycles are the results of the measurements and calculations respectively.

The calculations have shown that it is possible to obtain satisfactory background conditions with an expected the effect/background ratio near 30% if the vacuum within scattering cavity will be as low as 10^{-6} mb. Here it is appropriate to note that beside of all abovementioned sources of background that is possible to consider quantitatively another kind of background exists that could spoil the vacuum condition within central cavity just after reactor pulse. This is so called a radiation degassing of the cavity and the first collimator walls. The effect was studied [7] for steady reactor. The preliminary qualitative estimations gave us some hopes that this background has not to be essential for our case.

Before completion of these calculations there was no any confidence in the feasibility of the planned experiment. For verification of modeling results there were carried out the special test measurements. It was dug the under-reactor shaft of 11m depth, manufactured and installed the moderator, the first massive conical collimator and the under reactor shield. It was studied the spatial and depth distributions of thermal and fast neutrons inside of the mine filled by air. In comparison with the planned experiment there were no any vacuumed flight passes and whole collimation system. It was used a neutron detection system prepared specially for this experiment. In fig. 2 the results of test measurements for fast neutrons ($E_n > 0.5$ MeV) are shown together with the results of special modeling carried out for the abovementioned experimental conditions.

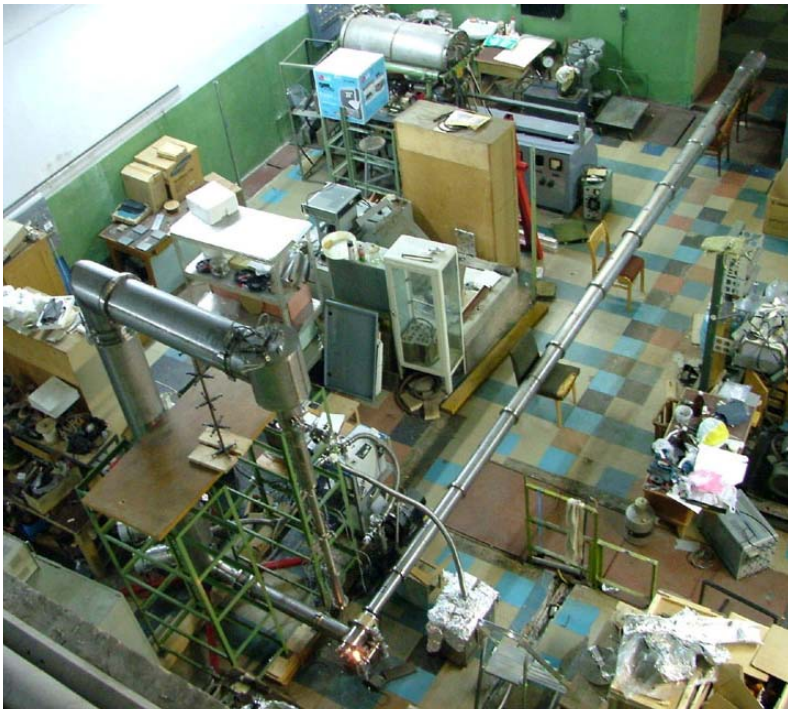

FIGURE 3. The vacuum tests of the set-up at Dubna

The respective comparison of the results for thermal neutrons was good too but it was verification of only special modeling of this experiment. But for fast neutrons as it follows from modeling the absolute value and energy dependence of the background are very close to the same obtained for the main experiment.

So the good agreement between experimental results and calculations demonstrated in fig. 2 gave us the firm grounds for final design of whole set-up and the neutron detector in particular.

The upper flight pass was manufactured and tested at Dubna. It was drilled a special whole in the ceiling of the reactor hall and after that this flight pass has been installed on the roof of the YAGUAR building. In parallel the middle part of the set-up and the lower flight pass were manufactured and installed at Dubna for vacuum tests.

Inside of scattering chamber and surrounding vacuumed channel it was achieved the pressure10^{-6}mb that was a satisfactory value for carrying out of *nn*-scattering. After completion of all tests the whole set-up was installed at the reactor hall.

Due to some technical problems the used collimation system was not optimal. Instead of pure ^{10}B ceramic collimators we were forced to use ones prepared with the mixture of ^{10}B and sulfur. The characteristics of such collimator are about three times worse than the designed ones. So the respective background/effect ratio was expected at the level of 70-80%.

But with these collimators it was possible to verify whole experimental technique and to measure the cross-section of *nn*-scattering with the accuracy ~ 20%.

Consider in more detail what requirements the neutron detector should match in real conditions of the experiment. In measurement of *nn*-scattering as modeling shows [6] for one reactor pulse during TOF interval (2-12) ms about 200 neutrons have to go throughout of the entrance detector window. At the same time a flux of fast neutrons and γ-quanta on the detector could reach ~10^4 and ~10^5 respectively. In calibration measurements with noble gases (He and Ar) the expected count rate at the detector is about 10^4 of scattered neutrons for one reactor burst. As a result of this consideration the neutron detector has to match the following rather strict requirements:

FIGURE 4. The installation of the set-up at the reactor

1) the maximal effectiveness(~ 100%) to thermal neutrons; 2) a very low sensitivity to fast neutrons and γ-quanta; 3) the high count rate ~10^6 n/s; 4) the satisfactory amplitude resolution ($\leq 20\%$).

The last condition is essential for a suppression of the background of fast neutrons and γ-quanta. The good enough amplitude resolution is necessary for precise determination of the effectiveness of the detector.

Only possibility to satisfy the abovementioned requirements is to use the gas proportional counter. But it was very difficult to match the condition 3 and 4 simultaneously. This task has been solved using special multi-section design and very fast flux preamplifiers shown in fig. 5. The each section forms practically the independent detector filled by the mixture of ^{3}He (0.5 b) + + CF_4 (0.7 b) with 4.5 kV electric supply and the separate preamplifier. The anodes are one layer grid with parallel needles of 20μm thickness spaced by 3mm.

Its effectiveness for thermal neutrons consists of 86% with the duration of detector signal ≤100 ns. An each signal is digitized and read out for following off-line analysis. Using the high enough coefficient of gas amplification ~10^3 in combination with the fast current preamplifiers we have managed to get rather satisfactory amplitude resolution about 10%. In fig. 6 a typical signal from one section of the detector induced by thermal neutron from YAGUAR reactor pulse is presented.

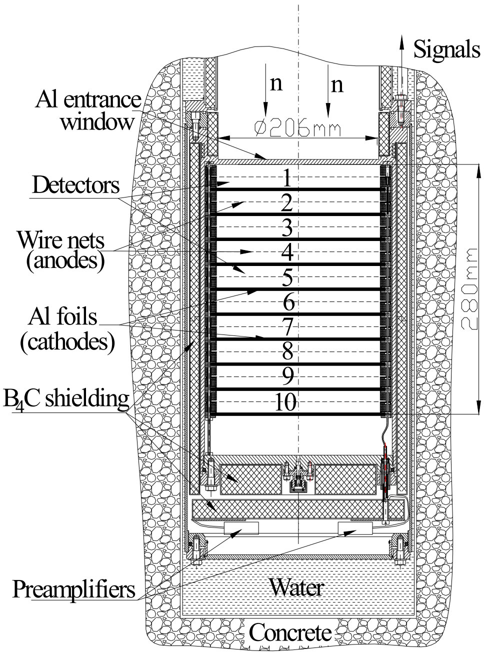

FIGURE 5. The layout of the neutron detector

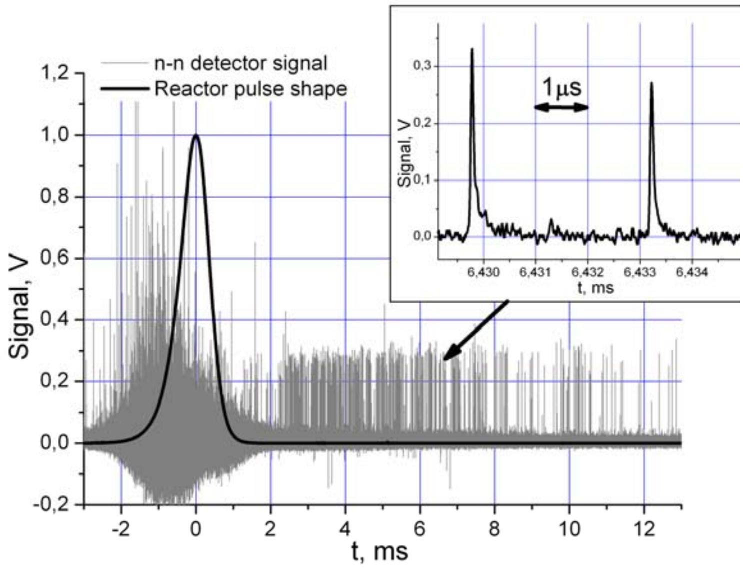

FIGURE 6. A signal from neutron detector (thin grey lines) in dependence on TOF. Each peak corresponds to neutron registration event. A black curve shows a time dependence of the reactor power during the pulse

EXPERIMENT WITH NOBLE GASES

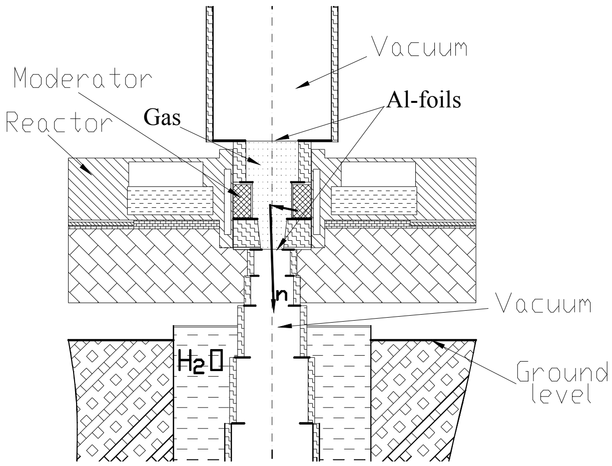

FIGURE 7. The scheme of measurements with noble gases

The last preliminary stage before the *nn*-cross-section measurement was the experiments with noble gases. The measurements of thermal neutron scattering on ^{4}He and Ar gases allow us to verify the whole experimental procedure and the method of data analysis. To reach this goal it is necessary to measure the respective cross-sections with the accuracy much better than it was planned to get for main *nn*-experiment (~5%). Beside that these measurements should be realized with minimal number of YAGUAR bursts. So the density of respective gaseous targets has to be as much as necessary to ensure $\approx 10^4$ detector counts per one burst. Taking into account known scattering cross-sections for ^{4}He and Ar the respective pressure of the targets should be ~10^{-1} mb. But at this very small pressure the essential uncertainties could arise due to degassing of scattering chamber walls. So the effectiveness of the detector for thermal neutrons was decreased in 10^3 times by changing of its filling (^{3}He (0.5 мb) +^{4}He (0.5 b) + CF_4 (0.7 b)). At the same time all other detector characteristics were preserved.

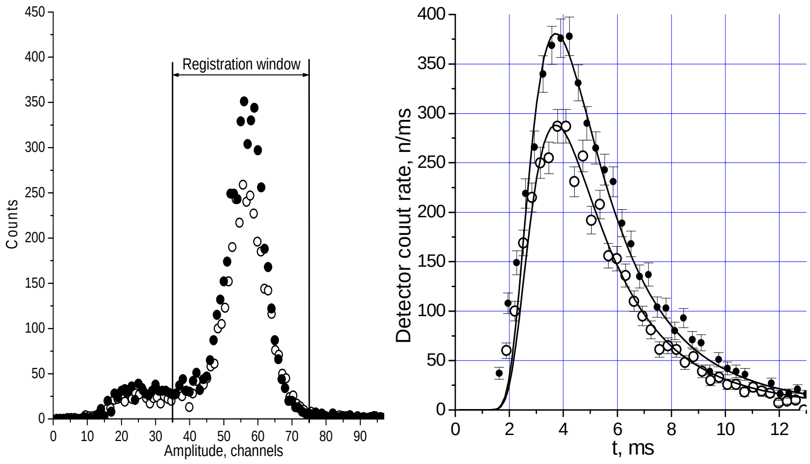

FIGURE 8. The amplitude (left) and TOF spectra of neutrons scattered by ^{4}He (black points) and Ar (open points) targets at 200mb pressure.

The scheme of gas measurements is shown in fig. 7. The gas target is separated from the rest vacuum volume by 40 μm aluminum foils.

In fig. 8 the results of measurements on ^{4}He for two reactor pulses summed over all ten detector sections are shown. The threshold in TOF measurements was fixed at 1.6ms. For the amplitude spectra the registration window was chosen to decrease maximally a contribution of fast neutrons and gamma quanta to the detector count.

In fig. 9 the normalized detector counts are presented in dependence on the pressure of gas targets at 20^{o}C.

The linear dependence in fig.9 of ^{4}He data corresponds fully to the results of modeling. The background in these measurements relates to scattering on Al foils. The special measurement without foils and with vacuum in the channel gave a result 0.05±0.05 n/MJ.

The detailed analysis of these data results in the ratio of the measured scattering cross-sections $\omega = \sigma(^4\text{He})/\sigma(\text{Ar}) = 1.236 \pm 0.046$ instead of the known value [8] $\omega = 1.2 \pm 0.03$. A good agreement of these two ratios confirms an overall validity of the developed experimental technique and the method of data analysis.

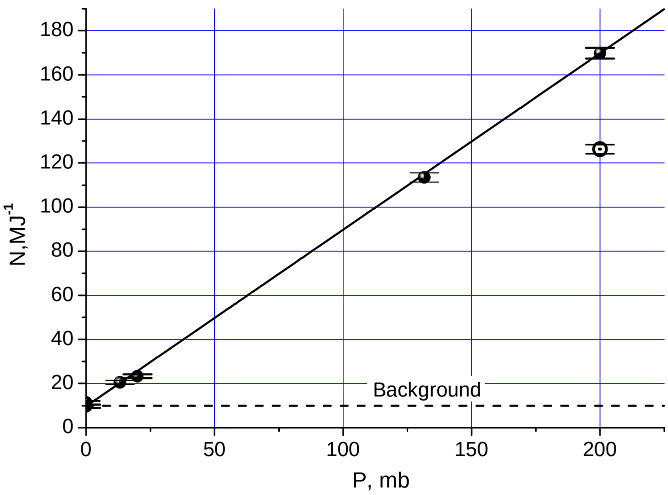

FIGURE 9. The results of measurements with noble gases normalized to 1MJ of the reactor energy release. Black points are for ^{4}He, the open one is for Ar.

The special measurements in stationary mode of the YAGUAR operation showed that the fast neutron background for realistic conditions of *nn*-experiment is not higher than 10 events for maximal (30MJ) pulse energy of the reactor. It consists of less than 10% of the expected effect of *nn*-scattering.

FIRST ATTEMPT OF MAIN EXPERIMENT

After successful completion of calibration measurement the detector was refilled for its original content, the whole volume was pumped out for high vacuum and the first measurements of *nn*-scattering have been done in April 2008. In fig. 10 it is shown TOF spectra for two reactor energies.

These spectra are very similar to the same shown in fig. 8. So it indicates that the detected neutrons are thermal ones. But the count rate is ~20 ÷ 30 times higher than expected number for *nn*-scattering.

The last number could be expressed in form [5]:

$$N_{nn} \sim \iint \frac{\Phi^2(t,\vec{r})}{v_0} \sigma_{nn} dt dV \sim \frac{F^2}{T v_0} \sigma_{nn} V$$

Here t is time, T is the burst duration, $\Phi(t,\vec{r})$ is the instantaneous neutron flux density, F = ∫Φ(t)dt is the neutron fluence, v_0 = 2200 м/s, and σ_{nn} is the nn scattering cross section. In a case of neutron burst duration depending on the burst energy, it is the fluence that is proportional to the burst energy.

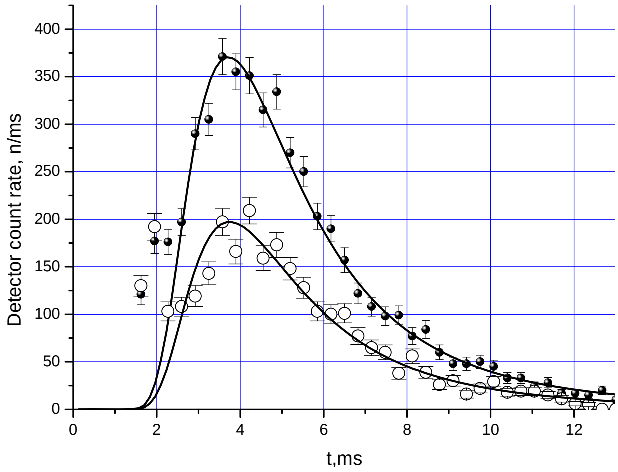

FIGURE 10. The TOF spectra measured with vacuumed scattering chamber for 31 MJ (black points) and 25MJ (open circles). The curves are a fit with Maxwellian distribution.

We see that the total number N_{nn} of the nn-scatterings is proportional to fluence squared (or to the burst energy squared) and is also reverse proportional to the pulse duration T. The latter for the reactor YAGUAR case, is in turn the reverse proportional to the pulse duration. As the result, the N_{nn} number of counts is expected to follow approximately the 3-rd power of the burst energy. In contrary, the number of scatterings from the channel walls and from the collimator edges is proportional to $\Phi(t,\vec{r})$ and, therefore, should have the linear dependence of the pulse energy.

In fig. 11 it is presented the results of all measurements with vacuumed scattering chamber. The total count of thermal neutrons detected in the proper time window for one reactor burst is shown in dependence of reactor energy.

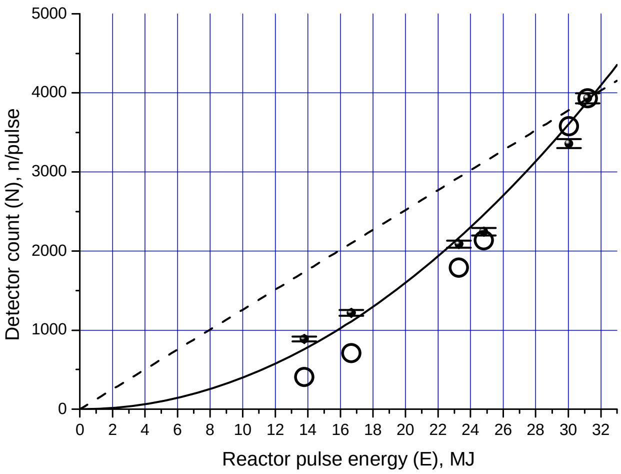

FIGURE 11. The black points are neutron counts *N* for different reactor energies *E*. The dashed line is $N \sim E$; the solid curve represents the dependence $N \sim E^2$ and open circles corresponds to the reactor energy dependence of the calculated N_{nn} values normalized conditionally to the measured number at 31MJ point.

It is clear that experimental points have approximately square energy dependence. A distinction from linear dependence indicates that during reactor pulse a number of objects on which thermal neutrons scatter is changed. In the case quadratic energy dependence the number of such objects is proportional the energy of the reactor pulse but not the neutron flux density. So these objects are accumulating within the reactor cavity during its pulse. The most probable candidates for these are gas molecules ejecting from the cavity walls due to its neutron and gamma irradiation during reactor burst. It is rather plausible that we have observed the effect of the radiative desorption.

CONCLUSION

As the result of six years hard work of DIANNA collaboration the full scale set-up aimed at the direct measurement of the cross-section of neutron-neutron scattering has been designed, manufactured and installed at the YAGUAR reactor hall. The planned technical parameters of the set-up have been achieved. The calibration measurements with noble gases have demonstrated that preliminary modeling was reliable and that the developed procedure of data analysis allows one to extract the respective cross-section with necessary accuracy.

The first attempt of *nn*-measurement has been done. The unexpected background of thermal neutrons proportional to a square of the reactor pulse energy was observed. It seems that this effect is connected with the radiative desorption of gas molecules from the walls of the central reactor cavity under neutron and gamma irradiation. The nature of this background and possible ways of its suppression has to be studies in nearest future.

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