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THE SPES PROJECT AT LNL*

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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 EURISOL. The key feature of SPES is to provide high intensity and high-quality beams of neutron rich nuclei to perform forefront research in nuclear structure, reaction dynamics and interdisciplinary fields like medical, biological and material sciences. The exotic isotopes will be reaccelerated by the ALPI Superconducting Linac at energies of 11 AMeV for masses in the region of $A = 130$ amu with an expected rate on target of 10^9 pps. This represent a substantial improvement to the actual available ISOL facilities both from the point of view of intensity and energy of the exotic beam.

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1. Introduction

Most of our present knowledge of nuclear properties has been gained by studying nuclei near the valley of beta stability or on the neutron-deficient side with respect to the two variables: excitation energy and spin. Very asymmetric combinations of protons and neutrons are expected to reveal new aspects of nuclear structure and reaction dynamics under extreme conditions of isospin.

The main goal of the SPES facility [1] is to provide an accelerator system to perform forefront research in nuclear physics by studying nuclei far from stability by the production of neutron-rich radioactive nuclei with mass in

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the range 80–160. The final energy of the radioactive beams on target will go up to 11 AMeV for $A = 130$, with an intensity in the range 10^7–10^9 pps depending on the extracted ion species. The bombarding energy achieved allows to overcome the Coulomb barrier in most systems and opens up new possibilities for experimental studies of neutron-rich nuclei employing different reaction mechanisms such as Coulomb excitation, inelastic scattering, single- and multiple-nucleon transfer, fusion reactions, *etc.*

The secondary goal of the facility is to develop an accelerator based interdisciplinary research centre by the use of the second high energy proton beam for applied physics and by developing an accelerator based Neutron Facility using the high proton current produced with the TRASCO injector, that is in an advanced construction phase and it is able to deliver a proton beam of 30 mA 5 MeV. The Neutron Facility has two main applications: the development of a Boron Neutron Capture Therapy (BNCT) installation to perform research in the treatment of cancer and an irradiation-facility (LENOS) for material research and cross section measurements. The expected neutron beam has a fluency of thermal neutrons of 10^9 n cm^{-2}s^{-1} at the output port of the moderator and a total rate of 10^{14} n s^{-1} from the beryllium target.

2. Physics case

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 and the nucleus decays 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 the absence of electrical repulsion between neutrons. The location of the neutron drip line is known 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 evolution of nuclear properties towards the neutron drip line depends on how the shell structure changes as a function of neutron excess. This evolution has consequences on the ground state properties (spin, parity, and electromagnetic moments) and on the single-particle and collective excitations. In particular, studies of neutron-rich nuclei beyond 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.

A powerful tool to study the evolution of the shell closures far from stability is provided by fusion and transfer reactions. For instance, one-particle transfer reactions allow one not only to determine the position of the single-particle states (providing information on the effective mass), but also their occupation probabilities via the spectroscopic factors, which provide detailed information on the mixing of single particle states with more complex configurations.

The location of even a few lowest-lying excited states may provide crucial information on the dynamics of nucleons in the nuclear medium. This is particularly so when looking for evidence of the occurrence of dynamic symmetries in nuclei far from stability, as the newly suggested "critical" symmetries which occur in transitional nuclei when the shape changes from spherical to deformed.

New modes of collective motion are also expected in connection with the formation of a neutron skin, namely oscillations 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.

The key role of radioactive beams in the field of nuclear astrophysics is mainly related to the production of heavy elements ($A > 60$) in the Universe. Stellar nucleosynthesis above Fe proceeds mainly through neutron capture in different sites, involving a wide range of neutron density, temperature and other stellar conditions. About half of the elements beyond Fe are produced via the r-process (rapid capture, so called because of the very short neutron capture times involved), leading to the production of very unstable nuclei, which only after production by neutron irradiation, decay back to the stability valley. Explosive scenarios, characterized by extremely high neutron densities and temperatures, such as Supernovae and X-ray bursts, are at present considered the most probable sites in which rapid capture processes occur. However, the exact sites and mechanism of r-process nucleosynthesis is at present still largely uncertain. The radioactive beams of SPES should allow one to extend measurements deep into the r-process region.

Despite the large number of experimental studies, so far it is still not possible to predict reliably the limits of nuclear stability or the behaviour of the Nuclear Equation of State (NEOS) at low and high baryon densities.

In particular, the asymmetry term in the NEOS is largely unknown but in the region close to saturation. However, it is just this energy which plays an important role in setting the stability limits. For this reason, it is quite challenging to investigate the behaviour of nuclear matter far from stability. Although the energy range is somewhat limited for studies of this kind, the neutron-rich ion beams of SPES will allow one to further extend the investigation of the NEOS along the isospin coordinate, in a region where it is largely unknown at low as well as high excitation energy.

Since years, the Italian community is at the forefront of most of the above fields at a competitive international level, as demonstrated by many recent experimental and theoretical activities, large collaborations, and initiatives which are in progress at LNL, LNS, and in several INFN Divisions. As a consequence, this community looks at SPES as an European pole of excellence in nuclear physics research for several years after its completion.

3. Facility description

3.1. Overview

The basic elements of the ISOL facilities are the primary accelerator, the production target coupled to the ion source (TIS), the charge breeder (or the charge exchange system), the beam transport system and the re-accelerator. According to the requirements of the experimental needs a High Resolution Mass Spectrometer (HRMS) can be part of the transport system.

SPES is designed to have a Cyclotron as primary accelerator able to supply at least 40 MeV 0.2 mA proton beam onto a UCx direct target to produce a fission rate of about 10^{13} fission/s. Thus, a total beam power of 8 kW has to be managed. A surface ionization source will be used with the possibility to add a laser device to improve the purity of the ionized exotic species. For this purpose a HRMS with a mass resolution 1/20000 is also planned. To reach the charge state and ion velocity that fit the requirement for injection into the PIAVE-ALPI acceleration system a Charge Breeder and 2 High Voltage platforms (HV $\sim$ 250 kV) will be used. The first platform will host the TIS and first stage mass separator, the second the Charge Breeder.

As the facility will handle radioactive species, special care is devoted to the radiation protection safety and several systems are added to prevent radiation hazards. A cryopanel device is used to collect not ionized species coming out from the Target Ion Source system and a closed circuit is adopted for the vacuum system gas exhaust. Closed circuits with heat exchange are also used for the cooling fluids of TIS and beam transport system where activation problems can arise. High radiation areas, like the TIS bunker, are ventilated through a nuclear ventilation system with at least two levels of depression to prevent the escape of activated aerosols. A Control System will integrate in a homogeneous architecture the many subsystems necessary for the operation of the facility: from the accelerator control to the radiation and safety survey.

3.2. Expected beams

Several factors have to be considered to determine the intensities and the ion species available for experiment in an ISOL facility. The production of isotopes inside the primary target is the first ingredient but a crucial point, as we are dealing with radioactive species, is the target release time, *i.e.* the time needed by the reaction products to reach the ionization source from inside the target grains, where they are produced. Then, following the path from production to reacceleration, several efficiencies have to be considered.

The in-target beam intensity at SPES has been determined starting from the fission fragment production yield calculated with the MCNPX [2] transportation Monte Carlo code in which the target geometry is included. The following diffusion and effusion of the exotic species inside the target was evaluated with both GEANT4 [3] and RIBO [4] Monte Carlo codes. The calculations have been tuned using the available experimental data from ISOLDE, ORNL and PNPI and the complete geometry of our target has been included. The release time for Sn isotopes has been evaluated to be of the order of 1 s, with release fraction of about 98% for ^{132}Sn ($T_{1/2} = 40$ s) and 40% for ^{133}Sn ($T_{1/2} = 1$ s).

Finally, source ionization and extraction, charge breeding, beam transport and reacceleration efficiencies have to be considered. Following the literature, we assumed 1+ and N+ (charge breeder) ionization efficiencies equal to 90% (1+) and 12% (N+) for Kr and Xe, 30% (1+) and 4% (N+) for Zn, Sr, Sn, I and Cd. The typical Linac ALPI transmission efficiency is 50%. The final estimated beam currents for the SPES facility are shown in Fig. 1 for some interesting species.

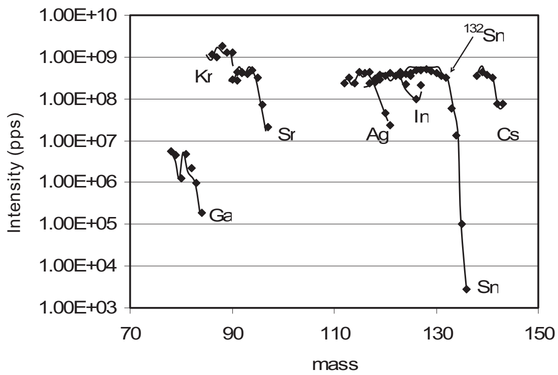

Fig. 1. Expected on-target intensities calculates considering emission, ionization and acceleration efficiencies (see text) for different isotopes.

3.3. Proton driver

A proton driver based on a cyclotron with energy 40–50 MeV and current 0.2 mA fulfils the requirements for the SPES project as the direct target is actually designed for 8 kW power. A driver with a capability of 50 kW (70 MeV, 0.75 mA) with the possibility of a current upgrade reaching 1.5 mA and a beam power of 100 kW is indeed very interesting for the development of the SPES project, as further developments of SPES will be in the direction to increase the maximum sustained power in the target, with the aim to increase the exotic beam intensity and to follow the EURISOL trend for a 100 kW direct target.

A commercial cyclotron, with characteristics which fulfill the needs for the SPES project, was recently developed by IBA: the Cyclone 70 (C70). The Cyclone 70 is an ambitious project that occupies a major role in the R&D activities of IBA Technology Group business unit. This cyclotron is a powerful and flexible tool that is the answer to the radiochemistry and oncology needs related to the ARRONAX (Accélérateur Recherche Radiochimie Oncologie Nantes) project [5]. The deliverables of the Cyclone 70 project for SPES are the following: accelerating beam H$-$, extracted beam H$+$, extracted energy continuously variable between 30 and 70 MeV, beam intensity 750 eμA (possible upgrading up to 1500 eμA).

The cyclotron is equipped with two exit ports allowing for dual beam extraction for protons. The unique magnet structure is composed of three layers: sector, pole and pole cover. Furthermore, compensation coils are wound around each of the poles in order to obtain the different isochronous fields. The RF system at about 30.4 MHz consists of a 200 kW RF amplifier coupled to a home-made cavity. Extraction is then obtained by stripping.

3.4. Target system

The UCx target is made by 7 disks (each ~ 1 mm thick and 4 cm diameter) to optimize power dissipation and release time of the fission products. The gap between the disks allow the an efficient cooling of the system by thermal radiation. The total amount of the U fissile material is only 28 g.

A detailed study has been performed to evaluate the thermo-mechanical behaviour with two codes: the generally used ANSYS [6] code and one provided by ENEA [7]. Experimental tests of the target principle were performed at the HRIBF facility (ORNL-USA). The main result is that, in the adopted configuration, the target does not melt and to reach the operating temperature it is necessary to supply external power. A strong R&D program is under development on the Direct Target subjects for material, characterization techniques and prototyping. The possibility to produce disks of carbides with the right dimensions has been proved developing and characterizing LaC and UCx pellets.

Collaborations with ISOLDE (CERN) and HRIBF (ORNL) have been established as well as participation to the EURISOL Task3. A detailed discussion of the target status and development can be found in the contribution to this conference by Andrighetto *et al.* [8].

The TIS system is developed following the EXCYT and ISOLDE design. The choice of ion source to be used has primarily been dictated by efficiency and secondarily by its capability of selective ionization. We consider three kinds of ion sources for SPES: the Surface Ion Source, the Forced Electron Beam Induced Arc Discharge (FEBIAD) and the Resonant Ionization Laser Ion Source (RILIS). All of these three sources are used at ISOLDE and they constitute a good reference point for further SPES goals in the ion-source development. The first version of the SPES TIS will be equipped with a Surface Ionization Source with the option to couple a Resonant Ionization Laser Ion Source as a second step in source development.

3.5. Beam transport and reacceleration

The secondary beam line transport system will handle the radioactive beam from the output of the ionization source to the low-energy experimental area and to the re-accelerator complex. One of the main problems to operate an ISOL facility is the beam purification since the extracted species are transported according to their M/q value. Due to the low rigidity of the beam, electrostatic quadrupoles can be used to focus and transport the beam. This guarantees a reliable beam handling and a very simple procedure to set the beam transport line.

The beam extracted from the source with 50 kV extraction potential, will cross through a first stage of m/z purification, which allows trapping the largest amount of radioactive contaminant. According to other facility, and to satisfy the previous constraint, we plan to use a small Wien filter, placed on the first HV platform just beyond the source. Furthermore a small magnetic dipole, like in the EXCYT design, can be also used. A mass resolving power ($M/\Delta M$) of 300 for this "analytical" magnet is acceptable. It will be followed by a 1/20000 High Resolution Mass Spectrometer (HRMS) which allows the isobar selection. To improve selection capability the HRMS shall operate at an input energy in the order of 200 keV. To fulfil this requirement the HV platform, where both target and first mass separator are mounted, is operated at 200 kV supplying 1+ beam at total energy of 250 keV.

To optimize the reacceleration, a Charge Breeder will be developed to increase the charge state to N+ before the injection of the exotic beam in the PIAVE Superconductive RFQ, which represents the first re-acceleration stage before the final injection in ALPI. The Charge Breeder acts as a trap where the 1+ ions are stopped and re-extracted with increased charge state.

To fulfil these requirements the Charge Breeder is mounted on a second HV platform operated at 250 kV; this allows to stop the incoming ions and to give the right energy to the out coming ones. The scheme of the transport line is shown in Fig. 2.

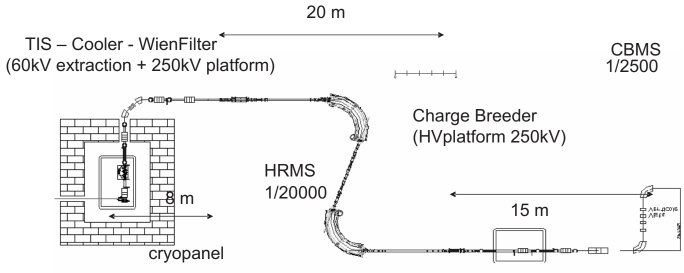

Fig. 2. Scheme of the transport line for the SPES exotic beams. For details see the text.

The reacceleration of the exotic species will be performed by the acceleration complex PIAVE-ALPI. The PIAVE injector is in regular operation at LNL since fall 2006. It is based on an ECR Ion Source (placed on a 350 kV platform), and on super-conducting RFQ able to accelerate ions with $A/q \leq 8.5$ up to 1.2 AMeV. For the SPES beams a transfer line from the Charge Breeder will be added. No main difficulties are expected as the ions coming from the Charge Breeder have similar characteristics to the ones produced in the present ECR. The linear accelerator ALPI, with a β range between 0.04 and 0.2 and CW operation. The quasi-continuous time structure and the possibility to adjust finely the output energy make it very well suited for nuclear physics experiments. A time structure suitable for TOF measurements can be implemented by a low energy bunching system.

In recent years ALPI underwent a number of significant upgrades which made it a world-class facility in heavy ion stable beam accelerators and which will represent an important added value for its use as a RIB accelerator as well. Figure 3 shows the increase of the equivalent voltage V_{eq} of ALPI along the years. In the histogram, the contribution to V_{eq} by the medium beta

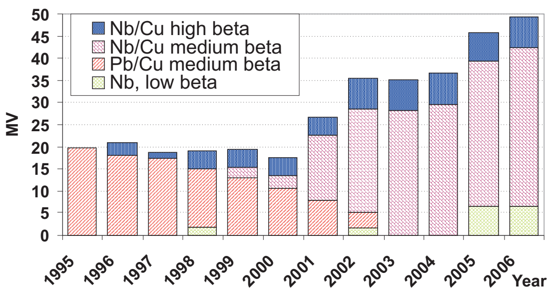

Fig. 3. Increase of the equivalent voltage V_{eq} of ALPI along the years.

Pb/Cu resonators, which were progressively replaced by Nb/Cu ones, can be noted. The contributions of the Nb/Cu high beta and of the full Nb low beta resonators are also shown.

With the aim to increase the final bombarding energy a first test with an external stripper station, located at 1/3 of ALPI, were successfully performed during 2008. The final ALPI energy can significantly increase according to the higher charge state produced in the stripper, the drawback is a $\sim 70\%$ transmission reduction due to the stripper itself. A further improvement of the final energy is possible with the installation of additional 6 cryostats with 24 high beta cavities.

3.6. Radioprotection aspects

Radiation safety aspects have a major impact on civil construction planning, control system design and special technological plants for the SPES facility. The main items addressed are the neutron and gamma production by the high energy and high current proton drivers and the radiation activity induced in the Direct Target by the uranium fission.The shielding for Cyclotron cave and Direct Target bunkers are dictated mainly by the neutron production rate and energy spectra. A shielding thickness of 3 m of concrete is necessary to have an annual ambient dose equivalent much less than 0.5 mSv/y, if concrete of 2.1 g/cm^3 density is considered. A reduced thickness is possible if special concrete or composite materials are used.To avoid the contamination risk by inlet of activated air a nuclear ventilation system will be installed to process the air of Cyclotron cave and Direct Target bunkers.

The activity induced inside the uranium target is the most severe source of risk. The target activation was evaluated and a shielding and handling system will allow to dismount the target with a remote operation. After 14 days of cooling down, the target can be removed with some care but in quite safe conditions. A minimum shield of 2 cm of lead and an operation distance of 2 m allows an eventual manual operation with a total dose of 1 mSv/h. To avoid contamination from radioactive gasses, a number of cryopanels will be installed to allow the gas condensation and a closed circuit will be used for the gas exhaust of the vacuum system with filtering and silos storage.

The radioactivity transported in the facility will be continuously monitored. The facility is designed to have at least two barriers between radioactive zone and the environment. Interlock valves ensure the containment of the target and a second barrier is the vacuum system. The target area is inside a two layer bunker with controlled and separate ventilation. Additional monitoring and bunkers will be added in the existing rooms if necessary, according to the expected radiation level. One of these elements is the Charge Breeder where large part of the exotic beam is lost. The accidental situations that may cause a release of radioactive material to outside of the site will be carefully considered and countermeasures will be adopted to minimize the impact on the environment with the goal to reduce the dispersion to 1 Bq/gr.

A detailed analysis of the risk will be performed by a specialized company with special regard to the radiation aspects. Generic and specific hazards will be analyzed. Among them earthquake, fire, overflow, explosion will be considered.

4. Summary and conclusions

The SPES project is one of the main Nuclear Physics development 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, Switzerland) and HRIBF (ORNL, USA). With SPIRAL2 (GANIL, France) 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.

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 possibility to operate at the same time the ALPI Superconductive Linac, the high current RFQ and the 2 exit ports Cyclotron give a large improvement to the research capabilities at LNL.

The first exotic beam at SPES is expected in 2014.

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