

Nuclear ground-state properties measured using ISOL production

Conseil scientifique de l'IN2P3 – le 26 octobre 2017

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Résumé

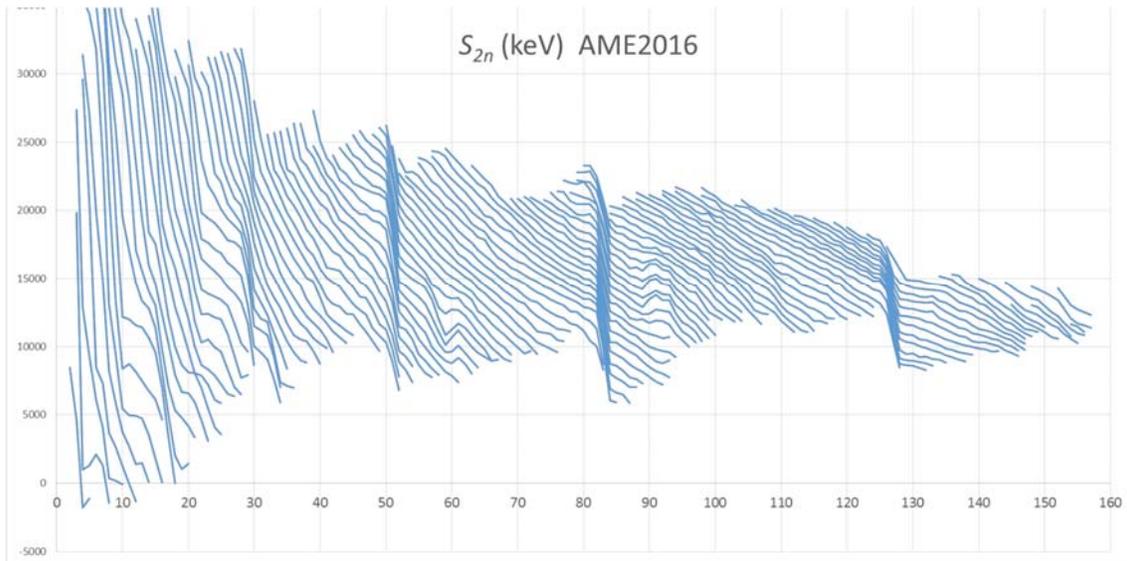
This document complements the one entitled « structure nucléaire dans les régions des nombres magiques de spin-orbite 28, 50 et 82 : apports et atouts des méthodes ISOL-basse-énergie » (by D. Verney), which gives more general overview. Here, three observables are discussed in the context of low-energy ISOL production: binding energies, charge radii and electromagnetic moments. The physics program, as pursued by collaborations involving IN2P3 physicists, is presented and discussed in the context of the DESIR and ALTO facilities. The associated methods - Penning-trap mass spectrometry, laser spectroscopy and (low-temperature) beta nuclear magnetic resonance – are discussed in another document (by P. Delahaye).

1. Scientific issues

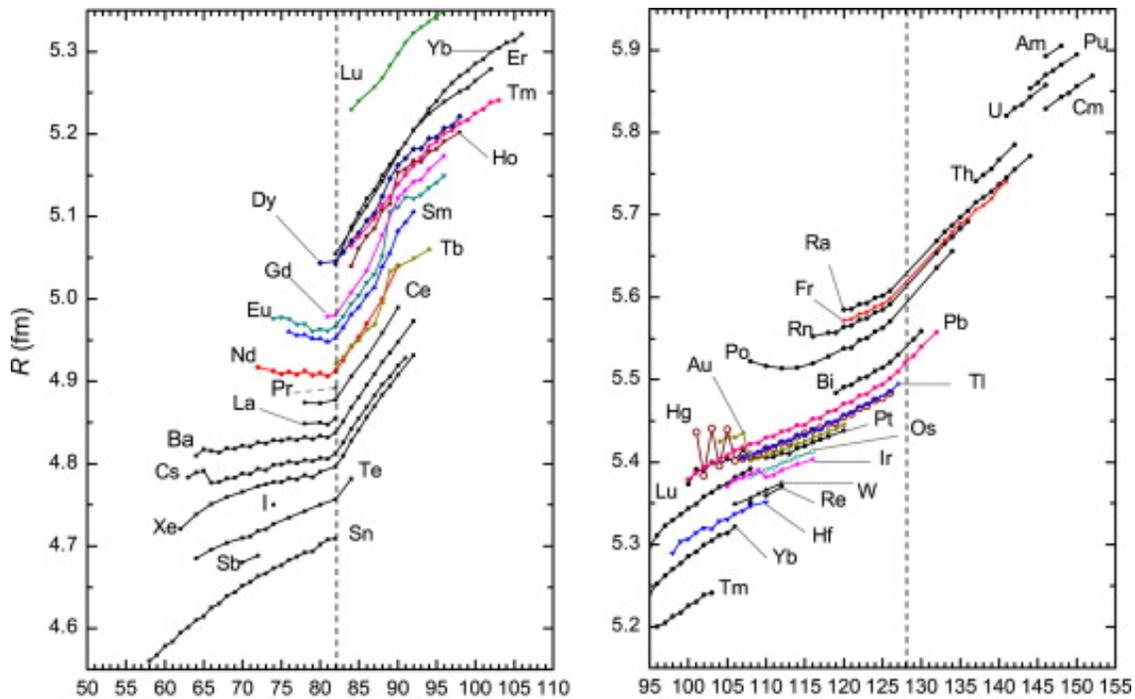
While decay spectroscopy brings a major part of the knowledge we associate with nuclear “structure”, the fundamental properties of nuclear ground states (and long-lived isomers, which are of particular interest for their special configurations) also bring us critical information necessary for a complete and correct nuclear theory. Complementing the more global features illustrated by masses and charge radii, nuclear moments and spins pinpoint the contributions of the individual nucleons. A brief description of these observables is given here.

The mass of a nuclide, through its binding energy, 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”.

Mass and decay data are collected and combined within the Atomic Mass Evaluation, the latest of which is AME2016 [M. Wang et al. Chin. Phys. C, 2017]. Data from AME2016 are shown in the following figure, as two-neutron-separation-energy mass differences with lines connecting isotopes of all elements. Generally, the energy required to remove two neutrons decreases with N . In addition to the shell closures readily visible at $N = 28, 50, 82$ and 126 , areas of particularly strong deformation can be seen, e.g. at $N = 60$ and 90 . These regions have given rise to the new paradigm of nuclear phase transitions.



The degree to which a nucleus is bound will be reflected by its size. 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. Effects of the nucleus on the atomic spectra are manifested by the hyperfine structure, which can be probed very sensitively by laser spectroscopy. Charge radii of selected isotopic chains are shown in the following figure as a function of N . (Source: I. Angeli and K.P. Marinova, *At. Data Nucl. Data Tables*, 2013). Again, shell effects are readily visible, as are changes in deformation (again, $N=90$, left panel) and (unlike the mass surface) shape coexistence for Hg and Au ($N=104$, right panel).



The hyperfine structure also allows measurements of 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. The latest evaluation for magnetic dipole moments is N.J. Stone, IAEA Report (2014) and for electric quadrupole moments: N.J. Stone, At. Data Nucl. Data Tables (2016). In addition to lasers, the spin orientation required for any nuclear moment measurement can also be achieved using implantation on a low-temperature surface in conjunction with nuclear magnetic resonance.

Recent physics results involving these observables obtained at ISOL facilities with collaborations involving IN2P3 physicists are given in section 4.

2. Project

The DESIR facility, under construction at GANIL in the framework of the SPIRAL2 project, is a state of the art experimental hall for apparatus devoted to various forms of spectroscopy and the measurement of ground-state properties. Two such setups, MLLTRAP (for masses and decay spectroscopy) and LINO (for radii and moments with lasers), are being developed in the meantime at the ALTO facility (along with POLAREX, a dilution refrigerator for measuring electromagnetic moments by low-temperature orientation and gamma spectroscopy). ALTO currently runs experiments with BEDO and TETRA for beta- and beta-delayed neutron studies. In parallel, the S3 low-energy branch is being built at GANIL. Using a front end called REGLIS, the low-energy branch will stop and neutralize mass-separated reaction products from S3 in a gas cell, where lasers will be used for selective ionization. The exotic ($N = Z$ and particularly heavy species produced by fusion-evaporation reactions) nuclides will then be sent to a MR-TOF mass spectrometer (called PILGRIM) and/or DESIR (see document of P. Delahaye).

Measuring the ground-state properties of mass, size, deformation and spin requires high precision. In the case of charge radii (and electromagnetic moments), a proven method is laser spectroscopy that probes the influence of the nucleus on the atomic system via the hyperfine structure. At today's ISOL facilities, the nuclides under study can be selectively ionized using stepwise laser excitation. First hints of isotope shifts can even be had by scanning the ionizing frequency (e.g. RILIS at ISOLDE; GISELE at SPIRAL2).

Because the binding energy is such a small component of the overall mass, measurements of exceptionally high precision are necessary, now routinely achieved with the advent of Penning trap mass spectrometry. Penning traps are now present at many of the world's radioactive facilities and the mass surface has undergone an impressive refinement over the last decade. DESIR will feature MLLTRAP after its commissioning phase at ALTO, which also includes the development of a novel technique for first measurements of conversion-electron lifetimes using trapped-alpha emitters.

Isomers can sometimes pose problems to spectroscopy when they are of moderate (<100 keV) energy or when they have beta-decaying branches. The superior resolving power of Penning traps now allows the isolation of low-lying isomeric states that complements

spectroscopy. A new instrument called PIPERADE is being built for trap-assisted spectroscopy at DESIR. PIPERADE was funded the ANR, coordinated by CENBG in partnership with CSNSM, GANIL and the MPIK in Heidelberg.

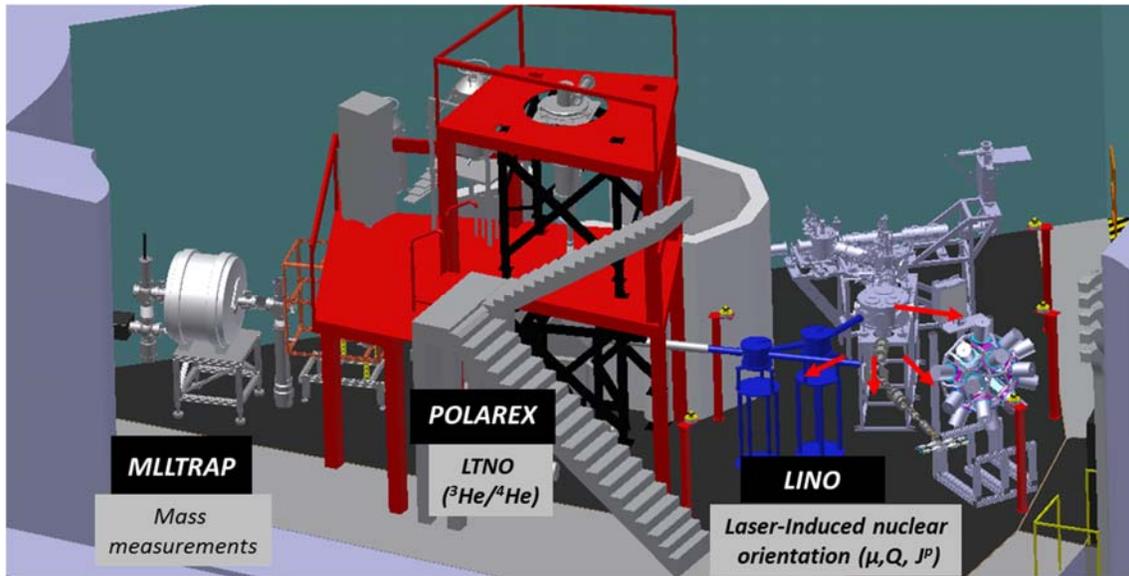
Necessary for such precision measurements are radioactive beams of sufficient intensity but especially, of low energy and superior optical quality. These characteristics are the hallmarks of the ISOL production technique.

The IN2P3 programs devoted to ground-state properties are essentially 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. To illustrate the state of the art, some highlights are given in section 4 from the ISOLDE experiments ISOLTRAP, COLLAPS, CRIS and NICOLE, as they include participation from IN2P3. (Some mass and decay-spectroscopy work has also been performed at TRIUMF's ISAC facility and at the JYFL-IGISOL facility.) Seeking to benefit from these superior techniques, developments are underway at the French facilities ALTO and GANIL.

SPIRAL2 will benefit from the Penning-trap revolution, at the DESIR facility. Penning-trap resolving power be brought to bear on the purification of fission products for decay spectroscopy (the BESTIOL/PIPERADE project). Thanks to efforts at the Ludwig Maximilians Universitaet in Munich, Penning-trap accuracy and sensitivity will also be available via the MLL trap setup, which will move to DESIR. The MLL trap was designed particularly with heavy elements in mind. As such, the coupling of DESIR to the S3 facility will allow important mass measurements of species from fusion-evaporation reactions: $N = Z$ nuclides and trans-actinide isotopes. This will be a unique installation for the extension of the mass surface to new regions, enhanced by a new R&D program of trapped-alpha-emitting-ion, electron-capture spectroscopy using a trap constructed from silicon strip detectors (within the *Terra Incognita* project of P210). This take place at the ALTO facility in Orsay. While waiting for commissioning of S3 and DESIR, these developments benefit from the availability of clean neutron-rich beams from photofission, which not only provide perfect conditions of commissioning but also opportunities for new physics in neutron-rich systems (see document of D. Verney).

3. Timeline

[Please see the overall document, by H. Savajols.] At present, IN2P3 physics programs for ground-state properties are pursued annually at ISOLDE with ISOLTRAP for masses and with COLLAPS and CRIS for radii and moments. Presently, an active program is pursued at ALTO for beta spectroscopy (BEDO) and delayed neutron detection (TETRA). Within the P210 project "*Terra Incognita*" the commissioning of the POLAREX setup is underway along with R&D for installing and operating MLLTRAP and LINO. Physics programs on neutron-rich species can be pursued in the short term while DESIR facility is being built. At GANIL, the commissioning of S3 and the associated low-energy branch, including REGLIS will open extremely interesting physics possibilities for $N = Z$ nuclides and trans-uranium elements. Moving MLLTRAP and LINO to DESIR will offer these interesting nuclides for precision measurements. ALTO would retain the capacity of performing spectroscopy with BEDO and POLAREX, which also offers interesting physics opportunities of interdisciplinary nature in material sciences and weak-interaction physics.



At the ALTO facility, three experiments under development devoted to nuclear ground-state properties make up the P2IO-funded project “Terra Incognita”. Also seen (right) is the operating BEDO decay station.

DESIR scientific program

- Coulomb laser spectroscopy
- Sub-barrier α spectroscopy (SAB)
- β - γ angular correlation, LPComp
- Mass measurements: MLLTRAP
- β -delayed charge part, Extension
- Trap-assisted β -decay, TAS

High quality 1+ RIB (10-60KV)

S³ LEB (REGLIS3):

- laser ionization source + MR-ToF
- refractory elements
- n-deficient nuclei & very heavy nuclei

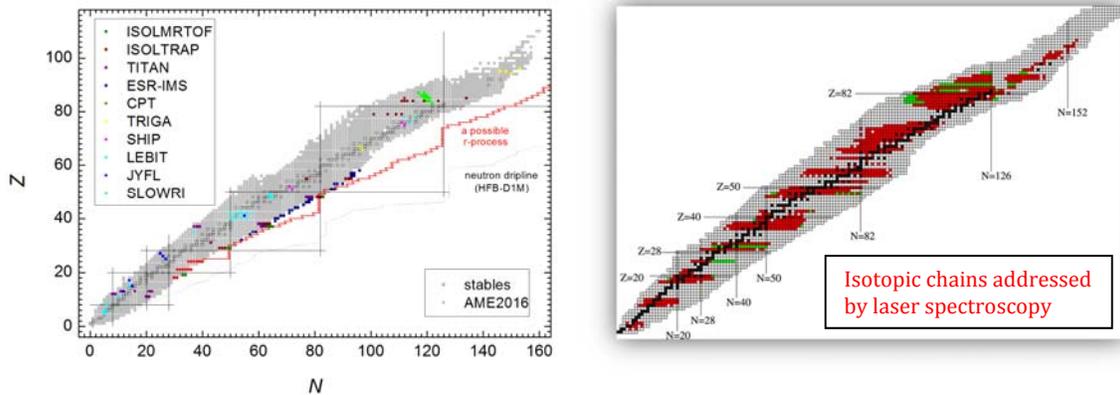
SPIRAL1:

- beam + target fragmentation
- ECR + FEBIAD + Surface ionization
- light nuclei

The new SPIRAL2 installations at GANIL, showing S3-LEB and DESIR, which can also receive beams from the upgraded SPIRAL1 facility (driver accelerators not shown).

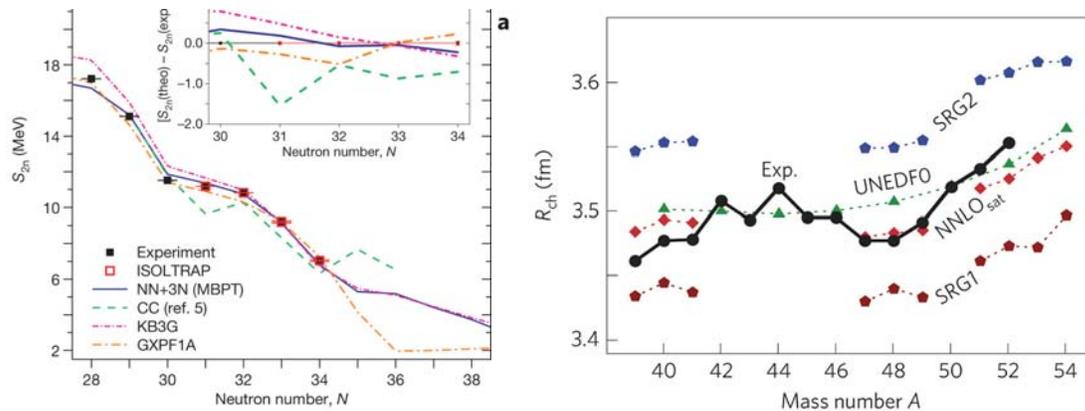
4. State of the art

Programs devoted to mass measurements are numerous worldwide. The following figures attest to the popularity and excellent performance of ISOL-based measurements of masses (left) and charge radii (right: from P. Campbell et al. Prog. Part. Nucl. Phys. 2016). Masses measured since 2014 are highlighted (left) with the overwhelming majority being on the neutron-rich side of the chart, illustrating the need of the SPIRAL2-S3 facility. The 11 different mass measurement programs attest to the competition in this field. Likewise, laser spectroscopy (right) is rather competitive as most of the isotopic chains have been measured (red and green). Apart from the COLLAPS and CRIS experiments at ISOLDE, ongoing programs at JYFL-IGISOL and TRIUMF-ISAC account for the majority of results. Charge radii data for Ir, Pt, and Au (see figure in section 2) were obtained from the IN2P3 COMPLIS experiment at ISOLDE during the period 1993-2003 (see: J. Sauvage et al. Hyp. Int. 129, 2000).



Some examples of recent results from collaborations performing measurements of ground-state properties with participation from IN2P3 physicists follow. A selected list of (recent) publications is appended to this report, which includes links to (most of) the work cited here.

A new magic number in Ca: building on beta-spectroscopy work from the Strasbourg group (F. Perrot et al. Phys. Rev. C, 2006) mass measurements of the exotic $^{52-54}\text{Ca}$ isotopes with a new MRTOF device at ISOLDE revealed the presence of a shell effect at $N = 32$ (left: from F. Wienholtz et al. Nature, 2013 with participation of the CSNSM).

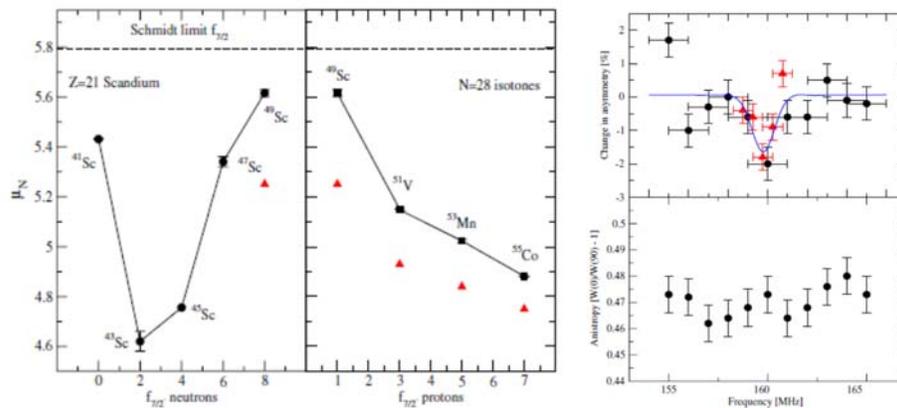


Often, charge radii data correlate with the mass data however a recent result from COLLAPS at ISOLDE (right: from R.F. Garcia Ruiz et al., Nature Physics 3645, 2016 with the participation of IPN) found that ^{52}Ca is "larger", in contrast to extra binding which

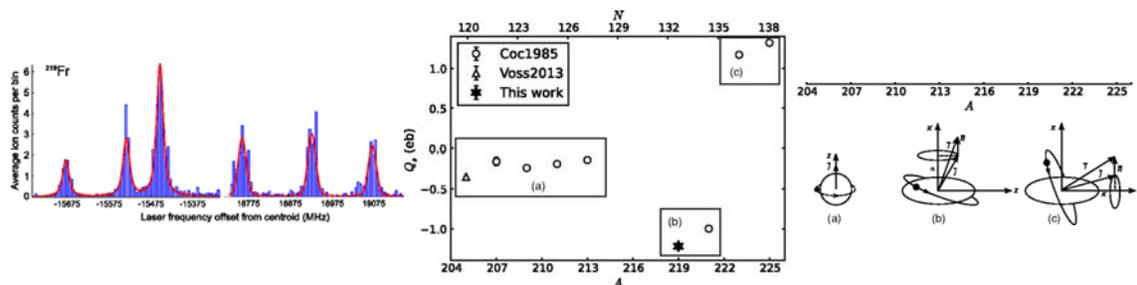
would make is smaller. Clearly the situation is not as simple as the stable doubly magic ^{48}Ca , whose charge radius is smaller than its neighbors. This is a nice indication of the complementarity of ground-state properties. It is also interesting to point out that the sensitivity improvement necessary to reach such exotic species results from the use of bunching the beams in the RFQs that were developed for mass measurements.

Probing the origin of the contrasting behavior in the calcium isotopes requires detailed spectroscopy but laser spectroscopy has also helped by measuring the quadrupole moment of ^{51}Ca (R.F. Garcia Ruiz et al. Phys. Rev. C, 2015) for which core breaking and deformed intruder orbitals play a role. Here, theoretical insight is gained from the large-scale shell model calculations of the IN2P3 group in Strasbourg.

Exploring moments and nuclear spins next to the doubly magic ^{48}Ca was also performed with the NICOLE experiment at ISOLDE by measuring the magnetic moment of the single $f_{7/2}$ proton state in ^{49}Sc , confirming the fundamental theory of nuclear magnetism. Shown in the following figure are (left) the magnetic moments of the Sc isotopes and $N = 28$ isotones and (right) the anisotropy measured by β -NMR of nuclides oriented at low temperature (from Otsubo et al. Phys. Rev. Lett, 2012 with participation by CSNSM).

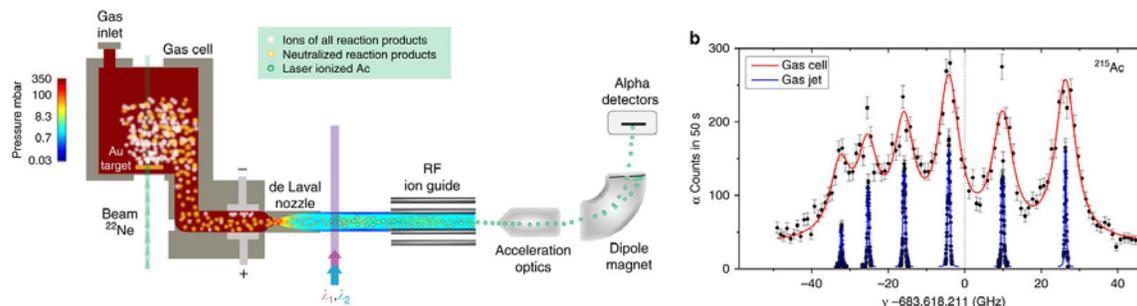


Another laser spectroscopy setup at ISOLDE is CRIS, which complements COLLAPS in using extremely sensitive multistep laser ionization. Recent improvements to CRIS have reduced the linewidth to almost that of the COLLAPS (20 MHz). The example here shows the quadrupole (left) measured hyperfine structure and (right) quadrupole moment of ^{219}Fr compared to the other isotopes made by the new CRIS setup (from R.P. de Groote et al., Phys. Rev. Lett., 2015) with participation by IPN.

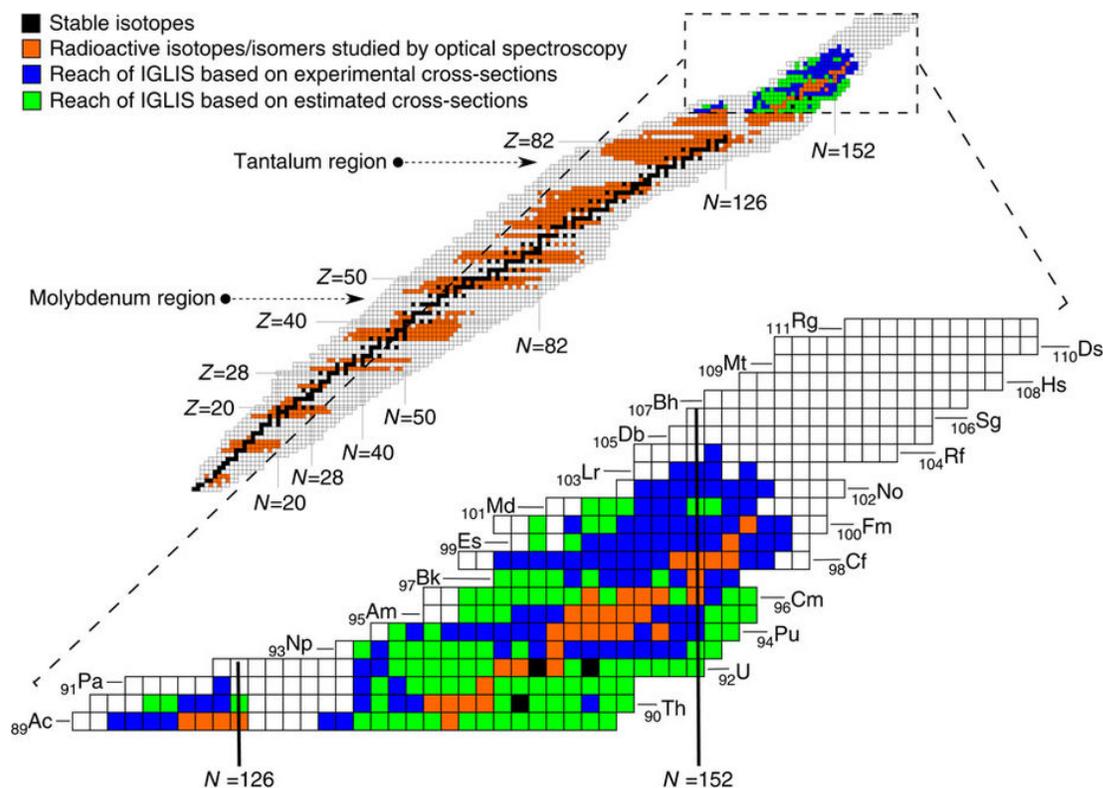


Other recent recents include the mass of ^{130}Cd , an r-process waiting-point nuclide (Atanasov et al. PRL 2015). See the corresponding document by M. Fallot. Such a result comes the using state of the art techniques for the experiment but also in selective production techniques such as laser ionization, neutron convertors and quartz lines.

For the experimental programs devoted to mass measurements and laser spectroscopy at SPIRAL2, many of the techniques developed in collaboration with groups from IN2P3 will be put into play. Shown below (left) is the REGLIS system as tested in Louvain that produced the beautiful hyperfine spectrum of ^{215}Ac (shown right – both figures from R. Ferrer et al. Nature Communications, 2017 - with participation from GANIL, LPC-Caen and IPN physicists).



The following figure is the trans-actinide region that can be produced with the heavy-ion beams of SPIRAL2. These nuclides are of particular interest since they are beyond the Coulomb limit and form bound nuclear systems solely because of quantum-mechanical nuclear shell effects. With the developments of MLLTRAP, PIPERADE and PILGRIM, mass measurements (as performed with the pioneering combination of gas-cell stopping and Penning-trap spectrometer SHIPTRAP) can now become a possibility at SPIRAL2. Likewise, this critical region is now within reach of the laser spectroscopy technique mentioned above.



In summary, France has played a major historical role in the establishment of on-line atomic-physics-rooted techniques. After the pioneering measurements of the Klapisch group at CERN, continued through the MISTRAL program, the CSNSM group is still very active in the ISOLTRAP program. Likewise, experiments in laser spectroscopy continued by IPN with the COMPLIS experiment are now performed annually by COLLAPS and CRIS with participation from IPN. At the ALTO facility, developments are underway for the use of MLLTRAP for mass measurements at DESIR and in-trap decay. The laser-based LINO project will include charge radii and nuclear moment measurements, ultimately at DESIR, while the low-temperature orientation program in Orsay will branch out from magnetic moment measurements of fission fragments to interdisciplinary material science and fundamental tests of weak-interaction physics. Finally, the successful developments of trapped-ion manipulation and laser spectroscopy will find a home at the SPIRAL/S3 facility with a large region of nuclides ripe for plunder.

5. Ressources et moyens

Quelles sont les ressources techniques et humaines disponibles pour le projet, et leur évolution temporelle passée (si applicable) et envisagée ? Pour un projet collaboratif, indiquer quelle fraction l'IN2P3 représente, en termes humains et financiers.

Ressources humaines : Lister les laboratoires impliqués à l'IN2P3, avec pour chacun, le nombre de physiciens permanents / non-permanents / ingénieurs impliqués, ainsi que l'équivalent FTE. Donner les noms, au moins des permanents, ainsi que la fraction de chacun dédiée au projet.

	Masses/traps	Laser spectroscopy	Low-T orientation
CENBG	4.0		
CSNSM	3.0	0.5	2.00
GANIL (S3/LEB)	2.0	2.5	
LPC	2.0	0.5	
IPNO	1.0	1.5	1.0
TOTAL	12.0	5.0	4.0

Table of FTE at IN2P3 laboratories for ISOL nuclear ground-state physics programs.

Ressources financières : Combien coûte le projet, globalement et à l'IN2P3 ? Quel budget est disponible ? Préciser les montants et les sources, ainsi que leur évolution temporelle. Un tableau année par année peut être judicieux.

[See corresponding document.]

6. Réalisations techniques

Quelles réalisations techniques sont envisagées, et comment seront-elles réalisées (interne, sous-traitance...) ? Préciser ici les besoins en personnel technique. Si des équipements spécifiques doivent être acquis, préciser leurs potentielles utilisations futures.

[See corresponding document.]

APPENDIX:

Selected bibliography of physics results for nuclear ground-state properties obtained at ISOL facilities by IN2P3 physicists in the last 5 years:

[Binding energy of \$^{79}\text{Cu}\$: Probing the structure of the doubly magic \$^{78}\text{Ni}\$ from only one proton away](#), A. Welker, Phys. Rev. Lett. (2017) in print

[Quadrupole moment of \$^{203}\text{Fr}\$](#) , S. G. Wilkins et al., Phys. Rev. C 96, 034317 (2017)

[Towards high-resolution laser ionization spectroscopy of the heaviest elements in supersonic gas jet expansion](#), R. Ferrer et al. Nature Comm. 8, 14520 (2017)

[Mass determination near N=20 for Al and Na isotopes](#), A. T. Gallant et al., Phys. Rev. C 96, 024325 (2017)

[Nuclear deformation in the A \$\approx\$ 100 region: Comparison between new masses and mean-field predictions](#), A. de Roubin et al., Phys. Rev. C 96, 014310 (2017)

[Penning-trap mass spectrometry and mean-field study of nuclear shape coexistence in the neutron-deficient lead region](#), V. Manea *et al.*, Phys. Rev. C 95, 054322 (2017)

[Laser and decay spectroscopy of the short-lived isotope \$^{214}\text{Fr}\$ in the vicinity of the N=126 shell closure](#), G. J. Farooq-Smith et al., Phys. Rev. C 94, 054305 (2016)

[Unexpectedly large charge radii of neutron-rich calcium isotopes](#), R. Garcia Ruiz et al. Nature Physics 12, 594 (2016)

[Combined high-resolution laser spectroscopy and nuclear decay spectroscopy for the study of the low-lying states in \$^{206}\text{Fr}\$, \$^{202}\text{At}\$, and \$^{198}\text{Bi}\$](#) , K. M. Lynch et al., Phys. Rev. C 93, 014319 (2016)

[Cu charge radii reveal a weak sub-shell effect at N=40](#), M. L. Bissell et al., Phys. Rev. C 93, 064318 (2016)

[Isomer Shift and Magnetic Moment of the Long-Lived \$1/2_+\$ Isomer in \$^{7930}\text{Zn}_{49}\$: Signature of Shape Coexistence near \$^{78}\text{Ni}\$](#) , X. F. Yang et al. Phys. Rev. Lett. 116, 182502 (2016)

[Simple Nuclear Structure in \$^{111-129}\text{Cd}\$ from Atomic Isomer Shifts](#)
D. T. Yordanov et al., Phys. Rev. Lett. 116, 032501 (2016)

[Observation of a crossover of \$S_{2n}\$ in the island of inversion from precision mass spectrometry](#)
A. A. Kwiatkowski et al., Phys. Rev. C 92, 061301(R) (2015)

[Precision Mass Measurements of \$^{129-131}\text{Cd}\$ and Their Impact on Stellar Nucleosynthesis via the Rapid Neutron Capture Process](#)

D. Atanasov et al., Phys. Rev. Lett. 115, 232501 (2015)

[Use of a Continuous Wave Laser and Pockels Cell for Sensitive High-Resolution Collinear Resonance Ionization Spectroscopy](#), R. P. de Groote et al., Phys. Rev. Lett. 115, 132501 (2015)

[Probing the N=32 Shell Closure below the Magic Proton Number Z=20: Mass Measurements of the Exotic Isotopes \$^{52,53}\text{K}\$](#) , M. Rosenbusch et al., Phys. Rev. Lett. 114, 202501 (2015)

[Penning trap mass measurements utilizing highly charged ions as a path to benchmark isospin-symmetry breaking corrections in \$^{74}\text{Rb}\$](#) , S. Malbrunot-Ettenauer et al., Phys. Rev. C 91, 045504 (2015)

[Evolution of nuclear ground-state properties of neutron-deficient isotopes around Z=82 from precision mass measurements](#), Ch. Böhm et al., Phys. Rev. C 90, 044307 (2014)

[Shell structure of potassium isotopes deduced from their magnetic moments](#), J. Papuga et al. Phys. Rev. C 90, 034321 (2014)

[Competition between pairing correlations and deformation from the odd-even mass staggering of francium and radium isotopes](#), S. Kreim et al., Phys. Rev. C 90, 024301 (2014)

[Laser spectroscopy of francium isotopes at the borders of the region of reflection asymmetry](#)

I. Budinčević et al., Phys. Rev. C 90, 014317 (2014)

[Magnetic properties of \$^{177}\text{Hf}\$ and \$^{180}\text{Hf}\$ in the strong-coupling deformed model](#), S. Muto et al., Phys. Rev. C 89, 044309 (2014)

[Electromagnetic moments of odd- \$A\$ \$^{193-203,211}\text{Po}\$ isotopes](#), M. D. Seliverstov et al., Phys. Rev. C 89, 034323 (2014)

[Collective degrees of freedom of neutron-rich \$A\approx 100\$ nuclei and the first mass measurement of the short-lived nuclide \$^{100}\text{Rb}\$](#) , V. Manea et al., Phys. Rev. C 88, 054322 (2013)

[Evidence for the extinction of the \$N=20\$ neutron-shell closure for \$^{32}\text{Mg}\$ from direct mass measurements](#), A. Chaudhuri et al., Phys. Rev. C 88, 054317 (2013)

[Collinear Resonance Ionization Spectroscopy of Neutron-Deficient Francium Isotopes](#)

K. T. Flanagan et al., Phys. Rev. Lett. 111, 212501 (2013)

[Mass spectrometry and decay spectroscopy of isomers across the \$Z=82\$ shell closure](#),

J. Stanja et al., Phys. Rev. C 88, 054304 (2013)

[Spins, Electromagnetic Moments, and Isomers of \$^{107-129}\text{Cd}\$](#) , D. T. Yordanov et al., Phys. Rev. Lett. 110, 192501 (2013)

[Plumbing Neutron Stars to New Depths with the Binding Energy of the Exotic Nuclide \$^{82}\text{Zn}\$](#) ,

R.N. Wolf et al., Phys. Rev. Lett. 110, 041101 (2013)

[Masses of exotic calcium isotopes pin down nuclear forces](#), F. Wienholtz et al., Nature 496, 346 (2013)

[Nuclear mean-square charge radii of \$^{63,64,66,68-82}\text{Ga}\$ nuclei: No anomalous behavior at \$N=32\$](#)

T. J. Procter et al., Phys. Rev. C 86, 034329 (2012)

[Surveying the \$N=40\$ island of inversion with new manganese masses](#), S. Naimi et al., Phys. Rev. C 86, 014325 (2012)

[Magnetic Dipole Moment of the Doubly-Closed-Shell Plus One Proton Nucleus \$^{49}\text{Sc}\$](#) ,

T. Ohtsubo et al., Phys. Rev. Lett. 109, 032504 (2012)

[Penning-trap mass spectrometry of highly charged, neutron-rich Rb and Sr isotopes in the vicinity of \$A\approx 100\$](#) , V. V. Simon et al., Phys. Rev. C 85, 064308 (2012)

[Elucidation of the Anomalous \$A=9\$ Isospin Quartet Behavior](#), M. Brodeur et al., Phys. Rev. Lett. 108, 212501 (2012)

[Penning-trap mass measurements of the neutron-rich K and Ca isotopes: Resurgence of the \$N=28\$ shell strength](#), A. Lapierre et al., Phys. Rev. C 85, 024317 (2012)

[Q Value and Half-Lives for the Double- \$\beta\$ -Decay Nuclide \$^{110}\text{Pd}\$](#) , D. Fink et al., Phys. Rev. Lett. 108, 062502 (2012)

[First Direct Mass Measurement of the Two-Neutron Halo Nucleus \$^6\text{He}\$ and Improved Mass for the Four-Neutron Halo \$^8\text{He}\$](#) , M. Brodeur et al., Phys. Rev. Lett. 108, 052504 (2012)