***ISOL-France Prospectives***

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7. ***Scientific Objectives***

The scientific objectives of this community are included in the Long Range Plane 2016/2017 of NuPECC. The fundamental properties measurements (i.e. masses, static electromagnetic moments, mean square charge radii and beta decay) allow the community to address the big general questions of nuclear physics.

Nevertheless, the performances of the ISOL technique coupled to the outstanding experimental devices developed and to be developed, allow to address the following specific questions among others:

1. How does the nuclear interaction evolve with the Isospin? What is the isospin dependence on the spin-orbit interaction? How do the shell closures evolve far away of the stability?
2. How to explain the collective phenomena from individual nucleon interaction? Can it be possible to describe the effects of spherical mean field and correlations beyond mean field?
3. Is there a physics beyond the standard model?
4. What is the origin of the elements of the universe? What are the nuclei relevant for the astrophysical process? How the nuclear properties affect the nucleosynthesis models?
5. What is the impact of nuclear physics on other disciplines?
6. Questions related to Heavy and Super Heavy elements

The questions 3-, 4-, 5- and 6- are not described in the present document as they are by themselves object of other prospectives that this community is part of and strongly supports.

* 1. ***Spin-Orbit Shell Closures approaching the drip line. How the nuclear interaction evolves with Isospin?***

The real origin, from a microscopic point of view, of the so-called “spin-orbit” shell closures is mysterious and still under debate. The most recent analysis of effective theories derived from QCD shows three different origins: *two-body spin-orbit term, tensor force and three body interaction*. The cause of these types of shell closure can then be generated by the individual action of each of these contributions or by a combination of them.

On the neutron-rich side of the nuclear chart, the shell closure effects and their origin play an important role in the nucleosynthesis process responsible for the formation of elements from Fe to U, and therefore are strongly related to the observed peaks in the solar abundance distribution and the r-process path.

The medium mass neutron rich nuclei, in particular fission products, play an important role as well, in the estimation of observables important for the safety of nuclear reactors and for fundamental and applied neutrino physics.

Ideally, it would be necessary to determine experimentally the differences in binding energy of the individual particles and their evolution when reaching the drip lines. Still, to disentangle in the measured observable the contribution to the gaps arising from the individual nucleons in a spherical configuration to that coming from correlations of other origins is an arduous task. To study these questions, it is indispensable to address on the one hand the *“single particle”* type nuclear properties and on the other hand the *collective behavior* of the nucleus, in both neutron-rich and neutron-deficient nuclei.

***1.2 Nucleon-nucleon interaction at the proton drip line. How the shell closure evolves far away of the stability?***

Neutron deficient nuclei close to the proton drip line, in particular 100Sn and its neighbors along the N=Z line, have awakened the interest of the worldwide physics community thanks to the large variety of different nuclear phenomena that the region presents. The fact that protons and neutrons occupy same shell orbitals translates into a maximum overlap of the wave functions of the two fermionic systems; thus proton-neutron pairing plays an important role in this area of the nuclear chart. The inherent symmetry of these nuclei makes them excellent candidates for the study of *proton-neutron pairing correlations and isospin breaking symmetry*. Moreover, the magicity of 100Sn and close-by nuclei is decisive for the course and the end of the *astrophysical rapid-proton capture process*. In addition, the nuclei in the region above 100Sn are known for presenting different types of radioactivity; *alpha and one or two proton emission, and cluster radioactivity predicted but non observed up to date in the region*. These types of decays are a useful tool for the study of the structure of these nuclei. Recently, it has been experimentally evidenced the existence for a new spin-alignment isoscalar (T=0) proton-neutron coupling scheme replacing the standard “seniority” coupling (T=1), leaving the question *if the T=0 correlation exists similar to BCS-Type ones for T=1 open*.

Little is known on single-particle energy (SPE) states and the residual interaction in the vicinity of 100Sn, and these parameters are of outstanding importance for *Large Scale Shell Model (LSSM) calculations*. Even though the effective interaction derived in different shell model calculations seems to reproduce correctly most of the experimental results available in the region, recent experimental outcomes highlight the subtleties of the SPE extrapolations and two-body matrix element (TBME) determination.

Recently, *ab-initio theoretical approaches* based on the chiral effective field theory computed with various coupled-cluster equation-of-motion (EOM) methods have been developed. This interaction describes binding energies, two-neutron separation energies and the 2+ excitation energies of nuclei up to neutron rich Ni-isotopes, but the charge radii are over-estimated large. Work is in progress to review the parametrization of the nuclear force. Therefore, spectroscopy information in the region will provide a powerful *test to ab-initio methods, DFT approaches and shell-model calculations.*

***1.3 Two meson exchange currents***

New advances in nuclear theory have allowed to use shell model techniques into an ab-initio approach, expanding ab-initio calculations to open shell nuclei. But a correct microscopic description of the nucleus requires a consistent description of electro-weak currents. Work is in progress to include electro-weak currents in these calculations, and it has been shown that magnetic moments are observables sensitive to this type of currents. Therefore, magnetic moment measurement in both neutron deficient and neutron rich nuclei are absolutely necessary to benchmark these theoretical developments.

The ISOL-France community foreseen to answer the above-mentioned question by measuring nuclear fundamental properties of ground and long-lived isomeric states. The measured observables provide a unique test for nuclear theory. The tools used will include high precision mass measurements, high precision laser spectroscopy and beta-decay of nuclei produced with low counting rates. These studies will address questions of shell-evolution, drip-line phenomena, collectivity, pairing and clustering of loosely bound nuclei. The limits of heavy nuclei, weak interaction and fundamental studies… etc.

1. ***Observables***
   1. **Binding energies**

The binding energy of a nuclei, is a quantity that is decisive for its size, shape, lifetime, decay mode, and internal nuclear structure. The mass also gives access to the energy available for reactions, which is of capital importance for e.g. stellar nucleosynthesis. The very limits of existence of bound nuclei are determined by the nucleon separation energies that are derived from masses. The small separation energies are important for understanding the nature of exotic phenomena at the drip lines, such as nuclear halos. One of the fundamental pillars of nuclear structure is the existence of magic numbers, which were discovered from mass differences (mostly) determined from beta decay and led to the formulation of the shell model. While the mass surface is an excellent indicator for shell structure, it can also show us if magic numbers disappear, due to so-called intruder orbitals. The landmark mass measurements of Thibault et al. Phys. Rev. C (1975) marked the loss of the N = 20 shell closure and the discovery of the associated “island of inversion”.

**2.2. Nuclear charge radius**

Complementing nuclear scattering experiments at high energies, measurements of the nuclear charge radius of isotopic chains reflects nuclear deformation and size effects, in a way similar to mass differences.

**2.3. Electromagnetic moments and nuclear spin**

The proton/neutron character of the active particles and the composition of the nuclear wave function as well as domination of collectivity (deformation) or single particle features (sphericity) can be obtained via nuclear magnetic moments, which are fingerprints of the nuclear wave function. Their sensitivity to the very small admixture of a specific (spin‐flip) type can prove essential, especially in regions where these orbit partners are the main driving force for the observed shell behavior. The electric quadrupole moments are a direct measure of nuclear deformation (which is also visible as an increase in charge radius, e.g. N = 90 for Sm above). Nuclear magnetic‐moment measurements strongly constrain the spin/parity assignment of the states of interest. Together with spin measurements the relevant nuclear states can be pinged down. It is worth to mention that the unambiguous determination of the total nuclear angular momentum is of outstanding importance and the most straight forward observable comparable with theory and it is of outstanding importance to benchmark theoretical developments.

**2.4. Beta decay**

Beta decay studies allow accessing low-energy spectroscopic information, half-lives, delayed emission (for instance –(2)n and its branching ratio Pn, P2n, …, but also in the future -p or maybe -cluster) and beta strength in exotic nuclei. The beta strength is a microscopic observable directly comparable with the predictions of microscopic models. Its joint experimental and theoretical study could improve our understanding of the residual interactions between nucleons and is complementary to integral observables such as half-lives or Pn. It was also shown that it brings pieces of information on the sign of the ground state deformation of the parent nucleus [ref if needed]. Recently it has appeared that beta decay could also constitute a new mean to probe the presence of low energy collective modes (for instance pygmy modes) [Scheck et al. Phys. Rev. Lett. 2016] in n-rich nuclei. Beyond their interest for nuclear structure, the presence of these low-lying collective modes modifies the r-process paths [S. Goriely PLB 1998]. The same topic could be explored in neutron-deficient nuclei. The study of E0 transitions will allow to study shape coexistence. The measurement of the shape of electron energy spectra from forbidden beta decays will allow constraining microscopic models needed for the r-process calculations. All the observables accessible experimentally through beta decay studies help constraining the nuclear models which are mandatory for nucleosynthesis calculations but play also an important role in nuclear applications such as reactor and neutrino physics.

1. ***Techniques***

**3.1 Measurements with electromagnetic traps**

The principle of these types of experiments is based on the isolation of the radioactive nucleus in order to study it without perturbation from the environment. The *Penning traps* combine electric and magnetic fields allowing to manipulate the ions by excitations selective of their natural movements. These types of traps are specially adapted for high-precision mass measurements (10-7 to 10-8) but they can also be used as a selection tool for further precision measurements, i.e. laser spectroscopy or beta decay studies. The purification resolution reached with the Penning trap technique (>106) allows not to separate only isobars but also isomers. The *Paul traps* on the other hand make use of only a RF electric field, they have a more polyvalent geometry adapted to decay experiments. Other devices as the Multi Reflection Time of Flight Mass Spectrometer(MR-TOF-MS) have been proving to provide excellent results when the counting rate of the exotic nuclei is low.

**3.2 Laser Spectroscopy**

High resolution laser spectroscopy in combination with radioactive beam facilities have being proven to provide an unique opportunity to study changes in the structure of nuclear ground (and isomeric) states. This technique is based on the interaction of the nucleus with the electron field of the atom. The nuclear interaction is treated as a perturbation to the electronic fine structure, where the atomic levels are splitted (hyperfine nuclear structure, HFS). The energy shift is arising from the nuclear magnetic moment and nuclear electric quadrupole moment. The HFS can be proven by means of high-resolution high-repetition lasers. This technique allows to measure in a model independent approach nuclear spins, multipole moments and deviations on the mean squared charge radii. It has both high sensitivity and high resolution with low background. Different types of laser spectroscopy techniques are available and complementary. In *gas-jet medium resolution laser spectroscopy, to be available at S3-LEB and* collinear high precision laser spectroscopy at ALTO and a near future DESIR.

**3.3 Beta decay measurements**

The selectivity of the beta decay measurements of radioactive beams give access to the characteristics of some excited states and ground state of the daughter nucleus. They allow to access to global nuclear properties. The ion collection is made generally by a *tape station* in order to evacuate the residual nuclear activity. The set-up is generally complemented by photon detectors. Two complementary gamma spectroscopy techniques can be used; one using high energy resolution detectors allowing to measure the first excited states in the most exotic nuclei and another (*Total Absorption Gamma-ray Spectroscopy (TAGS))* consisting in the complete measurement of the Gamow-Teller force by means of 4PI large volume scintillators. Neutron detectors are also used to measure beta-delayed neutron branches. Electron detectors are also used to measure the shape of the beta energy spectra and conversion electrons. For these experiments, the purification of the beam through laser spectroscopy or electromagnetic traps or an MR-TOF-MS is a key element of success.

1. ***Facilities***

The role of the French ISOL facilities is to deliver the beams needed by the nuclear to perform their scientific program. It includes the experimental devices needed to achieve their goal, these devices must be performant and competitive to stand out over other international facilities. The scientific program of the ISOL-France community is divided in three main regions of the nuclear chart (i.e. medium-mass neutron rich nuclei, light mass neutron and proton deficient nuclei, medium-mass neutron deficient nuclei and heavy and super-heavy elements). Each region is studied by different ISOL-methods and therefore three facilities exist and/or are being developed: *ALTO, GANIL-SPIRAL1, SPIRAL2/LINAG S3-LEB and DESIR.* Major developments are now underway at the French facilities ALTO and GANIL taking benefit of the experience gained by the community in experiments performed abroad at the other international facilities. These installations are perfectly complementary with ALTO producing neutron‐rich species, the SPIRAL1 producing light nuclei by fragmentation and and the soon‐to‐be‐commissioned S3/LEB facility targeting neutron‐deficient nuclei. The DESIR facility, under construction at GANIL, is a state of the art experimental hall for apparatus devoted to various forms of spectroscopy and the measurement of ground‐state properties. These facilities are presented in the following:

* 1. **Non-French facilities**

The IN2P3 programs devoted to ground‐state properties and decay spectroscopy have essentially (historically) been carried out at the ISOLDE facility, where the production of ISOL beams and the techniques associated with high resolution mass spectrometry and laser spectroscopy have all been pioneered. IN2P3 scientists also collaborate in programs at the IGISOL facility at JYFL (Finland) (mass measurements, TAGS, …), the ISAC facility at TRIUMF (Canada) and the SHIP low‐energy installation at GSI (Germany). Pursuing the existing physics programs at these facilities, beyond the transfer of expertise in cutting-edge techniques, ensures also a scientific positioning of the French community in the international landscape and legitimates the forthcoming studies that will be performed at the French facilities when available.

**4.2 ALTO**

The first objective of ALTO is to provide to the nuclear communities’ medium mass neutron rich beams and to maintain the expertise on the ISOL-type experiments of the French community. The mechanism of the production of the radioactive ions of this facility is the photo-fission (1011 fissions/s), a mechanism producing less contaminants. The radioactive ion beam is mass selected by using a magnetic dipole mass separator and a resonance ionization laser ion source. It’s then sent to the different experimental devices, i.e. station-PARRNe, TETRA, BEDO, POLAREX, LINO and MLLTRAP. PARRNe is a magnetic dipole mass separator with a resolution power of M/DeltaM = 1700 allowing the isobaric chain separation, but not of a single isobar. TETRA is a 3He neutron counter with a worldwide high neutron counter efficiency between 0 and some MeV. BEDO is a state-of-the art tape station where the trajectory tape has been adapted such there is a maximum space for other devices around the collection point, it allows to perform beta-gamma coincidence measurements and beta-gamma-neutron when coupled to the TETRA device. The system of nuclear orientation at low temperature (POLAREX) is operational and will be connected soon to the PARRNe separator. Two other devices are installed and under test: LINO and MLLTRAP. LINO is a collinear laser spectroscopy set-up which will allow to perform high resolution laser spectroscopy measurements and MLLTRAP for high-precision mass measurements. Both will benefit of the advantages of the ALTO beams, e.g neutron-rich silver beams, and will in a future be installed at the DESIR facility at GANIL.

* 1. **GANIL-SPIRAL1**

The SPIRAL1 installation profits of the stable beams of GANIL to produce radioactive ions by fragmentation. The system has evolved to a system using a FEBIAD source and an ECR charge breeder. This new installation will provide new beams not delivered by the old system. The list of new beams is progressively updated. These beams are delivered to the existing GANIL and to the LIRAT experimental line. The LIRAT experimental line is composed of a station of identification and decay and the LPC Trap to measure beta-neutrino angular correlations and the beta-decay of nuclei trapped. The SPIRAL1 line will be connected in a future to the DESIR facility, which will allow to fully take the advantage of the SPIRAL1 low-energy beams with further high-resolution purification and high-precision detection setups for mass measurements, laser sepectrosopy and beta decay studies.

* 1. **SPIRAL2/LINAG S3-LEB and DESIR**

**S3-LEB (Low Energy Branch)**

The REGLIS3 (“Rare Elements in-Gas Laser Ion source and Spectroscopy at S3”) is an international experimental device based on laser spectroscopy. It will be installed at the end of S3. It will serve in one hand as a ion source (selection in A and Z) of the nuclear species produced at S3 and on the other hand as spectroscopy device for HFS measurements of exotic nuclei, giving access to nuclear observables as nuclear moments, spins and deviation on the mean squared charge radii. The device is composed of a gas cell, where the ions of S3 will be stopped and neutralized, and a laser system to re-ionize the ions of interest. The ionized products will be further selected (QMF) to be sent to the MR-TOF-MS for additional purification and mass measurement. The combination of this set-up to the high intensity neutron deficient beams of S3 is an unique opportunity for nuclear studies near the proton drip line, reaching the doubly magic 100Sn nuclei, and in the heavy and super-heavy region.

**DESIR (Disintegration, Excitation, and Stockage of Radioactive beams)**

DESIR is the experimental hall that will host the experimental devices to perform nuclear studies with low energy beams. It will be at first fed by the SPIRAL1 beams (issues of fragmentation) and afterwards by the beams issue of the S3-LEB (issues of fusion-evaporation). DESIR is a polyvalent installation with complementary setups of an international collaboration. The radioactive ion beams entering the hall after being purified (RFQ-cooler and high-resolution separator and being conditioned in time and size (RFQ-cooler buncher GPIB) to match the experimental requirements. In the hall is envisages a first set of setups mainly dedicated to high precision mass measurements and extra purification (PIPERADE, LPCTrap, MLLTrap). Afterwards, other experimental platforms will be installed as LUMIERE ( laser room TiSa and Dye, Polarization line, CRIS) and BESTIOL (MONSTER, BELEN, GPDS/BEDO/SiCUBE, TAGS).

1. **Short-term Prospective and Needs**

The availability of the SPIRAL1 beams and the beams delivered by S3 will provide a unique opportunity to perform nuclear studies. It is worth to mention the nuclei close to mass 100. Mass measurements and laser spectroscopy will be accessible from 80Zr up to 100Sn and beyond. The N=Z nuclei are susceptible to provide unique information in a region where a competition between nuclear sphericity and deformation is manifested. Moreover, these exotic systems and their properties are relevant for the modelization of the rp process. (cf prospectives astro) Spectroscopic information of ground state and isomeric states on nuclei in the region will provide a unique test for nuclear models, in particular, the dipole magnetic moment measurements will help to elucidate the contribution of the two-meson exchange currents to the electromagnetic operators. These techniques and studies are as well mentioned on the Heavy and Super Heavy perspectives.

In order to achieve the ambitious physics program established by the collaboration and to place the ISOL-France facilities to the first-class worldwide rank, the community will foresee and need the support on:

1. The finalization on schedule of the S3 spectrometer, first beams are expected by beginning of 2023, any delay will be translated on a reduction of the physics impact of the experimental results
2. The accomplishment of the A/q=7 injector. The beams intensities delivered by this injector will place the facility as the number one for the production of neutron deficient radioactive beams for laser spectroscopy studies. Otherwise, the physics program will be strongly hampered leaving the most important nuclear systems out of reach experimentally.
3. Full installation of a complete laser system. Comparing with other installations, the number of available lasers for this type of studies is reduced. This type of physics requires a preliminary study of HFS of stable nuclei that can be performed only if the required lasers are available and functional. As an example, experiments type CRIS has 15 different lasers operational, while in the GISELE lab there is only 4.
4. Full development of the DESIR facility. This experimental hall will host first class experiments of high scientific impact, its completion is therefore of outmost importance.
5. Support to the experiments currently in preparation (in France) before the start of DESIR
6. Implementation of a laser assisted RF prove into the MR-TOF-MS device
7. Development of a universal gas cell

1. **Long Term Prospective and Needs**

In the long term, the community has identified two distinctives lines of action.

1. Development of a fission source to feed the DESIR facility. This source will provide the beams that are not produced either by SPIRAL1 or by S3-LEB. Therefore, it will give the possibility to DESIR to explore its maximal potentiality and allow the community to perform systematic studies from neutron-rich to neutron-deficient nuclei.
2. The construction of an electron collider in the continuation of DESIR. This prospective joins and supports strongly the one that made object by itself. The electron probe to the beams delivered by in that case DESIR will be of outstanding importance and will open new frontiers for the nuclear research. This device will address the charge distributions, transition densities, spectroscopic factors and correlations among others.