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The NArCoS project

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Summary. — With the advent of new facilities for radioactive ion beams, in particular for the neutron-rich ones with respect to the stable beams, it is necessary to develop neutron detection systems integrated with the charged-particle ones. The integration of the neutron signal, in experiments with neutron-rich beams, is an important improvement in order to study the property of the nuclear matter in extreme conditions. For this reason detectors using new materials have to be build. This contribution describes the NArCoS (Neutron Array for Correlation Studies) project having the purpose to built a new detector for neutrons and light charged particles. In particular it discusses the first tests, efficiency and resolution estimations will be presented.

1. – Introduction

The study of the dynamical evolution of a heavy-ion collision at Fermi energy is an active area of the present-day nuclear researches. One of the most important issues 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 shape of short mean life sources, including their mechanism formation and decay in determining the full reaction path. Among the most powerful experimental methods, the two (and multi)-particle intensity interferometry (HBT-Effect) of neutrons and charged particles is an important technique to reach those purposes. Many works, both from the experimental and theoretical sides have been done in the field of light charged particles (LCP), *e.g.*, for both like-particles correlations [1, 2] with p-p, d-d, etc. and unlike-particles, d-t, d-alpha, etc., systems. Also, some works [3,4] using heavier charged particles of intermediate-mass fragments (IMF typical values of atomic number in the range: $3 \leq Z \leq 25$) have been accomplished. 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. Gamma-gamma correlations have been also explored, *e.g.*, for spectroscopy and reaction studies at medium and high energies, but these studies deserve specific treatment and they are out of the present investigations. In the recent past, some measurements in almost 4π geometry have been performed with the TAPS [5] and MEDEA [6]). 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 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 that aims at developing a first prototype multi-detector plastic-scintillator (16 detection modules = 64 detection cells) devoted to detect neutrons in coincidence with LCP and IMFs with both good angular and energy resolution and reasonable efficiency. One candidate that is suggested for this purpose is an array of plastic scintillators EJ-276 (ex-EJ-299-33) [7, 8]. 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 [9] and used as ancillary detector, in coincidence with a 4π multiplicity filter for typical physical cases at Fermi energy. The new array allows for 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 assembling. A time of flight (TOF) measurement less than <1.2 ns global resolution will be guaranteed by the signal of the pulsed CS beam (<0.8 ns) as reference or alternatively, by an auxiliary detector like a MCP (micro channel plate device, <0.2 ns) able to measure the beam time spot (of intensity less than 10^6 cps) in a non-destructive way, coupled with the plastic mini-wall timing pulse characteristics (≤0.4 ns each module) of the NArCoS. The proposed prototype is expected to achieve a typical relative momentum resolution for coincidence pairs like n-n, less than 10 MeV/c on a TOF base line of 150 cm long, corresponding to a solid angle of 10 msr coverage.

2. – The project

Our project is to build a modular and versatile detector able to detect at the same time neutrons and charged particles with both high angular and energy resolution. The envisaged elementary-cell candidate for this project is a cube of 3 cm in dimension of a plastic scintillator material EJ276 (ex EJ299-33). Four cell cubes are consecutively assembled together in order to obtain an elementary segmented cluster having dimension of $3 \times 3 \times 12\,\text{cm}^3$. The estimation neutron detection efficiency, based on MC code, of one cluster is larger than >12% for neutron having energy between 1 MeV to 100 MeV. Our proposed prototype will be composed of 16 of these clusters (64 elementary cells) and it will achieve the dimension of $12 \times 12 \times 12\,\text{cm}^3$. Since the EJ276 plastic scintillator is not able to discriminate primary neutron against protons, but it is able to discriminate, γ and charged particles (see next chapter) [8] we plan to use a Double Sided Silicon Strip Detector (DSSSD) as veto detector in order to distinguish primary neutrons with respect

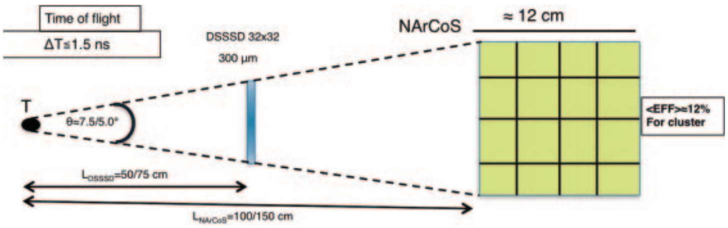

Fig. 1. – Schematic view of the NarCos prototype coupled with the DSSSD. Possible distances from the target positions are indicated.

to primary protons or other light charged particles. The DSSSD will geometrically match the wall of the plastic scintillators, positioned behind it, as is shown in fig. 1. We plan to use NArCoS at a typical distance of 100 cm far from the target or at the larger distance of 150 cm. In the first case it will cover an opening angle of 7.5°, corresponding to a solid angle of 14 msr ($\approx 0.11\%$ of 4π) with angular resolutions of 0.2° (detected using the DSSSD) for charged particles and 2° for neutrons. An estimation of the energy resolution for neutrons as predicted by TOF measurements is shown in fig. 2. In the second case it will cover 5°, with a solid angle of 7msr ($\approx 0.06\%$ of 4π) and angular resolutions of 0.15° for charged particles and 1.25° for neutrons.

The light signal coming out from the plastic scintillator will be readout by silicon technology under testing (Si-PD or Si-PM) and digitalized. Although yet in its prototype phase, the device fulfills the scientific requirements of different topics in a wide range from fundamental physic to applied one. For instance, having a so good angular resolution for both neutrons and charged particles, it will be possible to perform high-quality intensity interferometry studies (HBT-effect) between neutrons and charged light particles (*e.g.*, n-n, n-p correlation functions), so recovering the relatively poor investigations known by the literature till now, or it will be possible to further improve the correlation functions studies involving neutrons and massive particles, such as nuclear clusters, that, to our knowledge, had not been yet explored in the literature. These studies are very important

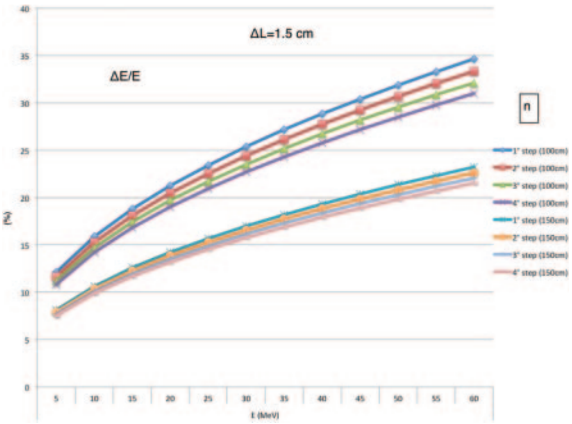

Fig. 2. – Estimation of energy resolution for neutrons as a function of neutron energy for two possibile distances and for the relative 4 steps alternatives of neutron interaction.

for the careful determination of the equation of state of asymmetric nuclear matter (ASYEOS) as a function of the baryonic density, that is a crucial ingredient in the nuclear astrophysics and the evolution of neutron stars. Evidently, apart for fundamental applications, our device is also useful for neutrons cross section, differential cross section and double differential cross secretion measurements, that, in particular for the energy domain of the present project, are crucial in order to test MC based code like GEANT4 or MCNPX [10]. Furthermore, its characteristic of modularity, transportability and good neutron efficiency, allow for different applications in beam radio protection diagnostic and medical treatments.

3. – Experimental results on EJ299-33

One elementary cell of the EJ299-33 plastic scintillator has been tested both in low-background and high-background conditions. In the first case the plastic γ-α PSD capabilities were tested by using ^{60}Co γ-source, ^{241}Am and ^{232}Th α-sources and AmBe for neutron and γ. The EJ 299-33 scintillator was optically coupled to a quartz window photomultiplier tube (PMT) 9514B manufactured by EMI operated at a bias of 1.7 KV. The emission wavelength of EJ 299-33 peaks at 420 nm and it matches approximately 70% of the spectral response of the photo cathode 9514B of the PM. For the energy calibration the ^{22}Na (1062 keV and 341 keV), ^{60}Co (1041 keV) and ^{137}Cs (447 keV) gamma sources were used (the gamma energies refer to the Compton edge [7]). A good linearity in energy calibration was achieved, as is shown in fig. 3.

A good separation among neutron, gamma and alpha particles was also achieved by a PSD method based on current signal integration windows and scatter-plot comparison, as can be seen in fig. 4. The output signal from the PMT detector was digitized by GET (General Electronics for TPC) electronics [11], which mainly consists of AsAd (ASIC and ADC) board and the AGET chip. The output photomultiplier signal was filtered with the AGET front-end analog filter and shaper (Sallen-Key filter) having a peaking time of 70 ns. The filtered signal (±1 V of maximum dynamics) was sampled by the GET at 100 MHz (10 ns-step) through storing in an analog memory based on a Switched Capacitor Array structure and was codified by a 12 bit ADC, allowing off line shape

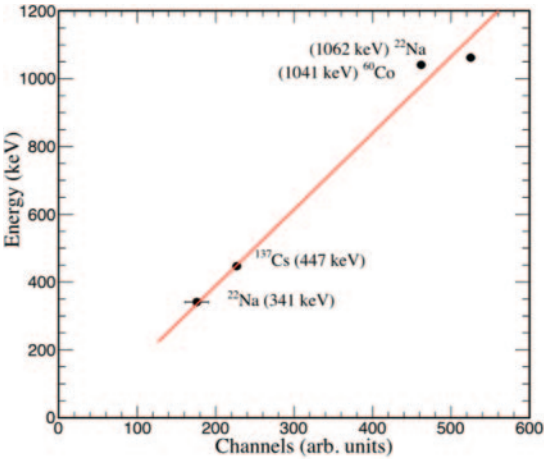

Fig. 3. – Linearity in energy calibration of the EJ299-33 for gamma sources [7].

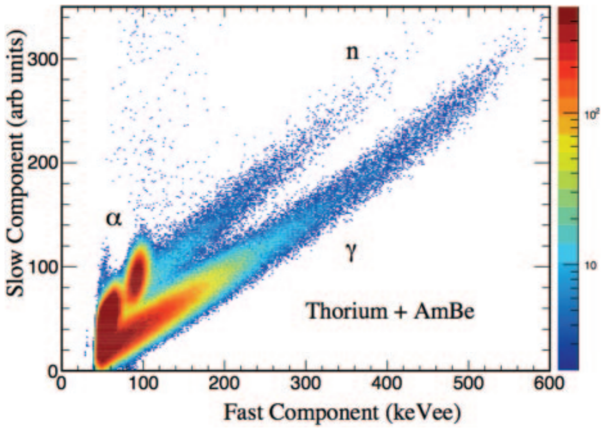

Fig. 4. – 2D plot of PSD showing alpha, neutron and gamma-ray discrimination taken with ^{232}Th and AmBe sources [7].

analysis of the detector output. The time off-set (trigger delay) of the digitized signal was about 1 μs in order to allow an accurate baseline restoring for each signal.

We achieved a very good Figure of Merit (FOM) = 1.03 for neutron-γ for the fast-component slices between 195 and 210 keVee (see fig. 4), We also estimated a neutron detection threshold of about 1 MeV and a discrimination threshold of about 2.5 MeV by using the following parametrization:

$$L_{out} = aE_{dep} - b[1 - e^{-cE_{dep}}]. \tag{1}$$

In our study we adopted the values of the parameters in eq. (1) as given by Lawrence *et al.* [12] for the specific case of EJ 299-33, by applying a small adaptation due to the slight difference in the signal time-integration, reported in ref. [12], with respect to our case, as they follow: $a = 0.8$, $b = 3.9$ and $c = 0.22$, of dimensions of MeVee $*$ MeV^{-1}, MeVee and MeV^{-1}, respectively; consequently, L_{out} is in MeVee and the E_{dep} is in MeV. In the high-background test we used the same acquisition system running in a real experiment, performed at LNS in Catania—14 MV Tandem accelerator, by using ^{24}Mg beams of energies in the range between 71 and 81 MeV, impinging on a thin ^{92}Zr target. Also in this high-background experiment we obtained a good separation between the gamma particles line, proton/neutron particles line and heavier particles as is indicated in fig. 5 (evidently, primary neutrons are seen in the protons $Z = 1$ line, due the fact that they generate protons, as main scattering process in the plastic scintillator).

In fig. 5 the y-axis is obtained by evaluating an exponential fit to the tail of the digitalized pulse (event by event mode, practically in the on line experiment) coming from the PM-tube (see fig. 6) [8]. Also in the case of high-background conditions we achieved good separations of FOM(γ, p) = 1.31 and FOM(p, α) = 1.51 for the Total component slices between 3.7 and 4.8 MeVee, and a FOM(γ,HI) = 0.51 for the Total component slices between 0.5 and 1.0 MeVee. We noticed that fig. 5 shows a real new efficient method of particles identification in 2D identification matrix, adopted in on-line mode for monitoring the different phases of the experiment in event by event modality. In fig. 5, the elastic scattering of the beam is clearly visible. Due to the high quenching of light, with respect to light charged particles, magnesium particles contaminated the

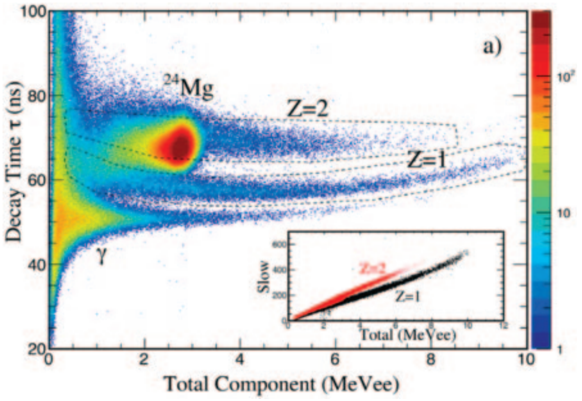

Fig. 5. – Decay time τ of the digitized signals, as obtained by exponential fits (see fig. 6 and text), as a function of the total component. Good separation of gamma-rays, $Z = 1$ and $Z = 2$ particles is seen. Empirical cuts (dashed lines) to separate $Z = 1$ and $Z = 2$ particle loci are shown; The insert shows the results of the cut-selection on the slow *vs.* total discrimination. The ^{24}Mg contribution of elastic scattering is clearly visible [8].

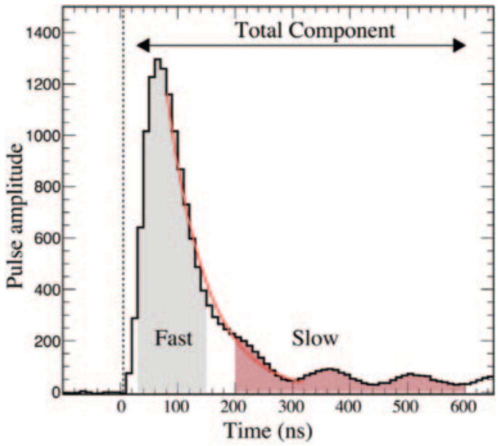

Fig. 6. – Digitized pulses from the GET electronics. The different windows used to define the components: fast, slow and total are shown. A typical exponential decay time fit is also indicated in the figure [8].

loci of the $Z = 2$. Figure 5 also shows (as insert in the bottom-right part), the more popular slow *vs.* total identification 2D matrix, corresponding to the same $Z = 1$ and $Z = 2$ loci of decay time total 2D matrix.

In ref. [8] a neutron detection efficiency of 5% has been evaluated for the 27 cm^3 elementary cell used in the experiment. The efficiency was reasonably evaluated by fitting the proton experimental spectrum, starting from protons and neutrons yields as predicted by the dominant fusion reaction $^{24}\mathrm{Mg} + {}^{92}\mathrm{Zr}$ at $E_{lab}(^{24}\mathrm{Mg}) = 71\,\mathrm{MeV}$.

4. – Conclusions and future perspectives

In conclusion in this paper we briefly discussed a new prototype-project of neutrons segmented correlator able to detect also charged particles with both high angular and energy resolutions. The prototype will be modular, compact and versatile with a full digital electronic readout system performed by silicon technology, it is important to note that many people involved in this project have experience on digitalization of the signals [13]. Our physical results, though obtained with a single detection module are encouraging for future developments and they will be easily extended for a compact configuration supported by a larger number of clusters, suitable for particle spectroscopy. Evidently the high quality of the neutron detections has to be further tested against cross-talk effects. Our segmented project is particularly adapted to study cross-talk effects and it will be the priority of our next step of experiments. We think that with the advent of the new facility for Radioactive Ion Beams (RIBs) like SPES and FRIBS in Italy, SPIRAL2 in France, FAIR in Germany, FRIB in USA, in particular with neutron-rich RIBs, detection of the neutron signal will be a mandatory requirement for future detection systems.

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