Union of Compact Accelerator-Driven Neutron Sources I & II

The SPES project: a second generation ISOL facility

Gianfranco Prete, Alberto Andrighetto, Juan Esposito, Pierfrancesco Mastinu, Jeffery Wyss

"INFN, Laboratori Nazionali di Legnaro,
"INFN Padova, via Marzolo 8, I-35131 Padova, Italy
"DiMSAT, University of Cassino, via Di Biasio 43, I-03043 Cassino (FR), Italy

Abstract

SPES is an INFN project to develop a Radioactive Ion Beam facility as an intermediate step toward EURISOL, the next generation European ISOL facility. The facility will be installed at the Laboratori Nazionali di Legnaro where the superconductive linac ALPI will reaccelerate the exotic beams at energies larger than 10 AMeV. Neutron-rich radioactive beams will be produced by proton-induced Uranium fission at an expected in-target fission rate of $10^{13}$ fissions per second.

As proton driver, a 70 MeV cyclotron with a total current of 0.750 mA shared on two exit ports will be installed. The key feature of SPES is to provide high intensity and high-quality beams of neutron-rich nuclei to perform forefront research in nuclear physics as well as to develop and interdisciplinary research center based on the cyclotron proton beam.

Neutron production at a rate of $10^{14}$ n/s is expected using the proton beam on thick target. The status of the project and the layout of the neutron facility will be presented.

Two facilities can be operated at the same time, with a capability of 5000 h per year each. The ISOL facility will use 0.2 mA to reach the goal of $10^{13}$ fissions per second and more than 0.5 mA will be available for applied physics applications, mainly neutron beam and medical isotopes production.

© 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of UCANS
Open access under CC BY-NC-ND license.

Keywords: radioactive beams; neutrons; radioisotopes

* Corresponding author. Tel.: +39-0498068649.
E-mail address: prete@lnl.infn.it.
1. Introduction

SPES is the acronym for “Selective Production of Exotic Species”. 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 interdisciplinary fields like medical, biological and material sciences. SPES is a second generation ISOL radioactive ion beam facility. It represents an intermediate step toward the future generation European ISOL facility EURISOL. 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 sustain a power of 10 kW. The primary proton beam is delivered by a Cyclotron accelerator with an energy of more then 40 MeV and a beam current of 200 μA. Neutron-rich radioactive ions will be produced by Uranium fission at an expected fission rate in the target of the order of $10^{13}$ fissions per second. 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 $10^8$ pps.

1.1. INFN and the Legnaro National Laboratories

In order to better underline the framework in which the SPES project is going to be developed, a short description of INFN and the Legnaro National Laboratory (LNL – Fig. 1) will be outlined in the following.

The INFN - the National Institute of Nuclear Physics - is an organization dedicated to the study of the fundamental constituents of matter, and conducts theoretical and experimental research in the fields of subnuclear, nuclear, and astroparticle physics. Fundamental research in these areas requires the use of cutting-edge technologies and instrumentation, which the INFN develops both in its own laboratories and in collaboration with the world of industry. These activities are conducted in close collaboration with the academic world. Research activity at the INFN is carried out at two complementary types of facilities: the Divisions (Sezioni) and the National Laboratories.

Each of the 19 Divisions is located at a university physics department. The Divisions thus provide a direct connection between the Institute and the academic world. The four Laboratories—in Catania, Frascati, Legnaro, and at Gran Sasso—are home to major facilities which are available to the national and international scientific community.

The INFN workforce includes about 2000 of its own employees, almost 2000 university employees involved in research conducted by the Institute, and 1300 young researchers, including undergraduate and graduate students and research fellows.

LNL is devoted to the study of nuclei, together with LNS (Catania), is located in the north Italy near Padova and is equipped with heavy-ion accelerator complex based on a 16 MV Tandem XTU, a Superconductive LINAC (ALPI) and a superconductive radiofrequency quadrupole (RFQ) heavy ion injector (PIAVE). The Tandem XTU can operate in a stand-alone mode or as an injector to ALPI. The PIAVE super-conducting RFQ injector 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 1.2 AMeV. The ALPI accelerator is a superconducting heavy ion LINAC, composed by 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 bent configuration: it is composed of two branches connected by an achromatic and isochronous U-bend. It uses three different kinds of cavities: Low Beta, Medium Beta and High Beta according to the different velocity along the acceleration path. In recent years, the medium energy QWR section was upgraded with a new Nb sputtered coating in substitution to the original Pb layer sputtered cavities. 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 and the energy of ions with mass around 130 amu and charge state 20+ to reach 10-12 MeV/n.

Fig. 1. The Laboratori Nazionali di Legnaro. The position of the SPES new buildings to be constructed is shown.
1.2. The SPES project

The SPES strategy is to develop a facility for Nuclear Physics research together with a facility for applied Physics based on the same technology and infrastructure.

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 region. 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 $10^{13}$ fission/s a proton beam current of 200µA (40MeV) is needed; the second beam, up to 500µA 70MeV, will be devoted to applications; mainly 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 a Pb target (mean energy 1MeV).

1.3. The SPES- ISOL main components

The ISOL technique for radioactive beam production is based on a driver accelerator which induces nuclear reactions inside a thick target. The reaction products are extracted from the target by thermal process, ionized 1+, isotope selected, ionized n+ and injected into a re-accelerator. In order to produce neutron-rich isotopes it is mandatory to perform fission reactions in Uranium or other actinide targets using protons, deuterons, neutrons or gammas.

![Fig. 2. SPES facility layout. Underground level: Cyclotron, two ISOL target caves, radioactive beam transport and applied physics caves are shown.](image)
The SPES choice is to use a proton beam to induce fission on a UCx target (Direct Target).

Fig. 2 shows schematically the SPES main elements located at underground level, a second floor at ground level hosting laboratories and services is not shown.

The driver is the proton cyclotron delivering beam on different targets. Two production ISOL targets are planned to be installed. 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 (n+). 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.

Two facilities for applied physics are planned: a neutron facility that make use of the proton beam to produce neutrons and an irradiation facility for production and study of radioisotopes for medical use.

2. The SPES physics

To understand the properties of a nucleus, apart from establishing the interaction between its components, it is necessary to determine the arrangement of the nucleons, i.e. the structure. 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 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 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 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 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 energy of SPES, it will be possible to address important questions related to the study of neutron-rich matter such as nuclear forces, level density, viscosity, barrier, neutron pairing and collective modes.

3. The ISOL front-end

The ISOL front-end is the system which couples the proton beam with the UCx target, the ion source and the first part of the transport line of the exotic beam. SPES adopted the ISOLDE design. The whole system was completed and is in operation at LNL for off-line tests.

3.1. The ISOL target system

The most critical element of the SPES ISOL facility is the Direct Target. The proposed target follows the basic design of the ISOLDE one but represents an innovation in term of capability to sustain the primary beam power. The design is carefully oriented to optimize the radiative cooling, taking advantage of the target system high operating temperature, which is in the order of 2000°C.

The SPES target is operated under vacuum and the 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. In order to optimize the heat dissipation along with the fission fragments evaporation, the SPES target consists of multiple thin disks housed in a cylindrical graphite box. It is composed of 7 UCx 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 [4]. The graphite box is housed inside a tubular hollow tungsten ohmic heater. In fact, due to the intense heat exchange by radiation, the proton beam is not sufficient to reach the operating temperature. This allows for a better thermal control of the target operation.

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 benchmark the simulations was carried out in collaboration with HRIBF, the Oak Ridge National Laboratory ISOL facility (USA).

3.2. 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 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. For alkalis and some rare earth elements, 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. This technique is under development implemented with the aim to produce beams as pure as possible (chemical selectivity) also for metal isotopes.

3.3. Beam selection and transport

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.

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 [6] and aims to produce ions with A/q less than 6 for A~130. The design is under study in collaboration with LPCS (Grenoble, France)

After a second spectrometer to clean the beam from the Charge Breeder impurities, the beam enters the superconductive linac ALPI for acceleration and delivery to experimental target. Considering the production rate of fissions in the target and the transfer efficiencies of 2% for the transmission from the 1+ source to the experimental target, the expected reaccelerated beam-on-target is in 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.

4. The SPES neutron facility

The capability of the proton cyclotron to supply two beams at the same time offers the possibility to operate a second target, besides the ISOL one.

The layout of SPES was designed in such a way to operate two targets at the same time distributing the beam according to a schedule that minimize the radiation problems. It should be considered that the activation of materials at a beam power of 20-30 kW do not allow to operate the same target for long time. A detail of the SPES layout is shown in Fig. 3; the proton beam can be sent to two ISOL target caves, two irradiation areas (mainly dedicated to neutron production) and to the radioisotopes production area. Considering a shift of two weeks with 2 days for beam preparation and 12 days of beam on target and 7 shifts for maintenance, we can offer at least 5000 hours per year of beam dedicated to the ISOL targets and 5000 for applications.
Two facilities for neutron production and applications are planned at SPES: a neutron-proton irradiation facility dedicated to the study of errors induced by radiation in electronics and a simulator of Generation IV reactor neutron spectra. The aim of this last project is the production of a neutron field with an energy shape similar to that present inside the new reactors to study cross sections for neutron capture, fission and others reactions induced by neutrons in selected isotopes relevant for the reactor operation.

4.1. The NEPIR facility

The neutron and proton irradiation facility (NEutron Proton IRradiation) is dedicated to Soft Error studies and reliability tests of state-of-the-art electronic devices and systems.

The NEPIR facility would offer three tools:
- An intense continuous “white” energy spectrum neutron source with a high degree of resemblance with the atmospheric one in the energy range 1->50 MeV. More than 60% of atmospheric neutrons with E > 1 MeV are in this energy range. The flux of neutrons in the 1<E<50 MeV energy range will be equal to the standard fluxes at existing facilities and, for non-standard applications (e.g. study rare SE effects), it will be possible to increase the flux tenfold. The beam will be wide and uniform allowing one to irradiate large electronic systems (e.g. entire computers, aircraft navigation
The neutron beam will propagate from the production targets to the user area through collimator with different apertures. Since the atmospheric neutron spectra is produced directly from the proton beam and the use of moderator is not necessary, the threshold energy of the neutron spectra is about a few keV. In such a configuration, the thermal part of the spectra is switched off. The thermal part can be reproduced by adding a small amount of moderator, which will thermalize the epithermal neutrons of the bare spectra. In such a way experimenters can determine the relative contributions of higher vs lower energy neutrons to the SE rate.

- A source of quasi mono-energetic neutrons (QMN) by using a selection of proton energies and a corresponding set of thin lithium targets to produce QMN beams with the peak energy controllable in the 11-65 MeV energy range. Whenever the full Cyclotron current will be necessary, a beryllium target can be used, since such material can sustain higher power, even if the spectra is “less” quasi-monochromatic.

- A general purpose source of direct protons of variable energy source with energy up to 70 MeV.

This new neutron facility will not study many important neutron induced effects that are known to occur at the highest energies (> 200 MeV), such as SEL and catastrophic Hard Errors like Single Event Burn-outs. The basic mechanisms of these interesting effects can be studied using heavy ion beams; although the correlation with neutron induced SEE is not immediate. Heavy ion SEE studies are routinely performed at Legnaro using the TANDEM and ALPI beams [7].

4.2. The FARETRA facility

The research on nuclear energy is actually concentrating on the next generation of fission reactors. As known, the final development of the Gen-IV/ADS-like reactors still requires lacking cross section data for several actinides and structural material isotopes in the energy range of interest (100 KeV<En<10 MeV).

In such cases, mainly for a class of short-lived nuclides, a valuable alternative to the standard experimental technique at running TOF facilities, like GELINA, n_TOF and LANSCE, is represented by integral cross sections measurements which exploit relatively intense neutron fluxes with suitable energy distributions. To meet such needs the FARETRA (FAst REactor simulator for TRAnsmutation studies) facility has been proposed.

The basic elements of the system are a neutron converter and a moderator. The neutron converter is a high power thick target of Ta or W, able to stop the cyclotron proton beam of 70 MeV 0.5 mA. The moderation structure will be able to translate the neutron spectrum to simulate the energy shape of the neutrons inside the reactor: a range from few keV to few MeV with a peak in the region 200-300 keV. Inside the moderator, some irradiation boxes will be obtained with an available volume of 500-1000 cm³, to host samples to be studied.

5. Conclusions

SPES will 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 Spes facility will open up new frontiers in the study of nuclei far from the line of stability and will allow addressing key science questions. This will place INFN at the forefront of Nuclear Physics Research in Europe well beyond the next decade.

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 XTU-Tandem and the 2 exit ports Cyclotron gives a large improvement to the research capabilities at LNL.

The proton beam available from the cyclotron will be used to feed two neutron facilities, opening the way to study Single Event Effects and to contribute to the research on Generation IV reactors.

SPES will offer the possibility to develop an accelerator based neutron facility at LNL and it is a good candidate to meet UCANS.

References

[1] SPES Technical Design Report 2008 ed. G. Prete and A. Covello INFN-LNL 223
http://spes.lnl.infn.it/
[2] Andrighetto A et al. 2010 Nucl. Phys. A 834 754c.
[3] Prete G et al. 2009 J. Phys. Conf. Ser. 168 012022.
[4] A. Andrighetto, C.M. Antonucci, S. Cevolani, C. Petrovich and M. Santana Leitner, Eur. Phys. J., A30 (2006)591.
[5] J. Lettry, Proceedings of the 1999 Particle Accelerator Conference, New York, 1999
[6] T.Lamy et al, Review of Scientific Instruments Vol. 73, Nb. 2 (2002) 717
[7] J.Wyss et.al, Nucl. Instr. and Meth. In Phys. Res. A, vol. 462, (2001) 426