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NArCoS: The new hodoscope for neutrons and charged particles

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Proper detection of neutrons and charged particles is motivated by the recent efforts to construct new facilities for radioactive ion beams (RIBs) worldwide. Detection of neutrons is an important opportunity to improve our understanding of nuclear spectroscopy and reaction dynamics, with the possibility of constraining theoretical models of the nuclear equation of state (NEoS) and investigating in-medium nuclear interactions. This topic also has important implications in the study of astrophysical objects, such as neutron stars. In this work, the state-of-the-art of Neutron Array for Correlation Studies (NArCoS), a new hodoscope for neutron and charged particles under construction in Catania (INFN), is briefly reviewed.

KEYWORDS

neutron detector, correlations, plastic scintillator, charged particle detector, SiPM

1 Introduction

The study of the dynamical evolution of a nuclear reaction and the spectroscopy of exotic unbound states at Fermi energies (10 AMeV < E/A < 100 AMeV) is a very active area in nuclear physics. In particular, thanks to the new facilities for radioactive ion beams (RIBs) that will be available in the future, it will be possible to reach large isospin asymmetry (beam) never obtained until now. Particle–particle correlations are a relevant technique to pin down this kind of information [1–6]. By using light-charged particle (LCP) correlations, many works have been conducted from theoretical and experimental perspectives in nuclear dynamics and nuclear structure studies with correlators of first [7, 8] and second generations, such as FARCOS [9–14]. Such correlation studies have also been explored for heavier charged particles, such as the intermediate mass fragments (IMFs), with an atomic number in the range $3 \le Z \le 25$ [2, 15], abundantly produced in heavy ion reactions.

Correlation techniques have been employed in the field of gamma-particle coincident emission for spectroscopy and reaction studies [16, 17]. In contrast, few investigations have been performed, including neutrons, particularly n-n, n-p, and n-IMF correlations [15, 18, 19]. In two- (or multiple-) particle correlation studies, it is crucial to preserve a good resolution of the relative linear momentum (in both intensity and detection angle) to extract experimental results as accurately as possible [20–22]. Following the large efforts of the community in the construction of new facilities for RIBs as FRAISE at INFN-LNS [23–25], the simultaneous detection of neutron and charged particles acquires new relevance.

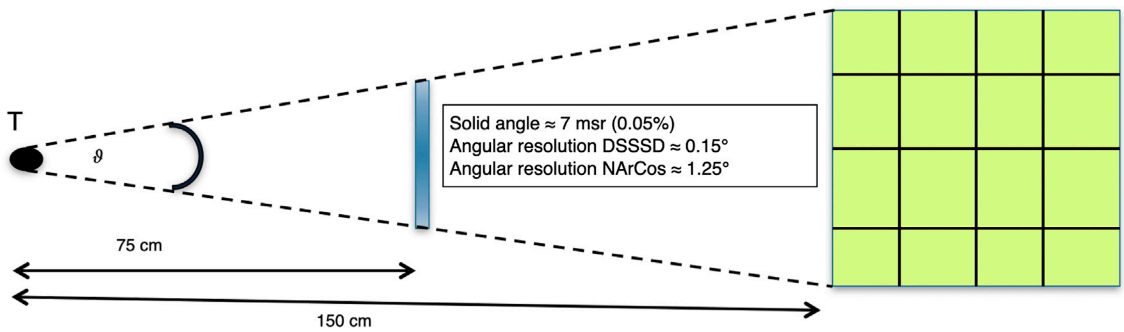

FIGURE 1
Schematic view of the setup of the prototype DSSSD + NArCoS in the final configuration; some distances from the target are also specified. *T* is the target position, and ϑ represents the angular coverage of the detector system in the laboratory frame (about 5°) [20–22, 31].

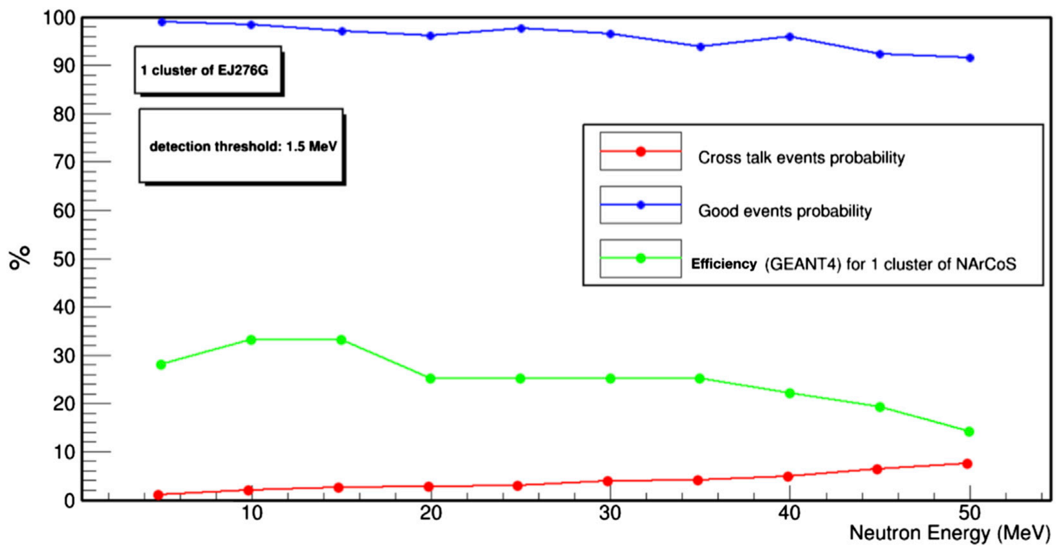

FIGURE 2
GEANT4 simulated cross-talk probability (red line), good events probability (blue line), and efficiency (green line). The detection threshold is 1.5 MeV. For details, see text and [20, 32].

2 The project

Starting from the design of a prototype, as described below, and after its full qualification and the demonstration of feasibility, the final goal is to build a neutron and LCP hodoscope with high angular (approximately 1° for neutrons and 0.1 for LCP), energy resolution (<10% for neutrons and approximately 1% for LCP), high granularity, and reasonable neutron detection efficiency (larger than 50%). We plan to use this new device mainly in the Fermi energy domain, where a transition in the reaction mechanisms has been observed [2]. After the testing and simulation phase, mainly done during a master's degree at the Università di Catania and INFN-LNS [26, 27], the accepted idea is the construction of an array of EJ276G scintillators [28] as the basic elementary cubic cell of 3 cm in size. This elementary cell can discriminate neutrons/protons from gammas and other LCPs using the pulse shape analysis (PSA) [29, 30]. In order to have a good compromise between granularity, angular resolution, and neutron detection efficiency, four elementary cells will be arranged in line, one behind the other (with respect to the particle trajectory) to obtain a cluster. The single cluster will have a dimension of $3 \times 3 \times 12$ cm^3. The efficiency mean value is around 25% for a neutron energy range of 5–50 MeV. If the Neutron Array for Correlation Studies (NArCos) prototype is placed at a distance of 150 cm from the target, the expected neutron angular resolution is on the order of 1° in the laboratory frame. Additionally, the expected energy resolution, measured with the time of flight (ToF), is of the order of 3%–8%, depending on neutron energy (considered as 5–50 MeV) and assuming a time resolution of 500 ps. Each elementary cell is independently read using a silicon photomultiplier (SiPM) with the electronic readout mounted directly on the back of each scintillator. The final analog signal is digitalized by the front-end electronics and the data acquisition system (DAQ). The final prototype will consist of 16 clusters (64 elementary cells) arranged in a cubic geometry with a dimension of approximately $12 \times 12 \times 12$ cm^3. It will be modular such that the mechanical and electronic configurations can be changed. The proposed device will work in air or under vacuum, in a stand-alone configuration or coupled with other detection systems, characterizing the collision pattern (the centrality of the collision), for example, the CHIMERA detector [2] at INFN-LNS in Catania. As neutrons are seen as protons from the plastic scintillator (proton-recoil technique), a veto detector is planned to be placed between the target and NArCoS to disentangle a primary proton from a neutron. The veto detector will be a double-sided silicon strip detector (DSSSD) of 300 µm thickness with an active strip area of $2 \times 64\ mm^2$ like the ones already exploited in the FARCOS correlator [9, 10, 27]. The DSSSD will improve the angular resolution to approximately 0.1° for charged particles. The energy measurement, identification of charged particles, and calibration procedures will benefit from the high energy resolution of the silicon detector. More details can be found in the literature [20–22, 27, 31]. Figure 1 shows a schematic view of the setup of the prototype DSSSD + NArCoS in the final configuration. One of the most important issues to be considered in a coincidence measurement is the cross-talk problem, which can be critical in the case of neutron detection. In fact, for a hodoscope based on elementary cells, the cross-talk may occur in many ways: the most typical case is when two or more elementary plastic cells detect a particle, even if only one neutron is reaching the detector.

This problem has an analogy with background determination and subtraction, and we plan to study it in depth, as in the case of cross-talk. At the state of the art, these problems are studied by the GEANT 4 simulation toolkit [32, 33]. As shown in Figure 2, in the case of only one cluster, the cross-talk probability goes from 1% for neutrons of 5 MeV–9% at 50 MeV (red line); instead, the good event probability (blue line) is the difference between the total and the cross-talk one. The expected neutron detection efficiency (green line) as a function of the neutron energy is also shown in Figure 2. Of course, this study needs to be extended for all prototype configurations by performing specific simulations and comparing results with experimental data.

3 Conclusion and perspectives

In conclusion, this study briefly presented the state of the art on the construction of a new correlator for neutron and charged particles. The results revealed so far by exploring the PSA capabilities of the EJ276G scintillator coupled to SiPM are encouraging, with a figure of merit (FoM) of 1.47 in the gamma from alpha particle separation [26, 27]. It is possible to build a modular and versatile detector array that can detect at the same time neutrons and charged particles with high angular and energy resolution and with reasonable neutron detection efficiency. The study will continue with simulations devoted to simulating the complete prototype setup and experiments on the beam. For example, one experiment/test (CROSS-TEST) will be performed at the beginning of 2023 at the INFN, Laboratori Nazionali di Legnaro. The project received a new impulse in terms of workforce and economical support thanks to the PRIN2021 ANCHISE (contract 2020H8YFRE), which will provide new studies for the next three years (2022–2024), focusing on a dedicated readout digital electronic and the best mechanical configuration. A detailed study on the cross-talk and background determination in simulations and experimental tests is planned. Thanks to this innovative detector, new and more precise experimental data will be available using stable and RIBs to improve our understanding of the in-medium nuclear interaction, equation of state of nuclear matter, nuclear dynamics, and spectroscopy of exotic unbound states produced in a nuclear reaction.

Author contributions

EP: writing the paper and fundamental contribution to data collection and data analysis. ED and PR: paper review and important contribution to data collection and data analysis. All the other coauthors: paper review and contribution to data collection and data analysis.

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Conflict of interest

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