

The SPES project: a second generation ISOL facility

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SPES (Selective Production of Exotic Species) is an INFN project to develop a Radioactive Ion Beam (RIB) facility as an intermediate step toward the future generation European ISOL facility EURISOL.

The aim of the SPES project is to provide high intensity and high-quality beams of neutron-rich nuclei to perform forefront research in nuclear structure, reaction dynamics and in interdisciplinary fields like medical, biological and material sciences. The SPES project is part of the INFN Road Map for the Nuclear Physics, it is supported by the Italian national laboratories LNL (Legnaro) and LNS (Catania). It is based on the ISOL method with an UCx Direct Target able to produce 10^{13} fission/s by proton induced fission in the UCx target. The primary proton beam is delivered by a Cyclotron accelerator with energy of more than 40 MeV and a beam current of 200 μ A and the target is designed to sustain a beam power of 8-10 kW. The exotic isotopes will be re-accelerated by the ALPI superconducting LINAC at energies of 10 AMeV and higher, for masses in the region of $A=130$ amu, with an expected rate on the secondary target of $10^7 - 10^9$ pps.

The status of the project will be reported pointing to the development of the target design and to the facility perspectives.

1. Introduction

Presently our knowledge about the structure of nuclei is mostly limited to nuclei close to the valley of stability or nuclei with a deficiency of neutrons. Only recently the availability of beams of unstable ions has given access to unexplored regions of the nuclear chart, especially on the neutron rich side. Starting from a nucleus on the stability line and adding successively neutrons, one observes that the binding energy of the last neutron decreases steadily until it vanishes decaying by neutron emission. The position in the nuclear chart where this happens defines the neutron drip line. It lies much farther away from the valley of stability than the corresponding drip line associated with protons, owing to the absence of electrical repulsion between neutrons. The location of the neutron drip line is largely unknown as experimental data are available only for nuclei with mass up to around 30. The interest in the study of nuclei with large neutron excess is not only focused on the location of the drip line but also on the investigation of the density dependence of the effective interaction

between the nucleons for exotic N/Z ratios. In fact, changes of the nuclear density and size in nuclei with increasing N/Z ratios are expected to lead to different nuclear symmetries and new excitation modes. While in the case of some very light nuclei a halo structure has been identified, for heavier nuclei the formation of a neutron skin has been predicted. The nuclear properties towards the neutron drip line depend on how the shell structure changes as a function of neutron excess. These changes have consequences on the ground state properties of the nuclei and on the single-particle and collective excitations. In particular, studies of neutron-rich nuclei beyond the doubly magic ^{132}Sn are of key importance to investigate the single-particle structure above the $N=82$ shell closure and find out how the effective interaction between valence nucleons behaves far from stability. New modes of collective motion are also expected in connection with the formation of a neutron skin, namely oscillation of the skin against the core, similar to the soft dipole mode already identified in the case of very light halo nuclei. Presently, neither

the thickness nor the detailed properties of the neutron skin of exotic nuclei are known. This information is needed to enable a quantitative description of compact systems like neutron stars, where exotic nuclei forming a Coulomb lattice are immersed in a sea of free neutrons, a system which is expected to display the

properties of both finite and infinite (nuclear matter) objects. At the beam energies of SPES, it will be possible to address questions related to the properties of neutron rich matter from the perspective of nuclear forces, level density, viscosity, barrier, neutron pairing and collective modes.



Fig. 1 The Laboratori Nazionali di Legnaro and the SPES area.

2. The LNL accelerator facilities

In order to better underline the framework in which the SPES project is going to be developed, a short description of the Legnaro National Laboratory (LNL - figure 1) will be briefly outlined in the following. The LNL heavy-ion accelerator complex is based on a 16 MV Tandem XTU, a Superconductive LINAC (ALPI) and a superconductive radiofrequency quadrupole (RFQ) heavy ion injector (PIAVE). The Tandem XTU is operating stand alone or as an injector to ALPI. The super-conducting RFQ injector PIAVE is based on an ECR Ion Source

(placed on a 350 kV platform) and on a super-conducting RFQ able to accelerate ions with $A/q < 8.5$ up to an energy/nucleon of 1.2 MeV/A. The ALPI accelerator is a superconducting heavy ion LINAC, composed of three quarter wave resonator (QWR) sections for a total of 80 cavities installed. It operates routinely at an equivalent voltage of 50 MV. The LINAC is constructed in a bended configuration: it is composed by two branches connected by an achromatic and isochronous U-bend. It uses three different kinds of cavities: Low Beta, Medium Beta and High Beta cavities, according to the

different velocity along the acceleration path. In the last years the cavities of the medium energy QWR section were upgraded using a new Nb sputtered coating in substitution to the original Pb sputtered layer. An upgrade program is on the way, to improve the accelerating fields of the present QWRs and adding more cavities in the Low Beta section. The final equivalent voltage is expected to exceed 70 MV in optimized conditions (all the resonators operating at the designed voltage, normalized transit time factor and synchronous phase taken into account). A further energy improvement has been tested recently installing a stripper station before the U-bend. In this condition the energy/nucleon increased by 20% (from 6.8 to 8.1 MeV/A for ^{136}Xe) with the drawback of a reduced transmission (30%).

3. The SPES project

SPES [1] is designed to provide neutron-rich radioactive nuclear beams (RIB) of final energies in the order of 10 - 13 MeV/A for nuclei in the $A = 80$ -130 mass regions. The radioactive ions will be produced with the ISOL technique using the proton induced fission on a Direct Target of UCx [2,3] and subsequently reaccelerated using the PIAVE ALPI accelerator complex. An Uranium fission rate of 10^{13} fission/s is foreseen.

A Cyclotron with a maximum current of 0.750 mA rowing two exit ports will be used as proton driver accelerator with variable energy (30-70 MeV).

Two proton beams can be operated at the same time sharing the total current of 0.750 mA. To reach a fission rate of 1013 fission/s a proton beam current of 200 μA (40 MeV) is needed; the second beam, up to 500 μA 70 MeV, will be devoted to applications as neutron production for material research and study of new isotopes for medical applications,

The expected rate of fast neutrons is estimated to be 10^{14} n s $^{-1}$. At the target output using Pb target (mean energy 1 MeV).

The SPES lay-out is shown in figures 2 and 3.

Figure 2 shows schematically the transfer line for the exotic beam. The general configuration of the SPES layout follows the one

of the EXCYT facility, the ISOL facility for proton-rich nuclei in operation at LNS (Catania, Italy). The production target and the first mass selection element will be housed in a high radiation bunker and mounted on a high voltage platform. Before the High Resolution Mass Spectrometer a cryopanel will be installed to prevent the beam line to be contaminated by radioactive gasses. After passing through the High Resolution Mass Spectrometer (HRMS), the selected isotopes will be stopped inside the Charge Breeder and extracted with increased charge. A final mass selector (CB_MassSelector) will be installed before reaching the PIAVE-ALPI accelerator, to clean the beam from the contaminations introduced by the Charge Breeder itself.

In figure 3 the ISOL facility is located in the white area, housing the cyclotron proton driver, the two RIB targets, the High Resolution Mass Spectrometer (HRMS) and the transfer lines. For safety reasons the ISOL facility is designed to be constructed 5 meter below ground level. The target development laboratory (not shown in figure 3) will be constructed at ground level above the ISOL facility. Two laboratories for applied physics and other applications are planned: one at the same level of the ISOL facility, which makes use of the Cyclotron proton beam, and another at ground level.

4. The target system

The most critical element of the SPES ISOL facility is the Direct Target. The proposed target represents an innovation in term of capability dissipate the primary beam power.

The SPES target design has been optimized in order to maximize the release efficiency and to exploit, at the same time, devices (basically the ion sources) developed in other laboratories. The energy deposited in the target material by the electromagnetic and nuclear interactions has to be removed, and because of the low pressure of the environment, the target can be only cooled by thermal radiation towards the container box surrounding it. In order to optimize the heat dissipation along with the fission fragments evaporation, the SPES target consists of multiple



Fig. 2 The lay out of the SPES ISOL facility .

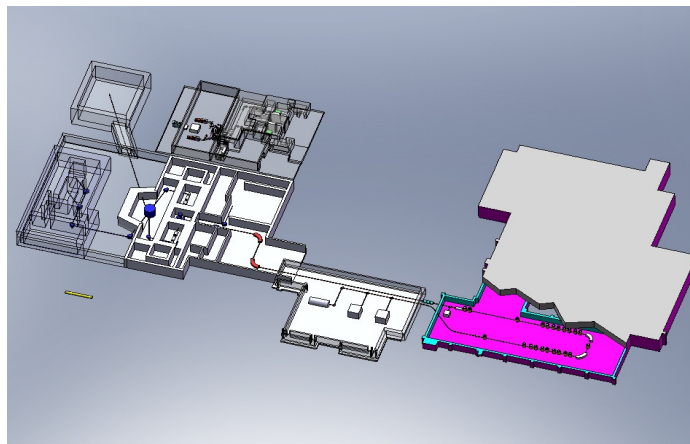


Fig. 3 The lay out of the SPES ISOL facility and connection to the reaccelerator.

thin disks housed in a cylindrical graphite box [4].

In this configuration only the protons with higher fission cross-section are exploited in the UC_x target discs, while the outgoing lower energy, less than about 15 MeV, is driven towards a passive graphite dump; as a consequence, the power deposited in the discs is lowered considerably and at the same time the number of fission reactions is maintained high. The SPES production target (see Figure 4 and 5) is composed of 7 UC_x co-axial disks (diameter and thickness of 40 and 1.3 mm, respectively), appropriately spaced in the axial direction in

order to dissipate by thermal radiation the average power of 8 kW due to the proton beam which, passing through them, induces nuclear reactions.

Two thin (200 μ m) circular windows made of graphite are located at the proton beam entrance to prevent the undesired emission of the radioactive nuclei, while four other circular graphite disks with thickness ranging from 0.8 up to 10 mm stop the proton beam after passing through the windows and the UC_x pellets. UC_x and graphite disks, are housed inside a tubular hollow box made of graphite, having an external diameter and an average length of 49 and 200 mm, respectively. The box is located under

vacuum inside a water-cooled chamber and has to maintain the average temperature of 2000°C: vacuum and high temperature are essential to enhance the radioactive nuclei extraction.

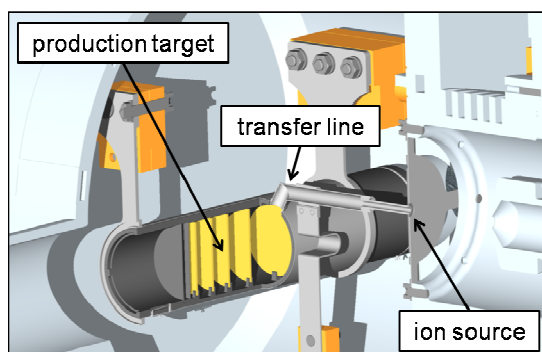


Fig. 4 Conceptual design of the SPES production target system.



Fig. 5 The first UO+nC pellet before the thermal process of carburization.

The proton beam power is not sufficient to heat the box up to the required temperature level due to the intense heat exchange by radiation from the graphite box to the water-cooled chamber. As a consequence, it is crucial to introduce an additional and independent heating and screening device. It is important to underline that this heating component is completely independent from the proton beam and, additionally, allows for a better thermal control of the target when the proton beam power is not stabilized, i.e. during the start-up and the shut-down procedures.

In the selection of the beam profile, a uniform distribution of the beam has been

chosen in order to flatten as much as possible the power deposition inside the disks and consequently, to reduce temperature gradients and thermal stresses.

An extensive simulation of the target behaviour for thermal and release properties is at the bases of the target-ion-source design. Experimental work to bench mark the simulations was carried out in collaboration with HRIBF, the Oak Ridge National Laboratory ISOL facility (USA). The production target is designed following the ISOLDE (CERN) and EXCYT (LNS, Catania) projects, devoting special care to the system for safety and radiation protection.

5. The ion source system

The interaction of the proton beam with the UCx target will produce fission fragments of neutron-rich isotopes that will be extracted by thermal motion and ionized at 1^+ charge state by a source directly connected with the production target.

The hot-cavity ion source chosen for the SPES project was designed at CERN (ISOLDE) [5]. The source has the basic structure of the standard high temperature RIB ion sources employed for on-line operation. The ionizer cavity is a W tube (34 mm length, 3 mm inner diameter and 1 mm wall thickness) resistively heated to near 2000°C. The isotopes produced in the target diffuse in the target material and after that will effuse through the transfer tube (its length is approximately equal to 100 mm) into the ionizer cavity where they undergo surface or laser ionization. The Surface ionization process can occur when an atom comes into contact with a hot metal surface. In the positive surface ionization, the transfer of a valence electron from the atom to the metal surface is energetically favourable for elements with an ionization potential lower than the work function of the metal. Ideally that atoms should be ionized $+1$, then extracted and accelerated to 60 keV of energy and after that injected in the transport system. For alkalis and some rare earth elements high ionization efficiencies can be achieved using the surface ionization technique. For most part of the others elements, the laser resonant photo-ionization, using the same hot cavity cell,

is the powerful method to achieve a sufficient selective exotic beams. This technique will be implemented in collaboration with the INFN section of Pavia. The aim is to produce a beam as pure as possible (chemical selectivity) also for metal isotopes, as shown in Figure 5.

performed in a ionization chamber, coupled to a time of flight mass spectrometer. This system is intended for a full diagnostic of LIS applied to the chemical elements belonging to the fission fragments selected by the SPES group.

6. The beam selection

		Light Metals				Nonmetals																											
GROUP		Ia		IIa																		IIIa	IVa	Va	VIa	VIIa	VIIIa						
		H Hydrogen 1,008 1		Li Lithium 6,94 3	Be Beryllium 9,013 4																	B Boron 10,82 5	C Carbon 12,011 6	N Nitrogen 14,008 7	O Oxygen 16 8	F Fluorine 19 9	Ne Neon 20,183 10						
																						Atomic Symbol Element Name Atomic Weight (****) Atomic Number											

Fig. 5 The main isotopes that will be ionized and extracted in the SPES project.

The laser ion source has been investigated in the past at Pavia University, as a spin-off of the atomic vapour laser isotope separation. As first step for the R&D of the photo-ionization process for SPES, dye laser will be used to generate resonant light source. In order to investigate the proper ionization path for the element of interest, Pavia laboratory is current using a Hollow Cathode Lamp (HCL) as atomizer. This device is a good and simple atoms reservoir for preliminary studies. The Optogalvanic Effect, OGE, is the detection system. The usual OGE rises from change of the impedance in the HCL discharge, due to the thermalization of resonant absorbed light. Such a thermalization leads to variation into ionization percentages also. In case of laser photionization, electrons and ions are produced during the laser pulse and in this case a fast OGE can be observed. After these preliminary studies, resonant atomic excitation and ionization will be

The selection and the transport of the low intensity exotic beam at low energy is a challenging task. Techniques already applied to the EXCYT beam are of reference for SPES; they include the High Resolution Mass Spectrometer, the online identification station and several systems for low current beam diagnostics. Before the injection in the PIAVE-ALPI Linac, the Charge Breeder is an essential element for an effective reacceleration as it increases the charge state from 1+ to n+. The SPES Charge Breeder is based on ECR method and aims to produce ions with A/q less than 6 for A~130.

A crucial task for the experimental use of radioactive beams is not only the beam intensity but also the beam quality. Special efforts have been dedicated to design a mass spectrometer with an effective mass resolution of at least 1/20000. Such design takes advantage of the 260 keV beam energy obtained with the HV

platforms. Such high selectivity results in an advantage also for the safety issue, reducing the problems of contaminations along the beam transport areas and in the target location.

The expected beam-on-target intensities are of the order of 10^8 pps for ^{132}Sn and ^{90}Kr , and of about 10^6 - 10^5 pps for ^{134}Sn and ^{95}Kr , considering a total efficiency of 2% for the transmission from the 1^+ source to the experimental target. Figure 6 shows the beam on target intensities expected for the final stage of the project.

7. The target front-end

At the moment, there are being started the off-line testing on the Target Front-end in the SPES laboratories at LNL, see Figure 7. The SPES target front-end has two major phases: the off-line testing with production of stable ion beams accelerated up to 30 keV, and the on-line production of RIBs accelerated up to 60 keV for the SPES facilities. We are actually in the first phase, generating beam by gas injection in the target chamber by mass marker.

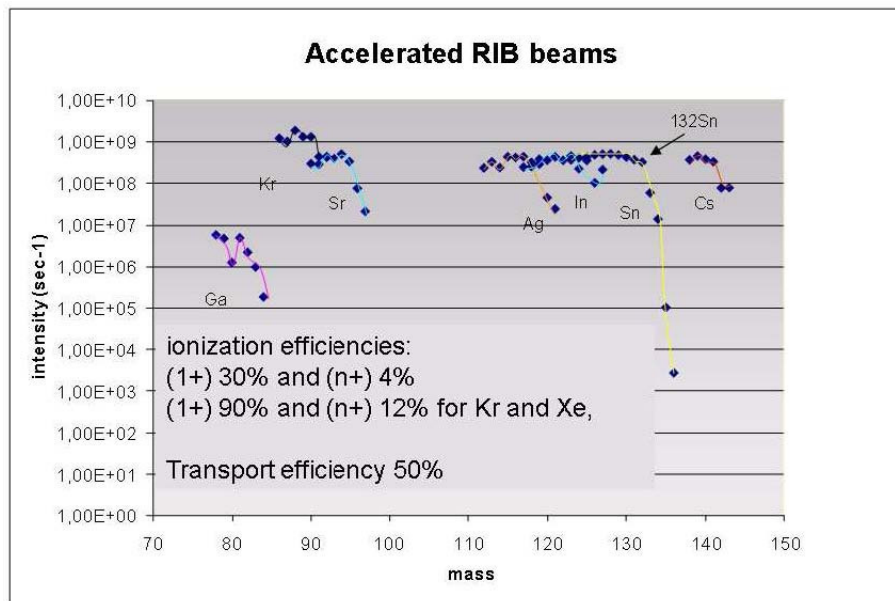


Fig. 6 Expected on-target intensities calculated considering emission, ionization and acceleration efficiencies for different isotopes.

The in-target beam intensities at SPES have been estimated from fission fragments production yields calculated with the MCNPX [6] Monte Carlo code in which the target geometry is included. The diffusion and effusion of the exotic species inside the target was evaluated with both GEANT4 [7] and RIBO [8] Monte Carlo codes. The calculations have been tuned using the available experimental data from ISOLDE, ORNL and PNPI taking into account the complete target geometry. Finally, source ionization and extraction, charge breeding, beam transport and re-acceleration efficiencies have been considered.

The neutral atoms will diffuse to the surface ionizer where, once charged +1, will be accelerated by the 30 kV of difference of potential with the extraction electrode; after the acceleration, the beam will find four electrical steerers (max 3.5 kV) to correct the position of its centroid in the transverse plane. The following stage on the front-end is the triplet of electrostatic quadruples (max voltage 3.5 kV) responsible of bringing a focus in a desired downstream point. It is expected that the source produce a beam with a transverse emittance 90% around the $6\pi \cdot \text{mm} \cdot \text{mrad}$ and a focus under 10mm of diameter. In the following months some diagnostic elements will be installed as

well as a laser ionizer that must improve the emittance and the mass selection.

infrastructures needs to be designed. The use of up-to-date techniques of nuclear engineering will result in a high security level of the installation:

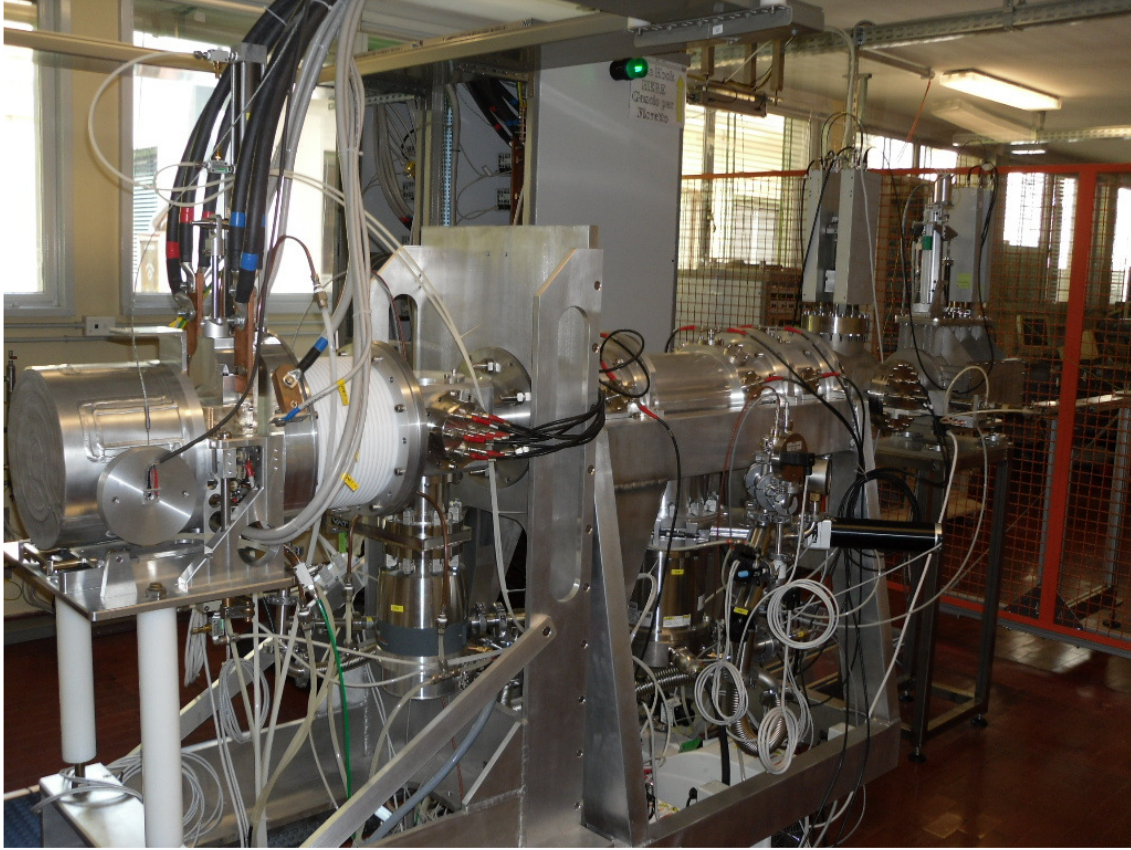


Fig. 6 The SPES ISOL Front-end

To predict the performance of the beam through the front-end, several computational simulations have been carried out using TraceWin [9], a code specialized in beam transport simulations. The numerical simulations start just after the ion source, in consequence it is very important to introduce good initial data. The initial data has been taken from experimental measurements done at ISOLDE, and the preliminary results are shown in Figure 8.

8. The control system

According to the estimated level of activation in the production target area (10^{13} Bq) special

the control system will integrate radiation management and survey as well as facility operation and safety infrastructures. Redundancies and fault tolerant PLC will be adopted in the low level layer of the control system while EPICS and LabView will be used in the general architecture and user front-end.

9. Conclusions

The SPES project is one of the main Nuclear Physics developments in Italy for the next years. It is organized as a wide collaboration among the INFN Divisions, Italian Universities and international Laboratories. The SPES

collaboration allows covering all the specific aspects of the project, also those outside the main competences available inside INFN. A strong link and support was established with ISOLDE (CERN, CH) and HRIBF (ORNL, USA). With SPIRAL2 (GANIL, F) there is a collaboration in the frame of LEA (Laboratorio Europeo Associato) which aims to share the technical developments and the scientific goals in the field of Nuclear Physics with exotic beams. Specific collaboration for target and charge breeder was opened with KEK (IPNS, Japan)

SPES is an up-to-date project in this field with a very competitive throughout representing a step forward to the European project EURISOL. The relevance of the project is not only related to the Nuclear Physics research but also to Astrophysics and Applied Physics: mainly for Nuclear Medicine, material research and nuclear power energy.

The first exotic beam at SPES is expected in 2014.

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