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INVESTIGATION OF NEUTRON PRE-EMISSION IN THE FUSION OF LOW ENERGY (49 MeV) ^{11}Li HALO NUCLEI WITH C-TARGETS

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Abstract. It is proposed to investigate experimentally for the first time the pre-emission of the halo neutrons in the fusion of low energy (49 MeV) ^{11}Li with ^{12}C targets. Due to the special intensity of the beam, its good focusing quality, the application of recently found properties of the target screening, this experiment anticipates a very good resolving power, so that the predictions of a recent theory concerning the appearance of an interference minimum in the C_{nn} correlation function could be efficiently tested. Since this experiment is expected to acquire the largest number of detected neutron pairs to date, this will allow the determination with higher accuracy of the radius of the ^{11}Li halo. The success in this direction will open the perspective for investigation the halo radiuses of Borromean halo nuclei like ^{6}He, ^{14}Be, ^{17}B.

Key words: Borromean halo nuclei, n-n Correlation function, Target screening effect.

1. INTRODUCTION

It was predicted in ref. [1] that, due to the very large radius of ^{11}Li, and due to the very low binding energy of the halo neutrons, one may expect that in a fusion process on a light target, the halo neutrons may not be absorbed together with the ^{9}Li core, but may be emitted in the early stage of the reaction. Indeed, the experimental investigation of Si(^{11}Li, fusion) has shown that a fair amount of fusion events [2] are preceded by the pre-emission of one or two halo neutrons. In ref. [2] was also found that in the position distribution of the halo neutrons, a very narrow forward neutron peak is present. Considering that this peak may be due to neutron pairs, it was decided to investigate the neutron pre-emission with much higher statistics by means of a detector array [3]. Indeed within the narrow forward peak (9 msr) a large number of n-n coincidences was found [4, 5]. Constructing the n-n correlation function, a serious problem appears connected with the low values of the correlation strength [6–8]. A possible explanation could be the residual correlation of the halo neutrons [9]. In ref. [9] an iterative calculation has been proposed to compensate for the residual correlation. But in ref. [6, 8] was observed that the iterative calculation increases the error considerably so that is no longer possible to draw any conclusion concerning the theoretical predictions. Ref. [6] proposes an experiment for getting the intrinsic correlation function by using ^{11}Li and ^{11}Be beams. The halo nucleus ^{11}Be would be ideal for the denominator of the correlation function construction, because it has only one halo neutron and therefore no residual correlation can be possible. In ref. [6] it was also proposed to do the new measurements, by using a C target instead a Si target because the target screening is lower in the case of C target, and the yield of halo neutron pre-emission is expected to be higher in this case. A preliminary estimation quoted in ref. [6] indicated that for a C target, the yield of halo neutron pre-emission is about 2 times higher than for a Si target. In ref. [12] it has been shown that more accurate calculation indicates that the yield of halo neutron pre-emission is expected to be ~3.5 times larger in the case of C-target than in the case of Si target. In par. 2 the target screening effect will be reviewed.

Recently, a new theory for C_{nn} correlation function has been proposed [10]. In this theory, the ^{11}Li halo nucleus is modeled as a three body system consisting of 2 neutrons and a core. It is shown that an interference minimum is present in C_{nn}, due to the coherence of the 2 halo neutrons. This theory will be briefly reviewed in paragraph 3. An analysis of the experimental requirement for the testing of this new theory will be presented in par. 3.1. The proposed experimental setup will be shown in par. 4. In par. 5, the simulation of the fusion process between the ^{11}Li projectiles and ^{12}C targets will be presented. The estimation of the number of fusions and of the detected neutron pairs will be discussed in par. 6. The possibility to test the new C_{nn} correlation function theory will be analyzed in par. 7. Afterwards, a discussion concerning the effect of evaporation of neutrons in the range of neutron pre-emission will follow in par. 8, and after that, an analysis of the neutron cross-talk effect, in par. 9. Finally the main conclusions are presented in par. 10.

2. THE INVESTIGATION OF THE TARGET SCREENING EFECT

The first application of sharp cut-off calculation to halo nuclei was done in Ref. [11] for ^{11}Be.

In ref. [12] the target screening effect on the pre-emission of halo neutrons from ^{11}Li halo nuclei was studied for the first time. It has been observed that from the experimentally measured number of single detected neutrons $s_i(E)$ and from the number of detected neutron pairs $p_i(E)$, one can, knowing the detection efficiencies, reconstruct the primary pre-emitted number of single neutrons N_{s0}^{C}, and number of primary pre-emitted neutron pairs N_{p0}. The pre-emission probability ζ in the presence of the target screening is given by:

$$\zeta = \frac{S_f}{S_{tot}},$$

in which S_f represents the free area not hindered by the target. One can express N_{s0}^{C} and N_{p0} as a function of ζ, by using the following expressions:

$$N_{s0}^{C} = 2N\zeta(1-\zeta).$$

It is easy to show that by dividing the 2 relations, one can eliminate N and get an expression relating the experimentally obtained N_{s0}^{C} and N_{p0} to ζ.

$$\zeta_{\exp} = \frac{2N_{p0}}{N_{s0}^{c} + 2N_{p0}}.$$

It turns out that for a Si target, $\zeta_{\exp} = 0.36 \pm 0.06$. An important observation is that ζ is an observable of the experiment since it can be obtained from the measured numbers of single detected neutrons and from the number of detected neutron pairs. The ζ probability can be calculated as a function of the halo nucleus radius, using the sharp cut-off formula for fusion reactions (see formula 8 in ref. [12]). In this way one could increase the precision in the determination of the ^{11}Li radius by increasing the detected number of pre-emitted halo neutrons. As will be shown in the present paper one may expect an increase of nearly by 2 orders of magnitude of the detected halo neutrons in comparison to previous experiments. It is expected that this property also allows investigation of Borromean halo nuclei such as ^{6}He, ^{14}Be and ^{17}B for which the R_H was not yet measured.

In Table 1 taken from ref. [12] the values of ζ probabilities are reproduced (column 4) calculated by the sharp cut-off formula 8, (ref. [12]) for 2 targets ^{12}C and Si (column 1) and for 3 values of R_H (column 2). In column 3 is shown the value of $\zeta_{\exp}$ obtained from the number of detected single neutrons and the number of detected neutron pairs (the error ±0.06 has been estimated). In columns 5, 6 and 7, the values of $P^{[1]}$, $P^{[2]}$ and $P_a^{[2]}$ calculated according the formulas (9), (10) and (11) in ref. [12] are given. In the last column it is shown that $P^{[1]}$, $P^{[2]}$ and $P_a^{[2]}$ probabilities satisfy the normalization conditions.

Table 1

Target	R_{HALO} [fm]	ζ_{exp}	ζ [%]	$P^{[1]}$ [%]	$P^{[2]}$ [%]	$P_a^{[2]}$ [%]	$\Sigma P^{[i]}$ [%]
^{12}C	4.8		70.1	41.8	49.2	8.9	~1
	4.2		61	47.5	37.2	15.1	~1
	3.6		46.9	49.8	22.0	28.1	~1
Si	4.8	36 ± 6	37.9	47.1	14.4	38.4	~1
	4.2		28.6	40.8	8.1	50.9	~1
	3.6		20.5	32.7	4.2	63.0	~1

It follows from Table 1 that in the case of ^{12}C target, the neutron pair pre-emission probability is a factor of ~3.5 larger than for Si target. By taking also into account that in a ^{12}C target, the number of nuclei/cm^3 is ~2 times larger than in the case of Si target, it follows that the number of pre-emitted neutron pairs is a factor of ~7 larger in the case of ^{12}C target than in the case of Si target.

3. A NEW THEORY OF C_{nn} CORRELATION FUNCTION

Very recently a new theory for the Borromean nuclei correlation function has been worked out [10]. The Borromean halo nucleus is modeled like a three body n-n-A that is 2 neutrons and a core denoted with the mass number A. To describe such a system, the authors of [10] are using a three body model in the limit of the zero-range approximation, which retains the essential physics of the weakly bound and the large two-neutron halo system. The interaction singularity is tamed in a renormalized zero-range model which is appropriate to the study of weakly bound three-body systems. The model is parameterized by a minimal number of physical inputs, which are directly related to known observables: the two neutron separation energy, S(2n), the neutron-neutron and neutron-core scattering length, (or the corresponding virtual and or bound state energies). In this new model, the asymptotic limit $C_{nn} \to 1$ is reached at much higher values of the relative momentum q than was found in previous data analyses. Due to the coherence of the neutrons in the halo and final state interaction, C_{nn} goes smoothly to the asymptotic limit only after displaying a minimum, as is shown in Fig. 1.

The model results (Fig. 1 insert) are given for three cases : S_{2n} = 0.29 MeV and E_{nA} = 0.05 MeV (solid line); S_{2n} = 0.37 MeV and E_{nA} = 0.8 MeV (dashed line); S_{2n} = 0.37 MeV and E_{nA} = 0.05 MeV (dotted line). In the main body of the figure, the solid curve (for r^{rms} = 8.5 fm [15]) presents the corresponding curve of the insert multiplied by 2.5; the dot-dot-dash curve, the model presented in [8] with r^{rms} = 8.3 fm. The experimental data are from [9] (solid circles) and [8] empty circles.

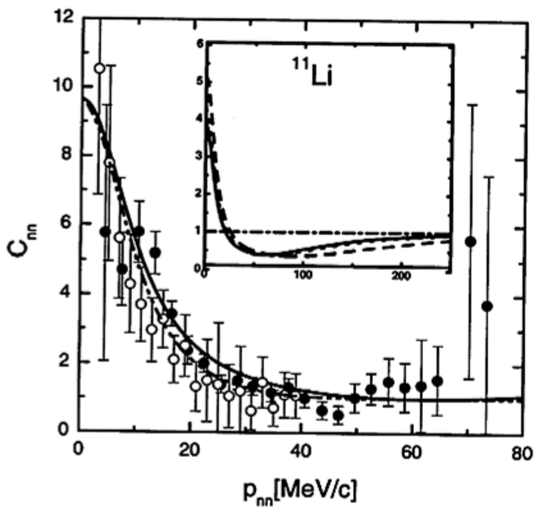

Fig. 1 – The correlation function C_{nn} for ^{11}Li as a function of relative momentum p_{nn}.

3.1. EXPERIMENTAL REQUIREMENT FOR THE TESTING OF THE NEW THEORY

In Fig. 2, the solid curve shown in the insert of Fig. 1 is presented. The open triangles represent C_{nn}, prior to the normalization. The solid circles represent C_{nn}, after normalization [10]. One can see that C_{nn} ($q = 20$ MeV/c) is approximately equal 1. At values of q larger than 20, C_{nn} becomes lower than 1 and for

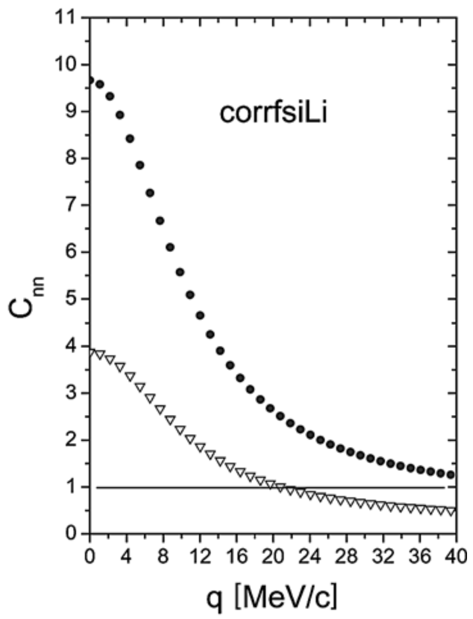

Fig. 2 – The open triangles are representing C_{nn} from the insert of Fig. 1 (solid curve). The challenge for the experiment is to resolve C_{nn} in the 20–40 MeV/c q range, taking into account the exp. errors.

q = 40 MeV/c, C_{nn} is approximately 0.5. The problem is if one could resolve C_{nn} in the q range 20–40 MeV/c taking into account the experimental errors.

4. THE PROPOSED EXPERIMENTAL SETUP

The energy of the incoming ^{11}Li beam is assumed to be 4.5A MeV. After passing through a Parallel plane avalanche detector (PPAC) in which the energy loss ΔE is very low (approx. 200 KeV), the beam will pass through a window foil into a vacuum chamber in which a Diamond detector target, (thickness ~ 0.12 mm) and a Si veto detector are placed. The dimensions of these detectors are: 10 mm × 10 mm × 0.12 mm, and 20 mm × 20 mm × 0.2 mm. The trigger of the experiment will be given by the coincidences $PPACxC - diamondx\overline{VetoSi}$.

The distribution of the beam energy in passing through the Diamond detector-target is shown in Fig. 4.

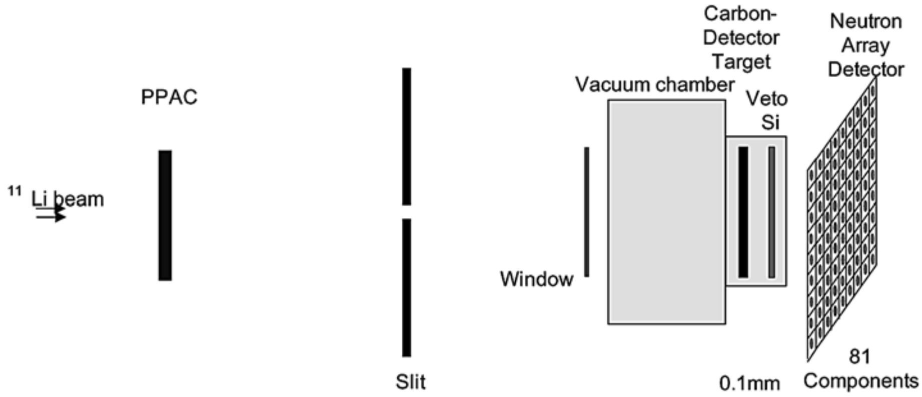

Fig. 3 – The Experimental Arrangement.

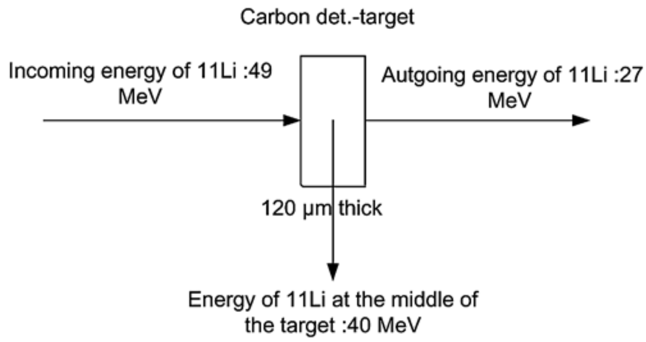

Fig. 4. Distribution of the ^{11}Li beam energy in passing through the Carbon-Diamond Detector-target.

5. SIMULATION OF THE FUSION PROCESS BETWEEN THE ^{11}Li PROJECTILES AND ^{12}C TARGETS

This simulation has been performed by using the Program PACE. The energy of ^{11}Li corresponding to the middle of the target (40 MeV) has been considered. At this energy the fusion cross-section $\sigma_{fusion} = 1204$ mb is given by the program PACE. The distribution of the evaporation residues is shown in Fig. 5.

In order to estimate the fusion cross-section expected in experimental measurements, one has to take into account the angular distribution of α-particles and of protons emitted from the compound nucleus. This is related to the fact that some of these particles are flying in the forward direction and by triggering the veto detector, are causing losses in the statistics of fusion events. In Fig. 6 it is shown the distribution for α particles and Fig. 7 the distribution for protons.

In the estimation of the number of α-particles escaping detection by the Veto-detector, the following correction has been introduced by taking into account that the range of 10 MeV α-particles in C is near 50 μm. Then from the total number of α-particles in the 0°–70°, half of spectrum with energy 0–10 MeV can be extracted. In this way, the fusion cross-section equal to 283 mb has been estima-

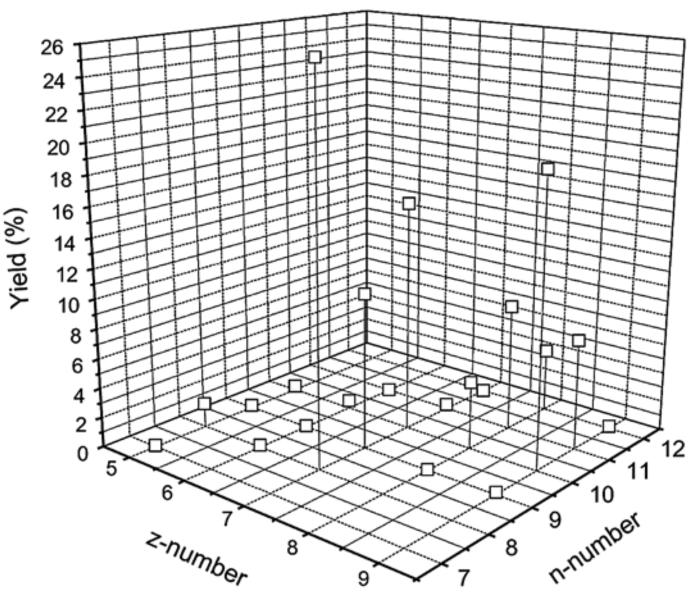

Fig. 5 – Yields of residual nuclei in the fusion of ^{11}Li (E = 40 MeV) with ^{12}C. The highest yields are ^{15}N(25.79%), ^{16}N(10.43%), ^{17}N(15.47%), ^{18}O(4.2%), ^{19}O(8.53%), ^{20}O(4.2%). ^{19}F(19.2%), ^{20}F(7.41%).The sum of these yields makes 95.63 from the total fusion cross-section which is ~1204 mb. The other yields are of the order of 1% or smaller.

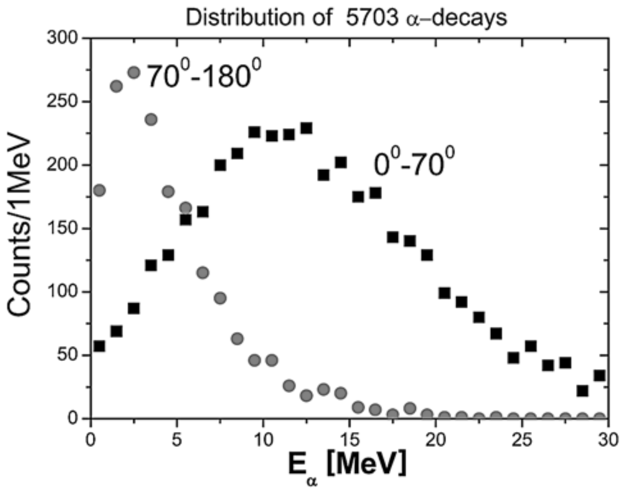

Fig. 6 – Angular distribution of α-particles as a function of energy in the 0°–70° and 70°–180° ranges. In the detection geometry (2×2 cm² Veto-Si detector separated by 5 mm from the Carbon-detector) α-particles are escaping detection for angles larger than 70°.

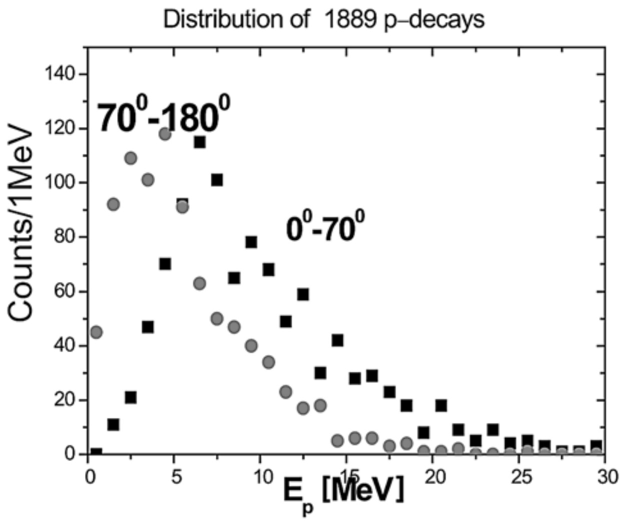

Fig. 7 – Angular distribution of protons as a function of energy in the 0°–70° and 70°–180° ranges. In the detection geometry (2×2 cm² Veto-Si detector separated by 5 mm from the Carbon-detector) protons are escaping detection for angles larger than 70°.

ted for the α-decay processes and 96.9 mb for the proton decay processes. Adding to these values the cross-sections corresponding to Fluorine residual nuclei, 321 mb, a total fusion cross-section equal to 701 mb remains, after taking into account the effect of decaying particles on the veto detector.

6. ESTIMATION OF THE NUMBER OF FUSIONS AND OF THE NUMBER OF DETECTED NEUTRON PAIRS

In estimation of the number of fusions, the ^{11}Li beam intensity was taken to be $3.8{\cdot}10^3$/s [16]. A figure of merit is the fact that this beam can be focused on an area of the order of few mm^2. In order to estimate the expected number of detected neutron pairs, the neutron detector efficiency was calculated by using the program MENATE [17]. This program calculates the efficiency by assuming the shape of detectors to be cylinders, in this case cylinders with the radius equal 2 cm. Since our detectors are of parallelepiped type with dimensions $4 \times 4 \times 12$ cm^3, the values calculated by MENATE were increased by 21%. The mean value of the neutron detection efficiency for a threshold equal to 0.6 MeVEE and for the target range 0–120 μm an efficiency $\varepsilon_n = 0.35$ was found. The estimated results are shown in Table 2.

Table 2

Quantity	Expression	Value
^{11}Li beam flux	Φ	$3.8 \cdot 10^3$
Target density (nr C/cm^2)	n_C	$1.35 \cdot 10^{21}$
Fusion cross-section	σ	701 mb
Number of fusions/shift	$\Phi * n_C * \sigma * 3600 * 12$	155870
Number of neutron pairs/shift	$\Phi * n_C * \sigma * 3600 * 12/2$	77935
Number of detected neutron pairs/shift	$\Phi * n_C * \sigma * \varepsilon_n^2 * 3600 * 12/2$	9547

7. POSSIBILITY TO TEST THE NEW C_{nn} CORRELATION FUNCTION THEORY

In Fig. 8 and Fig. 9 are compared the errors that can be obtained with a statistics of 1700 detected n-n coincidences [13, 14], and 17000 detected n-n coincidence close to the number that could be obtained in 2 shifts of measurements by using the ISACII facility (upper estimate).

One can see from the comparison of Fig. 8 with Fig. 9, that a remarkable increase in resolving power is expected in this proposed experiment at the ISACII facility.

8. THE EFFECT OF NEUTRON EVAPORATION IN THE RANGE OF NEUTRON PRE-EMISSION

In the PACE program the pre-equilibrium emission of neutrons is not taken into account. There is assumed that all emitted neutrons are evaporated. These neutrons are emitted isotropically. On the array detector placed at 150 cm from the target, are incident the neutrons emitted in forward direction in the angular range

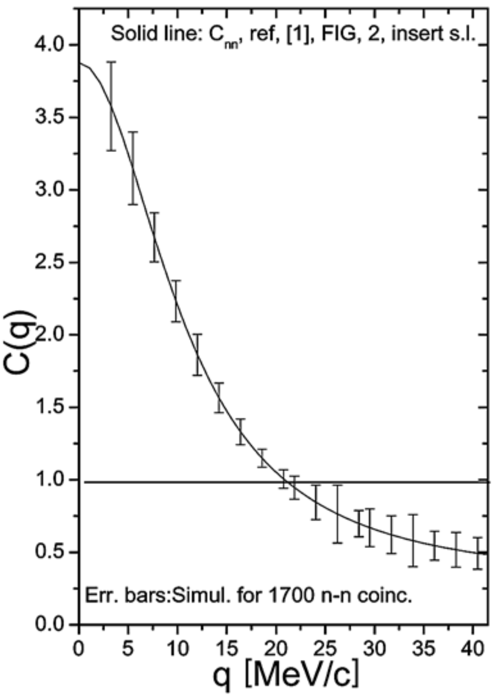

Fig. 8 – Simulation of error bars in $C(q)$ for a statistics of 1700 n-n detected coincidences [13, 14].

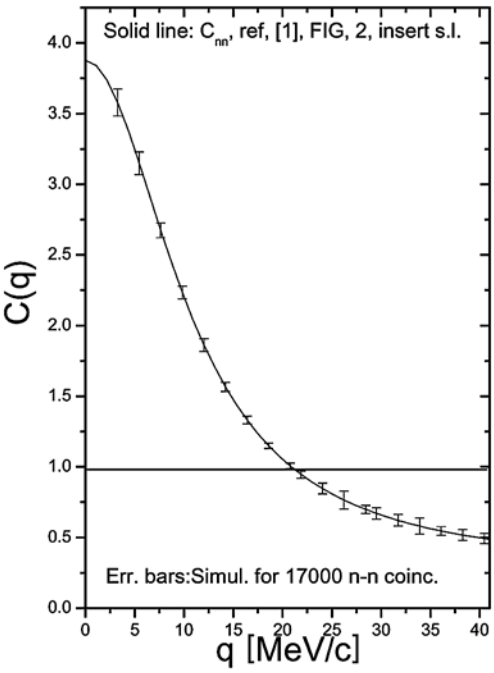

Fig. 9 – Simulation of error bars in $C(q)$ for a statistics of 17000 n-n detected coincidences, obtainable with ISAC2 in 2 shifts of measurements.

–10° to +10°. The number of these neutrons with energy in the range 3–5 MeV is about 450, for 20000 fusion reactions. On the other hand the number of pre-emission neutrons for 20000 fusion reactions is also about 20000 (see Table 1), so that the contribution of the evaporation neutrons in the range of pre-emitted neutrons is 450/20000 what means about 2.2%, which can be considered negligible. In reality this contribution has to be considered rather as an upper limit because a considerable number of neutrons 1/fusion is taken by the PACE program as an evaporation neutron instead as a pre-emission neutron.

9. THE NEUTRON CROSS-TALK EFFECT

In the simulations performed by MENATE program, was observed a considerable reduction of the cross-talk effect with decreasing neutron energy. At neutron energy as low as 3 MeV, complete disappearance of the cross-talk is obtained from the simulation with MENATE. In Fig. 10 the simulation done for adjacent detectors is shown.

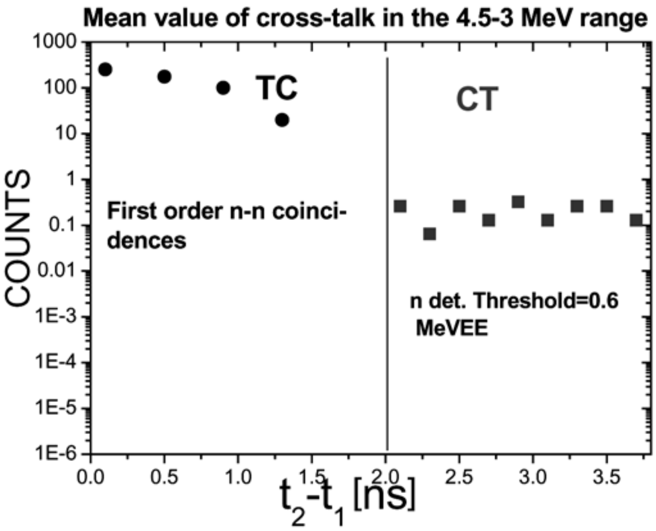

Fig. 10 – There is shown the cross-talk effect in the most disadvantageous case, that of first order n-n coincidences, that means adjacent detectors (minimum distance between detectors = 2 cm). One can see a complete separation between the true coincidence window TC, and the cross-talk window CT. One can see also an extension up to 2 ns, due to low velocity of the neutrons. The threshold of detectors was set 0.6 MeVEE.

In the experimental measurements, our own VME data acquisition system recently put into operation at the National Institute of Physics and Nuclear Engineering in Bucharest will be used. At present is the threshold calibration of the 81 neutron detectors in the array, by using the cosmic ray peak of 12 MeVEE measured with this system, is underway.

10. CONCLUSIONS

1. For the first time a neutron pre-emission experiment in the fusion of low energy (49 MeV) ^{11}Li halo nuclei with ^{12}C targets is proposed to be undertaken.

2. Due to the special intensity of the beam, its good focusing quality, the application of recently found properties of the target screening, this experiment presents a very good resolving power, so that the predictions of a recent theory concerning the appearance of an interference minimum in the C_{nn} correlation function can be efficiently tested.

3. This experiment being the first one to be performed with low energy neutrons could reveal new properties of the neutron-neutron final state interaction for example a shrinkage of the n-n correlation peak.

4. Since this experiment is expected to acquire the largest number of detected neutron pairs to date, this will allow the determination with higher accuracy of the radius of the ^{11}Li halo. The success in this direction will open the perspective for investigation the halo radiuses of Borromean halo nuclei like ^{6}He, ^{14}Be, ^{17}B.

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