IL NUOVO CIMENTO **45 C** (2022) 64
DOI 10.1393/ncc/i2022-22064-1

Colloquia: IWM-EC 2021

Recent results on the construction of a new correlator for neutrons and charged particles and for FARCOS

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received 12 May 2022

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 based on stack of plastic scintillators, featuring both good energy and angular resolution sensitive both to neutrons and charged particles within the same detection cell. We present in this work new results on the Pulse Shape Discrimination (PSD) capabilities of two very compact detection systems: the $3\times3\times3$ cm^3 EJ 276+SiPM and the $3\times3\times3$ cm^3 EJ 276G+SiPM (the latter green shifted version). In addition, we compare new results about the energy calibration and resolution of the FARCOS correlator in the CHIFAR experiment performed at LNS.

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1. – Introduction

The study of the dynamical evolution of a heavy ion collision at the Fermi energy is an active area at the present-day in both nuclear reaction and nuclear structure researches. It is of great interest for nuclear studies to constrain transport theory [1] and reaction models by the experimental determination of quantities sensitive to the isospin degree of freedom and to pin-down its influence on the evolutionary phase of a nuclear reaction at medium energies. One of the most important open questions is to probe the full time scale of a heavy ion reaction (from prompt emission, 10–50 fm/c, to sequential decays, *i.e.*, several hundreds of fm/c) and the shape configuration of short mean-life sources involved in the reaction process, their formation and decay. In this way, particular importance assumes the study of exotic nuclei far from the stability valley. These nuclei will be produced in a next future by available facilities for radioactive ion beams (RIBs). Among the most powerful experimental methods, aimed to pin-down the time scale of the early phase of the collision, particle-particle correlation [2-5], and in particular the two (and multi-) particle intensity interferometry (HBT-Effect) of neutrons and charged particles assumes a particular relevance. Many works, both from the experimental and theoretical sides have been done in the field of light charged particles (LCP), *e.g.*, for like-particles correlations with p-p, d-d, etc., systems [6] as well as unlike particles, d-t, d-alpha, etc., systems [7]. Also, some works [8,9] using heavier charged particles of intermediate mass fragments (IMF) with typical values of atomic number in the range: $3 \leq Z \leq 25$ have been accomplished. In contrast, few investigations have been reported by including uncharged particles in the main trigger and in particular for n-n, n-p, and n-IMF correlations [10, 11]. Moreover, also gamma-particle correlations for spectroscopy [12] and reaction dynamics [13, 14] are complementary important experimental tools. 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 nuclear sizes of 5–10 fermi, Fermi motion at normal density, etc.). In brief, we will present a preliminary research proposal aimed at developing a first prototype of multi-element plastic-scintillator array, NArCoS (Neutron Array for Correlation Studies) [15-17], integrating 16 detection linear stack modules by assembling 64 elementary detection cells, able to detect neutrons with reasonable efficiency in coincidence with LCPs and IMFs with both good angular and energy resolution. One candidate that is suggested for this purpose is an array of plastic scintillators EJ-276 (ex-EJ-299-33) [18-21]. In addition, latest result on the energy calibration of FARCOS in CHIFAR experiment will be reported, and also a preliminary estimation both of the total energy error and the electronic chain one.

2. – The results on SiPM readout of the EJ 276 and EJ 276G plastic scintillator

The tests were part of a master thesis work at the University of Catania [22]. The used setups were: the EJ 276 [23] optically coupled with a Hamamatzu SiPM mounted on the board of the i-Spector device from CAEN [24], the EJ 276G (green shifted version) coupled with the same readout device and the EJ 276G coupled with a photomultiplier tube by EMI. The test was carried out by means of different radioactive sources: ^{133}Ba, ^{137}Cs, ^{60}Co, ^{152}Eu for gamma and ^{241}Am for the alphas. The signal was digitalized using the CAEN digitizer (DT5720, 4 channels 12 bit 250 MS/s ADC in a range of 2 V). The energy calibration of the detection systems was performed in keVee using the gamma sources. Following the results in ref. [20], the 50% of the Compton edge was taken for a given energy of gamma in order to perform the energy calibration. The obtained energy calibration shows a good linearity in the range of about 200 and 1000 keVee (correlation coefficient $R^2 = 0.9996$). For the particle energies larger than 2500 keVee (including cosmic rays), a non linearity in the response function was observed in the case of the i-Spector device that is optimized for gamma ray spectroscopy.

Figure 1 shows the comparisons between two of the 3 detection setups used. In particular, the left panel of the figure shows the PSD discrimination capability of the EJ 276 coupled with the i-Spector and the right one shows the PSD discrimination for the EJ 276G + i-Spector. In the X-axis, the energy calibrated is reported in keVee. The Particle Identification Parameter (PIP) is reported in the Y-axis. The PIP connects the slow and fast component of the digitalized signals, according to the following formula:

$$PIP = 1 - \frac{fast}{tot} = \frac{tot - fast}{tot} = \frac{slow}{tot}. \tag{1}$$

In fig. 1, the alpha particles form the ^{241}Am radioactive source and the gammas from the ^{137}Cs source are indicated. By inspecting fig. 1 it is possible to observe that in the case of the EJ 276G there is a better separation between alpha and gamma. In the evidenced region between 200 and 400 keVee (on the left side) and 250 and 450 keVee (on the right side) we also calculate the Figure of Merit (FoM), defined by the relation

$$FoM = \frac{\mu_\alpha - \mu_\gamma}{FWHM_\alpha + FWHM_\gamma}. \tag{2}$$

In the formula, μ_α and μ_γ are the mean value parameters and the FWHM indicates the Full Width Half Maximum of the Gaussian fit performed on the corresponding peak. The values are FoM = 0.98 for the EJ 276 + i-Spector setup, FoM = 1.47 for the EJ 276G + i-Spector setup, and we also calculate the FoM = 1.03 for EJ 276G + PMT, 9514B

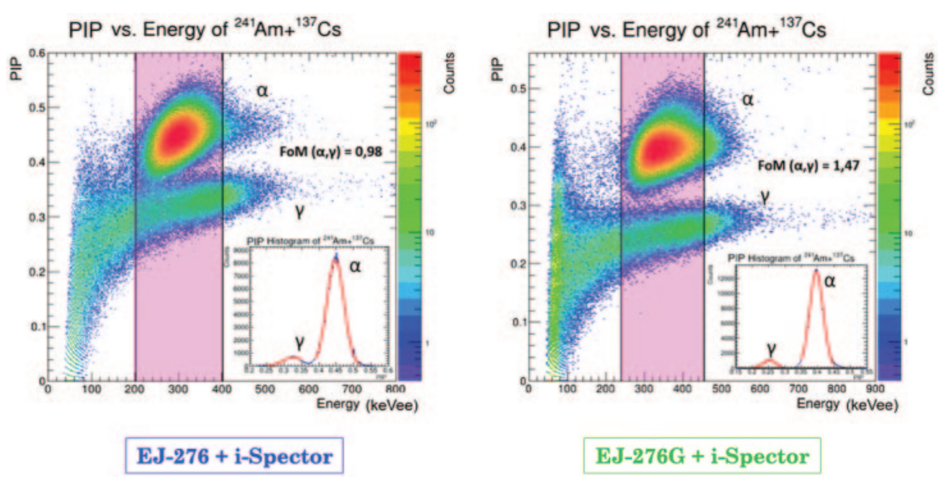

Fig. 1. – Comparison between the PSD Capabilities of the EJ 276 + i-Spector (left panel) and EJ 276G + i-Spector (right panel).

manufactured by EMI operated at a bias of 1.7 KV (the PMT setup is used as reference). As the main result, we observe that the setup having EJ 276G + i-Spector shows the best PSD capability. This result encourages our activity towards the construction of a neutron correlator using the green shifted version of the plastic scintillator coupled with a SiPM.

3. – Results of energy calibration of FARCOS correlator in the CHIFAR experiment

The new-generation correlator FARCOS (Femtoscope ARray for Correlations and Spectroscopy) [25, 26] is a modular array of telescopes based on three detection stages. The first two stages are composed of two Double Sided Silicon Strip Detectors (DSSSDs), each one having 32 vertical strips on the front side and 32 horizontal strips on the back one. The first and the second stages have a thickness of 300 μm and 1500 μm respectively. Both stages have a square geometry which is 64 mm in size. The last detection stage is assembled by four 6 cm thick CsI(Tl). FARCOS is now in its final version and ten on the twenty telescopes were used for the first time and coupled with the 4π multi-detector CHIMERA in the CHIFAR experiment, performed at the end of the 2019 at LNS. In that experiment, beams of ^{112,124}Sn were accelerated by the LNS Superconducting Cyclotron on targets of ^{58,64}Ni and ^{64}Zn at the bombarding energy of 20 AMeV. The experiment was performed in order to emphasize the isospin effects in the nuclear reaction at an energy substantially lower than 35 AMeV already studied in the past by the REVERSE and INKIISSY experiments. In the following we briefly show the results on the DSSSDs energy calibrations of the telescopes. Each of the 132 independent electronic channels of a telescope of FARCOS are treated with ASICs preamplifiers and digitalized by means the GET electronics [27].

The calibration was carried out, strip by strip, by means of the punch-through technique, in which the ^{7}Li, ^{7}Be, ^{9}Be particles in transmission in the first silicon stage are full stopped at the end of the second one (in exactly 1800 μm). In fact, once the path (range) of the particle in the detector is known, its energy is also known by tables of range and stopping power. After the linear fit procedures, a very good stability of the parameters of the fits was noticed. Within the error bars, sensitivities of 135 keV/ch and 153 keV/ch for the 300 μm and the 1500 μm were obtained, respectively. For both detection stages, the intercept of the linear fits are close to zero inside the error bars. These results indicate the good performances of the electronic chain.

In fig. 2 a 2D identification matrix is shown. The energy, in MeV, of the 300 μm DSSSD, is in the Y-axis. The energy of the second stage, in MeV is shown in the X-axis. The detected particles from alpha to Chlorine are indicated in the identification matrix. Notice that the full statistics of the strips of the telescope N. 8, *i.e.*, about 80 hours of data taken is considered.

Using the elastic scattering in the reactions O + Au @ 85 MeV (beam energy), C + Au @ 75 MeV and C + Au @ 65 MeV, with beams accelerated by the Tandem accelerator, we performed a preliminary estimation of the electronic error of the detection setup. In order to determine the electronic error of a telescope, as a preliminary study, only four strips of the telescope have been taken into account, and for each of them a Gaussian fit on the elastics peaks was performed.

Then the FWHMs of each of the four strips were obtained and finally their average values were taken into account.

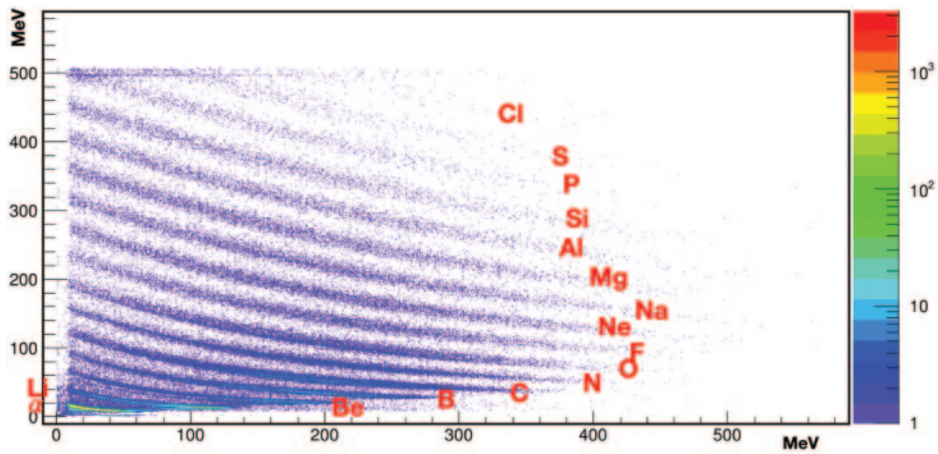

Fig. 2. – Telescope 8, 2D identification matrix, in the X-axis the energy (MeV) of the second stage, in the Y-axis the energy of the first one. The figure also shows the detected particles.

The FWHM and the average value of the peak energy were obtained for each telescope and for each elastic peak. Under the assumption that in a silicon detector the energy resolution is related to the number of h$^+$-e$^-$ produced from the ionization process, the full electronic errors (FWHM) are evaluated by a fit procedure determining the parameters a and b:

$$FMHM^2 = aE + b, \tag{3}$$

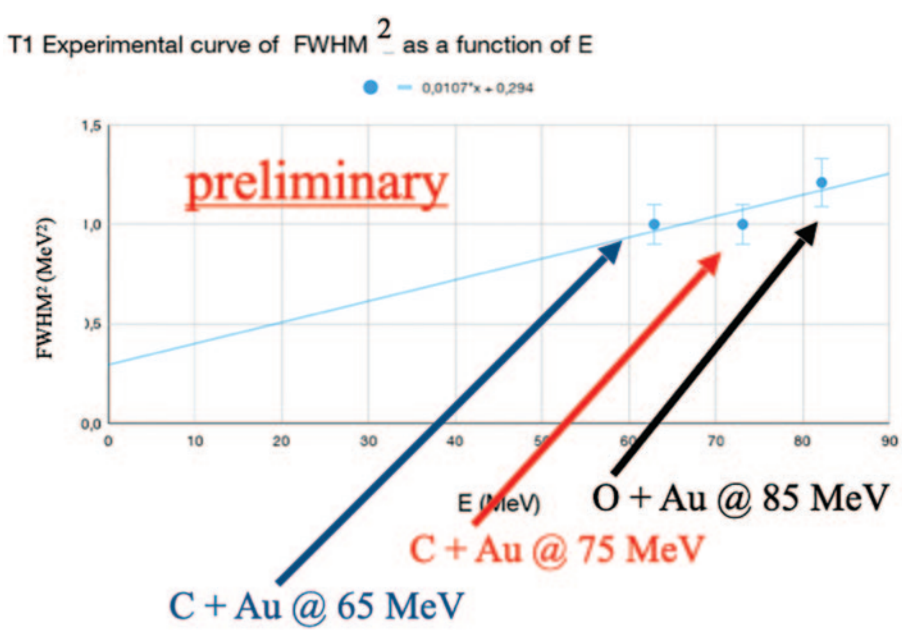

Fig. 3. – The experimental determination of the electronic error by means of the elastic scatterings (see text).

where the a parameter (energy dimensionally) is the differential increasing of the FWHM as a function of energy E, and parameter b (energy square dimensionally) is ideally, the square of the pure electronic contribution when $E = 0$.

Figure 3 shows a preliminary result for the case of the telescope number one.

In that case, an electronic error of 540 keV was calculated, representing about the 50% of the total error.

4. – Conclusions

We have shown the tests performed in low background conditions with the SiPM readout of the EJ 276 and EJ 276G plastic scintillator. Those tests have shown that the better capabilities in term of pulse shape discrimination are obtained in the EJ 276G coupled with the i-Spector: a good linearity has been obtained, even if a saturation effect has been observed, that will be overcome with dedicated read-out electronics. Regarding the analysis on the FARCOS detector, it has to be noticed that a good performance of the new electronic chain from the ASICs amplifier to the digitalization of the signal was achieved. In particular, a very good energy calibration (but time consuming) was achieved with a small energy error, half of it associated with the electronic line error.

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