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The SPES radioactive ion beam facility at the Legnaro National Laboratories and the EDM search

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Abstract. Radioactive ions can be used to amplify the sensitivity to symmetry violations. An example is the time reversal (T-) violation connected, assuming the charge conjugation, the parity and time reversal (CPT) symmetry, to the CP-violation. This is linked to the question of the role that CP violation plays in explaining the cosmological matter-antimatter asymmetry and the search for new physics beyond the Standard Model (SM). One of the most direct probes of such symmetry violation is the existence of a permanent electric dipole moment (EDM) of a particle or system. Octupole-deformed nuclei with high Z and A are expected to be among the best candidates for testing the limit of existence of EDM. The production, extraction and characterization of such unstable systems is part of the scientific program of the new SPES radioactive ion beam facility which is presently under construction at the Legnaro National Laboratories of INFN. In the following I will discuss the present status of the SPES facility and the scientific program foreseen for those studies.

1. Introduction: SPES, an acronym for Selective Production of Exotic Species, is a new infrastructure of the Italian Institute of Nuclear Physics (INFN) dedicated to forefront nuclear research and nuclear physics based applications. It is presently under construction at the Legnaro National Laboratories (LNL) and is expected to provide the first low energy radioactive ion beams in 2019. The facility will provide high-intensity and high-quality beams of unstable neutron-rich nuclei with the aim to perform forefront research in nuclear structure, reaction dynamics, nuclear astrophysics, fundamental interaction studies and interdisciplinary fields like medical, biological and material sciences. SPES is a second generation ISOL radioactive ion beam facility and represents an intermediate step toward the future European ISOL facility EURISOL. It is part of the European ISOL distributed facility (EURISOL-DF) presently under construction in Europe. The production of radioactive beams is based on a proton beam impinging on an uranium carbide (UCx) Direct Target able to sustain a maximum power of 8 kW. Neutron-rich radioactive ions are produced by Uranium fission at an expected maximum fission rate in the target of the order of $10^{13}$ fissions per second. The exotic isotopes after extraction and separation are re-accelerated by the ALPI superconducting linac of LNL at energies of 10 MeV/A or higher, for masses up to A=200 amu, with an expected rate on the secondary target of $10^7$-$10^9$ pps for the most prolific species.

2. The SPES radioactive ion beam facility: The realization of SPES strongly involves two national laboratories, the LNL and the Laboratori Nazionali del Sud (LNS), and other INFN sites located all over Italy. It is presently under construction at LNL and makes use of the Isol (Isotope separation on line) technique for the production of radioactive beams. A primary proton beam provided by a driver
accelerator, a cyclotron, induces nuclear reactions (mainly fissions) inside a thick, mainly uranium carbide, target. The reaction products are extracted from the target by thermal process due to the high temperature of the target-ion source system (exceeding 2000°C). Once reached the 1+ source, the products are ionized and extracted. After an isotopic selection obtained using a high resolution spectrometer and a further ionization to an higher n+ charge state, the exotic beam is injected into a re-accelerator, the ALPI superconductive linac. A pictorial sketch of the facility is shown in Fig. 1.

The driver accelerator is a 70 MeV proton cyclotron with two exit ports providing a total current of 750 μA. Two production Isol targets are planned to be installed and operated alternatively even if only one is presently under construction for budgetary reason. As the cyclotron can supply two beams at the same time, a second independent facility can be operated in parallel. In particular the high intensity proton beam will be used to produce radioisotopes for nuclear medicine as well as used as a neutron source. Concerning the latter possibility, the expected neutron production at SPES will exceed $10^{14}$ n/s with energy up to 70 MeV and a peak between 0.1 and 10 MeV according to target and moderator. The proton beam of the SPES cyclotron is suited for the production of new radioisotopes for medical applications. Taking advantage of the high energy and current, it opens up the possibility to produce $^{82}$Sr, $^{67}$Cu, and $^{47}$Sc isotopes to be used in therapy and diagnostics. The SPES cyclotron is shown in Fig. 2.

2.1 The Isol front-end: it is the part coupling the proton beam with the UCx target, the ion source and the first part of the transport line of the exotic beams. The whole system has been completed and is now in operation with stable beams at LNL for off-line tests. The most critical element of the SPES Isol facility is the Direct Target. It has been constructed following the basic design of the CERN ISOLDE target but represents an innovation in term of capability to sustain an higher primary beam power. The design is carefully oriented to optimize the radiative cooling, taking advantage of the target system's high operating temperature, which is of the order of 2000°C. The SPES target is designed in order to maximize the release efficiency and the heat dissipation. It consists of multiple thin disks housed in a cylindrical graphite box. The presently installed one 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 originated by the energy release of the proton beam which, passing through them, induces nuclear reactions. The graphite box is housed inside a tubular hollow tungsten ohmic heater. In fact, due to the intense heat exchange by radiation, the energy released by the proton beam is not sufficient to make the system reaching the operating temperature. This allows for a better thermal control of the target operation. At
the basis of the target-ion-source design there is an extensive simulation study of the target behaviour for thermal and release properties. Experimental work to benchmark the simulations was carried out in collaboration with HRIBF [1], the Oak Ridge National Laboratory Isol facility (USA) and the i-Themba Nuclear Physics Laboratory in Stellenbosch (South Africa).

Figure 2: The SPES cyclotron

2.2 The ion-source system: neutron-rich fission products are produced through the interaction of the proton beam with the UCx target. Such neutron rich nuclei are subsequently extracted by thermal motion and ionized at 1+ charge state by the Isol source, directly connected to the production target. The hot-cavity ion source chosen for the SPES facility was designed at CERN (ISOLDE) [2] and adapted to the LNL environment. The source has the basic structure of the standard high temperature radioactive ion sources employed for on-line operation. The ionizer cavity is a tungsten tube (34 mm length, 3 mm inner diameter and 1 mm wall thickness) resistively heated to near 2000°C. Due to the high temperature the isotopes produced in the target diffuse in the target material and then effuse through the transfer tube into the ionizer cavity where they undergo surface or laser ionization. The surface ionization process occurs 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 kind of 1+ source has good efficiency and selectivity for the elements like Rb, Cs, Ba. For most of the other elements it is preferable to apply laser resonant photo-ionization. It uses the same hot cavity cell and it is a powerful method to achieve sufficiently selected ionization. This technique, now under development in the laboratory, has been implemented with the aim to produce beams as pure as possible (chemical selectivity) also for metal isotopes. Very recently laser ionization of Sn ions has been achieved at LNL. Laser ionization schemes for other elements are presently under development in the newly created laser laboratory. To ionize elements with high ionization potential, as rare gasses, the plasma source is needed. This source ionizes all the elements without any selectivity. At SPES both surface, plasma and laser ion sources have been developed and are now in operation at the off line test stand.

2.3 Beam selection and transport: the ions after the extraction from the source undergo a first mass selection performed by a Wien Filter having a mass resolution of 1/100. The Wien filter is installed just after the first electrostatic quadrupole triplet inside the production bunker with the aim to confine the larger part of radioactivity inside this high shielded area. The transfer line toward the ALPI superconductive linac is equipped with several beam handling systems to purify the secondary ion beams. Purification is achieved by the combination of a Beam Cooler and an High Resolution Mass
Separator (HRMS) designed to reach 1/20000 mass resolution and installed inside the SPES building. Special efforts have been dedicated to reach such high mass resolution taking advantage of the emittance reduction provided by the Beam Cooler and of a 260 keV high voltage platform on which the mass separator is mounted. The mass separator is a scaled-up version of the separator designed for the CARIBU facility [3] in ANL (USA). In the SPES configuration the calculated resolution is of the order of 1/20000 constrained by an emittance of 3 mm mrad and an energy spread of 1.3 eV. Such high selectivity results in a strong advantage also for the safety issue, reducing the contaminations along the beam transport area, the re-accelerator and the final target location. The injection of the secondary beams in the ALPI superconducting linac requires an increase of the ion charge state from 1+ to n+. This is performed by means of a Charge Breeder. The SPES Charge Breeder is based on ECR method [4] and aims to produce ions with A/q up to 7 for masses of the order of A~130. The design and construction of the Charge Breeder has been performed in the framework of the SPES-SPIRAL2 collaboration at LPCS (Grenoble, France). The new design represents an upgraded version of the Phoenix booster in operation at LPSC. After the Charge Breeder a second mass separator with 1/1000 mass resolution is installed with the aim to clean the secondary beam from the contaminants introduced by the Charge Breeder itself (mainly contamination from stable gasses). The same basic configuration used for the HRMS is adopted. Finally an RFQ pre-accelerator is used to increase the secondary beam energy to match the ALPI acceptance. The layout of the radioactive beam line is shown in Fig. 1.

2.4 Exotic beam re-acceleration: the secondary beams after mass selection and n+ ionization are injected into the ALPI superconducting linac by a new RFQ that is operating in a CW mode (100% duty factor) at a resonant frequency of 80 MHz. This frequency is the same as that of the superconducting cavities used for the low-energy section of the ALPI linear accelerator. The injection energy of the ions is set to 5.7 keV/u. This choice is a compromise between the desire to reduce the ion energy to simplify the low energy injection and the RFQ bunching section design and the need to increase the beam rigidity in the 1+ transport line to reduce space charge effects. The extraction energy of the RFQ is set to 727 keV/u to optimize the beam dynamics of the superconducting linac ALPI. In the last year the ALPI linac has gone through a continuous upgrade in the number and performance of its accelerating cavities, and consequently in the maximum achievable transport efficiency and beam energy. In the context of such upgrade all the electromagnetic elements have been realigned and transport efficiency has been maximized.

2.5 Status of the SPES project: the SPES facility is presently in an advanced stage of construction at the LNL. The production building hosting the cyclotron and up to two Isol sources has been completed. The cyclotron, provided by the BEST company in Canada, after the low energy commissioning in the factory, has been delivered and brought to his final location - Fig.1. The commissioning and acceptance test of the accelerator was completed in 2017. The authorizations to operate the cyclotron have been obtained allowing the acceleration of the proton beam on non-fissile target at high power and the test of the UCx target up to a current of 5 μA. Very recently the proton beam has been accelerated inside the cyclotron up to the maximum energy and intensity. A further authorization request to run the UCx target at the designed power has been presented to the authorities. The physics design of the radioactive ion beam transfer line (1+ and n+) is completed and the reshaping of the ALPI beam line in the experimental hall has been performed to allow the installation of the Charge Breeder and of the low and high resolution mass separators. The Isol front-end is completed and under operation in the off-line laboratory to test ion sources, assembly and controls. The project is fully financed and the first reaccelerated exotic beam is expected for the end of 2019 [5].

3. Challenges of the SPES project: Our present knowledge of the structure of the nuclei is mostly limited to systems close to the valley of stability or nuclei with a deficiency of neutrons. Only recently unexplored regions of the nuclear chart, especially on the neutron-rich side, have become accessible due the availability of beams of unstable ions. Starting from a nucleus located on the stability line and
adding successively neutrons, the binding energy of the last neutron decreases steadily until it vanishes
and the system decays by neutron emission. The position in the nuclear chart where the neutron
emission starts defines the neutron drip line. Due to the absence of electrical repulsion between
neutrons, the neutron drip line lies much farther away from the valley of stability than the
 corresponding drip line associated with protons. The location of the neutron drip line is largely
unknown as experimental data are available only for light nuclei. Nuclei with large neutron excess are
of interest not only for the location of the neutron drip line but also for the investigation of the density
dependence of the effective interaction between the nucleons. Variations 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.

3.1 Structure of exotic nuclei and nuclei of astrophysical interest: The modification of nuclear
properties when moving towards the neutron drip line depends on the shell structure changes for
increasing neutron excess. As an example, 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,
the stability of the shell closure and to find out how the effective interaction between valence nucleons
behaves far from stability. In connection with the formation of a neutron skin new modes of collective
motion are also expected, namely oscillation of the skin against the core, similar to the soft dipole
mode already identified in the case of very light halo nuclei. Neither the thickness nor the detailed
properties of the neutron skin of exotic nuclei are presently known. This information is essential to
allow 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 displaying the properties of both
finite and infinite (nuclear matter) objects. At the energies of the secondary beams provided by the
SPES facility, 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.
Interesting areas where new data will be collected are those in the very neutron rich regions, where
shell evolution is a major issue. Investigations of the modification of the pairing interaction in the
nuclear medium will receive significant inputs by measurements of multi-nucleon transfer reactions to
specific nuclear states. Another important issue is the study of the basic nuclear properties, like
lifetimes, masses and neutron capture probabilities, for systems involved in the element formation in
the universe. Those quantities can allow to probe the predictive power of the nuclear models used to
predict the element abundancies in different astrophysical scenarios (for a detailed discussion see [6].

3.2 Fundamental Interactions: Exotic nuclei can be used to amplify the sensitivity to symmetry
violations. One example is CP/T violation. Parity (P), Time Reversal (T) and Charge Conjugations (C)
are discrete symmetry transformations. Strong and electromagnetic interactions are symmetric under
C, P and T separately and under CP and T whereas weak interaction is maximally antisymmetric under
P and C involving only left-handed neutrinos and right-handed antineutrinos. CP is also violated in
weak decays of kaons and b-mesons. CPT symmetry is also a requirement for any Lorenz-invariant
quantum-field theory. CPT symmetry requires the Electric Dipole Moment (EDM) of a particle d and

![Figure 3: EDM and parity and time-reversal invariances.](image)
the EDM of its antiparticle be equal in magnitude and opposite in sign. The determination of electric dipole moments (EDM), which violate parity (P) and time-reversal invariance (T), is one of the crucial steps to pinpoint physics beyond the Standard Model – Fig.3. Experiments can probe P-odd/T-odd observables in different systems. For the neutron and proton, the fundamental CP-violating interactions arise from a short range contribution and a long range contribution, the latter arising from the P-odd/T-odd pion-nucleon interactions. Paramagnetic atoms and molecules are most sensitive to electron EDM and the nuclear-spin independent electron-nucleus coupling. In diamagnetic atoms the dominant contributions are the nuclear-spin dependent electron-nucleus interaction and the Schiff moment, which also arises from long-range pion exchange and short range four-nucleon interactions. At present the most sensitive EDM search is performed on $^{199}$Hg and the upper limits already constrain various extension of the Standard Model [7].

Nuclear structure can strongly amplify the sensitivity of nuclear EDM measurements, in particular the occurrence of octupole deformation and enhanced octupole vibrations in nuclei lead to considerably larger Schiff moments inducing a contribution to an atomic EDM. Octupole collectivity is expected to arise when neutrons and protons near the Fermi surface populate states of opposite parity separated by total angular momentum $3\hbar$, which corresponds to proton and neutron numbers in the range $Z$ or $N \approx 34, 56, 88$ and $N \approx 134$. Those systems have reflection asymmetric shapes, which can lead to permanent octupole deformation or to octupole vibration. Especially in the case of stable octupole deformation a large intrinsic dipole moment is polarized along the nuclear-spin by P-odd/T-odd interactions. This leads to the nuclear Schiff moment which is further enhanced by the electric polarizability of the nucleus. Since the Schiff moment can be expressed as:

$$S \propto \eta \epsilon (\beta_2 \beta_3^2 Z A^{23/5} r_0^3)/(E_+ - E_-)$$

where $\eta$ represents the strength of the P-odd/T-odd interaction, $\beta_2$ and $\beta_3$ the quadrupole and octupole deformation parameters and $E_+$, $E_-$ the energies of the opposite parity states.

One of the most promising cases is the $^{229}$Pa nucleus where the splitting was originally reported to be as small as 0.22 keV and evidence of strong octupole correlations support a ground state parity doublet with spin $I=5/2$. Due to the octupole collectivity for an odd nucleus an enhancement factor up to the order of $10^4$ has been calculated respect to Hg nuclei [7]. Experimentally there is a strong evidence of octupole collectivity for nuclei in the A=200-226 mass region. This concerns interleaved even/odd parity states in even-$A$ nuclei, parity doublets in odd-$A$ nuclei and enhanced electric-dipole transition moments. One of the most stringent evidence of octupole collectivity concerns the large E3 strength found through Coulomb excitation measurements of radioactive beams of $^{220}$Rn and $^{224}$Ra at Isolde. A present experimental issue is the characterization of the octupole collectivity for nuclei like $^{220}$Pa and $^{225}$Ac. At SPES an experimental program is presently under discussion for Ac, Th and Pa nuclei aiming to the direct determination of the octupole strength (very challenging for odd systems) through Coulomb excitation and inelastic scattering experiments.

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