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NARCOS: A new correlator for neutrons and charged particles

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Summary. — The simultaneous neutron and charged particles detection in heavy-ion collisions is mandatory in the investigation of reaction mechanisms and in the study of the spectroscopy of nuclear states, characterized by neutron emission. The NarCoS (Neutron Array for Correlation Studies) array is a compact, modular, segmented transportable apparatus, consisting of EJ276G plastic scintillators, with excellent neutron detection capabilities and that combine the relevant neutron detection efficiency to high angular and energy resolution. It consists of an array of elementary detection cells of scintillators, optically coupled with a SiPM (Silicon PhotoMultiplier), to be arranged in various geometries, according to the case. The scintillating elementary cell has a dimension of $3\,\mathrm{cm}\times 3\,\mathrm{cm}\times 3\,\mathrm{cm}$. The construction and the development of such apparatus are realized in the framework of the Italian PRIN2020 ANCHISE project (Array for Neutron and Charged particles with HIgh linear momentum SElection). This contribution presents test results conducted with various types of sources and those relative to the preliminary analysis of the data obtained from the CROSSTEST experiment performed at the Laboratori Nazionali di Legnaro, to investigate the discrimination capabilities of the array.

1. – Introduction

The development of new facilities for producing Radioactive Ion Beams (RIBs) offers significant advancements in nuclear research, allowing the exploration of nuclear matter far from the stability valley, and to extend isospin studies to systems with a large difference in N/Z ratio. Specifically, experiments performed by using neutron rich beams emphasize the importance of developing a detector that can accurately identify both charged particles and neutrons, with excellent energy and angular precision [1, 2]. Such a device is crucial for in-depth studies of nuclear reactions and can be also applied in different uses in areas like medical diagnostics and radiation protection. By enabling precise measurements of particle properties, this technology will enhance our understanding of nuclear forces, reaction dynamics, and the synthesis of heavy elements in the universe. Different physics cases can be studied as for example the equation of state, nuclear reaction mechanisms [3-5] and clustering and molecular states [6]. In the study of the molecular states, structures in which valence neutrons give rise to covalent molecular binding effects, the correlations among neutrons and the other decay partners are used for the reconstruction of the level of parent nucleus, thus high-energy resolution capabilities are necessary. In order to investigate if the energy resolution obtained with NarCoS is high enough to discriminate the level of interest, the Heavy Ion Laboratory of Warsaw approved the study of the state at 6.86 MeV of ^{13}C.

In general, correlations between different reaction products are essential for the complete event reconstruction, making high energy resolution and particle discrimination the key for the detection system. This work presents the investigation into the capabilities of NArCoS in distinguishing neutrons from γ rays, as well as its timing performances.

2. – Description of NArCoS

NArCoS is currently under development in Catania and a part of it is realized in the ANCHISE (Array for Neutron and Charged particles with HIgh linear momentum SElection) project, which has been approved and funded by the Italian national PRIN2020 funding call. The project aims to create a compact, segmented, and transportable apparatus, composed of plastic scintillator detectors. Each detection cell in the array is a 3 cm-sided cube, with EJ276 (formerly EJ299-33) plastic scintillators, that are the best candidates for the detection material. Two versions of EJ276, the "white type" and the "green type," were evaluated for their performance in neutron detection and particle discrimination. Extensive investigations [1, 7-9] revealed that the green type material offers superior particle discrimination capabilities, while, as will be seen later in this work, the timing performance of both materials is comparable. Based on these findings, the green type, probably, will be selected for use in NArCoS. Each individual cell light signal is read out by an array of 25 silicon photomultipliers (SiPMs), providing high sensitivity and resolution. The full design of the prototype of NArCoS includes 64 detection cells, arranged into four matrices of 4×4 cubes. At present, the prototype of the electronic board houses just 9 elementary cells (fig. 1)and it integrates the SiPM readout boards, signal output channels, test inputs, temperature monitoring, and bias voltage input.

In NArCoS, the energy of detected neutrons is measured using the time-of-flight (ToF) technique. This method relies on the precise measurement of the time it takes for particles to travel from the point of interaction to the detector. The ToF is measured using either the radio-frequency signal of the cyclotron or a microchannel plate (MCP), particularly useful for low-intensity exotic beams, or by using kinematic coincidence techniques. This

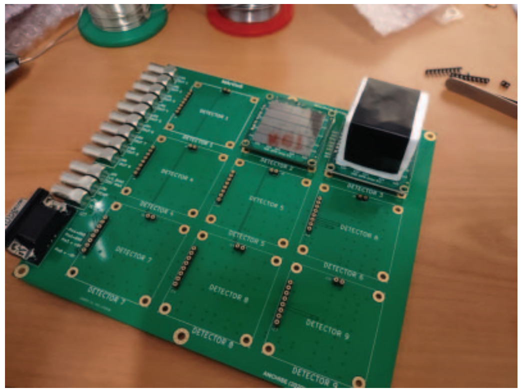


Fig. 1. – Prototype of the electronic board which integrates the SiPM readout boards, signal output channels, test inputs, temperature monitoring, and bias voltage input.

approach allows for precise energy measurements, which is fundamental for reaction dynamics or nuclear structure studies.

A balance between angular resolution and efficiency is crucial for obtaining accurate measurements in heavy-ion collision experiments. The surface area and total thickness of the NArCoS detector clusters have been designed to achieve the angular resolution required for correlation studies, aiming to get an angular precision of about 1°. At the same time, this setup ensures adequate neutron detection efficiency, in fact simulations performed by using the GEANT4 software estimate a neutron detection efficiency of around 9% for a single detection cell, while an entire cluster, irradiated by a point-like source reaches an efficiency of approximately 25% [10, 11].

3. – Discrimination capabilities

The NArCoS detector exhibits excellent discrimination capabilities, as demonstrated through various analysis conducted by using both beams and radioactive sources. These investigations aimed to evaluate the detector's ability to effectively distinguish between charged particles and γ rays. The results confirmed that the detector can reliably differentiate between these types of radiation, which is essential for accurate particle identification in nuclear reaction studies, for details look at refs. [7-9]. In this work, the results of the analysis of the detector's ability to discriminate between neutrons and γ rays are presented. The data were gathered during the CROSS-TEST experiment, where a 4.5 MeV proton beam, delivered by the CN facility at INFN-LNL, produced the neutron beam through interactions with LiF, with the energy ranging from 0 to 4.5 MeV and peaked around 3 MeV. The primary goal of the CROSS-TEST experiment was to investigate cross-talk effects between neighbouring detection cells, a dedicated paper is currently being prepared to present the findings relative to the cross-talk studies in detail.

Different variables were used for particle identification by constructing two-dimensional matrices, where each particle type populates a specific region of the plot. These variables were derived by integrating different time windows of the digitized signal, as shown in fig. 2. In addition to these time windows, other key variables include:

- Tau: defined as the slope of the exponential fit on the fall time of the logic signal.
- Tot: calculated by summing the Fast and Slow components.

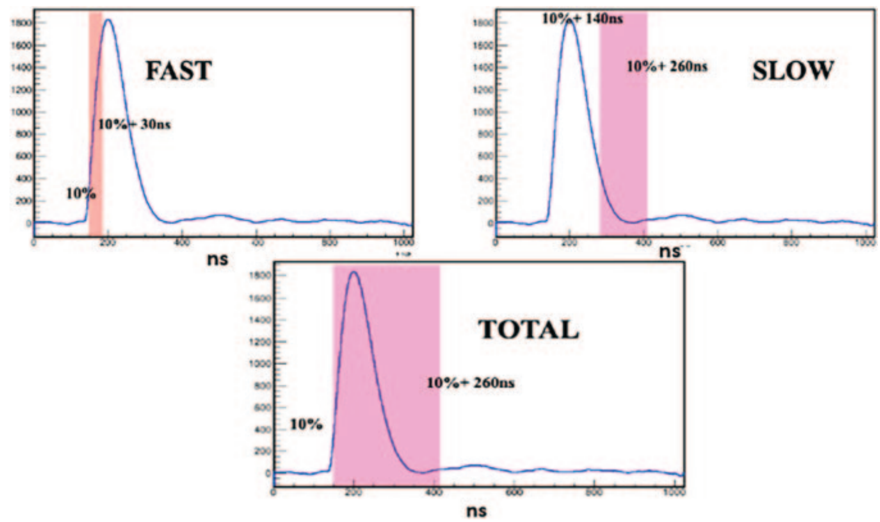


Fig. 2. – Variables used for particle identification, obtained by integrating different time windows of the digitized signal.

- PidTot: the ratio of Tot to Slow.
- PidTotal: the ratio of Total to Slow.

Figure 3 illustrates the pulse shape analysis achieved using different variables for one plastic detector of green type material. The different bidimensional matrices clearly demonstrate the high quality of discrimination between neutrons and γ rays, regardless of the selected variables. The separation between the two particle types is distinct, showcasing the effectiveness of the chosen variables. To quantify the discrimination performance of the detector, a figure of merit (FoM) was calculated, defined as the distance between the two peaks divided by the sum of the Full Width at Half Maximum (FWHM) of each peak, across different energy ranges. Specifically, the FoM was determined by dividing the energy range $0 < E < 1200\,\mathrm{keV}$ into $200\,\mathrm{keV}$ intervals and analysing the projections of the two-dimensional Tau *vs.* Total matrix onto the Tau (Y-axis). Figure 4 illustrates the FoM values obtained for each of the energy intervals: (0, 200); (200, 400); (400, 600); (600, 800); (800, 1000); and (1000, 1200) keVee. The Figure of Merit (FoM) was determined by following a specific calculation procedure. First, each peak within the relevant energy range was fitted separately using a Gaussian function. This resulted in six parameters, which were then used as inputs for a new fit of the entire spectrum. The fitting function for the full spectrum was a sum of two Gaussians, each representing one of the two particle types (indicated by the red line in the plot of fig. 4). The FoM value is shown in each panel of the figure. Good separation is seen from 600 keVee and higher, where the FoM is ≥ 1.

4. – Timing performance

Achieving high time resolution in NArCoS detector system needs to accurately measure particle energies. Studies focusing on evaluating the global time resolution of the plastic scintillator detectors were performed by analysing cosmic ray signals passing

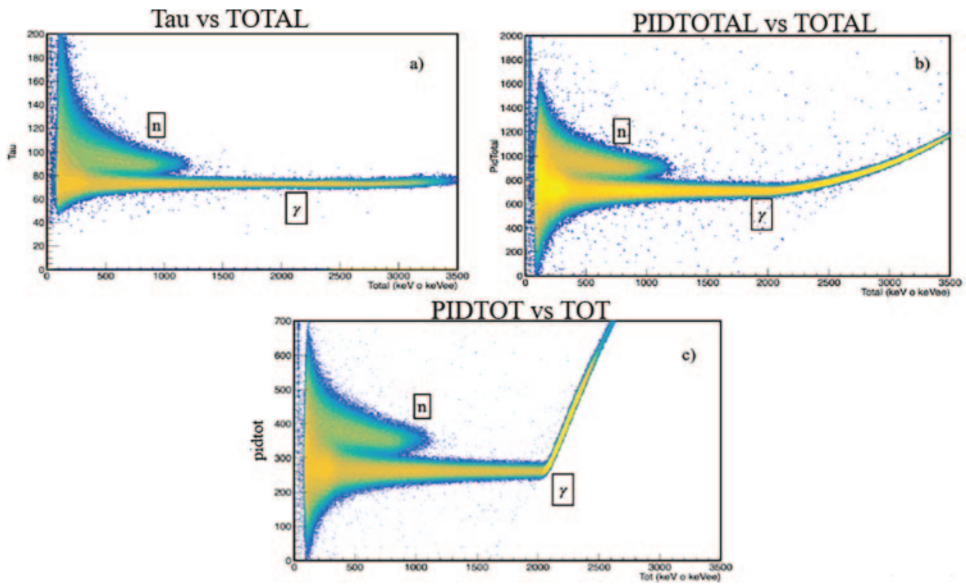


Fig. 3. – Pulse shape discrimination by using different variables, for one of the cells.

through pairs of contiguous detectors. In particular, time resolution is determined by the standard deviation of a Gaussian fit applied to the difference spectrum in time of the cosmic ray between two selected pairs of detectors. The time signal is defined as the time when the pulse signal reaches 10% of its maximum, in this work the preliminary results on the investigation of the time resolution of the two types of scintillating materials,

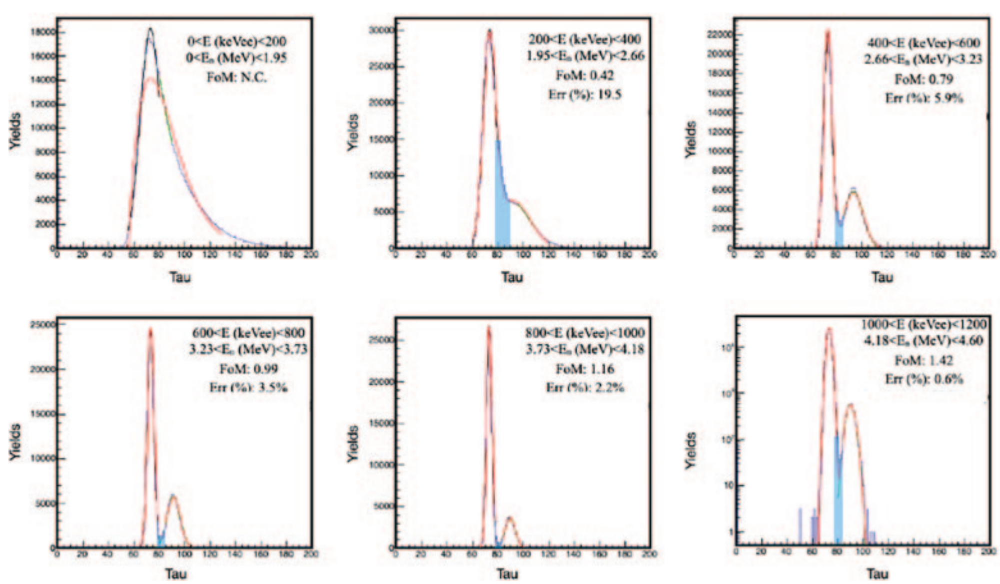
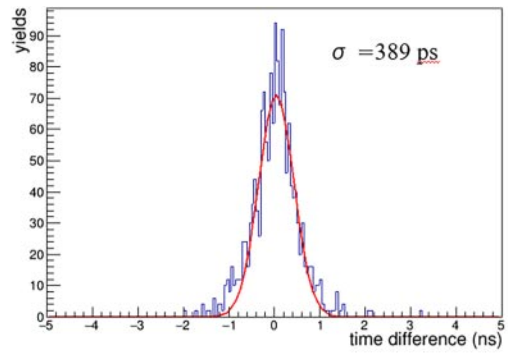


Fig. 4. – Figure of Merit values obtained for each of 200 KeVee energy intervals.



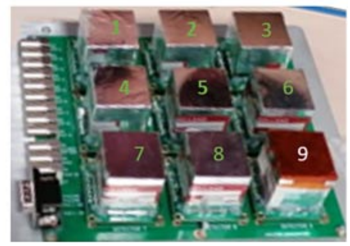


Fig. 5. – Left: difference time spectrum fitted with a Gaussian function (red line) for a pair of green type detectors; Right: the test setup with the first eight positions on the detection board occupied by EJ-276 Green Type detectors, while position nine housed an EJ-276 White Type detector.

EJ-276 Green Type and EJ-276 White Type, are presented to also assess any potential differences in their performance. For the test configuration, as shown in the right panel of fig. 5, where each position is labelled with a number, the first eight positions on the detection board were occupied by EJ-276 Green Type detectors, while the position nine housed an EJ-276 White Type detector. The analysis is focused on two detector pairs: detectors in positions 6 and 9 (Green and White types) and positions 3 and 6 (both Green Type). The condition of multiplicity equal to two was applied, ensuring that only cosmic rays punching through two contiguous detectors were considered. Additionally, energy thresholds of $E_1 > 3\,\mathrm{MeV}$ $E_2 > 3\,\mathrm{MeV}$ were set to filter out low-energy cosmic rays, allowing only high-energy events to be analysed (E_1 and E_2 are the energy released into the two detectors). The pair of cubes, selected for the analysis relative to the green type, comprising detectors 3 and 6 was chosen as detector 6 was also used to evaluate the performance of the EJ-276 White Type material. Despite the differing scintillator materials, no appreciable differences in time resolution were observed between the EJ-276 Green Type and EJ-276 White Type detectors, in fact in both cases a standard deviation $\sigma \simeq 385$ ps was obtained, by fitting the time difference spectrum with a Gaussian curve (red line), as shown in the left side of fig. 5 for the EJ-276 Green Type.

5. – Conclusions

Neutron detection plays a critical role in experiments involving neutron-rich nuclei, especially in heavy-ion collisions, where complete event reconstruction is essential. This work focused on evaluating the discrimination capabilities and timing performance of the newly developed NArCoS correlator. The modular, compact design of NArCoS, based on EJ276 plastic scintillators, demonstrated excellent capabilities in distinguishing neutrons from γ rays and delivering high time resolution. The comparison between two scintillating materials, EJ-276 Green Type and EJ-276, showed no significant difference in their performance, with both yielding a time resolution standard deviation of approximately 385 ps. Additionally, the calculated figure of merit (FoM) confirmed the detector's strong particle separation capabilities. These features make NArCoS a valuable tool for advancing the study of nuclear reactions and spectroscopy, where precise energy resolution and accurate particle identification are essential for understanding reaction mechanisms and nuclear structure.

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