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Latest results on a SiC detector system for RIBs and possible physics cases

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Summary. — Radioactive Ion Beams (RIBs) hold significant potential in the fields of nuclear physics and medical applications, particularly in particle therapy. The main hindrance to use RIBs for both nuclear physics research and clinical applications lies in their complex production processes and the limitation of low beam intensities. Ongoing research projects are indeed underway in Europe and around the world with the aim of assessing the advantages of RIBs with high intensity. These research projects are focused on advancements in accelerator technology, targetry, and detector systems. Regarding these latter aspects, Silicon Carbide (SiC) detectors show notable promise in the fields of nuclear and medical physics due to their unique characteristics. This paper discusses recent results in the development of a detector system based on SiC technology. The detector system will also be used in conjunction with the FraISe (Fragment In-flight Separator) facility, which will be available in the near future at the Laboratori Nazionali del Sud of INFN (INFN-LNS) in Catania.

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1. – Introduction

The employment of Radioactive Ion Beams (RIBs), particularly when delivered at high intensities ($\geq 10^6$ pps), is of paramount importance in pushing the boundaries of current understanding across a wide spectrum of scientific domains. They indeed offer a unique tool for addressing complex scientific questions in different fields. These fields encompass nuclear physics, nuclear astrophysics, and medicine. Regarding the first topic, our current understanding of nuclear structure and dynamics is largely limited to nuclei in proximity to the β-stability valley. To investigate deeper into unexplored regions of the nuclear chart, we depend on studies utilizing RIBs far from the stability [1-5]. In general, RIBs allow us to explore the existence of molecular structures involving α clusters [6-8], phenomena like neutron and proton halos [9-13], as well as the neutron skins [9, 14] and phenomena connected to this neutron excess, such as the low-lying excitation modes, referred to as Pygmy Dipole Resonance (PDR) [15]. Furthermore, RIBs have relevant connections with the Equation of State of nuclear matter (EoS). They also play a crucial role in astrophysics, since reactions involving unstable nuclei occur in many nucleosynthesis processes [16, 17]. As mentioned, RIBs can be employed for the production of radiopharmaceuticals and medical physics applications [18-20]. In fact, RIBs are potentially ideal projectiles for radiotherapy because their decay can be used to visualize the beam [20]. For instance, the results discussed in ref. [20] demonstrate that RIBs provide an improvement in image quality and signal-to-noise ratio compared to stable ions.

New research projects are currently underway in Europe and around the world to exploit the advantages of RIBs for nuclear structure and dynamics studies, as well as for clinical applications. In Italy, two facilities are in the final phase of construction: the SPES facility at Laboratori Nazionali di Legnaro (INFN-LNL) [18], that will use the ISOL tecnique, and the FraISe facility [21] at Laboratori Nazionali del Sud (INFN-LNS) that will use the In-Flight method. Both facilities, together, will enable a wide range of complementary studies in both nuclear and medical physics.

2. – Latest remarks on the FraISe facility at INFN-LNS

Over these years, INFN-LNS has been working on a new facility for producing high-intensity RIBs [22-25]. This facility, called FraISe (Fragment In-flight Separator), utilizes the In-Flight technique and employs primary beams with a beam power up to 3 kW. This represents a significant advancement compared to the previous FRIBs (in-Flight Radioactive Ion Beams) apparatus, which operated with primary beam powers up to $\approx$ 100 W. As known, in the In-Flight method, a fragment separator is used for magnetic selection but it cannot separate ions with the same mass/charge ratio. As a result, the output of this selection is a cocktail beam of different ions, with a maximized yield of the beam of interest, making it essential to characterize the beam components arriving at the target point on an event-by-event basis. In the FRIBs facility, a tagging device, dedicated to the CHIMERA multidetector beamline, and the ΔE-TOF technique were employed. This method included a Micro Channel Plate detector to produce the start signal for the Time of Flight (TOF) measurement and a Double Sided Silicon Strip Detector (DSSSD) 150-200 μm thick, placed downstream to provide the stop signal for TOF measurement, as well as information on the energy loss (ΔE) signal and beam profile [26]. Moreover, diagnostics elements, consisting of plastic scintillators and DSSSDs, were used along the beamline to ensure optimal beam transport from the production target to the end-use point. These diagnostics elements allowed for measurements of the beams total yield and beam profile reconstruction with a pixel resolution of 3×3 mm^2 (for details see ref. [21] and references therein). As mentioned, the limitation of the previous FRIBs facility was the maximum beam power delivered by the CS (100 W), which restricted experiments to nuclei close to the stability valley due to insufficient yields for nuclei far from stability. FraISe will allow to overcome this limitation, using primary beams with power up to 3 kW, thereby generating RIBs intensities ranging from 10^3 pps to 10^7 pps for nuclei far and close to stability, respectively. These intensities will increase the yield by a factor of ≈ 30 when compared to the FRIBs facility. The FraISe facility is housed in a bunker area of INFN-LNS, designed to provide safe air treatment and appropriate shielding. A new production target, CLIM, consisting of a rotating disk made of beryllium or carbon is used in FraISe [27]. This design allows for the distribution of the primary beam impact area on a circular crown with a mean radius of $\approx$ 10-15 cm, effectively controlling the target degradation and heating. Additionally, slit systems will be installed in the beamline, one at the plane of symmetry and the other at the exit of the fragment separator, which can be used to adjust the acceptance Δp/p and reject unwanted ions in the cocktail beam. An aluminum degrader/wedge may be introduced after the central slit to enhance the rejection of contaminants, similarly to the method used in the FRIBs facility [21, 24, 25]. The building construction upgrade has already been completed: the magnetic elements are almost all available at the LNS, and they will soon be installed along the beamline. In addition, during June-July 2023, the CLIM target system was successfully installed and tested in a dedicated vacuum chamber.

3. – Latest remarks on a detector system based on the SiC technology

A critical challenge when dealing with high-intensity beams is the need for specialized devices capable of measuring various features of RIBs. These devices must be able to operate in radioactively activated environments, which are expected to have high levels of direct and background irradiation due to the intense beam interactions. To address this issue, Silicon Carbide has been identified as a promising material due to its radiation hardness [28]. This choice is further supported by feasibility studies conducted through simulations and preliminary tests [24, 29]. A versatile detector system is currently under development to serve as a diagnostic tool for the FraISe facility, tagging element for the CHIMERA multidetector beamline, and for various applications, including medical ones. This system will also operate as an active wedge in the FraISe facility [21, 24, 25]. It will provide information on isotopic identification, beam intensity, energy, position, and beam profile. The composition of RIBs will be determined by measuring the ΔE energy loss of ions and the Time of Flight (TOF) between two detection systems. Alternatively, the TOF can be measured with respect to a reference time signal synchronized with the primary beams arrival at the production target, such as the Cyclotron radiofrequency signal. In detail, the system will consist of two arrays, each one made of single SiC detection pads with an area of 5 mm×5 mm monolithically assembled in 3×3 configuration with a thickness of 100 μm. Composing an array of several pads in rows and columns makes it possible to cover an area of $\approx 60\times30$ mm^2, wide enough for typical RIBs profiles in the high dispersion point. Such a segmentation sustain a maximum value of $\approx 10^7$ pps over the whole array. A sandwich configuration of two detection arrays located at a distance of few cm and with a half-pitch shift both in X and in Y, and readout in coincidence will improve the position resolution and partially recover for the dead region around each sensor die. Figure 1(a) shows a scheme of a monolithic 3×3

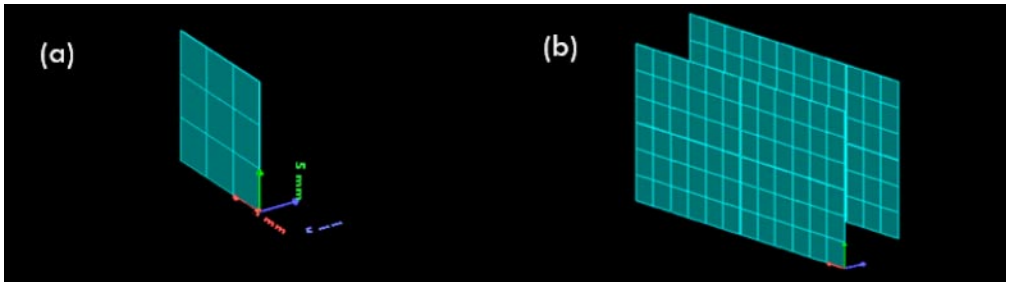

Fig. 1. – (a) Monolithic 3×3 SiC detector simulated with GEANT4 [33]. Each pad has a surface of 5×5 mm^2 and a thickness of 100 μm. (b) Arrays of monolithic SiC detectors simulated with GEANT4.

SiC detector, while fig. 1(b) displays a scheme of the detector arrays. The final system will be housed in a DN160 spherical cross to be located along the beam path and to be easily interchangeable, as it is necessary in a high dose region, where the SiC could be also activated when removed. Because an important issue will be to have a very high timing performance, a dedicated front-end in charge preamplifier configuration with fast decay has been designed to readout the full detection system [30-32]. Significant work has been undertaken to characterize the detectors in recent years [21], and this effort is currently ongoing. At the present time the focus is on optimizing detectors performance in terms of energy, timing, and spatial resolution, maximizing the signal-to-noise ratio. Additional work is being done to gain a thorough understanding of potential inter-pad and cross-talk effects. Figure 2 displays two pictures of a SiC detector mounted on a plastic support specifically realized with a 3D printer. Figure 3 shows an energy spectrum obtained with a mixed α source. In this case, a Mesytec MPR-16-Series preamplifier and a CAEN digitizer DT5725 250 MHz have been used. It's important to note that an activ work is being done to improve the signal-to-noise ratio and digitalization, particularly through filter optimization, in order to achieve better energy resolution.

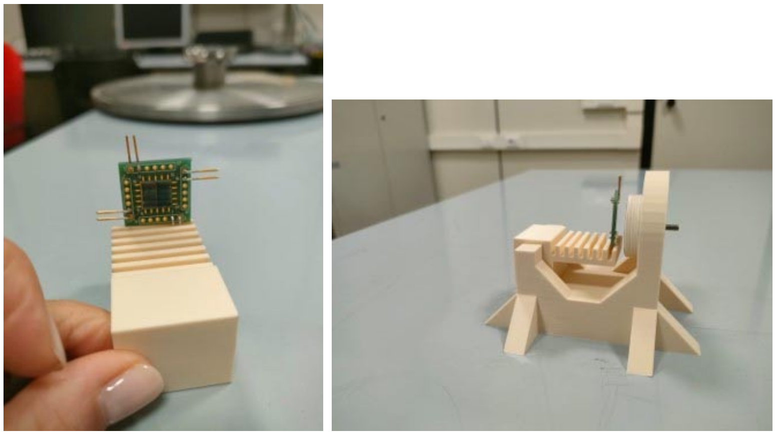

Fig. 2. – Pictures of SiC detectors mounted on a plastic support.

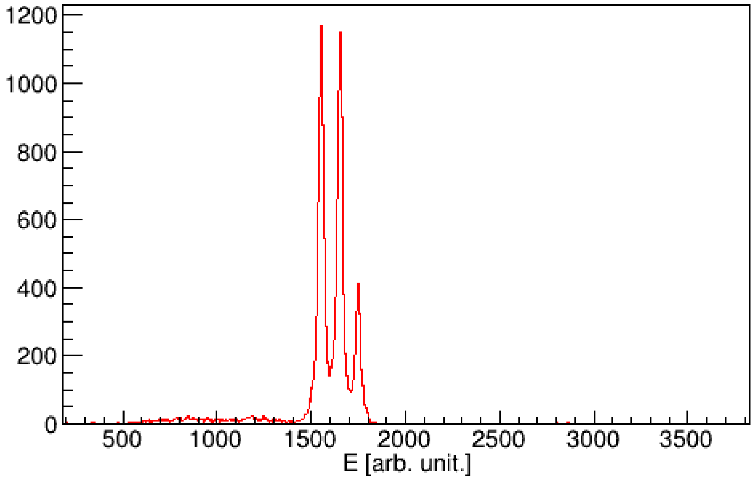

Fig. 3. – Energy spectrum obtained with a mixed α source.

4. – Some physics cases opportunities

FraISe facility is poised to become a highly competitive facility for producing unstable nuclei in the Fermi energy regime, particularly focusing on light and medium mass nuclei. Equipped with this advanced apparatus, researchers will have the opportunity to conduct a wide range of studies involving unstable nuclei, whether they are located near the stability valley or far from it. Among them, studies concerning the Isospin physics with high asymmetries in Heavy-Ion reactions at Fermi energies, explored with the CHIMERA multidetector in stable nuclei [34-37], clustering structure of α particles in neutron-rich isotopes [8, 38, 39], and nuclear reactions of interest in the astrophysical context will be performed, see for instance ref. [22] and references therein.

One exciting area of research that can be pursued at FraISe is the study of nuclei exhibiting neutron skin, exploring their link with an important excitation mode, known as Pygmy Dipole Resonance (PDR). The PDR is indeed a subject of intense theoretical and experimental research. Understanding such excitation mode is relevant in nuclear structure studies as well as in astrophysical processes. Researchers continue to investigate this resonance in order to gain a deeper insight regarding the behavior of exotic nuclei and their role in the universe. Several investigations have been performed on PDR worldwide, but some features remain currently not well understood, such as the degree of collectivity and the behaviour of the strenght as a function of the neutron number [15, 40]. At INFN-LNS in Catania, a noteworthy experiment was carried out to reveal the PDR in ^{68}Ni using an isoscalar carbon target [41]. In future, the use of RIBs makes it possible to conduct an important experimental campaing using several beams, at several beam energies, and employing both isoscalar and isovector probes. In detail, it could be important to investigate the PDR in the region of light and medium nuclei, such as ^{20}O, ^{34}Si, ^{38}S, ^{48}Ar and ^{68}Ni. The aim is also to measure the neutron-shell-occupancy dependence of the PDR both below and above the particle emission threshold. Such important topic could be investigated with high accuracy thanks to the use of the CsI(Tl) scintillators of the CHIMERA multidetector, employing the well-known capability of the array to detect γ-rays and resonance states [42,43], and the FARCOS array in its complete configuration [44,45]. The SiC tagging system will allow to identify the beam and extract important information on energy, time and beam profile. Moreover, the use of the new prototype of neutron detector, NARCOS, will allow to fully characterize the PDR decay [46,47]. Studies of interest for medical physics can also be conducted. For instance, it is of particular interest the study of ^{11}C, whose β^+ decay would allow the simultaneous use of imaging techniques (using γ emitted by positron annihilation) and energy dissipation techniques [19,20]. In this way, it could allow to perform treatments and diagnostics at the same time, differing from the stable nuclei for hadron therapy techniques.

5. – Conclusions

In this paper, the most recent developments in SiC detector arrays, specifically designed for high-intensity Radioactive Ion Beams detection have been reviewed. SiC detectors show great promise for the future of nuclear physics studies and medical applications due to their features, including radiation hardness, high-temperature operation, fast timing, and good energy resolution. Over these years, a significant work has been conducted through simulations and tests, confirming the potentiality of SiC detectors. Moreover, to optimize the high-timing performance requirements, SiC detector devices will be coupled with a fast custom frontend electronics. The current work and next steps are focused on a deeper undestarding of the SiC detectors, with the aim to maximize the energy, time and spatial resolution, the signal-to-noise ratio and to characterize in detail the inter-pad and cross-talk effects. Furthermore, in this contribution, some latest remarks on the FraISe facility at INFN-LNS, focusing on the physics case of Pygmy Dipole Resonance investigations, were also reported.

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