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SPES: THE INFN EXOTIC BEAM ISOL FACILITY AT THE LNL AND ITS FIRST DAY SCIENTIFIC PROGRAM*

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SPES (Selective Production of Exotic Species) is the INFN project for the construction of a Radioactive Ion Beam (RIB) facility based on the ISOL method. The SPES facility is under development at the Legnaro National Laboratories site and it will provide mostly neutron-rich exotic beams produced through the proton induced fission on a direct UC_x target. The expected SPES beam intensities, quality and energies (up to 11 MeV/A for $A = 130$) together with the up-to-date experimental apparatuses, which are at present and will be in the near future available at the LNL, will permit performing forefront research to study nuclear structure and nuclear dynamics in a region of the nuclear chart far from stability.

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1. Introduction

The INFN National Laboratories of Legnaro (LNL) and Catania (LNS) are considered as a unique Laboratory toward the European partners and, in particular, they are part of the ENSAR project, known as Transnational Access Activity within the European VII Framework Program, to provide all European researchers access to their infrastructures for nuclear and applied physics experimentation at the existing accelerators [1]. These activities are related to the well known European Large Scale Facilities framework.

In this context, the updated SPES project was born after a redefinition of the INFN financial plane and it is based on the competence and experience of the two National Laboratories, both from the point of view of the technological development on accelerators and sources, and for what concerns the experimental equipments to be used. SPES is, moreover, mentioned and supported in the NUPECC Long Range Plane [2]. The RIB project is mainly related to the development of an ISOL facility for neutron-rich exotic beam production, by means of a quite intense proton beam (of the order of few hundreds of μA), which is sent on a direct and sliced UC_x target, with the aim of producing up to 10^{13} fissions/s [3].

In the meanwhile, the chosen proton driver should give the possibility of performing also interdisciplinary physics studies and appliances, especially devoted to material analysis, neutron production and medical applications (like, for example, radioisotope production). Four different independent stages have been proposed with separate financial budgets: the α phase, related to the development and installation of the proton-driver and to the building construction, comprehensive of the production target achievement; the β phase, related to the RIBS transport and post-acceleration; the γ phase, dealing with the proton and neutron beam irradiation facilities; finally, the δ phase, related to medical applications and radioisotope production.

2. The SPES project

Technical details about the elements of SPES can be found in the Technical Design report of 2008 [4]. In particular, the SPES ISOL facility is based on a commercial 70 MeV Cyclotron as proton driver. It is produced by the BEST Theratronics company [5], designed to provide a beam intensity up to 750 μA with variable energy ranging between 35 and 70 MeV. The beam impinges on a direct multi-foil target (mainly UC_x) in order to reach the desired number of fissions, that is 10^{13} fissions/s [4]. Different Target-Ionization Sources systems (TIS) are under development and will be used in order to optimize the extraction efficiency of the desired isotopes and to minimize the beam contaminants. The radioactive beams (RIBs) will be selected through an High Resolution Mass Spectrometer (HRMS), before being transported towards the Charge Breeder stage. A cross section of the SPES layout is shown in Fig. 1: the Cyclotron area is shown on the right part. On the very right part of the layout, there is the area dedicated to applications. On the left side of the Cyclotron area, the two RIB production

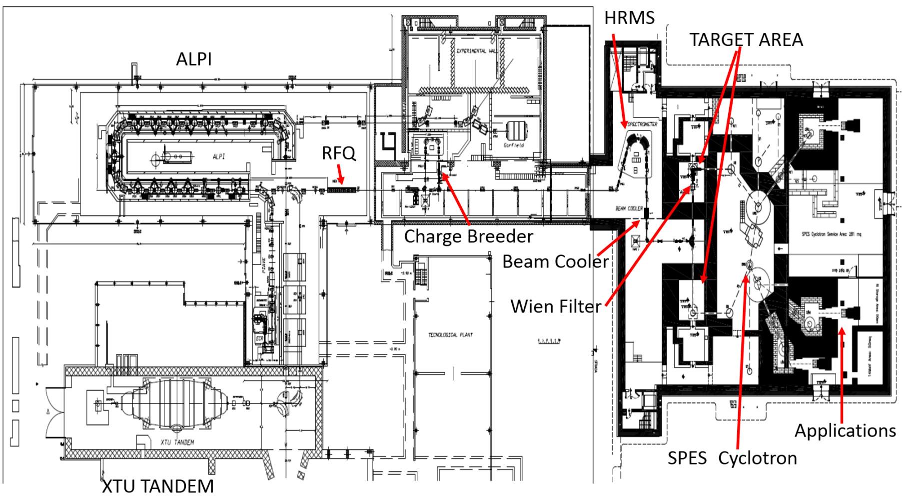

Fig. 1. The SPES layout.

target halls are shown. A first selection of the exotic beams is performed just at the exit of the TIS system by a Wien Filter and by the first 90° Dipole magnet ($\Delta M/M \simeq 1/200$). The transfer line is then designed to pass through a Beam Cooler stage, which is necessary to properly inject the beam into the HRMS ($\Delta M/M \simeq 1/20\,000$). The transport line proceeds down to the Charge Breeder, after which a further selection is provided by a Medium Resolution Mass Spectrometer MRMS ($\Delta M/M \simeq 1/1000$), necessary to clean up the beam from contamination originating from the breeding stadium. Finally, a new normal conductive RFQ injector is being designed to properly injet the RIBs into the Linac ALPI for the post-acceleration. The selected exotic beam will, eventually, reach the experimental area where the secondary target, provided by the user for the proposed experiments, will be set up. The building design has been approved and the ground breaking, which started few months ago, is proceeding fast as shown in the SPES construction site picture reported in Fig. 2.

Fig. 2. The SPES construction site.

2.1. The proton driver

The BEST Cyclotron is able to accelerate H^- beam, provided by an external multi-cusp ion source, up to the energy of 70 MeV. The proton extraction is performed by a stripping process and, therefore, the final energy can vary continuously between 35 and 70 MeV. The cyclotron is a compact four-sector machine, energized by a pair of room temperature conducting coils. Two independent extraction channels are placed at 180° and can provide two proton beams simultaneously. The H^- beam is provided by an external ion source with a current of about 15–20 mA, which is necessary to deliver the final designed current of 750 μA at the exit of the cyclotron. An axial transport line is used to inject the beam from the source to the cyclotron upwards to the spiral inflector which bends the beam 90° into the central region at the median plane.

The cyclotron is under construction and test in Ottawa (Canada) and it will be transported and commissioned at the LNL in 2014.

2.2. The Target-Ion Source systems

The interaction of the proton beam with the UC_x target will produce fission fragments, among which the neutron-rich isotopes of interest. The isotopes will be extracted by thermal motion and ionized at 1^+ charge state by a source directly connected with the production target. The expected effusion and diffusion times sum up to $t_{\rm tot} \simeq 1\,$s: this limit an efficient extraction to exotic species characterized by lifetimes larger than $\simeq 100$ ms. The target-ion source system is, therefore, one of the key elements of the SPES project: in particular, the target is based on a multi-foil structure design (7 thin UC_x disks for a total of 30 g of uranium) as shown in Fig. 3. The

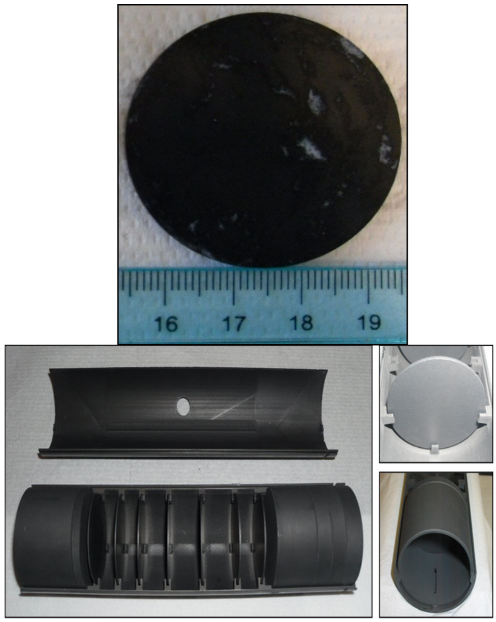

Fig. 3. The SPES multi-foil UC_x target.

power on target, considering a 40 MeV high intense proton beam (200 μA) is 8 kW. The resulting power density on target is such as to maintain the temperature well under the UC_x melting point ($\simeq$ 2350°C) [6]. The proposed target geometry has demonstrated to support much higher currents with respect to the compact configuration [7]. Besides UC_x different target materials (SiC, B_4C, ZrC, Al_2O_3, CeS, LaC_x, TaC *etc.*) are under development to produce also some neutron deficient beams. The production target is a part of the TIS system (Target-Ion Source). Different kinds of sources have been developed to optimize the extraction procedure for the different elements and to minimize the contamination: among them the Surface Ionization Source (SIS), the Plasma Ion Source (PIS) and the Laser Ionization Source (LIS). The hot-cavity ion source chosen for the SPES project is based on that one designed at CERN (ISOLDE) [8]. The basic structure of the standard high temperature RIB source has been chosen, with the ionizer cavity which is a tungsten tube (34 mm length, 3 mm inner diameter and 1 mm wall thickness) resistively heated up to 2 000°C. Due to the high temperature, the produced isotopes are forced to diffuse in the target material and lately to effuse through the transfer tube (the length of which is approximately 100 mm). They reach in this way the ionizer cavity, where they undergo surface or laser ionization. In particular, the surface ionization process occurs when atoms interact with a hot metal surface. The transfer of a valence electron from the atom to the metal surface is energetically favourable for the elements with an ionization potential lower than the work function of the metal: this is the case for alkalis and for some of the rare earth elements, where high ionization efficiencies can be achieved using the surface ionization technique. This 1^+ source has good efficiency and selectivity for the elements as Rb, Cs, Ba. For most part of the others elements, the laser resonant photo-ionization, using the same hot cavity cell, is a powerful method to achieve sufficiently selected exotic beams [9]. In order to ionize elements with high ionization potential, like the rare gasses, the plasma source is needed: this source easily ionize many elements, but it has the drawback of no selectivity. Both surface and plasma sources have been developed and in operation at the off-line test-bench laboratory, while the laser ionization technique is under development aiming at producing the most pure beams as possible (chemical selectivity) also for metal isotopes.

2.3. The beam selection and transport

The first mass selection, at the exit of the TIS system, is performed by a Wien Filter with $\simeq 1/100$ mass resolution, installed just after the first electrostatic quadrupole triplet inside the production bunker. The aim of the designed configuration is to confine the larger part of radioactivity inside the highly shielded area. The test bench, which has been developed and presently used off-line for all the TIS system tests, is shown in Fig. 4.

The transfer line toward ALPI is equipped with several beam handling systems to purify the beam. Beside the beam intensity, the beam quality and purity are, in fact, further crucial tasks to be kept under control in order to perform exotic beam experiments. Special efforts have been, therefore, dedicated to the design of a High Resolution Mass Spectrometer (HRMS) able to reach an effective mass resolution of at least 1/20 000. To reach this goal, the HRMS physics design in the SPES configuration is made so as to reach a resolution of $\Delta M/M \simeq 1/40\,000$, value which is constrained by values of 3π mm mrad in emittance and 1.3 eV in energy spread. In order to improve the beam emittance, a Beam Cooler element is being designed. Moreover, the mass spectrometer is mounted on a 260 keV High Voltage platform. The mass separator is a scaled-up version of the separator designed for CARIBU (Argonne) by Davids [10]. Before the injection in the Linac ALPI, the charge state of the accelerated elements will be increased from 1^+ to N^+: for this purpose in the SPES configuration a Charge Breeder based on ECR method

(working since 2010)

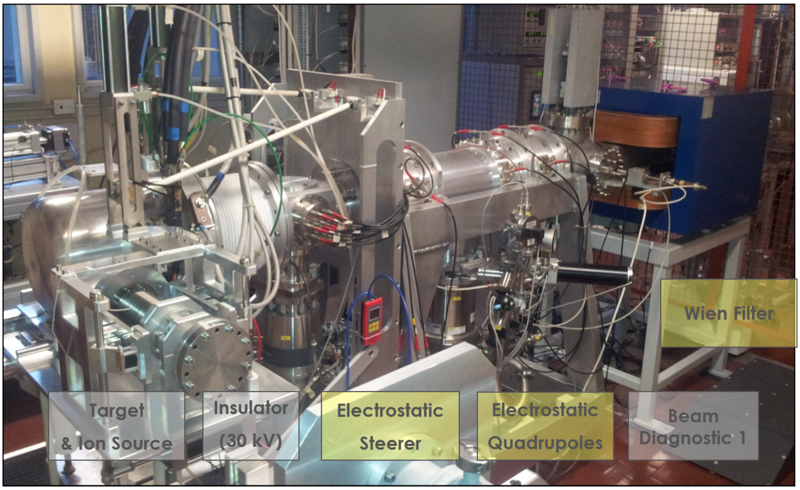

Fig. 4. The SPES test bench: from the left-hand side one can observe the proton beam line, the TIS system, the insulator, the electrostatic steerer, the electrostatic quadrupole and, finally, the Wien Filter selector.

is under development. The designed Charge Breeder aims at producing ions with $A/q \leq 6$ at $A \simeq 130$. The design and construction will be performed in the framework of the SPES–SPIRAL2 Collaboration at LPCS (Grenoble, France) following an up-graded version of the Phoenix booster [11]. After the Charge Breeder, a second mass separator MRMS with resolution $\Delta M/M \simeq 1/1000$ will be installed to purify the beam from the contaminants introduced by the Charge Breeder itself. The same basic configuration of the HRMS is adopted. After the Mass Spectrometer, a Medium Energy Beam Trasport (MEBT) line matches the beam to the injection acceptance of a CW normal conducting RFQ, which imparts to the beam the energy required by the velocity profile ($\beta_{\rm opt}$) at the entrance of ALPI. The RFQ [12] will operate in CW mode (100% duty factor) at 80 MHz (frequency of the lowest energy ALPI superconducting cavities).

2.4. The post-accelerator ALPI

The post-accelerator is the upgraded superconducting Linac ALPI, designed and developed in the 90s at the LNL [13]. The RFQ ion injection energy has been set to 5.7 keV$/u$. This choice is a compromise between the ion energy reduction needed to simplify both the Low Energy Beam Transfer (LEBT) and the RFQ bunching section design, and the need to reduce space charge effects increasing the beam rigidity in the 1^+ transport line.

The extraction energy of the RFQ has been set to 727 keV/u to optimize the beam dynamics of the post-accelerator. The ALPI machine underwent a major maintenance and upgrading in order to optimize the performance for the RIBs transport: a laser alignment has been performed to improve the transmittance along the machine. Moreover, an upgrading of the cavities has been made: the accelerating field of every cavity has been optimized and new cryostats have been added both in the high energy part and in the *low Beta* region: in this way, the expected final energy values are of the order of 10–11A MeV for $A/q = 6$. Finally, the LNL accelerator complex is undergoing a major upgrade of its control systems in order to integrate seamlessly with the operation of the overall SPES. The new control system (CS) will use modern network technologies to distribute its action on the campus area and will rely on networked services to fulfil its goals. The control software is based on EPICS [14].

2.5. Expected performances

The SPES performances in terms of beam intensities at the production/extraction point (after the ionization source 1^+) and at the secondary target (experiment) position (post-accelerated intensities) have been evaluated and reported in Ref. [16]. To evaluate the final *beam-on-experiment* intensities, the efficiencies of the source (effusion–diffusion, ionization and extraction), of the charge breeding, of the beam transport and re-acceleration have been evaluated, considering the different isotopes. As an example, a value for 1^+ (target-ion source) and N^+ (Charge Breeder) ionization efficiencies equal to 90% (1^+) and 12% (N^+) was used respectively for Kr and Xe, but only 30% (1^+) and 4% (N^+) for Zn, Sr, Sn, I and Cd. The Linac ALPI transmission efficiency has been conservatively considered 50%. The results have been validated comparing the intensities calculated through Monte Carlo calculation with the scaled up intensities (ratio of the SPES toward HRIBF [15] proton beam currents) obtained at HRIBF at the 1^+ position. Moreover, experimental tests have been performed using the proton beam at HRIBF on the SPES sliced target geometry: these tests confirmed the larger extraction efficiency from the source in the case of the SPES target with respect to the ORNL compact one [7]. Typical expected values for ^{132}Sn are 1.6×10^9 at 1^+ and 3.1×10^7 at N^+ respectively (this last considering a final energy of 11A MeV).

2.6. The project schedule

The SPES Project is now in its realization stage. The building work started in February 2013 and it is on schedule. The Cyclotron and its ancillary systems are under test at the BEST Theratronics in Ottawa. The beam line towards the production target is under construction. All the other components and the refurbishment of the LNL Linac ALPI accelerator is on-going. The SPES up-to-date schedule is shown in Fig. 5.

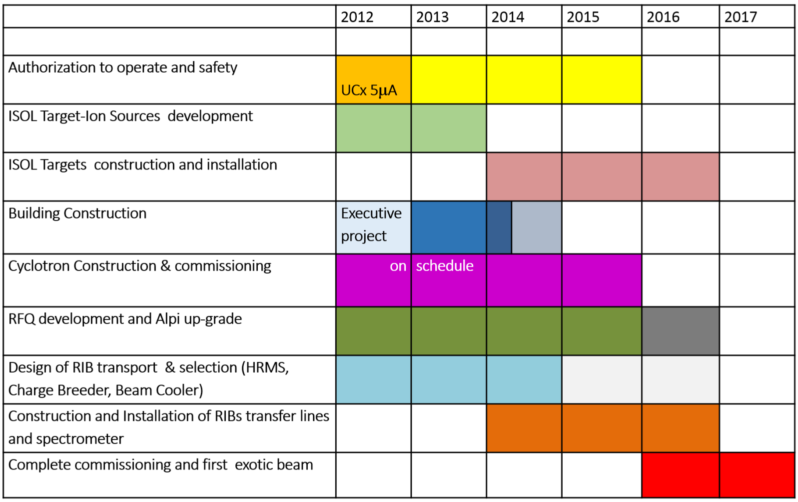

Fig. 5. The SPES schedule.

3. Physics cases and instrumentation

The SPES scientific program is under discussion based on the long-standing experience in nuclear structure and dynamics studies of the LNL and LNS user community. In particular, one of the traditional fields is the study of nuclei under extreme conditions, that is the study of the evolution of nuclear structure towards the region far from stability in terms of excitation energy (decay and behaviour of hot nuclei), high spin states (highly rotating nuclei), and, finally, high isospin (high N over Z ratio). Far from stability, some basic truths of nuclear physics, which were previously deduced studying nuclear systems lying close to the stability valley, have to be revised (nuclear radius behaviour, shell evolution and magic numbers survival, nucleon–nucleon correlations, cluster structure *etc.*).

3.1. SPES Scientific Workshops

On the bases of these many questions, a first call for Letters of Intent was submitted to Users in 2010 and several proposals have been discussed during the SPES2010 International Workshop, held in Legnaro in November 2010. The major number of the presented LoI were based on the equipments which are already installed at the LNL or under development. Further meetings have been organized: a SPES School on Experimental Techniques with RIBs, some one-day Workshops to finalize the proposals on five selected items: Transfer Reactions (Naples 2012), Coulomb Excitation (Florence 2012), Isospin in Reaction Mechanisms (Catania 2013), Collective Excitations of Exotic Nuclei (Milan 2013), Fusion–Evaporation Reactions with RIBs (to be held at the LNL, 2014) together with the Second SPES International Workshop (May 2014).

3.2. Coulomb Excitation at SPES

Coulomb Excitation (CE) is a very precise tool to measure the collectivity of nuclear excitations and, in particular, to study nuclear shapes. It selectively populates collective degrees of freedom with cross sections that are a direct and sensitive measurement of the multipole moments. This technique has been extensively used with stable nuclei but the advent of energetic radioactive ion beams makes it possible to use radioactive projectiles. Different proposals, using inverse kinematics, have been presented during the workshop to study nuclei in the Sn or in the Ni, Se, Zn and Cu region in order to study the shell evolution and the nuclear interaction as a function of the growing number of neutrons. CE is confirmed to be the best candidate for start-up experiments with RIBs at SPES, as the available bombarding energies and beam intensities meet well the experimental needs. Moreover, the relatively low currents required allow to perform studies up to the most weakly populated exotic nuclei. A tool, which will be very important in such a kind of measurements, is the GALILEO γ-ray detector [18], which is presently under development at the LNL, coupled to different ancillaries for the experiment tagging.

3.3. Direct reactions at SPES

Mechanisms and processes like Coulomb Excitation, transfer from inelastic to collective states and single particle transfer are essentially well described by one-step mechanism. However, already when dealing with the transfer of couple of nucleons, the processes become much more complicated: the multi-nucleon transfer mechanisms are therefore quite difficult to be properly described. From the stripping and pick-up of one neutron or proton, one can obtain information about the shell structure of the two colliding nuclei, while the exchange of many nucleons allows to study nuclear correlations, in particular the pairing ones, in the nuclear medium. By measuring important observables, like mass, charge, Q-value distributions and cross sections of transfer reaction products in suitable light and heavy exotic ion reactions, the contribution of the neutron–proton correlation, the density dependence of the pairing forces and the possibility of studying the onset of super-currents with very large number of neutrons transferred among the colliding nuclei can be studied. Moreover, using nuclei with an extended neutron distribution the coupling to the continuum could be disentangled in the formation of the compound nucleus and overall in the dissipation of energy and angular momentum. These processes have been addressed and studied at Legnaro since many years with stable beams and, in particular, there was a very large campaign performed using the PRISMA spectrometer coupled to a quite efficient γ-ray array (initially CLARA and then AGATA) [17]. In this way, the structure of moderately n-rich nuclei have been studied performing a complete γ-ray spectroscopy study of different nuclei reconstructing the angular momentum, parity and life time.

3.4. The isospin degree of freedom at SPES

The behaviour and the correlations between neutrons and protons in the nuclear matter are known to strongly affect both nuclear structure and reaction dynamics. In particular, the nucleon–nucleon interaction, the nucleon effective mass, the competition between mean field and nucleon–nucleon collision are all dependent on the charge/mass asymmetry of the considered nuclear system. Isospin symmetry breaking effects in nuclear structure, like, for example, the isospin mixing or non-conserving forces, can be experimentally evidenced by observing the distorsion of the γ-ray emission from Giant Dipole Resonances (Dynamic Dipole) and/or the differences in isobaric states of mirror nuclei. In nuclear reactions, by comparing several de-excitation channels in reactions with different N/Z ratio in the entrance channel and/or in the composite system, isospin effects can be evidenced: they are related to a variation in the relaxation times of those degrees of freedom, which are correlated to the asymmetry term in the nuclear equation of state. Radioactive beams makes it possible to reach much larger N/Z asymmetries, while the combination of exotic and stable beams results in a very large number of target–projectile combinations that allows to perform a systematic study of the phenomenon. Available tools are the GARFIELD apparatus [19] and the FAZIA demonstrator [20] eventually coupled to neutron (NEDA) [21] or γ-rays arrays (GALILEO, PARIS [22]).

3.5. Fusion–evaporation at SPES

The behaviour of heavy-ion fusion cross sections at energies far below the barrier is also of interest: measurements of very small fusion cross sections (down to 10–20 nb), below the energy where the fusion barrier distribution vanishes, have unexpectedly shown that the slope of the excitation function continues increasing at lower energies, on the contrary of what expected in barrier penetration phenomena. This was named *hindrance effect* and it has been proposed to be related to a repulsive term in the ion–ion potential which simulates the effect of nuclear incompressibility. The neutron-rich exotic beams from SPES will allow to shed light on the physics underlying hindrance at low energies in a variety of cases and can be afforded with the PRISMA spectrometer at the LNL [23].

4. Conclusions and outlooks

The SPES project is under construction and accelerated exotic beams are foreseen in the forthcoming years. Collaborations are growing up around new performing instrumention to afford the second generation of ISOL facilities like SPES, SPIRAL2 and HIE-ISOLDE. Complementary campaigns will be performed in order to achieve important results for nuclear structure and dynamics studying the nuclear matter far from the stability valley.

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