The EXOTIC project at INFN-LNL

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Abstract

The low-energy light radioactive ion beam in-flight facility EXOTIC and the associated experimental set-up,operational at Legnaro National Laboratories of the National Institute of Nuclear Physics (LNL-INFN, Italy) and designed for nuclear physics and nuclear astrophysics experiments, were described. The outline of the experimental program carried out employing the produced radioactive ion beams was presented and the perspectives of the EXOTIC project were discussed.

Key words: *radioactive ion beams; position sensitive detectors; gas track detectors; astrophysics; Legnaro National Laboratory.*

El proyecto EXOTIC en INFN-LNL

Resumen

Se describe la instalación EXOTIC de haz de iones radioactivos ligeros de baja energía en vuelo y la configuración experimental asociada, en operación en el Laboratorio Nacional de Legnaro del Instituto Nacional de Física Nuclear (LNL-INFN, Italia) y diseñada para experimentos de física nuclear y astrofísica nuclear. Se presenta el esquema del programa experimental llevado a cabo empleando los haces iónicos radioactivos producidos y se discuten las perspectivas del proyecto EXOTIC.

Palabras clave: *haces de iones radiactivos; detectores de localizacion; detectores de trazas gaseosas; astrofisica; Laboratorio Nacional Legnaro.*

Introduction

Experiments with radioactive (exotic) nuclei allow to explore the properties of isotopes that have a proton-to-neutron ratio very different from the stable ones, measure cross sections of important reactions for the stellar nucleosynthesis occurring in explosive astrophysical environments, constrain the isospin-dependent nucleon-nucleon interaction in neutron-rich nuclei and in neutron stars, synthesize superheavy elements and test physics beyond the standard model.

While several large-scale and small-scale Radioactive Ion Beam (RIB) facilities are actually operating worldwide, future infrastructures like SPES (LNL-INFN, Italy), SPIRAL2 (France), HIE-ISOLDE (CERN), FRIB (USA), FAIR (Germany), EURISOL (Europe) are aimed at delivering RIBs with the highest intensity and purity and with good ion optical quality for investigating unreachable parts of the nuclear chart.

Along with the construction of new RIB infrastructures, a continuous development of detection arrays is under way. Depending on the radioactive ion incident energy and on the class of reactions to be studied, different experimental set-ups were built for the detection of charged particles. In this paper we describe the EXOTIC project, consisting of the EXOTIC RIB facility and the associated experimental apparatus,developed at LNL-INFN, Italy.

Materials and methods

EXOTIC facility andexperimental program

The EXOTIC facility [1-4] is dedicated to the in-flight production of low-energy light RIBs, by inverse kinematics nuclear reactions using the intense heavy-ion beams from the LNL Tandem XTU accelerator hitting a light gas target (H_2, D_2, ^3He, ^4He). The main characteristics of the facility, displayed in the left-hand side of

Fig. 1, are a large RIB acceptance of the optics elementsand a large capability to suppress all the unwanted scattered beams. It consists of: i) a production gas target that is a 5 cm-long cylindrical cell with entrance (ϕ=14 mm) and exit (ϕ=16 mm) windows made of 2,2 μm(1,83 mg/cm^2) thick HAVAR foil, operating at room or at liquid N_2 temperatures with an operational pressure up to 1 atm; ii) a beam selection and transport system consisting of: a triplet of large diameter quadrupole lenses (ϕ=160 mm), a 30° bending magnet, a Wien filter and a second triplet of quadrupole lenses placed before the reaction chamber. The Wien filter eliminates to a very large extent the tails of the primary beam that pass through the system with the same magnetic rigidity. In order to stop the RIB contaminants, different slit sets are installed along the beamline. All the slit sets are mounted on movable arms to be adjusted to the envelope of the considered RIB. The total length of the facility from the production target to the reaction target is 8,34 m. The beamline characteristics are the following: $\Delta E/E=\pm10\%$, $\Delta p/p=\pm5\%$, $\Delta\theta= \pm50$ mrad, $\Delta\phi=\pm65$ mrad, $\Delta\Omega\sim10$ msr, $B\rho=0{,}98$ Tm.

So far, RIBs of ^{7}Be, ^{8}B, ^{17}F, ^{15}O, ^{8}Li, ^{10}C and ^{11}C, in the energy range 3-5 MeV/nucleon have been delivered with intensities about 10^6, 10^3, 10^5, $4*10^4$, 10^5, $5*10^3$ and $2*10^5$ pps, respectively, and with a high purity of 98-99% (apart from the ^{8}B that has a lower purity). This renders the EXOTIC facility competitive compared with other first generation small-scale in-flight facilities.

The envisioned experimental program at EXOTIC aims at:

1) studying reaction mechanisms induced by light exotic nuclei impinging on medium- and heavy-mass targets at incident energies near the Coulomb barrier of the colliding system. In this energy range, the peculiar features of exotic nuclei, such as excess of neutrons or protons, low binding energy, halo structure, neutron or proton dominated surface, influence the elastic scattering and the fusion process giving a picture that is rather different from that of well bound species (for a review see for instance [5]). Despite the efforts carried out so far, the understanding of nuclear reaction mechanisms in collisions involving exotic and weakly-bound nuclei is still a very challenging task. In the considered measurements the charged products emitted in direct nuclear reactions (elastic and inelastic scattering, nucleon transfer, breakup of the weakly bound projectile) and the light charged particles emitted in fusion-evaporation reactions should be charge and mass identified. A Full-Width-at-Half-Maximum (FWHM) energy resolution of ~250-400 keV is needed in the most demanding cases for discriminating the elastic from the inelastic scattering of the projectile from the target, depending on the considered colliding nuclei: ~250 (400) keV for a ^{11}Be (^{17}F) projectile impinging on a ^{58}Ni or ^{208}Pb target. A large detection solid angle is requested to compensate the low RIB intensity, in the most favorable cases limited to a few orders of magnitude

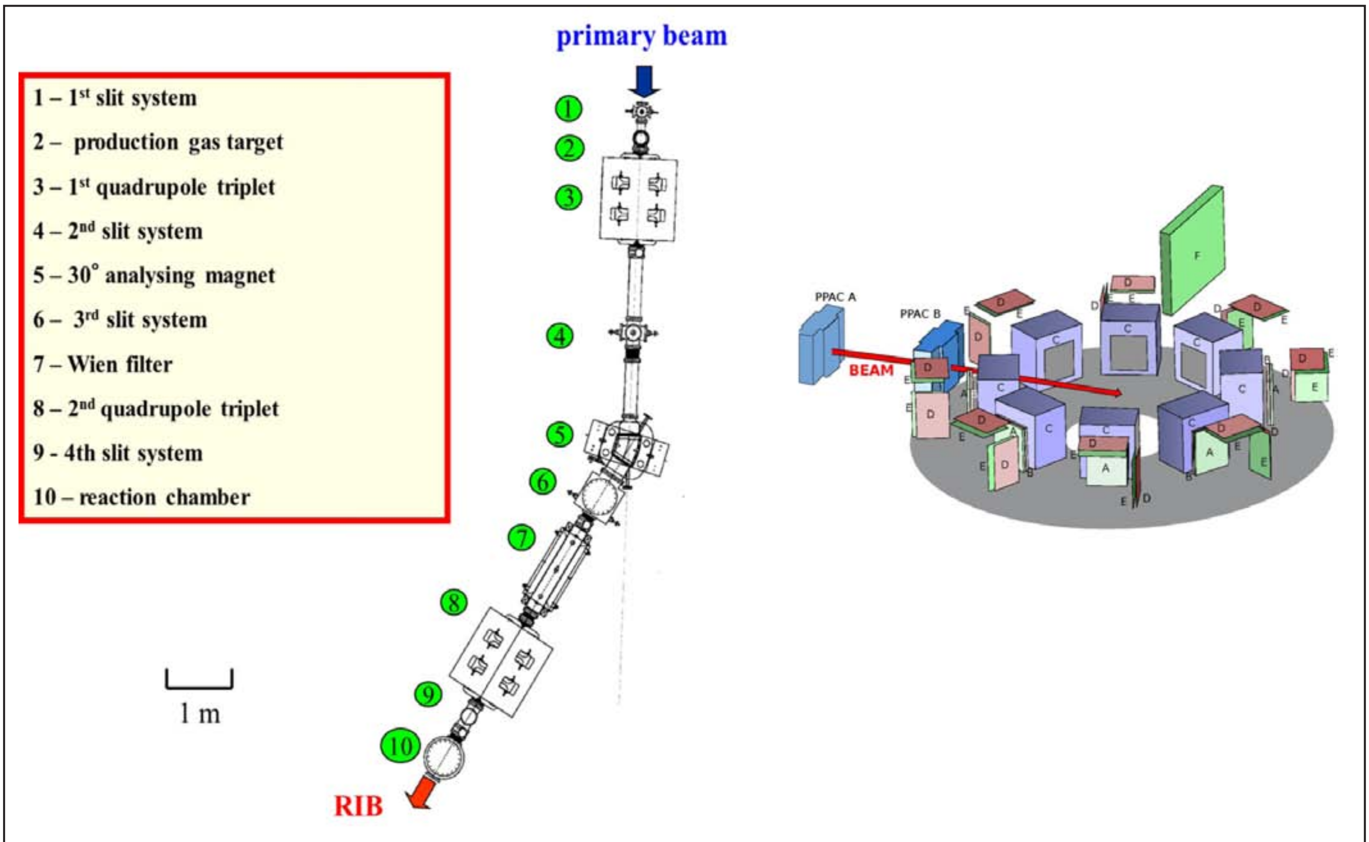

Figure 1. (Left-hand side) Schematic layout of the EXOTIC facility. (Right-hand side) The position sensitive PPACs (PPAC A and PPAC B) for the RIB tracking system and the detection system, EXPADES, placed in the reaction chamber at the end of the EXOTIC facility (element 10 in the schematic layout).The beam enters in the reaction chamber from the left passing through PPAC A and PPAC B. For details see text.

less than typical stable beams, and to allow detection of coincident breakup particles emitted at large relative angles while a high granularity would allow detection of coincident breakup particles emitted at small relative angles. A FWHM time resolution of ~1-1,5 ns is sufficient for discriminating protons, α particles and heavy-ions for flight paths larger than 10 cm and for the event-by event rejection of contaminant beams. It has to be noticed here, that for nuclear reactions induced by in-flight produced RIBs, the overall experimental energy resolution is often limited by the energetic spread of the RIB and by the energy loss and energy straggling of the ions in the target that should be thick enough to compensate the low intensity of the beam;

2) studying αclustering phenomena in light exotic nuclei [6], employing the Thick Target Inverse Kinematic (TTIK) scattering technique [7], with the RIB impinging ona ^{4}He gas target. The pressure of the gas is tuned such that the RIB completely stops in the gas while the energetic recoiling light target nuclei, due to their low-rate of energy loss, can traverse the gas and be recorded by the detectors. The TTIK method is particularly useful for measurements with low-intensity RIBs since it allows to measure the elastic scattering excitation function over a wide energy range by using a single beam energy. The experimental requirements for the detection array are: a good energy resolution, high granularity to reconstruct the interaction point and the beam energy at the interaction point and light particle identification. A FWHM time resolution of ~1-1,5 ns is enough for separating elastic scattering from other processes in most of the cases. It is worthnoting that the TTIK method helps improving the overall experimental energy resolution;

3) performing measurements of astrophysical interest with RIBs impinging on solid or gas light targets in inverse kinematics: among the different processes of stellar nucleosynthesis forming elements heavier than ^{9}Be, the rapid proton-capture and αp processes, occurring in explosive astrophysical environments such as novae, x-ray bursters and type Ia supernovae, are those than can be investigated by using the EXOTIC RIBs. Moreover, experiments based on the Trojan Horse Method (THM) [8] are considered. In the latter measurements, two among the three charged reaction products in the final state need to be detected with a ~2% FWHM energy resolution and a FWHM angular resolution better than ~1° [9].

4) performing measurements of fusion-evaporation cross sections at near- and sub-barrier energies. In this kind of experiments, the EXOTIC facility designed for the in-flight production of low-energy light RIBs, is employed as a separator of evaporation residues from the incident beam (stable or RIB). The evaporation residues are transported and detected at the focal plane of the facility.

Experimental set-up

The design of a high-performance detection system suitable for the above mentioned experiments must meet several requirements:

a) event-by-event beam tracking capabilities to account for the typical poor emittance of in-flight produced RIBs in conjuction with a good time resolution for Time of Flight (TOF) measurements and a fast signal for handling counting rates up to 106 Hz;

b) charge and mass identification of the reaction products with the highest achievable energy resolution;

c) a solid angle coverage as large as possible;

d) high segmentation to achieve good angular resolution and for reducing pile up events and low-energy events coming from the radioactive decay of the elastically scattered projectiles;

e) flexibility in order to be suitable for different experimental needs.

The experimental set-up [10] installed at the focal plane of the facility and displayed in the right-hand side of Fig. 1 consists of: (a) the RIB tracking system and (b) EXPADES, a new charged-particle telescope array. It satisfies the previously mentioned requisites for studies with low-energy light RIBs, moreover, it has the additional advantages of compactness andportability. The components of the EXPADES array can be easily reconfigured to suit many experiments while it can be used as an ancillary detection system with γ-ray and neutron arrays.

The two Parallel Plate Avalanche Counters (PPACs) of the tracking system, are position-sensitive, fast, high-transparency detectors, radiation hard which can sustain counting rates up to ~106 Hz. They are placed 909 mm (PPAC A) and 365 mm (PPAC B) upstream the reaction target (see Fig. 1, right-hand side). PPAC B is positioned at the entrance of the reaction chamber (element 10 in the schematic layout of the facility shown in Fig.1, left-hand side) to provide an event-by-event reconstruction of the trajectory of the RIB particles and a time reference for TOF measurements. The PPACs are filled with isobutane (C_4H_{10}) at a working pressure of 10-20 mbar and have entrance and exit windows that are made of 1,5 μm-thick mylar foil. The detector has a three-electrode structure: a central cathode and two anodes, placed symmetrically with respect to the cathode at a distance of 2,4 mm. The detector active area is 62 x 62 mm^2. The cathode is made of a 1,5 μm-thick stretched mylar foil while each anode is a mesh of 60 gold-plated tungsten 20 μm-thick wires in the x and y directions, with a spacing of 1 mm. The wires of the first anode are oriented horizontally and those of the second one vertically. The position information of a particle crossing the PPAC isextracted from the anode signals by using a delay-line readout. The 1 mm resolution of the two PPACs allows us to reconstruct the position of the event on the reaction target with a 2,3 mm position resolution. The cathode signal is used as a reference time for TOF measurements and for trigger purposes. The FWHM time resolution of a PPAC is about 0,9 ns.

EXPADES is an array of eight telescopes arranged in a cylindrical configuration around the reaction target (see Fig. 1, right-hand side). The telescope structure is flexible and is composed of two Double Side Silicon Strip Detectors (DSSSDs) and/or an Ionization Chamber (IC), depending on the experimental requests. We use 40/60 μm-thick DSSSDs for the ΔE stage (elements B in Fig. 1), whereas we adopt 300 μm-thick DSSSDs for the E_{res} layer (elements A in Fig. 1), manufactured by Micron Semiconductor Ltd. Each DSSSD has 32 junction and 32 ohmic elements (strips). The strips are 64-mm long, with 2 mm pitch size and 40 μm inter-strip separation. The junction strips of the frontyside are oriented orthogonally to the ohmic strips of the back x side, defining thus a 2x2mm^2 pixel structure. For experiments requiring the detection of more energetic particles than those stopped in the E_{res} layer, few 1 μm-thick DSSSDs were recently purchased, to substitute the 300 μm-thick DSSSDs or to be used in addition to the previous stages.

The choice of the electronic front end of the DSSSDs was based on a compromise between the requirement for high granularity, good energy and good time resolution and that to maintain low the overall cost. Application Specific Integrated Circuit (ASIC)-based electronics was employed for the treatment of the E_{res} signals. ASIC electronics allows us tohandle 32 energy signals of each side of the 300 μm-thick E_{res}DSSSD, ensuring a high granularity with a very low cost at the expense, however, of the possibility to perform TOF measurements with the requested time resolution(due to the lack of a constant fraction discriminator in the chip).To compensate the above drawback, for the signal readout of 40/60 μm DSSSD ΔEstage a compact low-noise electronics with an adequate dynamic range for the considered experiments (~100 MeV full range) and good energy and timing characteristics was developed by our collaboration.

In some experiments, the unambiguous identification by means of the ΔE-E_{res} technique of reaction products with range in silicon shorter than 40/60 μm might be of crucial relevance.A valid alternative to allow for ΔE-E_{res} identification of all the considered ions, is the use of an IC that can be handled easily, presents thickness uniformity, possibility to tune the effective thickness by changing the gas pressure, offers the chance of a large detection surface and does not present radiation damage problems. Thus, the construction of eight transverse-field ICs was undertaken. The ICs (elements C in Fig. 1, right-hand side)can be used as an alternative ΔEstage or to build up more complex triple telescopes. The IC is filled with carbon tetrafluoride (CF_4) at an operational gas pressure that can be varied up to 100 mbar, depending on the incident ion energy and on the species to be detected. It has 65x 65mm^2 entrance and exit windows made of 1,5 μm-thick mylar foil and an active depth along the ion direction of 61,5 mm.

The low-noise charge-sensitive preamplifiers for the ΔEDSSSDs (element D in Fig. 1, right-hand side), those of the ICs (not displayed in Fig. 1) as well as theboards containing the ASIC electronics (elements E in Fig. 1, right-hand side)for the E_{res}DSSSDs are placed under vacuum in the proximity of the array. This was done mainly for three reasons:

1) to have a compact set-up (detectors + electronics);
2) to minimize the internal and external connections and
3) to overcome the environmental noise at the EXOTIC beamline.

In this way, we manage to keep as low as possible the DSSSDs electronic thresholds, typically 300-500 keV.

The distance of the EXPADES telescopes from the target can be varied continuouslyfrom a minimum value of 105 mm to a maximum of 225 mm, which corresponds to an angular resolution for a pixel from $\Delta\theta = 1°$ to 0,5°. The maximum solid angle coverage (achieved in the configuration with only DSSSDs in use) is 2,72sr, that is 22% of 4πsr. When all eight ICs are employed, the DSSSDs have to be placed at a minimum distance of 225 mm from the target position and the maximum solid angle coverage decreases to 0,64sr(5% of 4πsr).

The whole EXPADES array and the PPACB are housed in the reaction chamber, placed at the final focal plane of the EXOTIC facility. To allow the realization of experiments with RIBs impinging on both solid and gas reaction targets, a small chamber housing the PPAC B was built. When requested, this small chamber isolates, through a 2 μm-thick HAVAR window, the two PPACs and the beam line (held at vacuum) from the reaction chamber that is filled with gas at pressures ranging from 0,4 to 1 bar.

Results and discussion

Studies on nuclear reactions and astrophysics

The RIBs of the EXOTIC facility and the above described experimental set-up have been used so far, in the framework of international collaborations, for the study of nuclear reaction dynamicsat Coulomb barrier energies [11-16] and α clustering phenomena in the light exotic nuclei ^{19}Ne and ^{15}O [17]. Moreover, a first experiment of astrophysical interest was performed by means of the THM for the study of the ^{7}Be(n, α)^{4}He reaction [18]. Other astrophysically important reactions are planned to be investigated. For example, the ^{8}B beam can be employed to have an accurate knowledge of the rate of the ^{8}B(p,γ)^{9}C reaction, important in hot *pp*-chains as it can provide a starting point for an alternative path across the A = 8 mass gap. By developing a radioactive ^{18}Ne beam, the ^{18}Ne(α,p)^{21}Na reaction could be studied at astrophysical energies to provide a link between the Hot CNO cycle and the *rp*-process. Other measurements relevant to astrophysics can be performed such as the ^{30}P(p,γ)^{31}S with a ^{30}P beam, essential for the production of heavy elements (from Si to Ca) in the explosion of O-Ne novae and in particular to explain the anomalously high ^{30}Si/^{28}Si rate measured in pre-solar grains of possible ONe novae origin.

Conclusions

Summary and perspectives

Finally, first encouraging results have been obtained for the use of the EXOTIC facility for sub-barrier fusion-evaporation cross section measurements [19]. The fusion reactions can be induced by the stable beams of the LNL Tandem XTU accelerator and also by the neutron-rich RIBs of the SPES (Selective Production of Exotic Species) ISOL-type facility, in construction at INFN-LNL.

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Recibido: 13 de febrero de 2018
Aceptado: 29 de mayo de 2018