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Cross talk and diaphony in neutron detectors

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A neutron which enters a detector can be scattered into a neighbouring detector. If the neutron is registered in each detector the effect will be called "cross talk", and if a hit is registered only in the neighbouring detector, the effect is described as "diaphony". An experiment performed with the AMPHORA multidetector showed that diaphony and cross talk severely alter the neutron detection in small granularity NE213 cells. In this experiment, four out of five neutron coincidences between neighbours were due to cross talk. Up to one out of four detected neutrons is induced by a neutron entering a neighbouring detector. The Monte Carlo code Menate showed that there is no simple way to extract true coincidences from cross talks and that a CsI cristal placed in front of the NE213 cell (phostron detector) induces an enhancement of the cross talk rate. The main consequences of diaphony and cross talk are: an enhancement of the measured multiplicity and of the small relative angle coincidences, and a smoothing of the laboratory angular distribution.

1. Introduction

Many correlation experiments involve the detection of coincident neutrons at low relative angles. Interferometric experiments are now dealing more and more with neutrons in order to avoid Coulomb effects. The multidetector AMPHORA, located at the SARA facility in Grenoble, France, is designed to detect neutrons as well as charged particles with low granularity detectors. We investigate whether AMPHORA and other such multidetectors are reliable when detecting coincident neutrons.

2. Background

In small granularity neutron detection experiments, new specific instrumental problems occur due to the fact that the ranges of the neutrons (or the gamma rays) inside the scintillators used for their detection, are non-negligible compared with the dimensions of the detectors. Furthermore, elastic and inelastic scattering can strongly deviate their trajectories. Thus, when the detectors are close to each other, a neutron produced in the target can pass through several detectors. Depending on the amount of light deposited in each detector, it may, or may not, be detected. A neutron which crosses successively two detectors may produce two main effects. We label these two effects cross talk and diaphony:

a) *Cross talk*: this occurs when the neutron deposits enough light to be detected in both detectors. This phenomenon leads to an overestimation of the total number of neutrons emitted from the target and of the number of correlations at low relative angles. This first effect is very crucial for neutron interferometry measurements at low relative momenta. If the number of small relative angle coincidences is increased, and if the difference between the energy deposited in each detector is not too high, then the effect of the cross talk will be modification of the apparent size of the emitting source.

b) *Diaphony*: if the incoming neutron is detected only by the second detector, then, in this case, two effects will affect the measurements: the detected angles will be incorrect, and the velocity of the neutron, deduced either from the time of flight or from the light deposit, will be underestimated.

The existence of these problems poses two main questions for the experimental physicist when analysing neutron detection data:

Question 1 (Q1): What is the probability P_n that a detected neutron was scattered from a neighbouring detector? What is the dependence of this probability on

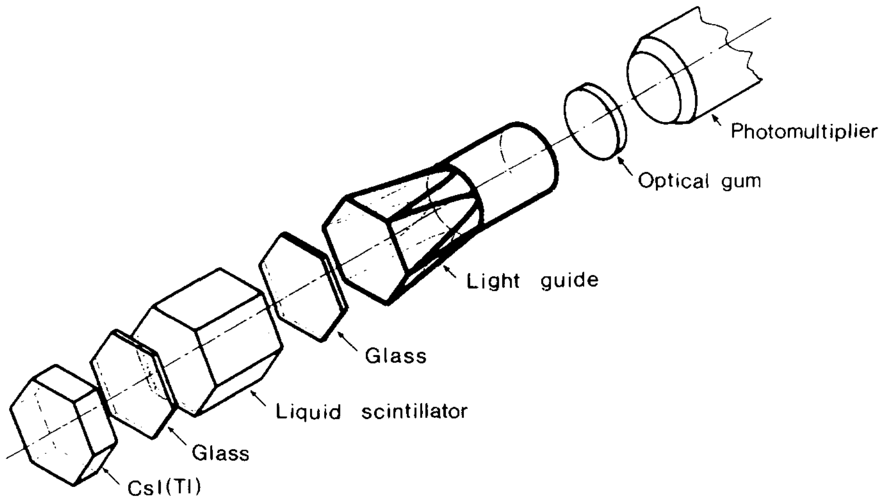

Fig. 1. Exploded view of one of the front wall cells, as mounted for light particle and neutron detection.

the energy $P_n(E)$? The answer to this question depends on both the diaphony and the cross talk effects.

Question 2 (Q2): When a coincidence is registered between two neighbouring detectors, what is the probability that it is due to cross talk? The parameter associated with this effect will be the cross talk ratio $R_{ct} = N_{ct}/N_c$, where N_{ct} is the number of cross talk events and N_c the total number of detected coincidences.

3. Experiment

In order to answer these two questions, and try to create a filtering procedure for true coincidences, a test experiment was done with the multidetector AMPHORA and a simulation code called "Menate" was written.

3.1. The detector array AMPHORA

The AMPHORA detection system [1], located at the SARA facility in Grenoble, is a scintillation multidetector designed for the purpose of intermediate energy reaction studies. Its 140 detectors cover 82% of the 4π space. AMPHORA is made of one backward bowl including 92 trapezoidal detectors, and one spherical forward wall situated at 140 cm from the target, on which 48 hexagonal detectors are arranged.

Some AMPHORA detectors [2] (fig. 1) are composed of two detection systems:
- one CsI(Tl) crystal of thickness 32 mm, for the discrimination of charged particles,
- one neutron detection module (an NE213 liquid scintillator cell) of thickness 75 mm.

The entry surface of these detectors is 70 cm^2 (corresponding to hexagons of 5.2 cm dimension (edge)).

Both detection systems deliver a light pulse to a unique photomultiplier. Two charge samples of the anode impulsion, C1 ($t = 40$ ns, $\Delta t = 400$ ns) and C2 ($t = 0$, $\Delta t = 30$ ns) allow neutron–gamma identification in the liquid scintillator (fig. 2), and two others, C3 ($t = 0$, $\Delta t = 400$ ns) and C4 ($t = 1600$ ns, $\Delta t = 1000$ ns) provide identification of charged particles in the cesium iodide. In the experiment described below, the threshold

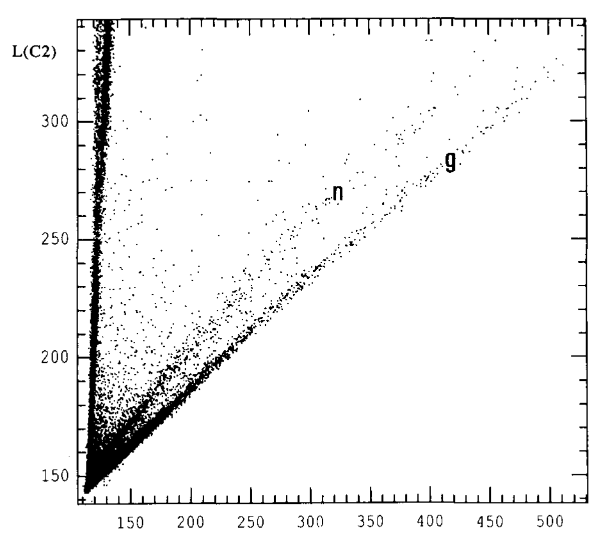

Fig. 2. Two-dimensional identification map obtained using an NE213 liquid scintillator with a 3.5 cm CsI(Tl) front window. L(C1) and L(C2) are the light integrals within C1 ($t = 40$ ns, $\Delta t = 400$ ns) and C2 ($t = 0$, $\Delta t = 30$ ns). n stands for neutron and g stands for gamma.

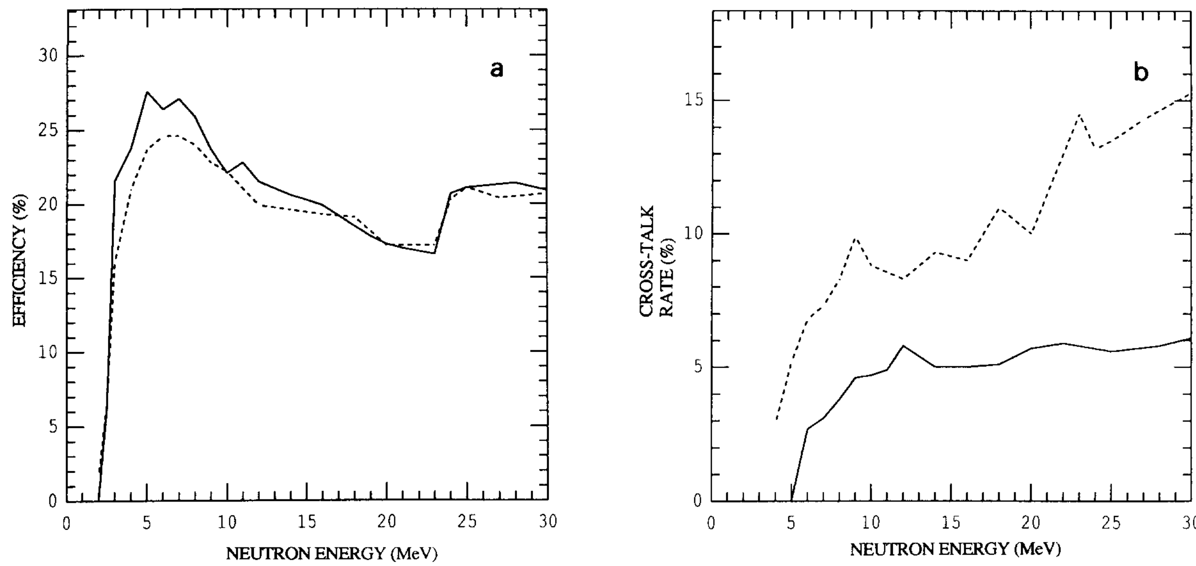

Fig. 3. (a) Simulated efficiency curve as a function of the energy of the incoming neutron for the NE213 cell alone (full line) and the CsI + NE213 detector (dotted line). (b) Simulated cross talk ratio for a detector surrounded with neighbours. The seven detectors are made of an NE213 cell alone (full line) or a CsI cristal coupled with an NE213 cell (dotted line).

values of all the detectors were fixed at 2.4 MeV (neutron energy). The neutron efficiency curve of the complete detector with no neighbour is given in fig. 3a. The lower spectrum corresponds to the complete detector (CsI + NE213), whereas the upper curve corresponds to the NE213 cell alone. One can see that the CsI crystal induces a small loss of efficiency. These curves were simulated with the code Menate (described below) for a threshold value of 0.8 MeV electron equivalent.

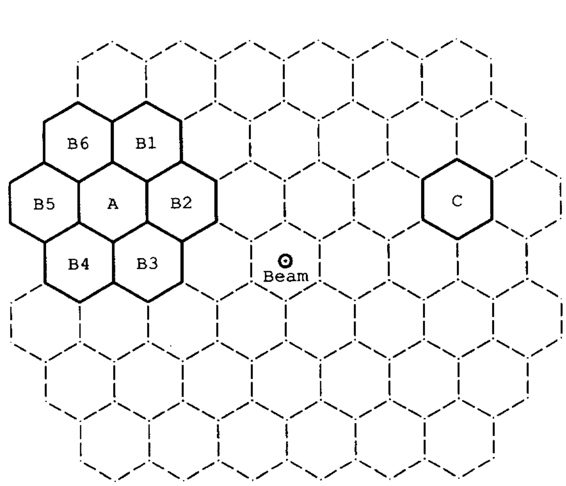

Fig. 4. Experimental setup. The dotted line hexagons are the detectors removed from the AMPHORA front wall. Detector A is submitted to the influence of its neighbours, whereas C is used as a reference (the edge of the hexagons is 5.2 cm).

3.2. Experimental arrangement

Some features of the front wall of AMPHORA make it very sensitive to cross talk and diaphony: the detectors touch each other, they cover only 0.004 sr and they are sensitive to cross talk and diaphony induced both by neutrons and gammas.

To investigate these effects, a test experiment was carried out using a subset of AMPHORA detectors. Among the 48 hexagonal cells making up the front wall, only 8 were retained. The A detector, placed at the polar angle $\theta = 6.8°$ with respect to the beam axis and azimuthal angle $\phi = 30°$, was surrounded by 6 detectors B_1 to B_6. The C detector, isolated, was placed symetrically to A at the angle $\theta = 6.8°$ and $\phi = 150°$ (fig. 4). Thus A was submitted to the influence of its neighbours whereas C was used as a reference. A 0.1 nA, 20 MeV/A ^{16}O beam was used on a thick copper target. The data acquisition was triggered when one of the 8 detectors was hit and the identification parameters cited above plus the times $t_A - t_{HF}$, $t_A - t_C$ and $t_A - t_{B_i}$ were stored.

4. Probabilities that a detected neutron has come from a neighbouring detector

4.1. Evaluation using singles counting rates

An evaluation of P_n was obtained by comparing the number of neutrons detected by A, the B's and C. The counting rates are given in table 1. In order to answer

Table 1
Count rates for inclusive neutron detection (second column) and for coincidences with B and C detectors (third column) or neutrons or γ rays (fourth column)

Detector	Counting rates	Coincidences (n in A, n)	Coincidences (n in A, n or γ)
A	37750	116427	116427
C	29084	87	136
B1	30800	1188	1601
B2	37016	1311	1817
B3	33062	1222	1732
B4	36692	1443	1956
B5	28216	1169	1601
B6	34025	1528	1583
⟨B⟩	33302	1310	1785

question Q1, the P_n probability was calculated for detector A by two different methods, using the fact that detector A is subjected to 6 cross talk and diaphony contributions from its neighbours whereas each B_i only receives 3 and C none.

We denote by n_A the number of neutrons detected in A, n_B the average number detected by each B_i, n_C the number detected by C, n_n the number of neutrons scattered by one detector to one neighbour and n_{true} the number of neutrons that would have been detected if there were neither diaphony nor cross talk. The quantity n_{true} is supposed to be the same for A, B and C because the θ angle with respect to the beam is the same for A, C and the barycenter of the B's. With this hypothesis, one can write:

$$n_A = n_{true} + 6n_n, \quad (1)$$

$$n_B = n_{true} + 3n_n, \quad (2)$$

$$n_C = n_{true}, \quad (3)$$

$$P_n = 6n_n/n_A. \quad (4)$$

Thus, the variable P_n can be calculated in two different ways designated by P_{n1} and P_{n2}:

$$P_{n1} = (n_A - n_C)/n_A, \quad (5)$$

$$P_{n2} = 2(1 - n_B/n_A). \quad (6)$$

Furthermore, the ratio R_r is introduced as a measure of the reliability of the results:

$$R_r = (n_C - n_{true})/n_C. \quad (7)$$

R_r can be written using only n_A, n_B and n_C by eliminating n_n from eqs. (1) and (2):

$$R_r = (n_C - 2n_B + n_A)/n_C. \quad (8)$$

Using the values given in table 1, one obtains:

$$P_{n1} = 23.0\% \pm 0.8\%,$$

$$P_{n2} = 23.6\% \pm 1.9\%,$$

$$R_r = 0.8\% \pm 2.5\%.$$

The errors take into account only the counting rates assuming a Poisson distribution.

The agreement between the two values of P_n is satisfactory. We notice that P_{n1} does not depend on n_B and P_{n2} does not depend on n_C. The resulting small value of R_r should be considered as a proof of the good beam alignement and of no excessive discrepancy between the detector thresholds and efficiencies.

4.2. Evaluation from coincidence data

Further information can be derived from the study of coincidences between A and one of the B_i. Events with a neutron detected in A and a neutron or a gamma (which can be produced by an incident neutron) in one of the B_i are selected. With the counting rates given in table 1 one obtains the value $P_n = 6(1785 - 136)/116427 = 8.5\%$ (the coincidence rate between A and C is supposed to represent the true coincidences). This probability is much smaller than the true probability for a neutron to be scattered from a neighbouring detector as many neutrons do not deposit enough light in the B's to be detected, or are scattered by the CsI part of the detector toward A. Whatever the technique, no more than 8.5% out of 23% false detections can be rejected. If both particles detected in A and B are identified as neutrons, then the probability is decreased to $P_n = 6(1310 - 87)/116427 = 6.3\%$.

5. Probability that a coincidence is due to a cross talk

We now consider the case when two neutrons are detected simultaneously. The number of coincidences between A and the 7 other detectors are given in table 1. There are only 87 "true" coincidences between A and C. If one makes the simple hypothesis that the number of true coincidences between A and one of the B_i is the same as between A and C then one can answer the question Q2, that is $R_{ct} = (1310 - 87)/1310 = 93.4\%$. This value does not take into account the fact that the number of true coincidences of A with one of the B's is likely to be higher than with C. To solve this problem, we calculate the mean number of coincidences between two detectors B_i and B_j (B_i and B_j being nonadjacent, they will be called "distant" detectors). The simulation code showed that the probability for a cross talk between two distant detectors is 0.0263 of the probability for a cross talk between two neighbours, so that this distant cross talk effect can be neglected. In the experiment, the cross talk rate between two distant detectors was found to be only 4.9 times lower than the cross talk between A and a B_i. With the new hypothesis that the number of true coincidences is the same between distant detectors and between neighbours, the cross talk rate is lowered to the value $R_{ct} = 80\%$.

The $t_A - t_{B_i}$ spectra (fig. 5a) show clearly an enhancement near $t_A = t_{B_i}$. Those two peaks on the lower

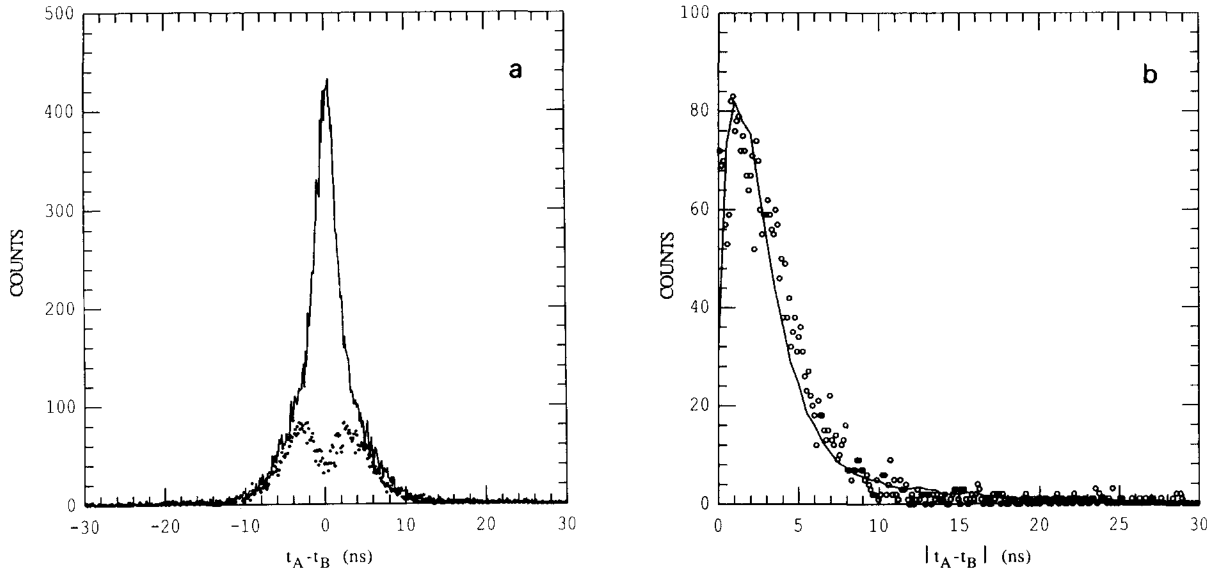

Fig. 5. (a) Time difference between detections in detector A and one of the B's, for neutron–neutron coincidence (dots) and neutron–neutron or neutron–gamma coincidences (full line curve). (b) Time difference between neutron detections for simulation data (full line curve) and experiment (circles).

spectrum (a neutron detected in A in coincidence with a neutron in a B_i) with the same amplitude are a signature for cross talk. The first peak corresponds to events in which the neutron first enters B_i and then induces a cross talk event with A, while the second one corresponds to the events in which the neutron first enters A. As most of these events are due to cross talk, the mean value $\langle | t_A - t_{B_i} | \rangle$ is equal to the mean time of flight of a cross talk neutron between two detectors. This result has been studied using the simulation code (see below). The upper spectrum corresponds to the events in which one neutron or one gamma is detected in A and at least in one of the B's. In the lower spectrum 94.7% of the counting rate is situated in the two cross talk peaks, that is in the region $| t_A - t_{B_i} | < 20$ ns whereas only 30% is located in the same region in the A/C correlation spectrum.

6. Energy dependence

A study was also made of the relation between the cross talk probability and the energy of the incoming neutron. The energy of the neutrons is deduced from their time of flight. The two primary energy spectra were constructed selecting the neutron clouds in the NE213 identification spectra of the detectors A and B's (fig. 2). The first energy spectrum includes all the neutrons detected in A, while the second one, includes only the neutrons in coincidence with a neutron in one of the B's (fig. 6). The ratio of this two spectra shows that there is a minimum energy below which the incoming neutrons cannot induce a cross talk event. This energy is about twice the detection threshold. Above this energy the cross talk ratio increases slowly towards a constant value. This effect has already been observed in a different geometrical setup by Husson [9,10] with a simulation code derived from that of Cecil et al. [7]. Husson proposed to consider the mean value of the flat

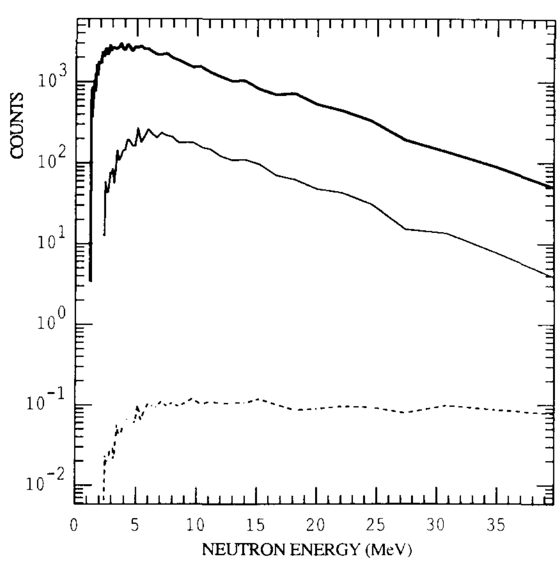

Fig. 6. Neutron energy spectra deduced from the time of flight of neutrons detected in A with no selection (bold curve), or by imposing a coincidence in one of the B's (full line curve). The dotted curve is the ratio of the upper two curves.

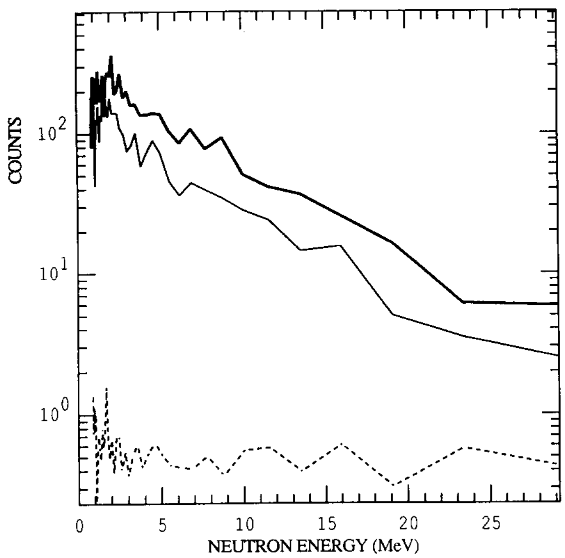

Fig. 7. Neutron energy spectra deduced from the time of flight, for neutrons detected in A (bold curve) and C (full line curve). The dotted curve is the ratio of the upper two curves.

plateau as a more significant probability P_n (here P_n = 9% which is of course higher than the value found by integration over the whole energy spectrum and subtraction of the number of true coincidences, P_n = 6.3%). Further evidence for absence of a strong influence of the energy of the incoming neutron on the cross talk rate can be seen on the ratio curve between the energy spectra of A and C (fig. 7). This ratio is constant over the whole energy range. This means that the energy spectrum of the neutrons detected in A after scattering from its neighbourhood is roughly the same as the spectrum of neutrons detected in A entering by its front surface.

7. Preliminary conclusions

Two consequences can be extracted from these two sets of spectra:

- There is no way to isolate true correlations by imposing conditions on the time of flight of the neutrons. The only (unrealistic) way would be to choose a high efficiency threshold and to select the neutrons with an energy inferior to twice this threshold. As there is no strong correlation between the kinetic energy of the incoming neutron and its light deposit in the NE213 scintillator, the amount of light deposited is not useful for discriminating between true and false coincidences.
- The influence of the cross talk neutrons on the energy spectrum of a given detector can be neglected.

8. The simulation code Menate

A simulation code has been constructed to calculate the efficiency, the diaphony and the cross talk in CsI + NE213 detectors. This code showed the need to take these effects into account in the experiment.

8.1. Physical data

The code makes use of, for the NE213 scintillators, much physical data used by Cecil et al. in their own code. Hence, where applicable, its results are in good agreement with those given in ref. [7]. Table 2 gives the list of reactions taken into account and the appropriate references (cross sections were assumed to be the same for cesium and iodide).

The code works recursively: the features of every neutron or gamma created by a reaction are saved in a stack. Therefore, all the neutrons and gammas are followed until they escape from the detector (in the case of an efficiency study) or the set of detectors (in the case of a cross talk/diaphony study). The light deposited by each charged particle (electrons, protons and alphas) is calculated as soon as those particles are created. It is assumed that the protons and alphas are absorbed by the interfaces between detectors, so that the true light deposit depends on the effective range [7].

The incident particles can be neutrons or gammas with an energy smaller than 100 MeV and the threshold (in MeV equivalent electron) is chosen by the user. The calculation time on a micro-VAX station 3400 for the efficiency of a 10 MeV neutron is about 0.01 s.

8.2. Geometrical features

The code was first written for the study of the AMPHORA front wall detectors, but the geometrical

Table 2
References for I, C and H cross sections included in the code Menate

Reaction	Q values	Cross sections
I(n,n′)		[5]
I(n,α)	[11]	[3,12]
I(n,p)	[11]	[3,12]
I(n,γ)	[11]	[12]
I(n,n)		[5]
I(n,2n)	[11]	[3,12]
C(n,2n)	[6]	[7]
C(n,n′)		[7]
C(n,α)	[11]	[7,8]
C(n,n′3α)	[6]	[7,8]
C(n,n)		[5]
C(n,np)	[6]	[8]
C(n,p)	[11]	[8]
H(n,np)		[7,8]

characteristics of the detectors can be modified by the user. Therefore the code is adapted to the study of other detector configurations. The fixed features are:
- the detectors are placed in a honeycomb frame,
- they are composed of NE213 and/or CsI cells,
- their section is hexagonal.

The degrees of freedom are:
- the entry surface of the detectors,
- the length of the CsI and NE213 parts (each one can be set to zero).

For cross talk and diaphony calculations,
- the number and localization of the detectors in the honeycomb frame,
- the choice of the detector hit by the incident neutron or gamma ray,
- the type of interface between detectors (permeable or not to gamma rays).

8.3. Simulation results

The simulation code cannot give any answer to question Q2 because of the lack of information about the neutron relative angle correlations. For this reason, we will focus on question Q1.

The input for the simulation consists of the geometrical features of the test experiment and a reasonable neutron spectrum (in fact the spectrum derived from the experimental time-of-flight). The code simulates an isotropic emission of neutrons incident on the front face of detector A, and computes the number of hits in one of the B's over the number of hits in A. This ratio is equal to the probability P_n defined above for the events with a neutron or a gamma detected in coincidence (cross talks). The simulation for one million incoming neutrons gives: $P_n = 10.2\%$. The fact that this value is a little higher than the one measured ($P_n = 8.5\%$) is explained by the assumptions (geometrical description of the detectors, "permeability" of the interfaces to the gamma rays $\cdots$) which where made and whose effect is to emphasize the cross talk and diaphony ratios. The mean efficiency over the energy range is found to be 21.6% (fig. 3a).

The code showed that events in which one neutron is detected in A and in more than one B_i are far from negligible: the ratio between the number of neutrons inducing simple cross talk (hits in A and one B_i) over the number of neutrons inducing higher order cross talk (hits in A and several B's) is only 2.4. On the other hand, the number of cross talk events between A and C (less than 0.002% of the incoming neutrons) can be neglected.

Fig. 3b shows the dependence of the simulated P_n probability on the energy of the incoming neutron. The upper and the lower curves correspond respectively to the entire detector (CsI + NE213, imposing that the neutron induces a reaction in the NE213 part) and to the NE213 cell alone.

As in the experiment, the time difference between the two detections in case of cross talk, has been studied with the simulation code. The curve obtained shows the same enhancement near $|t_A - t_{B_i}| = 0$. The simulation and the experiment give very similar values for the mean time difference between the two hits in the case of coincident detections. They are respectively 3.2 and 3.8 ns (fig. 5b). Some few simulated cross talk events are separated by a large time difference. In fact most of the light deposited, in this case, in the neighbouring detector, is due to gamma rays created by a I(n, γ) ($Q = 6.7971$ MeV) reaction induced by a very slow neutron rescattered from the NE213 cell and only a small amount by H(n, np) reactions. Therefore, the secondary hit should be seen as a gamma detection. However the clouds allowing the discrimination in the NE213 spectrum are not clearly separated at low energy. As there are not many observed experimental coincidences with a large time difference, it remains possible that an important part of them is due to this class of events. Thus, time discrimination would not be sufficient to isolate true coincidences from cross talk events.

9. Conclusion

The experiment as well as the simulation code have shown that cross talk and diaphony prevent AMPHORA and other such small granularity liquid scintillator multidetectors from measuring small relative angle correlations with neutrons. The existence of both phenomena will substantially modify certain measurements:

– In our experiment, more than four out of five coincidences between two neighbouring detectors are due to cross talk. Hence, a simple first step correction would be to retain one neutron each time a pair of neighbouring detectors is hit (or maybe six out of five pairs). However, this correction does not take into account either the diaphony effects or the false triple coincidences which were shown to be non-negligible by the simulation code.

– Most of the cross talk events occur in the first ring surrounding the first detector (the code showed that the probability to see cross talk with the first ring is 19 times higher than with the second ring, and more than a hundred times higher than with the third ring). Thus the small relative angle coincidence rate will be increased. We have shown that this effect cannot be corrected, firstly because the rate of true coincidences is too low, secondly because the comparison between the time of flight and the light deposit is not sufficient to separate these coincidences from cross talk events.

– The laboratory angular distribution will be smoothed mainly because of diaphony.

On the other hand, two observables do not seem to be modified: the neutron energy spectrum and the multiplicity spectrum: as only 6.3% of the detected neutrons are due to cross talk, the resulting enhancement of the multiplicity remains acceptable.

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