TWO-NEUTRON INTERFEROMETRY MEASUREMENTS

J. Pluta, G. Bizard, P. Desesquelles, A. Dlugosz, O. Dorvaux,
P. Duda, D. Durand, B. Erazmus, F. Hanappe, B. Jakobsson,
C. Lebrun, F. R. Lecolley, R. Lednicky, P. Leszczynski,
K. Mikhailov, K. Miller, B. Noren, T. Pawlak, M. Przewlocki,
O. Skeppstedt, A. Stavinsky L. Stuttgé, B. Tamin, K. Wosinska

Rapport Interne SUBATECH 97-28
TWO-NEUTRON INTERFEROMETRY MEASUREMENTS

J. Pluta$^{1,5}$, G. Bizard$^2$, P. Desesquelles$^3$, A. Dlugosz$^1$, O. Dorvaux$^4$, P. Duda$^1$, D. Durand$^2$, B. Erazmus$^5$, F. Hanappe$^6$, B. Jakobsson$^7$, C. Lebrun$^5$, F.R. Lecolley$^2$, R. Lednicky$^8$, P. Leszczyński$^1$, K. Mikhailov$^9$, K. Miller$^1$, B. Noren$^7$, T. Pawlak$^1$, M. Przewłocki$^1$, O. Skeppstedt$^{10}$, A. Stavinsky$^9$, L. Stuttge$^4$, B. Tamain$^2$, K. Wosińska$^1$

$^1$Institute of Physics, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, Poland,
$^2$Laboratoire de Physique Corpusculaire, IN2P3, CNRS/ISMRA, F-14050, Caen Cedex, France
$^3$Institut des Sciences Nucleaires, IN2P3/CNRS, et Universite Joseph Fourier, 53 Av. des Martyrs, F-38026, Grenoble cedex, France
$^4$Institute de Rechereches Subatomiques, IN2P3-CNRS / Université Luis Pasteur, BP28, F67037 Strasbourg Cedex 2, France,
$^5$SUBATECH, URM Universite, Ecole des Mines, IN2P3/CNRS, 4, rue Alfred Kastler, La Chantrerie, BP 20722, 44307 Nantes cedex 3, France
$^6$Université Libre de Bruxelles, CP229, Av. F. D. Roosevelt, 50, B1050, Bruxelles, Belgium,
$^7$University of Lund, Cosmic and Subatomic Physics, Solvegatan 14, S-223 62 Lund, Sweden
$^8$Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 18040 Prague 8, Czech Republic
$^9$Institute of Theoretical and Experimental Physics, Cheremushkinskaya 25, Moscow, Russia
$^{10}$Department of Physics, Chalmers University of Technology, S412 96 Göteborg, Sweden

Abstract

The results of analysis of two-neutron correlations in the region of small relative velocities are presented. The influence of spurious correlations on the form of correlation function is considered in detail. Data analysis and computer simulations were performed for a specific detector configuration with close angular position and different distances between the target and detector modules. The features of different methods of cross-talk elimination are examined. The proposed method is verified and the first results of cross-talk free correlation functions measured with the DEMON detector at GANIL are presented for the Ar-Au reaction at 60 MeV/u.
1 Introduction

Interferometry measurements represent a specific kind of experimental technique in nuclear and particle physics. First - the measurement is always of coincidence type, second - the relative velocities of considered particles are always small, third - as a rule the particles are identical. These conditions induce a lot of problems in practical realisation of interferometry measurements. Indeed, if two particles are identical and are emitted in the same collision with almost the same velocity vectors, they are often indistinguishable also for the measuring devices.

Despite of these difficulties the nuclear interferometry methods are widely used for the analysis of heavy ion, hadron and lepton collisions starting from low energies up to the greatest accessible ones [1]. This interest is justified as the interferometry methods permit to link the correlations of particles with the space-time parameters of their emission [2, 3, 4, 5, 6, 7, 8]. Such an information is not accessible to direct measurements and cannot be easily obtained with the other methods. Particle correlations in the region of small relative velocities arise due to strong and Coulomb final state interaction and quantum-statistics i.e. (anti)symmetrization of the wave function of identical (fermions) bosons (see, e.g. [6]).

Interferometry with neutrons has a special position here since neutrons are insensitive to the long-range Coulomb interaction. First - it means that the parameters characterising neutron emission are not influenced by the Coulomb field. Second - the repulsive Coulomb forces wash-out the pairs of like charged particles from the region of interest, that of the smallest momentum difference, which is not the case for neutrons. It makes the neutron-neutron correlation measurements more sensitive to the space-time characteristics and supply also some supplementary information about the role of Coulomb interaction by comparison with the proton-proton correlation analysis. The comparison with proton-neutron correlations can further reveal the role of the Coulomb repulsion due to the charged source [9]. Thus, neutrons represent a good probe to determine the parameters of the emitting source.

In spite of the great interest to the interferometry measurements with neutrons the experimental results on neutron-neutron correlations are relatively scarce. This is mainly due to the specific experimental problems arising when two neutrons with close velocities have to be registered in coincidence [10, 11, 12, 13, 14, 15, 16, 17].

2 Real and spurious coincidences

The main neutron registration technique consists in indirect detection of the light deposited by scattered protons or other nuclei in liquid or solid scintillators. In most cases the detector length is chosen to be of the same order as the mean free path of neutrons, so the neutrons rarely deposit all their energy in the detector module. The detection efficiency is usually far from 100% and the amount of light deposited is only weakly correlated with the velocity of the incoming neutron. Hence, the time of flight technique is used to determine the neutron energy.

In a multimodular detection system the same neutron can interact in several modules. If the neutron is scattered in one module without being registered and
later on is detected in another one then the diaphony takes place. If the same neutron is registered in two or more detectors - the cross-talk (c-t) effect occurs [12]. The diaphony leads to the distortion of the emission angle and the energy of the registered neutrons. The c-t effect simulates the detection of two or more neutrons in coincidence leading to a strong spurious correlation [12].

In the case of one-particle distributions the c-t effects are usually small or even negligible. In interferometry measurements, involving the detection of neutrons in coincidence and at small relative angles, this effect can strongly affect the results of measurements. In fact, this is the reason preventing the use of the numerous neutron detectors packed in close geometry for the interferometry measurements. The interferometry measurements with neutrons require rather specific experimental approach.

Since the cross-talk effects decrease with increasing distance between detectors, it seems reasonable to keep this distance as large as possible. However, large distances between detectors correspond to large angular intervals which are not desirable in the interferometry measurements. A natural way to solve this problem is to put detectors at a large distance \( d \) from the target. Does this solution decrease the cross-talk to coincidence ratio?

Let us take the simplest example of two detectors located at the same distance from the target (Fig. 1a). In the case of a fixed angle between detectors (\( \alpha = const \)), the distance between them, \( h \), is linearly related to \( d \). The relation between registration probabilities, \( P \), and the distance \( d \) is:

- single particle registration: \( P_s \sim 1/d^2 \),
- coincidence registration
  of two uncorrelated neutrons: \( P_c = P_s^2 \sim 1/d^4 \),
- cross-talk registration: \( P_{c-t} \sim P_s \cdot \frac{1}{h^2} \sim \frac{1}{d^2 h^2} \sim 1/d^4 \).

Thus the ratio of cross-talk to coincidence probability does not depend on the target-detector distance \( d \). This ratio even increases as a second power of the distance \( d \) in the case when \( h = const \) (Fig. 1b):

\[
\frac{P_{c-t}}{P_c} \sim \frac{1}{d^2 h^2} \sim \frac{1}{d^4} = \frac{d^2}{h^2} \sim d^2.
\]

Since the probability of coincidence registration is inversely proportional to the 4th power of \( d \), it appears much more favourable to make this distance as small as possible, contrary to the first-sight impression.

However, the requirements on the accuracy of the time-of-flight technique and on the necessary angular resolution impose a limit on the minimal distance between target and detectors. Namely for these reasons and not due to the cross-talk this distance cannot be too small in the interferometry measurements.
3 Cross-talk elimination methods

The reduction of the probability of cross-talks by increasing the distance between detectors appears to be inadequate for interferometry analysis. There exist however methods to recognise and eliminate the cross-talk events based on simple and well defined criteria [14].

The first one concerns the time difference between the registration of two coincident neutrons. Corresponding geometrical relations are shown in Fig. 2a. If detector (1) has registered a primary neutron with the energy $E_1$ and detector (2) has detected a cross-talk from detector (1) then the registration time difference $\Delta t = t_2 - t_1$ will be greater then the time defined by the minimal distance between detectors $h_{\text{min}}$ and the velocity of the scattered neutron, $v(E_{\text{rest}})$. This velocity depends on the energy loss in the first detector, $E_{\text{rest}} = E_1 - E_{\text{loss}}$, and can be deduced from the detector response function. The condition

$$\Delta t < h_{\text{min}} / v(E_{\text{rest}}),$$

(2)

excludes cross-talk.

The interaction of the neutron inside a detector, especially in the case of large detector volumes and large energies, is frequently a many step process with different reaction channels involved. The response function can be therefore determined only in an approximate way. To be sure that a cross-talk will not be taken as a true coincidence, a stronger condition of the cross-talk absence was proposed [16]:

$$\frac{1}{2} m \left( \frac{h_{\text{min}}}{\Delta t} \right)^2 > E_1.$$

(3)

Both these conditions express essentially the same. The velocity of a c-t neutron has to be smaller than some limiting value which, in the first case, is taken from the detector response function. In the second case the maximal velocity is that of the primary neutron.

By introducing these conditions a cross-talk free window is defined for the differences of neutron momenta, $(P_1 - P_2)$. The width of this window depends on the detector geometry and the initial neutron momentum, $P_1$. Assuming that the greatest possible momentum of the c-t neutron equals $P_1$, the width of this window can be expressed as

$$0 < (P_1 - P_2) < P_1 h/(h + d)$$

(4)

where $h$ and $d$ are the distances between detector and between detectors and target, respectively.

It is an important feature for interferometry measurements as the correlation effect is just located in the region of the smallest momentum differences. The width of this region cannot be too small, however, as the correlations in the region of small relative momenta are determined with respect to the region of greater momentum differences where the correlation effect is absent.

In fact, the minimal length of the vector of momentum difference is defined by the relative angle between detectors. For small relative angles an approximate relation can be written:

$$P_1 h/d < |\Delta \vec{P}| < P_1 \sqrt{(h/(h + d))^2 + (h/d)^2}$$

(5)
Usually the distance $h$ is much smaller than $d$ and this relation defines a band in the neutron momentum differences. For a given detector configuration the width of this band depends only on the value of neutron momenta.

$$P_1 h/d < |\Delta P| < \sqrt{2} P_1 h/d$$  

(6)

This condition defines a relation between the width and position of the cross-talk free interval and the momentum value of faster neutron. Small momentum differences are populated by neutron pairs with small momenta. With the increase of momentum difference the absolute values of the corresponding neutron momenta increase as well. It means also that the direction of the vector of momentum difference is limited to some interval. In the approximation of eq. (6) the angle between the pair momentum and momentum difference vectors cannot be smaller than about 45°.

These constraints can strongly affect the form of the correlation function. It is especially important if due to physical reasons there exist correlation between the neutron momentum and the strength of correlation or if the analysis concerns the directional dependence of correlation effects.

The second condition proposed in [14] takes into account the relation between $E_{\text{rest}}$ and the pulse height, $PH$, coming from the second detector. The maximal value of the pulse height can be now deduced from the second detector response function on the base of the $E_{\text{rest}}$ value. The cross talk is impossible when

$$PH_2 > PH_{\text{max}}(E_{\text{rest}}).$$  

(7)

The bias introduced by this condition is smeared out by the dispersion of the energy loss and is related rather to the angular dependence of the cross-talk events for different energies of induced neutrons.

4 The Chalmers experiment simulations

A dedicated cross-talk measurement has been performed at the Chalmers University of Technology in Goteborg [15]. A set up of two neutron detectors was arranged in the way that one detector was irradiated by the source of neutrons placed at the distance of 3 m and the second was shielded through the shadow bar. The second detector was rotated around the first on the 0.75m radius. Two peaks were observed in the time of flight spectra of the second detector: first - coming from the neutrons passing by the shadow bar, second - due to cross-talk neutrons coming from the first detector. The heights of peaks and their relative positions have demonstrated the probability and energy relations of the cross talk events.

Using the Monte-Carlo code MENATE [12] we have performed the computer simulations of this experiment with the two-fold intention: first - to verify the simulation code for defined primary neutron energy (14 MeV), second - to find dependencies of the c-t probability on the relative angular position of the detectors and for different energies of incident neutrons. Fig. 3 presents an example of the considered angular configuration. All detectors were "irradiated" by neutrons but only the central one was not shielded by the shadow bar. It was supposed that the
shadow bar absorbs 99.8% of neutrons. Fig. 4 presents the results of the test. This figure can be compared with Fig. 8 in [15]. The same two peaks appear there except for the experimental noise. The change of the height and position of the left peaks, which belong to the neutrons passing through the shadow bar, reflects simply the change of the distance from the neutron source.

The peaks on the right hand side belong to the cross-talk neutrons. It is essential for the interferometry measurements that the number of c-t in the backward direction is much smaller than in the forward one. It is also important that the time of flight positions of directly registered neutrons and the c-t neutrons emitted backward are clearly separated.

Fig. 5 presents quantitative estimations of the dependencies of c-t and diaphony probabilities on the relative angle in the considered case. The values are given for four incident neutron energies and two thresholds of neutron registration. Here also some features are useful for interferometry. First – the number of c-t is not always greatest for the smallest angles, second – the relations between c-t and diaphony depends strongly on the threshold, third – for greater energies the difference between the numbers of forward and backward c-t are small. All these features follow from the energy and angular dependence of neutron scattering in a given experimental set up.

5 Detector configuration for interferometry

The detector configuration in the Chalmers experiment, though well defined, introduces some confusion between different effects important for the interferometry measurements. Change of the angular positions of the detectors, while keeping their distance constant, changes also the relative angle between detectors as seen from the source of neutrons. It means that the vector of the momentum difference will be different for different angles $\theta$.

Fig. 6 presents the test configuration with a constant angular position of the detectors with respect to the neutron source. Fig. 7 shows the same dependencies as in the Fig. 5 but for this new configuration. In this case the largest amount of c-t appears for the configurations with almost the same distances between the source of neutrons and both detectors (positions 4 and 5 in Fig. 6). It appears that keeping detectors at the same distance from the target is the worst solution from the point of view of the c-t contamination.

Let us consider now the situation when the c-t event is taken as a real coincidence. The measured momentum difference is defined by the measured energies and the relative angle between detectors. The energy of each neutron is determined by the time of flight measurement which depends also on the target-detector distance. For the forward c-t this distance is greater than for the backward one. Fig. 8 presents the distributions of the neutron momentum $k^*$ in the rest frame of the neutron pair for different neutron energies and different angular combinations. The information collected there presents the quantitative estimate of the possible influence of c-t on the form of the two-neutron correlation function. Particularly important is the fact that the c-t events in the backward direction are shifted towards greater $k^*$ values. In
this case the parasite c-t effect is eliminated from the region of the smallest relative momenta where the true correlation effect is expected.

6 Cross-talk and distance-energy relation

Let us put the two neutron detectors at different distances from the emitting source (target). The geometrical relations are illustrated in the Fig. 2 b,c. Index (1) is now attributed to the close detector and index (2) – to the far one. Neutron energies are supposed to be measured by the time of flight method. If c-t occurs it is always possible to verify experimentally its direction, forward or backward. Taking: $\Delta E = E_2 - E_1$ and $\Delta d = d_2 - d_1$ the forward and backward c-t can be distinguished by the relations:

1) $\Delta E \cdot \Delta d < 0 \quad - forward.$ \hspace{1cm} (8)

2) $\Delta E \cdot \Delta d > 0 \quad - backward.$ \hspace{1cm} (9)

Let us reject now all the two-neutron combinations fulfilling the first condition. By doing this all the forward c-t are rejected. Regarding the c-t in the backward direction, their probability is much smaller than in the forward one and their admixture is located at the relative momenta far from the interferometry region.

The condition (8) does not contain any physical constraints and does not introduce any artificial correlations. The price for the bias free c-t elimination is the rejection of a half of randomly selected coincidences. A possible asymmetry in the registration of coincidences due to different solid angles of two detectors and due to their different positions with respect to the beam can be compensated by a second pair of the detectors in the opposite configuration. Usually, in interferometry measurements more than two detectors are used and it is possible to arrange their configuration allowing for such a compensation and thus - for a bias free c-t elimination.

In practical applications it is more convenient to work with directly measurable quantities in order to take into account the effects of the experimental resolution related to the finite detectors sizes, fluctuations of the free path of neutrons inside the modules etc. In our case it means the substitution of the neutron energies in the selection condition by the directly measured time of flight.

Thus, if $\Delta t = (t_2 - t_1)$ is the measured time of flight difference then the forward and backward c-t can be distinguished by the relations:

1) $\Delta t > + t_{c-t}^{min}(f) \quad - forward.$ \hspace{1cm} (10)

2) $\Delta t < - t_{c-t}^{min}(b) \quad - backward.$ \hspace{1cm} (11)

Here $t_{c-t}^{min}$ is the minimal time of c-t between the two detectors which can be taken equal to $(h_{min}/d_1)t_1$ for the first condition and $(h_{min}/d_2)t_2$ for the second one. The sizes of the detectors and their relative positions should be included in the determination of the $h_{min}$ value. In principle, one can calculate $t_{c-t}^{min}$ based on the detector response function provided that this function is really well known.
The two cases defined in Eqs. (10) and (11) can be clearly distinguished experimentally. The intermediate region defined by the conditions

\[-t_{c-t}^{\text{min}}(b) < \Delta t < +t_{c-t}^{\text{min}}(f)\] (12)

corresponds to the cross-talk free region considered earlier for the case of equal distances between target and detector.

Fig. 8 demonstrates common points and differences of the two considered approaches. The equidistant detector configuration corresponds approximately to the position 5 of the side detector. The configurations with different target-detector distances correspond to the position 1 (forward c-t) and to the position 8 (backward c-t). The distances between the dashed vertical lines in Fig. 8 and the peaks define the cross-talk free regions. In all cases the lines and peaks are well separated. In forward direction the width of this gap appears to be almost independent of the angular position of the side detectors. The reason is a decrease of the velocity of the c-t neutron with the decreasing distance between the central and the side detector. As a result these c-t neutrons have similar time of flight values.

For the backward direction the situation is just opposite. The c-t neutron velocity decreases with the increasing distance between detectors, thus leading to a rapid growth of the width of c-t free interval. Simultaneously, the probability of the backward c-t decreases with the decreasing detector distance.

For the detector configuration 8 the c-t neutrons are located outside the region of correlation effect for all the considered primary neutron energies. The amount of c-t is about one order of magnitude smaller than in the case of equal distances from the target (compare the numbers of entries for position 8 and 5). The increase of the width of the c-t free interval with the increasing primary neutron energy seen for each angular configuration just reflects the correlation between the total and relative neutron momenta induced by the finite minimal angular distance between the detectors (as discussed above).

Working with the configuration 8 and 1 all neutrons scattered into the detector 1 can be rejected by the condition (8) or (10). The c-t neutrons registered in the detector 8 are accepted by this selection. Fig. 8 demonstrates how many of such c-t events are accepted and where they are located in the k* scale. One can apply also the condition (12) removing the backward c-t as well, introducing however some momentum dependence in the region outside the correlation effect.

For the correlation analysis it is important to estimate how large is the ratio between the c-t effect and the number of real coincidences in different regions of the momentum differences. Such an analysis has been performed using the real experimental data.

7 Experimental test with the DEMON detector

The method of c-t elimination based on the configuration with the detectors placed at different distances from the target and using the relation (8) was proposed in [18] with the aim to be applied for the (n,n) interferometry measurements with the
DEMONT detector [19]. Earlier, the neutron detectors were located at different
distances from the target in the first neutron-neutron correlation measurement [10].
However, the background pairs were subtracted in this experiment on the base of
additional measurements with the shadow-bar in front of selected detectors. Re-
cently, the distance-energy relations were used to eliminate the c-t events in the
two-neutron correlation analysis [17].

In order to verify the cross-talk elimination methods a test measurement has
been made in the frame of some experiments performed in 1994 with the DEMON
detector at GANIL [20]. A set of 96 detectors was installed in a cylindrical form
around the target with the mean distance between the target and detectors of about
2m. Fig 9. shows the angular distribution of the registered neutrons. The $\theta$ and $\phi$
represent the vertical and horizontal angles respectively. A subset of 12 detectors
was arranged in a close angular configuration in order to obtain small momentum
differences. These detectors were put in three different distances from the target
(1.5, 2.0, 2.5)m. The reaction studied was Ar + Au at 60 MeV/u. Neutrons were
registered by the time of flight method. Charged particles were separated with the
plastic veto detectors or absorbed in the 5mm lead layer placed in front of the main
modules. The details of the experiment can be found elsewhere [20].

The correlation analysis was performed for the sample of events with at least 2
registered neutrons. The correlation function was calculated as the ratio:

$$C(k^*) = N_e(k^*)/N_0(k^*)$$

(13)

where $N_e(k^*)$ and $N_0(k^*)$ are the numbers of neutron pairs combined from neutrons
taken from the same and different events, respectively. Both distributions were
normalised to the same numbers of pairs in the region outside the correlation effect
($k^* > 0.05 GeV/c$). The pairs of neutrons from different events were submitted to
the same selection procedure as those from the same events.

Figs.10 and 11 present the examples of the two-neutron correlation functions and
and corresponding $k^*$ distributions for different detector configurations and different
selection criteria. They agree well with the results of simulations shown in Fig. 8. In
the region of small $k^*$ values the increase of statistics coming from the interferometry
block of detectors is seen in Fig. 11. Regarding the relations between the c-t and the
real coincidences it is important that the number of pairs with possible c-t (stars)
becomes noticeable at $k^*$ of about 30 MeV/c only, being in this region of some
orders of magnitude smaller than the number of pairs for which the c-t is forbidden
by the selection criteria (full circles). It means that the backward c-t is practically
negligible and does not introduce the distortion of the correlation function. The c-t
effect on the correlation function in the equidistant configuration ($d_1 = d_2$) will be
discussed below.

Fig 12. presents some examples of the experimental correlation functions ob-
tained for different cuts in the kinetic energies of the registered neutrons. The
detector combinations with different distances from the target were used and the c-t
elimination method was applied. The strength of the correlation effects increases
with the increasing minimal neutron energy. This increase is related to different
phases of nucleon emission. Fast nucleons are emitted predominately in the initial
stage of the collision and the slow ones appear mainly in the later evaporation stage. (The physical analysis of these data will be presented in a separate paper.)

A comparison of different methods of c-t rejection is illustrated in Fig. 13. One can see that the method of c-t rejection applied for the detectors with equal distances from the target gives a sort of maximum for the k* values of about 20MeV and some other structures are present as well. Such a strange behaviour of the correlation function points out serious methodical problems of the correlation measurements in the equidistant configuration.

The upper part of this figure, together with Fig. 12, indicates the origin of such an unexpected form. The two-dimensional plots show the relations between k* and the absolute value of the momenta of the selected neutrons. The left part of this figure contains pairs detected by the detectors located in different distances from the target, the right part is for the detectors at the same distances. The main difference is in the clear band seen for the small k* values in the case of equal distances. This band is a direct consequence of the cross-talk rejection method applied here (cf. Eq.(3)). The smallest values of k* are populated by the smallest neutron momenta. Another band starting at about 30 MeV/c corresponds to the detector configuration with the large angular distance.

The relation between the dependencies observed in Fig. 12 and Fig. 13 is quite transparent. Fig. 12 shows that the correlation effect increases with the increasing neutron momenta. This physical effect is also reflected in the complicated behaviour seen in Fig. 13 for the equidistant detector configuration. The mixture of methodical and physical effects seen in this figure makes practically impossible a direct comparison of the experimental correlation function with the theoretical predictions. These problems can be even more pronounced in the directional dependence of the correlation function.

8 Conclusions

1. The cross-talk effect changes essentially the form of the two-neutron correlation function in the region of small momentum difference.

2. The passive methods of cross-talk elimination by the increase of the distances between detectors are practically inefficient.

3. The method based on the kinematical relations between the energies of registered neutrons introduces strong correlations between the momentum and the momentum difference if the distances between the target and the detector modules are the same.

4. A bias-free cross-talk elimination appears to be possible using the detector configuration with different distances from the target and introducing certain kinematical conditions for the selection of the two-neutron systems.
References


FIGURE CAPTIONS

Fig. 1. The detector configurations illustrating the probability relations between cross-talk and coincidences.

Fig. 2. Distance-energy relations for cross-talk events: a) - the same distance from the neutron source, b), c) - different distances.

Fig. 3. A set of neutron detectors used for the computer simulations of the Chalmers University experiment.

Fig. 4. The results of simulations of the Chalmers experiment (to be compared with Fig. 8 of ref. [15]).

Fig. 5. The probabilities of the cross-talk and diaphony for the detector configuration presented in Fig. 3.

Fig. 6. The test configuration of neutron detectors for the interferometry measurements.

Fig. 7. The probabilities of the cross-talk and diaphony for the detector configuration presented in Fig. 6. The numbers on the horizontal axes correspond to the detector positions defined in Fig. 6.

Fig. 8. The distributions of the cross-talk events in the relative momentum when treating these events as real coincidences. The figure columns from left to right correspond to the primary neutron energies 14, 50, and 95 MeV, respectively. The figure rows correspond to the different detector positions defined in Fig. 6.

Fig. 9. The angular distribution of neutrons registered in the experiment E240 with the DEMON detector at GANIL. A special block of close-packed detectors placed at different distances from the target is seen in the region of θ = 50°.

Fig. 10. The two-neutron correlation functions for different selection criteria. Neutrons with energies greater than 5 MeV were selected.

Fig. 11. The distributions of the half of relative momentum (k*) for the neutron pairs selected by different criteria.

Fig. 12. The examples of cross-talk free correlation functions for different cuts in the neutron energies.

Fig. 13. Upper part - relation between the relative momentum (k*) and the absolute values of neutron momenta for different (left) and equal (right) distances between detectors and the source of neutrons. Lower part - the corresponding correlation functions. Neutrons with energies greater than 10 MeV were selected.
Fig. 1.
CROSS-TALK REJECTION METHODS

a) 
\[ d_1 = d_2 \]

b) 
\[ d_1 < d_2, E_1 > E_2 \implies \Delta E \Delta d < 0 \]

c) 
\[ d_1 < d_2, E_1 < E_2 \implies \Delta E \Delta d > 0 \]

Fig. 2.
Fig. 3.
TOF spectra from shielded detector

Fig. 4.
Probability of cross-talk and diaphony

Cross-talk

Diaphony

Energy threshold (e.e.)=
- 0.2 MeV
- 1.0 MeV

Neutron energy=
- 3.0 MeV
- 14.0 MeV
- 50.0 MeV
- 95.0 MeV

Fig. 5.
Fig. 6.
Probability of cross-talk and diaphony

Cross-talk

Diaphony

Energy threshold (e.e.) =
- □ - 0.2 MeV
- ○ - 1.0 MeV

Neutron energy =
- a) - 3.0 MeV
- b) - 14.0 MeV
- c) - 50.0 MeV
- d) - 95.0 MeV

Fig. 7.
Fig. 8.
Fig. 9.
Fig. 10.
Ar+Au, 60 MeV, $E_k > 5$ MeV

$\Delta N / \Delta k^*$

Fig. 11.

$k^*$, MeV/c
Ar+Au, 60 MeV/c, E240, DEMON at GANIL

Fig. 12.

$C(k^\ast)$ vs $k^\ast$, GeV/c

- ○ $E_{kn} > 20$ MeV
- ● $E_{kn} > 10$ MeV
- ★ $E_{kn} > 5$ MeV
Fig. 13.