INVESTIGATIONS OF THE NEUTRON CROSS-TALK EFFECT IN DEMON DETECTORS

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1. Introduction

The experiment on fragment-neutron angular correlations, aimed at the investigation of the influence of fragment angular momentum (spin) on the neutron emission process is performed at Strasbourg (France) [1] using the CORA setup, which consists of the double ionization chamber CODIS [2] for measuring the fission fragments and a set of DEMON neutron detectors [3]. It is well established that the prompt neutrons evaporated from the fragments of nuclear fission are emitted anisotropically with respect to the fission axis, main source of the anisotropy being the kinematic focusing of the neutrons, emitted from the moving fragments [4, 5]. However, various attempts to analyze the experimental data on neutron emission anisotropy lead to a conclusion that the anisotropy cannot be fully described only by the kinematic focusing, but an additional component of the neutron emission should exist, which is either isotropic (or close to isotropic) in the laboratory system – so called scission neutrons, or anisotropic in the center-of-mass system of the fission fragments [6], which leads to a slight change in the neutron emission anisotropy in the laboratory system, observed experimentally.

In the CORA experiment triple fragment-neutron-neutron angular correlations in the spontaneous fission of ^{252}Cf are analyzed, which are supposed to be sensitive to the anisotropy of the neutron emission with respect to the fragment spin direction. The preliminary analysis of the experimental data showed that one of the most important sources of the background is the so called cross talk effect – scattering of neutrons between neighboring DEMON detectors. The main aim of the present work is to obtain quantitative characteristics of the cross-talk effect in the DEMON detectors.

In order to investigate the cross talk effect and its influence on the main experiment two dedicated measurements have been performed. In both of them an Am-Be neutron source was used, which emits only one neutron at a time, thus any measured neutron-neutron coincidence in two or more neutron detectors should be due the cross talk effect. In the first experiment two separate DEMON detectors were placed at a distance to the Am-Be neutron source, approximately corresponding to the geometry of the main experiment. Neutron-neutron coincidences were measured as a function of the distance between the two DEMON detectors. In the second experiment the same Am-Be neutron source was placed at the position of the ^{252}Cf source and neutron-neutron coincidences were measured with the full set of DEMON detectors.

The main parameter of the cross talk effect, which can be measured, is its probability. If a neutron is registered in detector a, then scattered and registered in detector b, the probability of such a process in terms of measurable values can be defined as

$$P_{ab} = N_{ab}/N_a \tag{1}$$

where N_a is the number of neutrons registered in detector a and N_{ab} is the number of neutrons which were scattered from detector a and registered in both detectors a and b in coincidence. It can be shown that the probability of cross talk observation, defined in such a way, is equal to

$$P_{ab}(E_n) = p_{ab}(E_n) \times \epsilon_b(E'_n) \tag{2}$$

where p_{ab} is the probability of neutron scattering from detector a to detector b, E_n and E'_n – energies of the incident and scattered neutron, and ϵ_b is the detection efficiency of detector b.

2. Experiment with two detectors

In this experiment one DEMON detector was placed at a fixed position at a distance 75 cm from the source to the front side of the detector. The second detector was placed at six different positions with distances between the centers of the two detectors: 27.5, 33.5, 40.0, 46.0, 53.0 and 59.0 cm; and distances from the front side of the second detector to the source: 77.0, 75.0, 75.0, 74.0, 75.0 and 82.0 cm, respectively. In addition, a BaF_2 detector was placed near the source and was used as a trigger by gamma-rays, emitted in coincidence with neutrons. For each DEMON detector the time-of-flight was measured with respect to the BaF_2 signal, as well as the standard Q_{total} and Q_{slow} values – total and slow parts of the collected charge, allowing for the n-gamma discrimination.

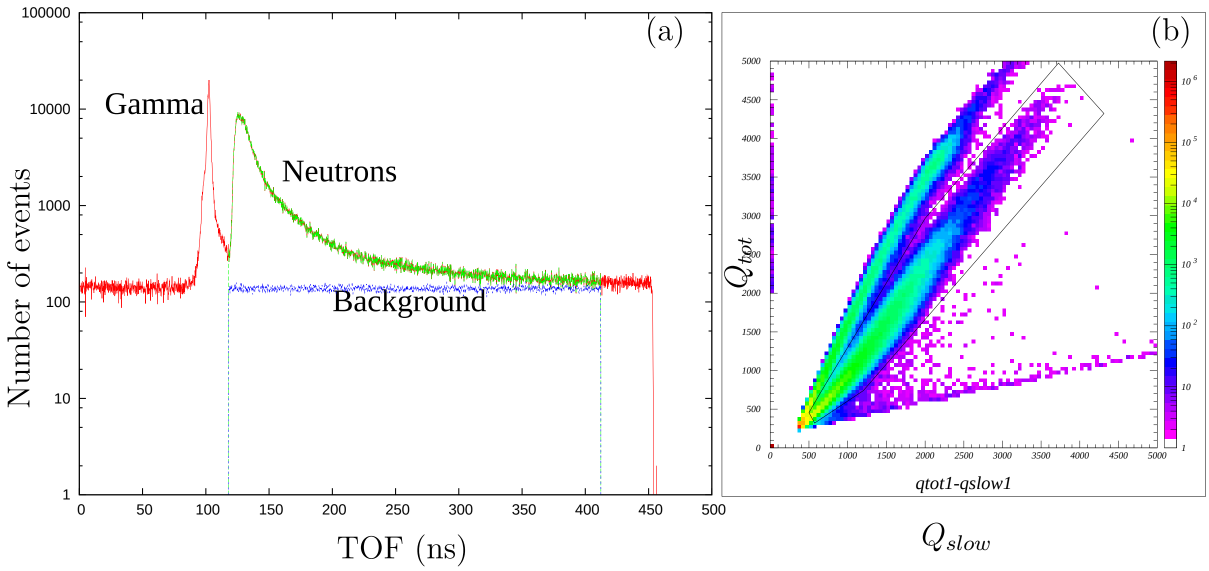

Figure 1: (a) TOF spectrum from detector 1. (b) Neutron-gamma separation plot.

The TOF spectrum from detector 1 is shown in Fig.1 (a). At this distance the time-of-flight parameter could be effectively used for neutron-gamma separation. The background was assumed to be constant in time, it was determined from the region on the left side from the gamma peak and extrapolated to the full spectrum. The time of appearance of the coincident signals in detectors 1 and 2 relative to the start signal from BaF_2 was used for the identification of the primary and scattered neutrons – the earlier signal was always interpreted as the primary event. Those events which appeared in both detectors within a coincidence window of 10 nsec were assumed to be neutron-gamma cross talk events (most probably due to the $(n, n'\gamma)$ process) and were excluded from the analysis.

Another method of neutron-gamma separation is provided by the pulse-shape analysis of DEMON signals. Figure 1 (b) shows the Q_{total}/Q_{slow} plot with neutron events selected by a polygon. As one can see from the TOF spectrum, the admixture of gamma-ray events in the neutron part is rather small, thus the time-of-flight method could be used alone for the n-gamma separation. The Q_{total}/Q_{slow} method is less accurate, especially in the region of small amplitudes where neutrons and gamma-rays practically overlap, so it was used only as extra more strict criterion in addition to the time-of-flight separation.

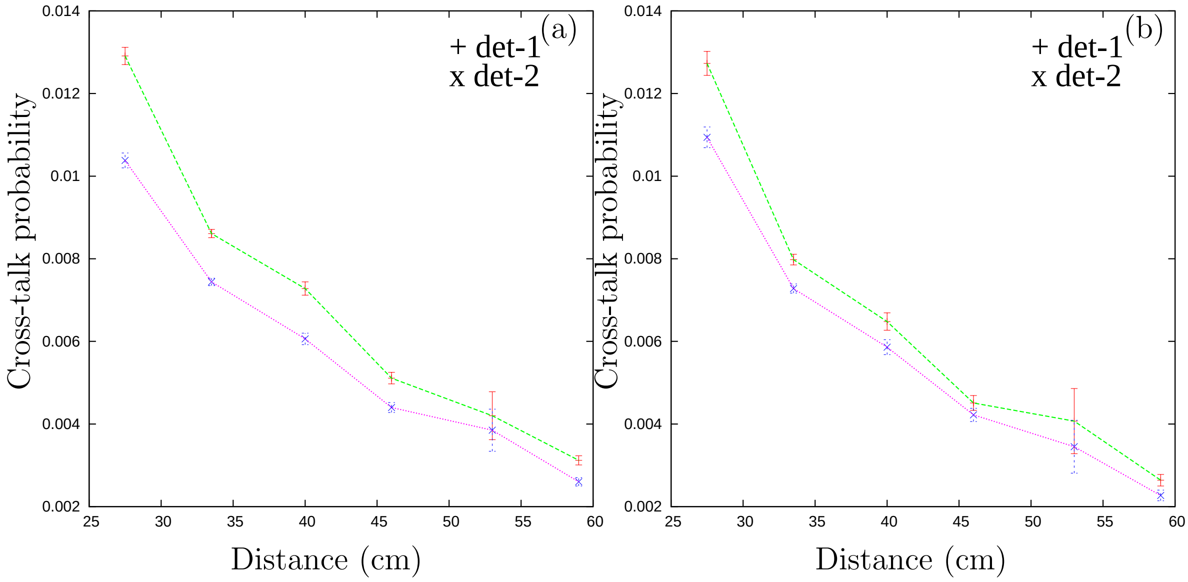

Figure 2: Cross talk probability as a function of the distance between two DEMON detectors. (a): only TOF n-gamma separation; (b): TOF + Q_{total}/Q_{slow} n-gamma separation.

Figure 2 shows the dependence of the cross talk probability, as defined by formula (1), on the distance between the centers of two DEMON detectors with TOF n-gamma separation (left) and with TOF + Q_{total}/Q_{slow} n-gamma separation (right). Two curves correspond to the scattering from detector 1 to detector 2 and vice versa. One can see that the addition of more strict Q_{total}/Q_{slow} criterion practically doesn't influence the probability of the cross talk effect. The difference of the effects for detectors 1 and 2 is explained by different settings of the electronic detection threshold, which resulted in different detection efficiency and different cross talk probabilities according to formula (2). In our further analysis only the TOF n-gamma separation method was used.

The dependence of the cross talk effect on the energy of incident neutrons has been also analyzed. Neutron energy was determined by the time-of-flight method, and the cross talk probability as a function of distance was plotted for several intervals of incident (primary) neutron energy. It is shown in Fig. 3 (left) for the neutrons scattered from detector 1 to detector 2. The cross talk probability slightly increases with the increase of the neutron energy. Such an increase is indeed expected according to formula (2). It turns out that the most important parameter, responsible for the magnitude of the cross talk effect, is the efficiency of detector b, which is mainly governed by the setting of the energy detection threshold. For the DEMON detectors this threshold is typically between 500 keV and 1 MeV. For low energy incident neutrons, hitting detector a, there will be always relatively large number of scattered neutrons, which fall below the detection threshold in detector b. Such events will not be registered in the experiment and will not contribute to the observable cross talk effect. With an increase of the neutron energy the number of those neutrons which fall below the threshold will decrease, thus increasing the detection efficiency and, in turn, the observable cross talk effect.

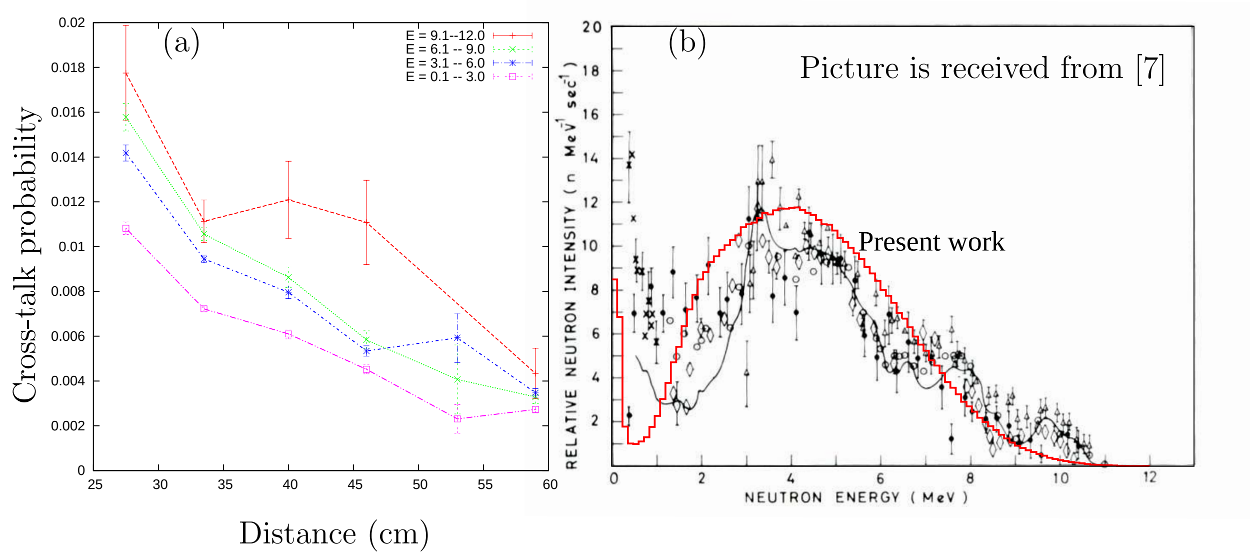

Figure 3: Left: Cross talk probability as a function of the distance between two DEMON detectors for different incident neutron energies, from bottom to top: 0.1–3 MeV; 3.1–6 MeV; 6.1–9 MeV; 9.1–12 MeV. Right: Energy spectrum of neutrons from the Am-Be source, reconstructed using the time-of-flight method and compared to literature data.

An attempt to obtain spectrum of neutron energies from Am-Be source by TOF method was made. As the length of the detector (20 cm) is comparable with the distance to the source, there is rather large uncertainty in the neutron flight paths as long as information about a place of interaction of neutrons in detector is absent. In order to account for this uncertainty in the process of conversion from TOF to neutron energy the interaction point of each event was randomly distributed along the full length of the sensitive part of the detector. The resulting neutron energy spectrum appeared to be smoothed. It is plotted as thick line in Fig. 3 (right) in comparison with results of other experiments and calculated curve from [7].

2. Experiment with sixty detectors

Sixty DEMON detectors, which were installed for the CORA experiment, were used in the second part of the present work. The geomentry of the experiment, as well as the electronics remained basically the same as in the main experiment with only minor modification. The DEMON detectors were placed in nearly spherical geometry around the source. Two types of mechanical support, each holding 5 DEMON detectors were used (see Fig. 4). Ten such supports (five of each type) were placed in a circle around the source in alternating order. Thus, there were 5 horizontal rings of 10 DEMON detectors each, and two rings (top and bottom) of 5 DEMON detectors. The distance from the source to the front side of the detectors in the middle ring was 60 cm. Schematically top view of the positions of all detectors is shown in Fig. 5.

In this test measurement an additional BaF_2 detector was used in the same way as in the experiment with two DEMON detectors. It was placed in the lower part of the installation in such a way that the Am-Be source could be placed on it, being in the geometrical center of the set-up, e.g. in the position of the ^{252}Cf fission source. The lower hemisphere of the full installation was partially shaded by the BaF_2 detector. This changed slightly the counting rates of the detectors located in the lower hemisphere and the energy spectrum of the neutrons, registered by those detectors, but we believe that it didn't have any significant influence on the properties of the cross talk effect.

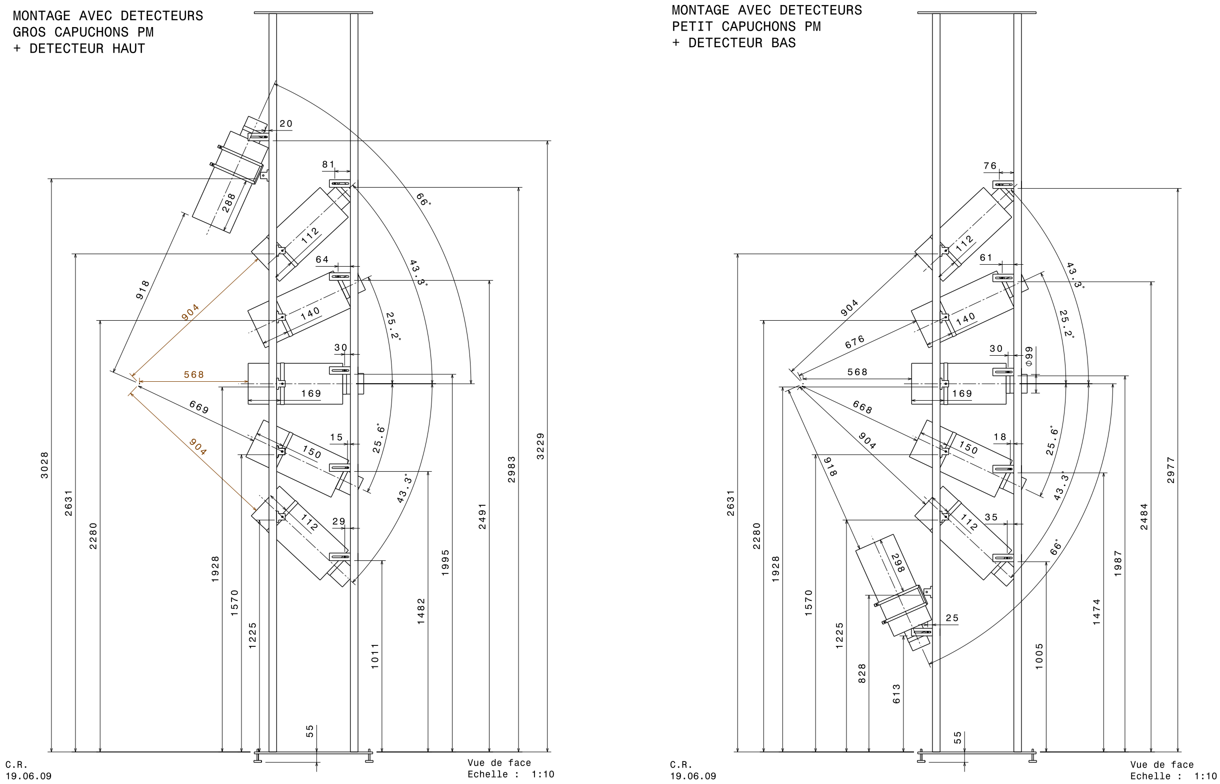

Figure 4: Two types of DEMON supporting structures used in the experiment

As in the experiment with two detectors, BaF_2 was used as a start for the time-of-flight measurement, and for each DEMON detector the TOF, Q_{total} and Q_{slow} parameters were recorded. A coincidence between the BaF_2 and any of the DEMON detectors was used as a trigger. Those events which occurred simultaneously in any pair of DEMON detectors within a given coincidence time window and which were identified as neutron events were assumed to be the cross talk events. The background due to random coincidences was determined for each DEMON detector in the same way as in the first part of the present work. For simplicity reasons neutrons and gamma-rays were separated using only the time-of-flight method, keeping in mind the result from the first experiment which demonstrated that the more strict Q_{total}/Q_{slow} n-gamma separation doesn't change the measured probability of the effect. As in the experiment with two detectors, the event, which arrived first after the start signal from BaF_2, was assumed to be the primary neutron event, all subsequent events were assumed to be scattered ones. Those events which occurred within a time window of 10 nsec after the primary event were counted as neutron-gamma cross talk and were excluded from the analysis.

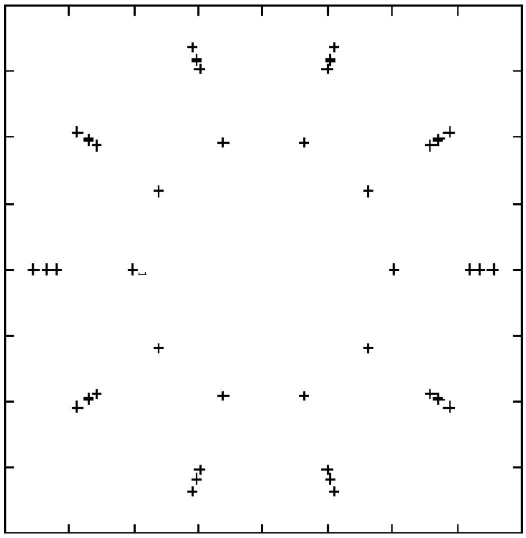

Figure 5: Top view of positions of detectors

During the experiment more than 128 millions events were collected. Only two-fold coincidences between any pair of DEMON detectors were analyzed as cross-talk events. Higher multiplicities give only minor contribution to the effect.

Figure 6 (left) shows the normalized total number of events collected by seven horizontal rings of DEMON detectors. The rings are numbered from top to bottom. The total number of counts in each ring is divided by the number of detectors in the ring (five detectors in rings 1 and 7 and ten detectors in rings 2–6). In addition, it is weighted by the squared inverse distance to the corresponding ring to compensate for the differences in solid angle. In the right side of Fig. 6 the mean number of double coincidences in the same rings is plotted, normalized to the corresponding number of single coincidences. In both plots all measured events were summed up, without separation of neutrons and gamma-rays. The first figure demonstrates the differences in efficiencies of the DEMON detectors. It predictably drops for those detectors, which are located in the lower hemisphere, as they are partially shaded by the BaF_2 detector. The second plot, which shows the ratio of multiplicities 1 and 2 for each ring, indicates the differences of the cross talk probability for each ring, albeit both, for neutrons and gamma-rays. One can see that the presence of the BaF_2 detector has almost no influence on it (except for the slight difference at ring 7). The increase of the cross talk for the central rings is easily explained by the closer distance between neighboring detectors in these rings.

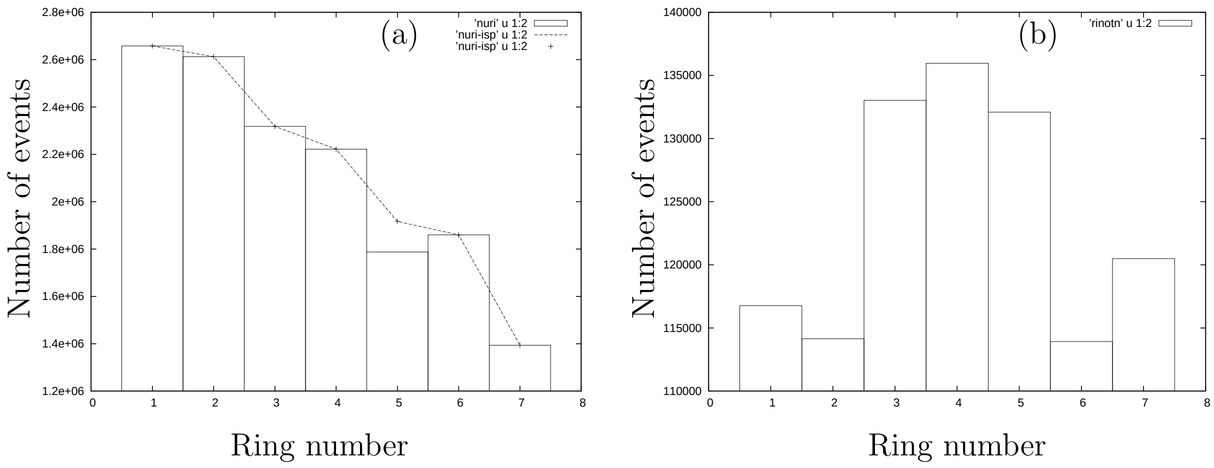

Figure 6: Left: Mean number of events with multiplicity 1 registered in in each ring of detectors. Right: Mean number of events with multiplicity 2, normalized to multiplicity 1, registered in each ring of detectors. Rings are numbered from top to bottom.

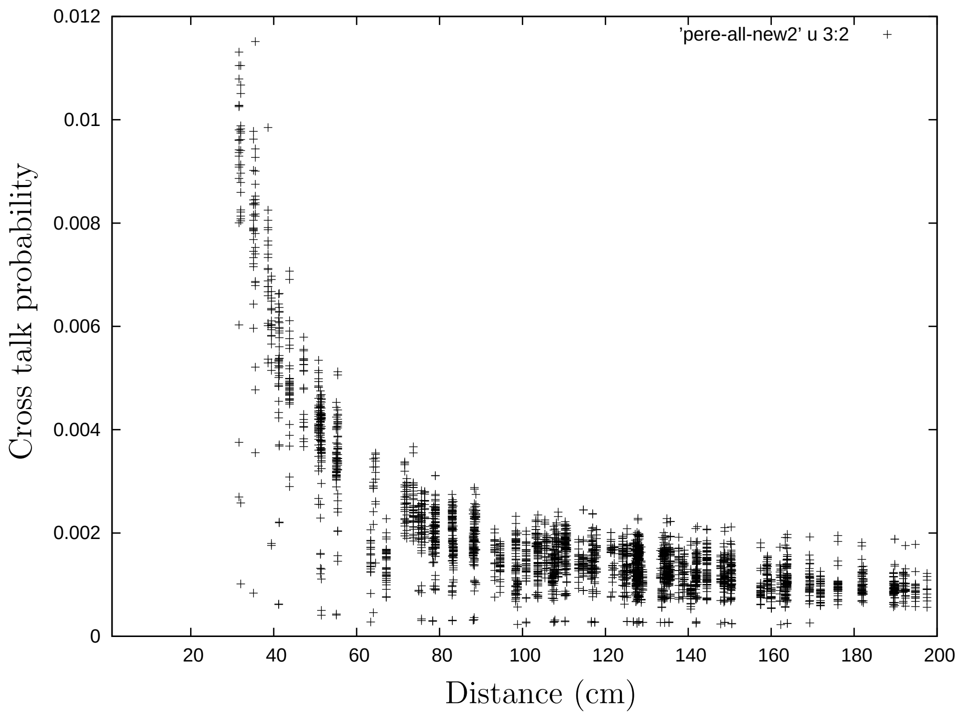

Figure 7: Cross talk probability as a function of distance between two detectors for all possible pairs of detectors.

From all obtained statistics the events with multiplicity 2 for all 60 detectors were analyzed in the following steps:

1. Neutrons were separated from gamma-rays using time-of-flight spectra, as in Fig. 1(a).
2. The primary neutron event was assumed to be the one having smaller TOF value with respect to the start signal from the BaF_2 detector. The second event was assumed to be scattered one.

3. If value $tof(2) - tof(1)$ was smaller than 10 ns, such an event was supposed to be neutron-gamma scattering and was excluded from the analysis.

4. For all pairs of detectors total number of neutron-neutron coincidences N_{ab} and N_{ba} (see formula 1) was determined. At the same time, number of single neutron events in each detector was counted.

5. The cross talk probability was determined for each pair of detectors as the ratio between the number of coincident and single events, as defined by formula 1.

The resulting cross talk probability is plotted in Fig. 7 as a function of the distance between two detectors for all possible pairs of DEMON detectors.

3. Conclusions

The dedicated experiments on cross talk with two DEMON detectors and with sixty detectors in the same arrangement as the main experiment demonstrated that the probability of its registration is about 1% when the distance between the centers of the detectors is about 30 cm. It drops by a factor of 5 when the distance increases by a factor of 2 to 60 cm. More strict $n - \gamma$ separation using Q_{total}/Q_{slow} plots doesn't change the probability of the cross talk observation. The main factor which has large influence on the measured cross talk effect is the neutron detection efficiency of the second detector (the one which measures scattered neutrons). A possible way to reduce the cross talk effect in an experiment would be to increase the registration threshold of all detectors. Application of a special filter for cross talk rejection, as it was proposed in [8] and tested in [9] is even more efficient way for reducing the background in the experimental data, caused by the cross talk effect. The final plot (Fig. 7) shows large fluctuations in cross talk detection probabilities between different pairs of detectors even at the similar distances between them. The reason for these discrepancies is most probably the above mentioned differences in the detection efficiency, which is caused by different settings of electronic thresholds or different amplification of the signals in individual detectors.

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