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NArCoS project for nuclear physics and applications

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Summary. — With the advent of new facilities for radioactive ion beams it is necessary to develop neutron detection systems integrated with charged-particle ones. The integration of the neutron signal, especially in the case of neutron-rich beams, becomes a mandatory requirement in order to study the property of the nuclear matter in extreme conditions. For this reason, new detectors using new materials have to be built. NArCoS (Neutron ARray for COrrelation Studies) is a project aimed at the design of a new detector featuring both good energy and angular resolution sensitive to neutrons and charged particles with the same detection cell. We present in this contribution new results on the estimation of the detection efficiency and of the cross-talk performed via GEANT4 simulations. In addition we compare through experimental measurements a module with the EJ276 green shifted scintillator coupled with a silicon photodiode with respect to one featuring an EJ276 (standard version) and a silicon photomultiplier.

1. – Introduction

The study of the dynamical evolution of a heavy-ion collision at Fermi energy is an active area of the state-of-the-art researches in both nuclear reaction and structure studies. One of the most important open problems is to probe the full time scale of the emission pattern (from 10–50 fm/c to several hundreds of fm/c) and the spatial configuration shapes of short mean life sources, including their mechanism of formation and decay, in determining the full reaction path. One of the most important issues in nuclear studies is to pin-down nuclear matter transport properties and reaction mechanisms by the experimental determination of quantities sensitive to the isospin degree of freedom and its influences on the evolutionary phase of a nuclear reaction at medium energies [1]. Among the most powerful experimental methods aimed at studying the reaction dynamics in the early stages of the collision, the two (and multi)-particle intensity interferometry (HBT effect) of neutrons and charged particles is an important technique. Many works, from both the experimental and the theoretical sides have been performed in the field of light charged particles (LCP), *e.g.*, for both like-particles correlations with p-p, d-d, etc., and un-like particles, d-t, d-alpha [2-4]. References [5, 6] report studies for correlations of heavier charged particles as intermediate mass fragments (IMFs) whose typical atomic number ranges $3 \leq Z \leq 25$. In contrast, few investigations have been performed by including uncharged particles in the main trigger and in particular for n-n, n-p, and n-IMF correlations. Studies with gamma-gamma correlations have been also explored, *e.g.*, for spectroscopy and reaction studies at medium and high energies. In the recent past, some measurements in almost 4π geometry have been performed with the TAPS [7] and MEDEA [8] arrays. In any of two (or multiple) particles HBT correlation studies, it is crucial to preserve good relative linear momentum resolution (in both intensity and detection angle) in order to extract sufficiently accurate experimental information (with respect to the typical characteristics of the nuclear matter, *e.g.*, typical sizes of 5–10 fm, Fermi motion at normal density, sound velocity in medium).

In brief in this work we will present a research proposal aimed at developing a first prototype multi-detector plastic-scintillator (16 detection modules = 64 elementary detection cells) devoted to the detection of neutrons in coincidence with LCPs and IMFs with both good angular and energy resolution and reasonable neutron efficiency. One candidate that is suggested for this purpose is an array of plastic scintillators EJ-276 (former EJ-299-33) [9, 10]. The proposed array will be used in conjunction with double-side silicon strip detectors, as position-sensitive charged-particles active veto, *e.g.*, identical to the ones largely tested and used in FARCOS [11-13] and used as ancillary detector, in coincidence with a 4π multiplicity filter for the typical physical cases at Fermi energy. The new array allows the implementation of an efficient pulse shape discrimination (PSD) on the basis of its high-quality timing response characteristics. Good angular resolution, timing and compact solid angle coverage are expected to be achieved by using an appropriate size of the single module and a compact geometry (mini-wall) for the fully assembly.

The combination of the resolution of the RF signal of the INFN LNS CS beam (<0.8 ns), or conversely, of an auxiliary detector like a micro-channel plate (<0.2 ns) able to non-destructively provide the start signal of the beam spot (of intensity lower than 10^6 cps) with the NArCoS plastic mini-wall timing resolution (<0.4 ns each module) of the NArCoS allows a resolution better than 1.2 ns in the time-of-flight (TOF) measurement.

The proposed prototype is expected to achieve a typical relative velocity resolution for coincidence pairs like n-n, less than 10 MeV/c on a TOF 150 cm long path, corresponding to a solid angle of 7 mSr coverage.

2. – The project

2·1. *Description.* – Our final goal is to build a modular and versatile multi-detector array (NArCoS) in order to identify at the same time neutrons and charged particles with both high angular and energy resolution. After some studies, a good candidate for a single elementary cell is a cube ($3 \times 3 \times 3\,\mathrm{cm}^3$ in dimension) of the plastic scintillator EJ276 (similar in structure to the previosus EJ299-33). A stack of four consecutively assembled cells forms a segmented cluster having dimension of $3 \times 3 \times 12\,\mathrm{cm}^3$. The active area and total thickness of the cluster have been fixed in order to match with the angular resolution required for correlation studies ($\approx 1°$) and a reasonable neutron efficiency at the Fermi energy, where the maximum of the proton kinetic energy is expected to be less than about 200 MeV.

Since the EJ276 scintillator is able to discriminate neutron (protons) against gamma rays and charged particles [9, 10] we plan to use a 300 μm of thick double-sided silicon strip detector (DSSSD) featuring an active area of $64 \times 64\,\mathrm{cm}^2$, with 32 vertical strips in the front side and 32 horizontal strips in the back side, acting as veto detector in order to distinguish primary neutrons against primary protons or other primary light charged particles. In a possible configurations, the DSSSD —at a distance of 75 cm from the target— geometrically fits with the full surface coverage of the entrance surface of the plastic scintillators wall (4×4 elementary modules in a window-like configuration featuring a total surface of $144\,\mathrm{cm}^2$, as is shown in fig. 1). In this geometrical configuration the prototype covers an opening angle of about 5° in the laboratory frame, corresponding to a solid angle of $\approx$7 mSr (0.05% of 4π) with angular resolutions of 0.15° for charged particles (detected using the DSSSD) and 1.125° for neutrons [14-16]. Estimations of the energy resolution for neutrons and light charged particles achievable with time-of-flight (TOF) measurements are shown in figs. 2 and 3. The predictions were obtained by considering a time resolution of $\Delta T = 0.5$ ns, and an indetermination of the interaction point of the neutron within the scintillator of 1.5 cm (the elementary interacting cell is a cube of $27\,\mathrm{cm}^3$). The four lines shown in fig. 2 represent the energy resolution obtained in the corresponding cell of one cluster of NArCoS. Figure 3 shows the predicted energy resolution for light charged particles that have enough energy to punch through the 300 μm of silicon detector.

The estimated neutron detection efficiency, based on the simulation software GEANT4 [17, 18] (using the QGSP BIC HP library for the interaction between neutron and the scintillator) shows a mean value $\approx$9% for one detection cell and $\approx$25% for one cluster (irradiated by a point-like source at reasonable energy threshold). Figure 4 shows the results of the simulations aimed at determining the neutron detection efficiency obtained for one elementary cell and fig. 5 shows the efficiency for one cluster, for

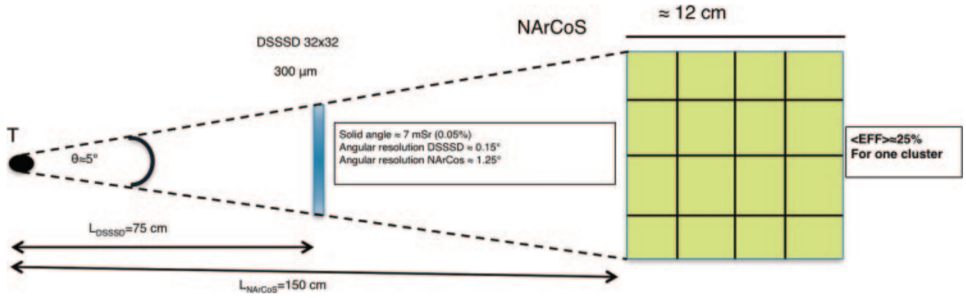

Fig. 1. – Schematic view of the NArCos prototype coupled with the DSSSD. Possible distances from the target positions are indicated [14-16].

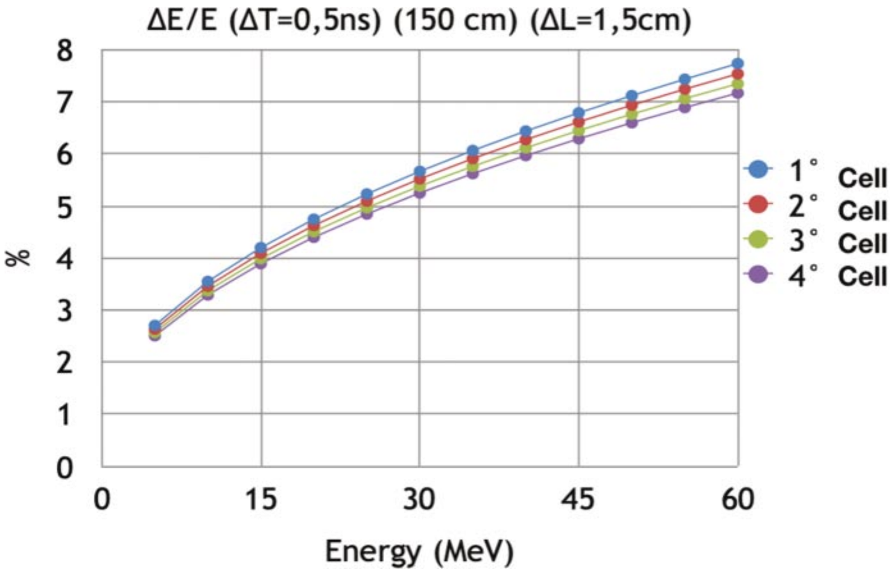

Fig. 2. – Predicted energy resolution for neutrons from the TOF technique. Each line represents one of the four elementary cells of a cluster (see text), the considered time resolution (500 ps) follows the assumption to use a fast detector as start of the TOF (*e.g.*, a MCP).

incident neutron energies ranging from 5 and 50 MeV (5 MeV steps) and by considering different energy threshold values. In previous studies [9, 10], we assumed that the most likely identification threshold value is 1.5 MeV (equivalent silicon energy deposition for charged particles).

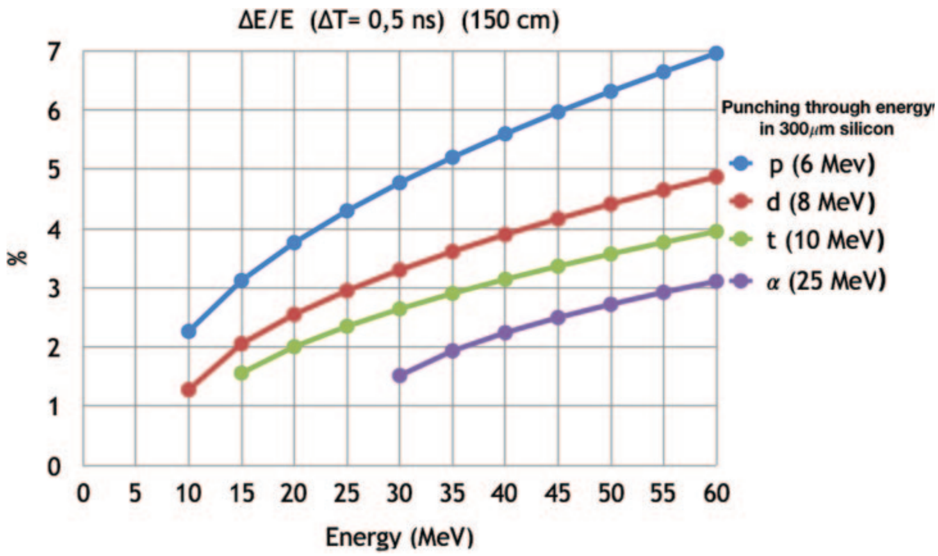

Fig. 3. – Predicted energy resolution for light charged particles from the TOF technique, the considered time resolution (500 ps) follows the assumption to use a fast detector as start of the TOF (*e.g.*, a MCP).

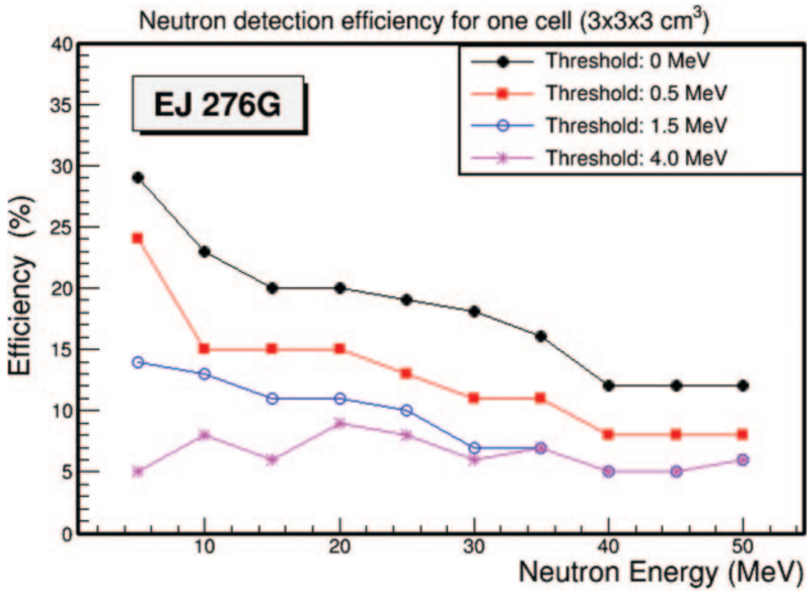

Fig. 4. – GEANT4 [17, 18] efficiency simulations for one elementary cell. The lines represent different considered threshold values [15, 16].

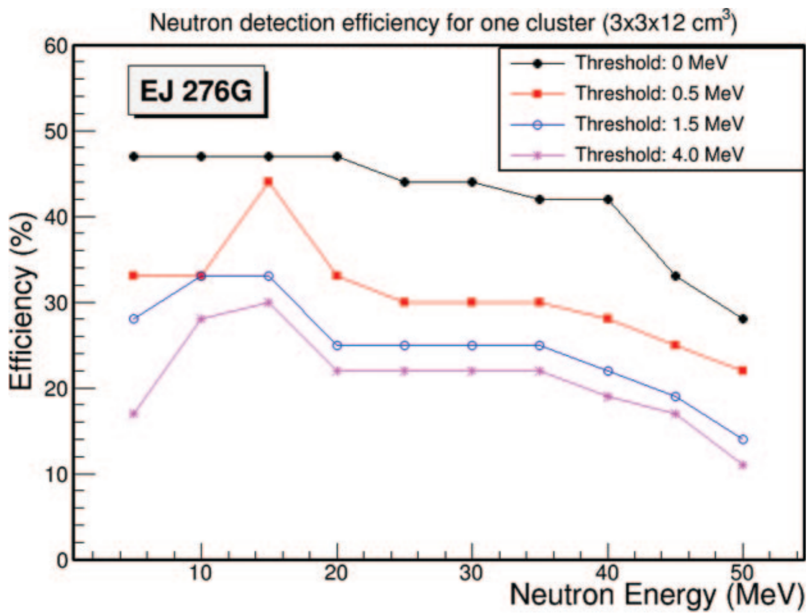

Fig. 5. – GEANT4 [17, 18] efficiency simulations for one cluster. The lines represent different considered threshold values [15, 16].

In order to have a very compact and segmented detector the light signal coming out from the plastic scintillator will be read-out by silicon technology under testing, silicon photodiode (Si-PD) or silicon photomultiplier (Si-PM) and it will be digitalized.

2·2. *The cross-talk problem.* – In coincidence measurements one of the biggest issues is represented by the cross-talk problem, which mimicks true coincidences. This problem could affect the measurement of more than one of the interested particles. In the specific case of a neutron correlator, made by many elementary detection cells, it may occur in different ways. For instance, a neutron can interact sequentially with two or more elementary cells. In a typical plastic material, one of the most probable interactions is the elastic scattering with a hydrogen nucleus, so that the so-called proton recoil, interacting with the plastic scintillator produces scintillation photons. There is a probability that the scattered neutron, continuing its path in another elementary cell, could interact with another hydrogen nucleus, so generating a second detectable proton recoil nucleus (by the n-p interaction). Of course, in order to be efficiently detected, the two recoiling protons (the first and the second one) must deposit enough energy to overcome the threshold value in order to produce sufficient scintillation light to be seen by the photon-electron transducer (*e.g.*, silicon photo-diode or Si-PM). It is clear that this kind of cross-talk can occur either in two adjacent or well spatially separated elementary cells. Another case of cross-talk can occur, for instance, when, after the first elastic scattering the recoil nucleus has enough energy to share its energy between two adjacent cells (punching through effect).

Figure 6 shows a preliminary study of the cross-talk probability for the case of only one cluster (four consecutively elementary cells) as computed by means of the GEANT4 code [16]. No pile-up due to the re-scattering by environments (see below) is considered. The red line represents the cross-talk probability for neutron from 5 MeV to 50 MeV (5 MeV steps). The detection threshold is assumed to be 1.5 MeV. This probability increases slowly from about 1% at 5 MeV up to 9% at 50 MeV. In the cross-talk probability all the possible cross-talk events simulated by the software are included. The blue line

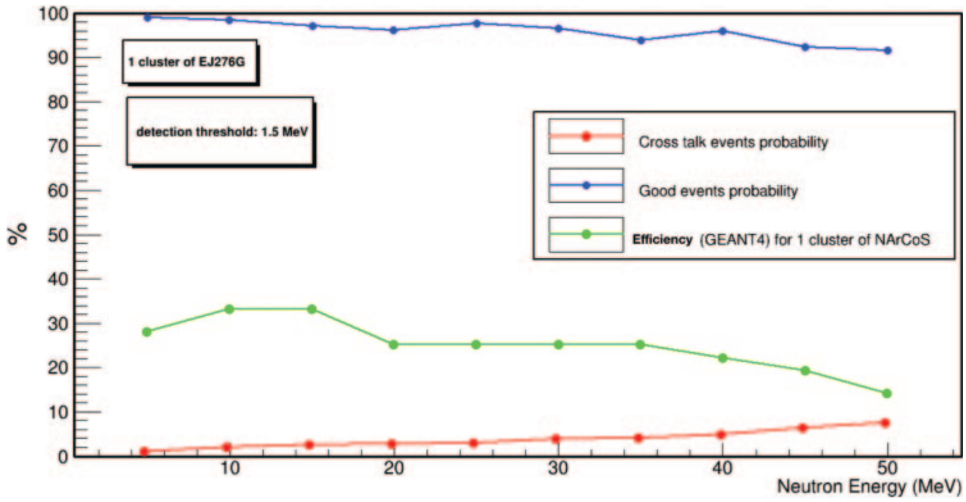

Fig. 6. – GEANT4 simulated cross-talk probability (red line), good events probability (blue line) and efficiency (green line) for detail see text.

is the complementary set, *i.e.*, the probability of good events. The two probabilities are calculated taking into account the detection efficiency in the plastic scintillator (green line). The next step will be to estimate the cross-talk probability extending the number of clusters up to the final configuration. The final and more difficult step is to try to disentangle between a good event and a bad event (cross-talk events plus pile-up). In the past, with a different detection system Colonna *et al.* [19] studied the influence of the cross-talk in a real coincident measurement and published a complex methodology to try to separate good events from bad events [19]. Another issue is represented to the background treatment and subtraction. The background is a different problem with respect to the intrinsic cross-talk because it is caused by neutrons that can be re-scattered from the environment (scattering chamber and/or other detector systems). In this case, the possible coincident event (within the resolving time of the coincidence system) is seen like a real neutron-neutron event coming from nuclear reactions induced by the beam projectile on the target nuclei.

2˙3. *Latest result.* – The latest, preliminary, results concern the test of the plastic readout by using silicon technology.

In particular during the CHIFAR experiment (see below) performed at Laboratori Nazionali del Sud (LNS) of INFN and carried out in 2019 (November) the EJ276G (green shifted version) was coupled with a Si-photodiode of $28 \times 28\,\mathrm{mm}^2$ produced by the Hamamatsu (S3584 series) while another EJ276 (the ordinary version) was coupled with a silicon photomultiplier equipped with its own readout electronic produced by CAEN (i-SPECTOR), both devices match the size of an elementary cell ($3 \times 3 \times 3\,\mathrm{cm}^3$). The overall experimental setup consisted of ten FARCOS [11-13] telescopes —used for the first time— coupled with the 4π detector array CHIMERA [20], in order to detect charged particles from the heavy-ion collisions in the reactions ^{124}Xe and ^{122,124}Sn on ^{64}Zn and on ^{58,64}Ni at the bombarding energy of 20 MeV/A. The aim of the experiment was to detect with the high angular resolution of FARCOS intermediate mass fragments (IMFs) in order to study other nuclear physics phenomena, like isospin drift and diffusion, nuclear fragmentation and dynamical projectile fission, already studied at the higher energy of 35 MeV/A [6, 21-25]. In the future, FARCOS and NArCoS detectors coupled with CHIMERA allow probing other nuclear physics phenomena (fusion and fission) at lower energies [26-28] and the nuclear structure exploiting also gamma detection [29-33].

Figures 7 and 8, represent very preliminary on-line data taken in the CHIFAR experiment. Figure 7 shows some results of EJ276G coupled with the silicon photodiode (Si-PD). In fig. 7 the used transducer was a SiPD able to transduce the scintillation light

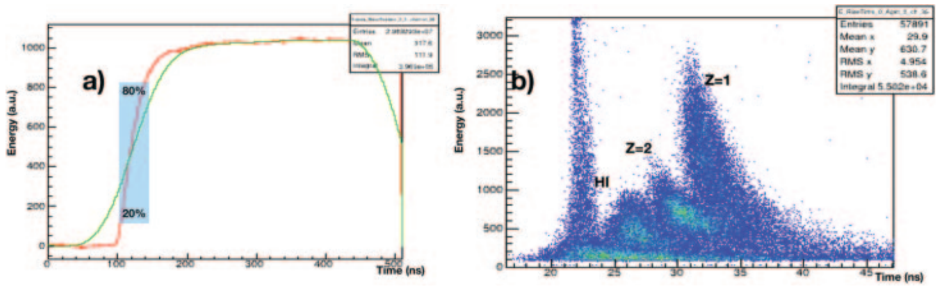

Fig. 7. – EJ276G coupled with a silicon photodiode. (a) Example of a digitalized signal with GET electronic [34]. (b) Plastic+SiPD PSD discrimination, total energy *vs.* signal rise time.

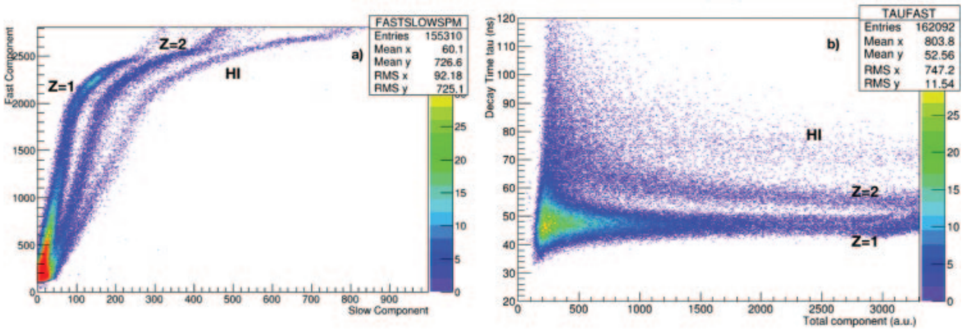

Fig. 8. – EJ276 coupled with a silicon photomultiplier (i-SPECTOR). (a) Fast *vs.* slow component 2D identification matrix. (b) Decay time *vs.* total energy (for more detail see [10]).

in an electric signal to test PSD capabilities. Figure 7(a) shows an example of a signal digitized by using the GET electronics [34] at 50 MHz sampling frequency. Figure 7(b) shows the PSD 2D identification matrix energy *vs.* rise time (20%–80%). Figure 8 shows the same results in the case of the EJ276 (standard version) coupled with a silicon photomultiplier (Si-PM) powered at 40V (i-SPECTOR).

Figure 8(a) shows the usual two-dimensional fast component as a function of the slow component of the digitized signal (see fig. 7(a)) produced in the plastic scintillator, where it is possible to observe three well-separated clusters related to $Z = 1$, $Z = 2$ and heavy ions. A clear saturation of the signal due to high amplification of the Si-PM that, unfortunately, was not possible to reduce, is also present in fig. 8(a). Figure 8(b) shows the 2D identification matrix obtained with a novel identification technique, as was discussed in ref. [9], where the decay time of the digitized signal is analyzed as a function of the total amplitude of the particle signal produced in the scintillator.

3. – Conclusion and perspectives

In conclusion, in this paper we briefly described the first step project aimed at building a neutron correlator able to simultaneously detect both neutrons and charged particles. The results carried out so far for the EJ276 plastic scintillator coupled with PM are encouraging [9, 10]. It seems now possible to build a versatile and modular detector for neutrons and light charged particles with high angular and energy resolution, read-out by using silicon technology and signal digitization. The background and the correlation yields due to cross-talk and their influence on the experimental results are going on using the GEANT4 software. The first studies and results on the EJ-276G (green shifted version) coupled with Si-PD and on the EJ-276 coupled with Si-PMs (CAEN i-SPECTOR), including PSD capability, encourage to continue the test inspecting their timing properties, energy resolution, PSD capabilities and neutron efficiency. We also plan as soon as possible to start tests and measurements with more than a single cell or some clusters in order to experimentally study the cross-talk problem and its influence in a coincidence-real experiment.

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