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Past and future detector arrays for complete event reconstruction in heavy-ion reactions

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Summary. — Complex and more and more complete detector arrays have been developed in the last two decades, or are in advanced design stage, in different laboratories. Such arrays are necessary to fully characterize nuclear reactions induced by stable and exotic beams. The need for contemporary detection of charged particles, and/or γ-rays, and/or neutrons, has been stressed in many fields of nuclear structure and reaction dynamics, with particular attention to the improvement of both high angular and energy resolution. Some examples of detection systems adapted to various energy ranges is discussed. Emphasis is given to the possible update of relatively old 4π detectors with new electronics and new detection methods.

1. – Introduction

The availability of radioactive beams, and the need of their efficient use, has pushed the development of very complete detection systems able to fully reconstruct the events of interest. This short review will mainly concentrate on the efforts performed in European laboratories. Few examples of some classes of detection systems will be given. Because the new detection systems are triggered by the need to solve specific problems, we will go trough the description of the solution of such problems. A short section will be also dedicated to the possibility given by the new digital electronics nowadays available. As a typical example, some details will be given on the characteristics of the new GET electronics. The last section will be dedicated to the use of an old detection system, such as CHIMERA [1-6], as a possible prototype of a new complete detection system able to detect and identify not only charged particles but also, at the same time, γ-rays and neutrons.

2. – Detection needs

2˙1. *Large solid angle.* – With radioactive beams usually we have to deal with rather low beam intensity. The simplest way to solve this problem is to increase as much as possible the solid angle coverage of the detection system. Therefore for the development of such facilities many investments have been done to develop a number of large solid angle or even 4π detection systems. At FAIR, the R3B detection system [7], composed by many sub-detectors, is in advanced construction phase. In particular the CALIFA [8] detector is designed to be mounted around the target, to detect and identify both light particles and γ-rays. The big GLAD superconducting magnet [9] is placed at forward angles in order to discriminate, by tracking, charged particles, and to allow a simpler neutrons detection around $0°$. Various detection systems are studied to cover the detection of high-energy charged particles, while Neuland [10] is used for the neutron detection. The most performing European array for γ-ray detection, AGATA [11] is in operation at GANIL, the 1π phase of this detector should be soon completed. The dream is to built a complete 4π array, with unprecedented resolution, even if the detector cost and also construction difficulties have up to now slowed down the complete evolution of this project. PARIS [12] is another array that in principle should reach a 4π coverage, with the aim to detect high energy γ-rays. Again resolution of this array, built with phoswhich detectors, should be largely improved with respect to previous high energy γ-ray arrays based for instance on BaF_2 scintillators as TAPS [13], Medea [14] or HECTOR [15]. NEDA [16] is the new, 2π, high-efficiency, neutron detector system, for neutron multiplicity measurement. It is going to be coupled with various arrays like AGATA or others. A dedicated presentation about this detector is available in these proceedings [17] where more details can be found. Various charged particle detector systems with small size but large angular coverage and low material budget, like Gaspard [18], are going to be assembled with the aim to be coupled to such γ and neutron arrays, for the channel selection and identification. A new 4π detector, FAZIA [19], characterized by unprecedented charged particles identification properties is also under construction. Another big challenge is the construction of active target detectors, like the ACTAR [20] project. Using the target material as an active detection area, such detectors guarantees the lowest possible energy threshold for particle detection. Kinematic methods, energy loss measurements, or tracking inside magnetic fields, can be used with such new kind of detectors for particle identification. Some of such detector are shown in fig. 1. Many of the detectors of the present list are still in the construction phase, however many experiments are going or are planned using their prototypes, or some combination of new and old detectors. Examples are the campaign presented to GANIL PAC for the use of the MUGAST array, alone and in combination with AGATA. This detector is mounted combining the old MUST2 [21] detector, with prototypes of GASPARD and TRACE [22] arrays covering as much as possible of the angular region around the target. Another proposed campaign still at GANIL is the one with the coupling of FAZIA prototype with the INDRA [23] detector.

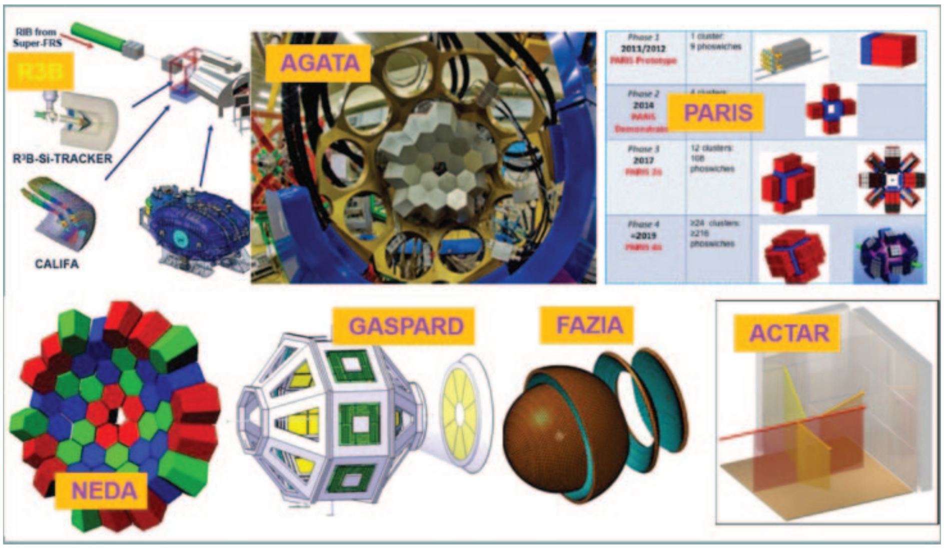

Fig. 1. – Pictograph view of some of the detectors here described.

2˙2. *Selectivity.* – The generally small beam intensity of radioactive beams, coupled with their intrinsic radioactivity, generates a relatively small signal to noise ratio in radiation detectors. To increase this ratio, allowing the measurement of low cross section events, one must increase the sensitivity of the detection system. One of the most useful way is to use a very selective device as a magnetic spectrometer able to fully select and identify the emitted particles. One largely used device is for instance the VAMOS [24] spectrometer at GANIL. This large acceptance spectrometer was built with such purpose, for the use of SPIRAL beams. After some years of use and various improvements, it is now able to fully identify even very-high-Z charged particles. VAMOS is coupled to the AGATA detector for a long experimental campaign. Using VAMOS, heavy residue produced in fusion, fission or deep inelastic reactions, can be mass and charge identified, allowing for a simpler identification of the γ-ray cascade produced by the decay of very exotic nuclei. Other examples of devices able to produce selective triggers are the very large solid angle arrays for the detection of light charged particles. Such devices are again put in coincidence with Germanium arrays like AGATA or Galileo [25] at LNL where SPES beams are in preparation. Such detection systems are able to detect and identify protons and α-particles and so, to select particular decay path in fusion reactions, again enabling to improve the signal over background ratio. Examples of such detectors are Diamant [26] at GANIL or Euclides [27] at LNL. NEDA will be used, coupled to AGATA, to enhance the visibility of γ emitted by nuclei populated in neutron decay channels. AGATA itself is a detector built to improve the signal-to-noise ratio. In fact, with the reconstruction of the detection point of the γ-ray, due to the high segmentation of the detector, and to the full digital acquisition, allowing for a beautiful shape analysis of collected signals, one has an unprecedented ability to perform Doppler shift correction. This largely improves the already good resolution of detected signals, so again increasing the signal-to-noise ratio. Also FAZIA detector with its spectacular isotopic identification is able to enhance the signal-to-noise ratio allowing the selection of very exotic isotopes.

2·3. *Increase of the target thickness.* – Another approach to improve the signal-to-noise ratio is to increase the reaction rate, with an increase of the target thickness. Obviously there are problems, the energy lost by particles in the target can be high with degradation of the energy resolution or even lost of events, if particles are stopped inside the target. These problems can be solved by an active target. In such detectors, a large chamber is filled with gas of the desired species. The electrons, generated by particles traveling inside the detector, are collected and amplified by an electric field and some amplifier devices like GEM or micromegas or others. A good position sensitivity of the detected particles can be obtained in three dimension. The X-Y dimension of the electrode, where electrons are collected, give two of them. The time of arrival of the signal is instead proportional to the third Z dimension. MAYA [28] was one of the first active target demonstrating the utility of such a device. ACTAR is the evolution of such detection concept with improved position sensitivity, and larger size. It is also possible to mount this detector inside a γ-ray detection array like PARIS, in order to measure coincidence γ-particles. An active target can also run inside a magnetic field, in order to improve particle identification capability. The electrode segmentation in ACTAR is much larger than in MAYA detector, therefore, a much larger number of electronic channels is needed. To allow the construction of such a detector, a new compact electronics was designed, the so-called GET, Generic Electronics for TPCs [29]. We will shortly describe this electronics in next section.

3. – Digital electronics: the GET case

In the last decade the development of more and more powerful digital devices, the availability of fast, relatively low cost, data storage devices, and the improvement of data transmission speed, due to fiber optic technology, allowed the development of new digital data acquisition systems. In such data acquisitions the complete shape of the signal can be stored. This is a big advantage because the signal treatment can be changed and adapted to any different experimental condition. Sophisticated software filter can be applied to clean signal from noise. The pedestal can be measured event by event, largely improving resolution. Pulse shape analysis of the detector signal can be applied, improving particle identification capabilities, but also cleaning pile up events. Last, but not least, very sophisticated filters can also be optimized to extract more precise timing information. One of the last developed digital ACQ SYSTEM is the GET one. Some test about this electronics are presented in another contribution to this conference [30], therefore only a short description is inserted here. This electronics was developed, in the last years, with the aim to produce a low-cost and very flexible electronics for the new generation of TPC under construction in the world. Many laboratories joined their efforts to build such new electronics (IRFU-CEA-Saclay, GANIL, CENBG-Bordeaux, MSU, RIKEN), and nowadays it is adopted or tested by more than 20 detector systems under construction or available in the world. The flexibility of such electronics is shown by the fact that many detector systems, that now are going to use it, are different than TPCs. The base of such electronics is an ASIC developed by the Saclay laboratory, the AGET chip [31]. In this chip, 64 channels are available with a complete electronic chain from preamplifier, shaper and discriminator. Moreover an array of capacitors is able to store the signal of each channel before digitalization. Four AGET chips are arranged in a module called ASAD (256 Channels/board). Four of such modules are controlled and read by a CoBo card (Concentrator Board). CoBo cards are mounted inside a microTCA crate, where a MUTANT card is also mounted for the trigger handling. In one crate up to 11 CoBo can be mounted and up to 3 crates can be used, for a maximum of about 33 thousand channels. Details on the results obtained with such kind of electronics can be found in [32].

4. – A complete detection system

The dream of any experimentalist is a powerful detector able to detect and identify every think produced in a reaction. Often one has available only very specialized devices able to see either γ-rays or charged particles (light or heavy) or neutrons. However, to correctly interpret the results one has to do assumptions on what was not seen with the available detector. In general charged particles detectors at intermediate energies have more stages for the charge identification using the ΔE-E method and the last stage is a scintillator allowing to stop fast light particles. Scintillators are often able to detect not only light particles but also γ-rays and neutrons with not negligible efficiency due to their thickness. Therefore one has simply to look to these "background events" and try to get the maximum information from what is seen by the detector. An example of the possible use of relatively old 4π detectors for intermediate energy as complete detectors, is given by the CHIMERA array. CHIMERA was built at the end of last century and is constituted by 1192 two stage telescopes with silicon and CsI(Tl) detectors, photo-diode readout is used for the CsI(Tl) stage. Since the beginning of the experimental use of CHIMERA, some attempts were performed to check the possibility to detect neutrons with the CsI(Tl) stage of the telescopes. The simplest way is to use an anti-coincidence with silicon detector and look to signals identified as charged particles with fast-slow analysis in CsI(Tl) [33]. Some interesting scatter plots where reported, with the identification of neutrons detected with both n,α and n,p reactions. In fig. 5(a) of ref. [33] a Fast-Slow identification scatter plot obtained in anti-coincidence with silicon detector signal is shown. Unfortunately, the small energy loss of protons in silicon detectors reduces the reliability of such a detection method, also possible misalignments and detector malfunctions can perturb the obtained results. More recently this method has been revised, due to the use of a new detection system FARCOS [34, 35] coupled to CHIMERA. The FARCOS detectors, cover some of the telescopes of CHIMERA that can be therefore used as neutron detectors, in fact they cannot see charged particles. In this case the signal to noise ratio is better under control and reliable results were obtained [36]. Other methods where also used to identify neutrons emitted in binary kinematics [37], with the detection in coincidence of the reaction partner. In fig. 2 the single and coincidence spectra of charged particles detected in a silicon detector in the reaction $p(^7\mathrm{Li}, n)^7\mathrm{Be}$ is shown. The coincidence data are obtained looking to the CsI(Tl) signals detected in the kinematic conjugated detector. γ-rays were identified in such detector in coincidence. They are produced by n,γ reactions inside the scintillator. The ^{7}Be peak is well evidenced in the coincidence spectrum of fig. 2 and a detection efficiency of the order of 4% was measured using such detection method.

As above evidenced, using fast-slow discrimination with CHIMERA CsI(Tl), we are able to perform particle identification, obtaining beautiful identification of p,d,t, ^{3}He, α-particles and Li isotopes, but also γ-ray identification. Only recently, however, attempts were performed to use such γ-ray information. In a recent work [38] it was shown the ability of CHIMERA detector to correctly detect γ-ray from the decay of the 4.44 MeV excited level of ^{12}C. Angular distributions of detected γ-ray were correctly determined in the center of mass of the emitting nucleus. $E2$ behavior of the decay γ-ray was observed, also the spin-flip process was measured using proton beam to excite the resonance. In

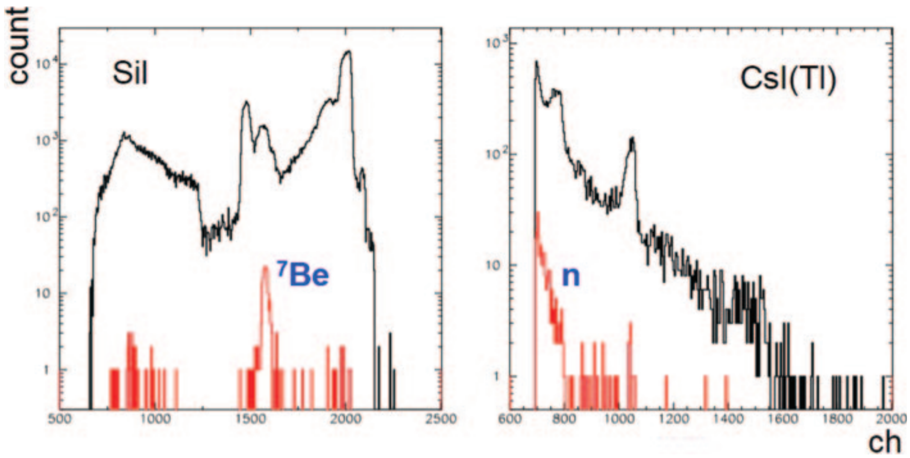

Fig. 2. – Energy spectra collected in silicon and CsI(Tl) detector in kinematic coincidence in the reaction $p(^7\mathrm{Li}, n)^7\mathrm{Be}$. Black spectra single, red spectra coincidence ^{7}Be and neutron (detcted as γ after n,γ process are shown.

fig. 3 we show an example of the γ-ray spectrum measured in coincidence with proton inelastic scattering. The background was evaluated looking to coincidences with elastic scattering. The use of the complete information that can be collected with CHIMERA is very important for some class of experiments that can be performed both with stable and unstable beams. One of this experiments is the search for the isoscalar excitation of the Pygmy resonance in ^{68}Ni. It has been recently performed at LNS using the fragmentation beam produced by the FRIBs facility of the LAB [39, 40] and the CHIMERA detector complemented at forward angles by the prototype of the FARCOS detector. FARCOS was used to detect the ^{68}Ni scattered by a ^{12}C target used with the aim to excite, by isoscalar mode, the Pygmy resonance. The CsI(Tl) of the CHIMERA sphere (detectors

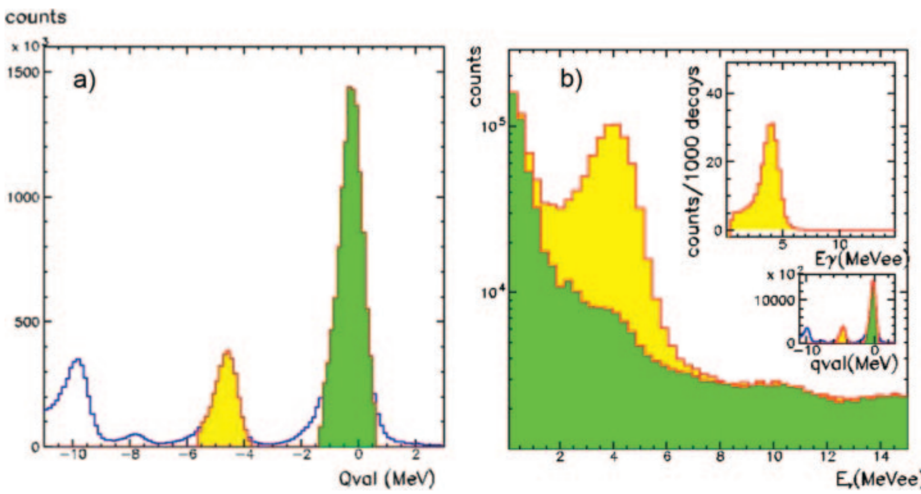

Fig. 3. – a) Qvalue spectrum of the reaction $p(^{12}\mathrm{C}, p)^{12}\mathrm{C}^*$. b) γ-ray energy spectrum obtained in CsI(Tl) in coincidence with the 4.44 MeV Q-value peak and with elastic scattering.

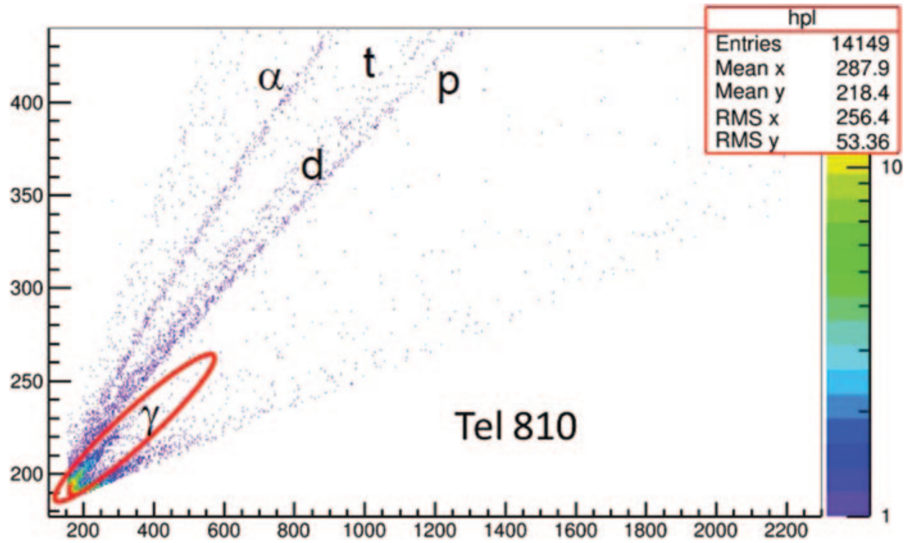

Fig. 4. – Fast-slow identification scatter plot of particles detected in a CsI(Tl) of the CHIMERA sphere. The lines of p,d,t and α are shown, γ-rays are evidenced with an ellipse.

from 30° to 176° placed at 40 cm from the target) were used to detect and identify γ-rays. CsI(Tl) were calibrated using the 4.44 MeV γ-ray produced by the $p+^{12}$C reaction at 24 MeV, as shown in fig. 3. Beautiful γ-ray identification was obtained using as reference signal for fast slow gates the signal delivered by the Micro Channel plate for the beam identification [41]. In fig. 4 an example of such beautiful identification is given. Forward CsI(Tl) covered by FARCOS detectors where used to detect neutrons from the decay of the Pygmy resonance. In fact it is expected that such resonance has about 95% of its decay probability via neutron emission. In fig. 5 two fast slow identification scatter plots are shown from CsI(Tl) detectors belonging to ring 2 of CHIMERA. The first one (fig. 5(a)) was not covered by FARCOS and many particles can be seen. The second one (fig. 5(b)) was a detector covered by FARCOS. A smaller amount of particles is seen also in such CsI(Tl). These particles are generated in CsI(Tl) by neutron interaction, and represent the searched neutrons. Data analysis is in progress and soon results will be presented.

It is important to notice that we are upgrading the electronics of CsI(Tl) detectors of the CHIMERA array by replacing the old analog electronics with the new GET one. Very beautiful results have been obtained with improvement of energy resolution of the CsI(Tl) detectors and decrease of detection and identification threshold. Using a double gain technique we are in fact able now to detect also γ-rays as low as 500 keV, while with the old electronics the detection threshold was around 2 MeV. Moreover, the new electronics is now able to provide a trigger signal also for the CsI(Tl), that was not well working in the old CHIMERA electronics chain. Very interesting perspectives are opened by the renewed use of such detector, also in view of the future high intensity upgrading of the LNS Cyclotron and of the consequent availability of more intense fragmentation beams from the new fragment separator in project phase.

In conclusion we can say that many new detection systems are in operation or are going to be developed for future experiments with exotic beams. Also renewed arrays as

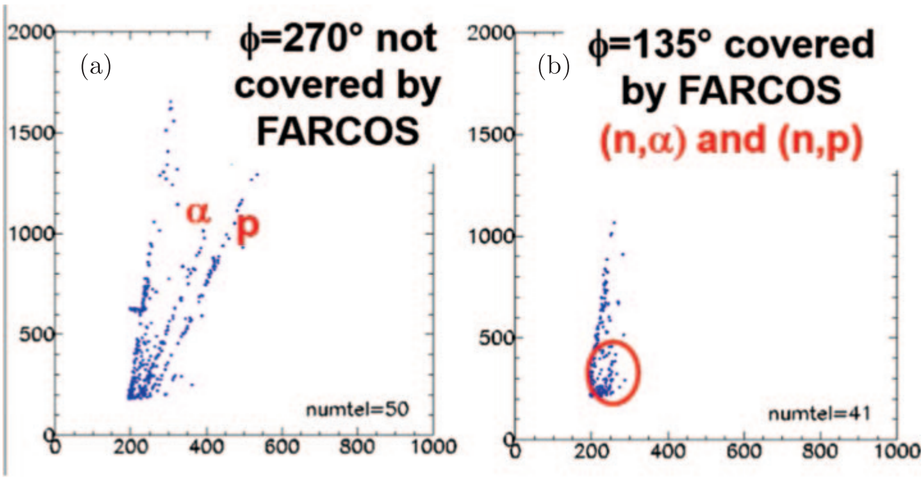

Fig. 5. – Fast-slow identification scatter plot of particles detected in CsI(Tl) of the second CHIMERA ring. a) The detector at 270° is not covered by FARCOS and ligth particles are seen. b) The detector at 135°, covered by FARCOS shows only few particles, generated by neutron interaction in CsI(Tl), evidenced with a circle.

CHIMERA or INDRA can however provide amazing information and represent a step toward the availability of DREAM complete detectors.

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