Letter of Intent for SPIRAL2

The DESIR facility

(Désintégration, excitation et stockage d'ions radioactifs)
(Decay, excitation and storage of radioactive ions)

I. Introduction

The SPIRAL2 facility at GANIL will produce radioactive isotopes ranging from the lightest to very heavy elements beyond uranium. Different production mechanisms will be utilised: fission of ^{238}U to produce medium-mass, neutron-rich isotopes, fusion evaporation for medium-mass, neutron-deficient nuclei, and transfer and deep-inelastic reactions for light to heavy nuclei closer to the line of β stability. Therefore, the SPIRAL2 driver accelerator will accelerate deuterons to 40 MeV and medium-mass, heavy ions to 14.5 MeV/nucleon with a mass-over-charge ratio of 3. The deuteron beam will be used to induce fission of ^{238}U in a thick target, whereas the heavy ion beams can be used either to produce radioactive isotopes in a thick target – ion-source ensemble or in a thin target coupled to a separator-spectrometer. Of interest for the present letter of intent is the thick-target approach.

After their production in the thick target, the nuclei of interest must quickly and efficiently diffuse to the surface of the target/catcher material, be released from there and be transferred into a region into a region where they can be ionised with a suitable method (surface, plasma or laser ionisation). This target – ion-source ensemble will be installed on a high-voltage platform, which will produce ion beams of a few tens of keV. These ion beams can then be used either at an ISOL facility, where e.g. decay studies, laser spectroscopy, mass measurements can be performed, or they can be accelerated by the CIME cyclotron and be used to induce nuclear reactions.

The DESIR collaboration, formed after the SPIRAL2 workshop on low-energy physics at GANIL in July 2005, proposes the construction of an experimental facility to exploit the low-energy beams from SPIRAL and SPIRAL2. In the interest of efficiency, certain arrangements and instrumentation are necessary to allow for parallel operation of the low-energy part and the post-accelerator. In addition, experiments performed at other ISOL facilities (e.g., ISOLDE or ISAC) show that a high degree of purity is necessary for the ions beams. The most efficient and universal way of achieving isotopically pure beams is a high-resolution mass separator.

The present letter of intent lays out the physics case that will be addressed at the DESIR facility of GANIL and describes the instrumentation needed to reach the scientific goals. In the second section, we describe the beam preparation and beam handling schemes we propose to produce suitable ISOL beams for experiments. The third section deals with laser spectroscopy to study ground-state and isomer properties. The fourth section presents the envisaged studies in decay spectroscopy of radioactive species with some emphasis on new ideas of applying mass spectrometry for trap-assisted measurements. The fifth section covers the topics of symmetry tests and studies of fundamental interaction for which atom and ion traps play an important role. The final chapter presents a first design for the facility itself.

II. Beam handling

The technology of so-called “beam handling” has developed in the last 15 years in attempts to improve the signal-to-background ratio in experiments on exotic nuclides and to prepare beams for injection into a sensitive apparatus. Increased production of exotic nuclides always brings higher levels of radioactive contamination. Therefore, in order to keep pace with intensity upgrades, the elaboration of new experimental apparati must be accompanied by the development of techniques for efficient beam purification. This is not only true from a radioprotection standpoint but also for the preservation of sensitive experimental detectors. The purification and preparation of rare, radioactive ion beams is critical for their use in experiments. The case of SPIRAL2, as a next-generation facility, is important since the question of isobaric contamination will play a determinant role in whether experiments with low-energy beams can be performed or not.

The following distinctions can be made when discussing beam handling:

- Beam transport: successive focusing and steering of the beam to take it over a given distance using adapted optical elements (quadrupoles, kickers, benders).
- Mass separation (of an ion beam): the use of a magnetic field to selectively deflect a given mass with a given resolving power which will determine the degree (distance) of separation (isotopic, isobaric and, in the case of Penning traps, isomeric).
- Beam purification: the idea of distilling or filtering a beam to rid it of unwanted contamination by other chemical species or neighbouring isotopes – performed using (laser) ionization or mass separation.
- Beam cooling: increasing the brilliance of a beam (as distinct from intensity) by dissipatively reducing the beam emittance, requiring a confinement to counteract the diffusive thermalisation (i.e. a linear Paul trap, a cylindrical Penning trap, or perhaps a miniature storage ring).
- Beam preparation: the conditioning of a beam within phase-space e.g. simply by beam transport (handling) in the transverse plane for a focused or parallel beam, or by bunching to provide an energy or time focus on the longitudinal axis, requiring a storage device (and beam cooling).

Purification is performed in the production area (in order to transport a minimum of activity) whereas preparation is usually done in the experimental area. Transport is, of course, required everywhere. Laser ionization is performed directly at the source whereas mass separation occurs after a first leg of beam transport. Preparation requires ion cooling and storage and, as such, must be performed after sufficient purification of the beam. As these devices are rather complicated, they are usually part of the experimental apparatus – or at least located close to the experiments and operated by physicists running experiments.

A high-resolution separator for DESIR

Selective laser ionization and high resolution mass spectrometry in Penning traps have set high standards for beam purification. However, the laser method still allows high surface-ionization and the Penning trap is still vulnerable to high levels of contamination. The “classic” solution of high-resolution dipole magnets also suffers from the constant-product law of transmission and resolving power (i.e. you cannot have both at once) which is why new R&D is underway to find a compact solution that can offer high transmission and high resolving power to furnish pure samples of exotic nuclides. For example the so-called ion circus, a novel ion trap of segmented, circular geometry (resembling a miniature storage ring) that aims to simultaneously cool and mass-separate rare isotope beams from super-abundant contaminations. Another interesting development combines cooling and selective laser-ionization in a so-called laser ion-source trap (LIST).

Penning traps (e.g. ISOLTRAP) achieve resolving powers of over 10 million but with two important conditions: there are not more than a few ions in the trap, and the half-life is not much shorter than the (several seconds) storage time required. REXTRAP, on the other hand, can store 10^9 ions – but with very modest resolving power. Thus Penning traps will not provide us with a scheme for sufficient mass separation of very intense beams. Due to the robustness required, combined with the need for speed (i.e. in going farther from stability where the half-lives only get shorter), it seems that any serious attempt at isobaric mass separation will have to adopt the double-dipole scheme.

In Figure BH-1, an illustration is given for the *A*=132 chain, showing that the resolving power required to separate ^{132}Sn from the isobaric (n-rich) neighbours is about 10,000. Such a feat is presently impossible. For example, at ISOLDE and even according to the design values, achieving 10,000 with the ISOLDE HRS would be possible with only 25% transmission.

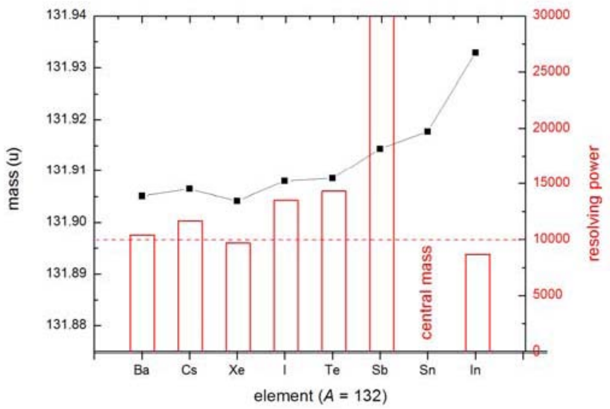

Figure BH-1: Graph of the mass of the neutron-rich A=132 isobars (Xe stable) and the resolving power necessary for separation with respect to Sn (Z=50). The minimum resolving power is 10,000.

A high-resolution separator concept has been elaborated in the framework of the EURISOL study (by T.J. Giles at CERN-ISOLDE). This concept, illustrated in Fig. BH-2, uses a variable pole gap designed to correct for distortions and requires no electrostatic corrections.

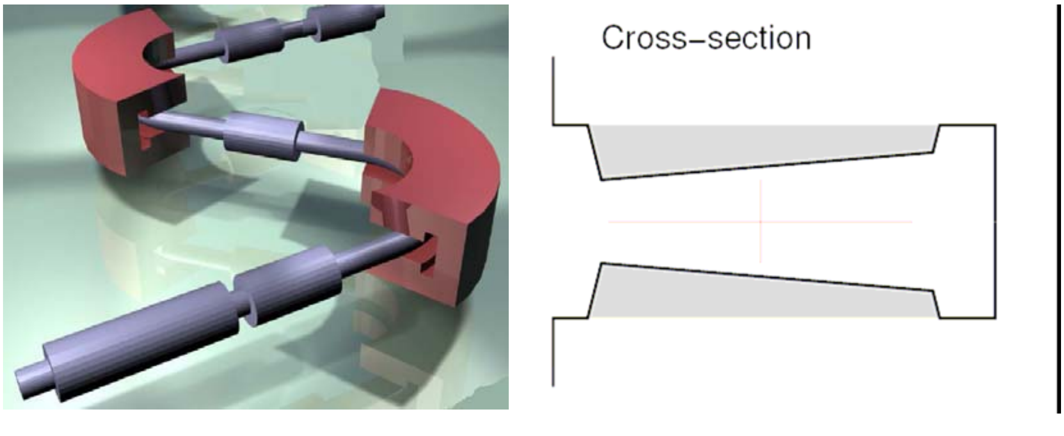

Figure BH-2: Schematic drawing of the DESIR high-resolution separator, based on the EURISOL design by T. Giles but using only two, 135-degree magnets with a tailored gap. (Right) cross-section of the magnet gap.

To obtain the necessary resolving power without a loss in intensity, a reduction in beam emittance will be necessary. Beam optics calculations (using GIOSP) shown in Fig. BH-3 demonstrate that a resolving power of 20,000 could be obtained using two dipoles but would require an emittance of much less than 1 π-mm-mrad (at 30 keV). Such a small emittance will require the installation of a beam cooler before the separator. The intensities of SPIRAL2 will greatly exceed present beam-cooling technology, requiring an important R&D effort.

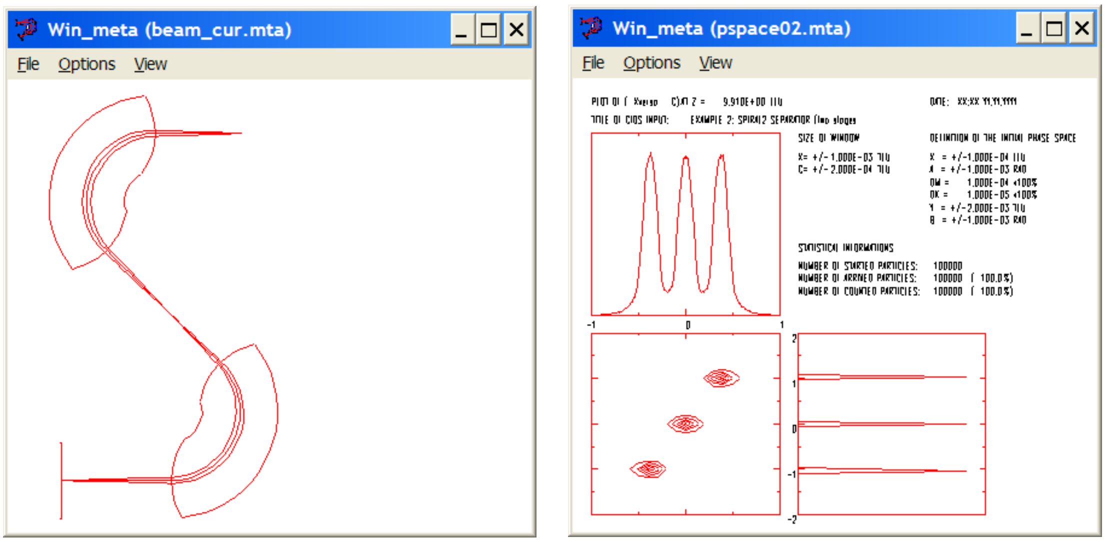

Figure BH-3: Beam optics calculations using GIOSP showing (left) the geometry and (right) the mass dispersion obtained with 30-keV beam emittances of 0.1 π-mm-mrad in the horizontal and 0.1 π-mm-mrad in the vertical planes.

Beam preparation for spectroscopy using a Penning trap

As mentioned above, Penning traps offer superior mass separation capabilities. After an initial mass separation and bunching stage, a purified sample of a relatively modest number of ions can be injected into a Penning trap where even isomeric resolving power can be brought to bear. As shown in Fig. BH-4, the trap can be used to prepare a well-defined (point-like) source for spectroscopy studies as well as providing additional mass purification if required. Due to the magnetic field, charged particle detectors can be placed far from the source to avoid gamma background.

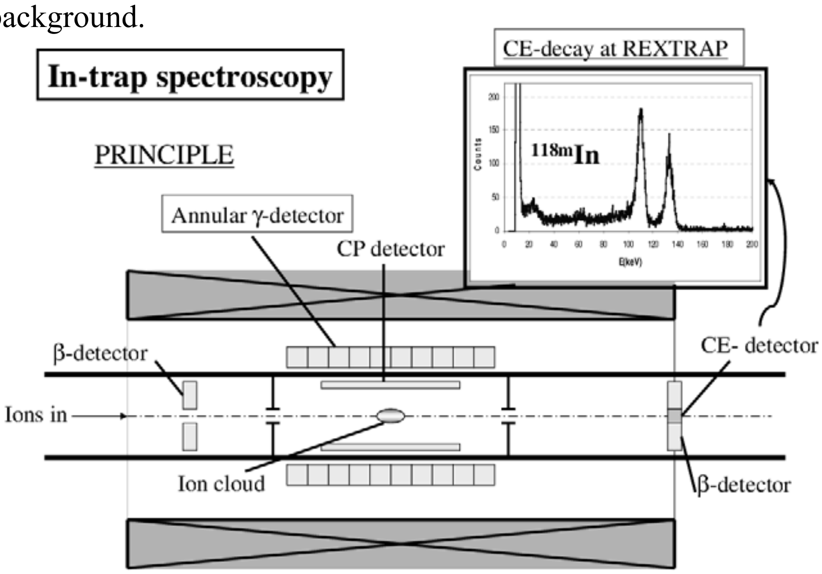

Figure BH-4: Illustration of trap-assisted spectroscopy. Mass-separated ions with the correct time structure are stored in a Penning trap surrounded by charged-particle detectors.

Penning traps are now established as the instrument of choice for mass measurements as well. We intend to provide for the possibility of cyclotron resonance excitation in the DESIR Penning trap in order to measure decay *Q*-values of exotic nuclides. Such an instrument would complement the many other Penning traps planned and currently in use for mass measurements of very high precision.

III. Laser spectroscopy: the LUMIERE project (Laser Utilisation for Measurement and Ionization of Exotic Radioactive Elements)

Atomic physics and optical techniques have played an important role to study the behaviour of nuclear matter at low excitation energy. This study is possible with the observation of the magnetic and electrostatic hyperfine structure in optical spectra as well as the influence of nuclear charge radii on the isotope shifts between different isotopes of a given element.

For 30 years, lasers were used at accelerators to measure these quantities and the best example is the observation of the sudden change in the nuclear charge radius in the mercury isotopes showing a large shape transition at mid-shell (N=108). Today with different techniques, laser spectroscopy still continues to deliver key information on properties of nuclear ground states and long-lived isomers with the measurement of the spin, the magnetic moment, the quadrupole moment and the change in the mean square charge radius between two isotopes. These experimental data are highly accurate and the nuclear parameters can be extracted model-independently which constitute a stringent test for nuclear models.

The technique mainly used is the collinear laser spectroscopy for its versatility and the high precision that it gives. A laser beam is sent collinearly with an ion or atomic beam of the same size, such that they can resonantly interact. The laser frequency is scanned in order to record the complete hyperfine spectrum from which one can extract the nuclear quantities.

Another issue related to collinear laser spectroscopy is the possibility to polarize the nuclear spins. A high degree of electronic polarization can be achieved by optical pumping with circularly polarized laser light. Via hyperfine coupling, this polarization is transferred to the nucleus and after implantation in a suitable crystal, the magnetic and quadrupole moment of the nucleus can be measured with high precision using a radiofrequency field.

To study the hyperfine anomaly or to have access to higher order nuclear moments (octupole and hexadecapole) one can use ion traps. Once again, the combination of the laser optical pumping and the radiofrequency scan inside a hyperfine multiplet gives a precision of 10^{-9} on the magnetic hyperfine constant, allowing to reach the forth order in nuclear deformation. In a Paul trap, the motion amplitude of the ions is large compared to the microwave wavelength so that, at first order, one does not have a Doppler effect which explains the precision reached.

At SPIRAL2 and its low-energy beam facility DESIR, there is an opportunity of building three kinds of setup to try to cover the whole nuclear chart. A ß-NMR setup will be suitable to study precisely the moments of key cases and, in combination with collinear hyperfine spectroscopy, get unambiguous spin assignments. With a collinear spectroscopy setup, we will have the possibility to study series of isotopes in the intermediate and heavy mass regions. For the heavy elements, a double laser+RF spectroscopy in a Paul trap will be used to study the hyperfine anomaly and higher-order moments up to very high precision.

Collinear laser spectroscopy

Thanks to its high precision and high versatility, collinear laser spectroscopy of atoms and ions is the most employed method since many years. Laser spectroscopy has now been performed over quite a substantial range of the chart of nuclei. However, especially in the region of refractory elements and in the magic regions far from stability, a lot of elements still has to be studied.

The beam **requirements for collinear laser spectroscopy** studies on exotic radioactive nuclei are:

- purity of the beam > 50%
- minimum lifetime of the state: 1 ms
- minimum yield: 5000/s

The precision obtained is of the order of 10^{-3} on the charge radius, 10^{-2} on the magnetic moment and 10% on the quadrupole moment.

The physics cases to address:

1) *The N=50 region:*

This region is of particular interest, especially from an astrophysical point of view. In neutron stars, several light neutron-rich nuclei are produced and the question to address is how nuclear matter is distributed in these nuclei. Another issue is to determine how thick can be the neutron skin for nuclei far from stability? From the measurement of the charge radius, one has access to the neutron radius. A key element would be germanium which is produced in large quantities in neutron stars. So the measurements of the charge radius change of this element and its neighbours (Zn, As, Ga, Se) over the magic shell N=50 using collinear laser spectroscopy will answer this question.

Another typical example of an element that has to be studied is of course nickel as close as possible to ^{78}Ni. How can the charge radius evolve so far from stability? Is this doubly-magic nucleus still spherical?

2) *The N=64 region:*

In the “deformed region” containing Rb (Z=37), Sr (Z=38) and Y (Z=39), strongly oblate shapes are predicted beyond N=64 for ground- and long-lived isomeric states.

3) *The N=82 region:*

For all the studied elements between tellurium (Z=52) and samarium (Z=62), the charge radius change exhibit a kink at N=82 showing an increase in deformation beyond this magic number. The interesting feature is that the more one approaches tin (Z=50) the less pronounced is the kink (see Fig. LS-1). A lot of nuclear models predict that no kink is present at N=82 for tin, a fact which should be a signature of a neutron skin for the very neutron-rich isotopes. Studying tin very far from stability will be a very stringent test for these nuclear models. In contrast, indium (Z=49), iodine (Z=53) and cadmium (Z=48) should present interesting kinks at N=82. Silver isotopes (Z=48) have been studied until A=110. This element is the heaviest in this region to show a sizeable shape change at N=60. The heaviest one could have interesting shapes.

4) *The refractory elements around Z=40*

A lot of shape transitions have already been observed in the Zr region. Far from stability, one should observe more and more shape instability in zirconium (Z=40), molybdenum (Z=42), technetium (Z=43) and ruthenium (Z=44) where nothing is known.

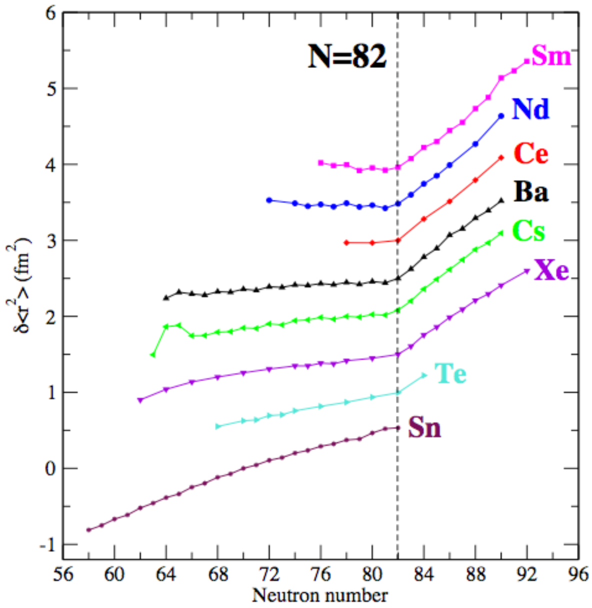

Figure LS-1: Charge radius change in the N=82 region. The king after N=82 is characteristic for deformation.

5) *The rare earth elements and beyond*

This region presents a lot of very deformed nuclei among the barium (Z=56), neodymium (Z=60) and samarium (Z=62) isotopes. The aim is to study all these elements and beyond to reach the transitional region around mercury (Z=80). A lot of refractory elements around hafnium (Z=72) still have to be studied.

This large physics program can cover a large part of the nuclear chart far from stability. The measurements of the mean square charge radius and of the nuclear moments of such exotic nuclei will be a stringent test for nuclear models.

Nuclear magnetic resonance with observation of ß-decay asymmetry (ß-NMR)

With the collinear laser spectroscopy set-up that will be present at the DESIR facility, it will be possible to polarize radioactive beams using circularly polarized laser light. Using spin-polarized beams it is possible to apply the β-NMR (Nuclear Magnetic Resonance) method to measure precisely the nuclear g-factor after the radioactive beam is implanted in a suitable crystal that is placed between the poles of an electromagnet. One can also measure the nuclear quadrupole moment if a crystal with a suitable electric field gradient is used as implantation host.

The beam requirements for β-NMR studies of exotic radioactive nuclei are:

- purity of the beam > 50%
- lifetime of the state: 1 ms – 10 s
- minimum yield: 5000/s
- possibility to resonantly excite the element (for polarization through optical pumping with a circularly polarized CW laser beam)

This method of measuring the moments of nuclear ground or isomeric states is complementary to the collinear laser spectroscopy technique itself, which also allows for measuring the magnetic and quadrupole moments of long-lived radioactive beams using CW laser light.

Advantages of β-NMR are:

- by combining the information deduced from a hyperfine structure measurement (the magnetic moment) and from a β-NMR measurement (the g-factor), it is possible to unambiguously assign the spin of the investigated nuclear state (e.g. as done recently for ^{31}Mg). It is in particular important in regions far from stability to firmly assign the spin of a few nuclear states, in order to then deduce information on the spins of their mother or daughters via e.g. β-decay spectroscopy experiments.
- β-NMR yields the nuclear moments with a precision of better than 0.1% (for g-factor) and 1% (for Q-moment), thus allowing to probe small changes in the nuclear wave function, e.g. contributions from particle-hole excitations and intruder configurations in the wave function, core polarization effects, etc. In particular, the hyperfine anomaly over an isotope series can be investigated.
- β-NMR measurements are very sensitive: with yields of only a few 1000/s, precise results can be obtained in a reasonable amount of beam time.
- the β-NMR technique can be used to measure small quadrupole moments that are not accessible using the collinear laser spectroscopy method alone.

With the SPIRAL2 facility, many beams of very exotic nuclei will become accessible for such studies, e.g. in the neutron-rich regions around ^{78}Ni and ^{132}Sn. In the figures below, the isotopes in the regions above ^{78}Ni (Fig. LS-2) and around ^{132}Sn (Fig. LS-3) are shown and those with suitable lifetimes for β-NMR studies are on the right of the yellow band. These figures are also available for laser spectroscopy.

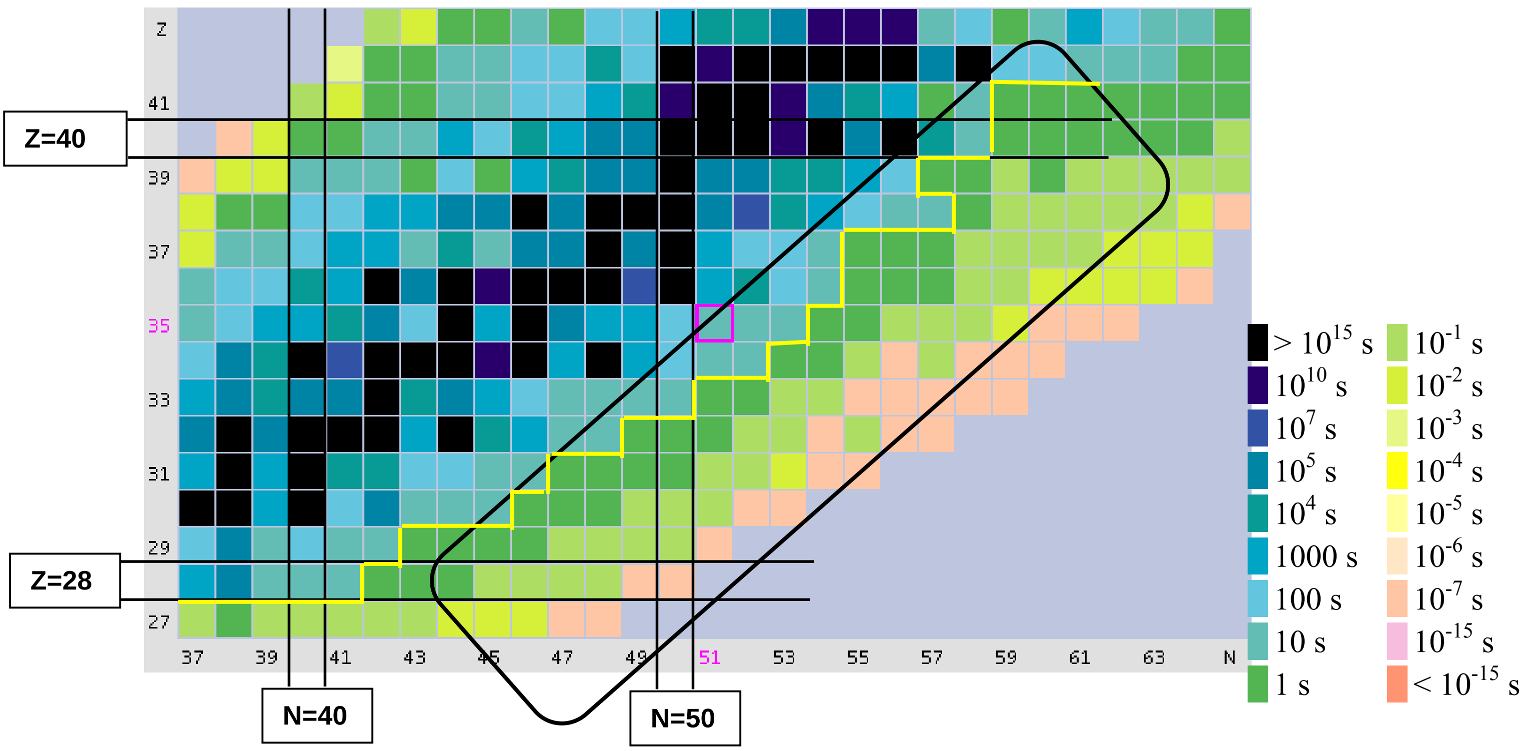

Figure LS-2: Part of the nuclear chart in the neutron-rich region above ^{78}Ni, which will be produced by deuteron-induced fission. The elements at the right of the yellow line have suitable lifetimes for performing β-NMR measurements.

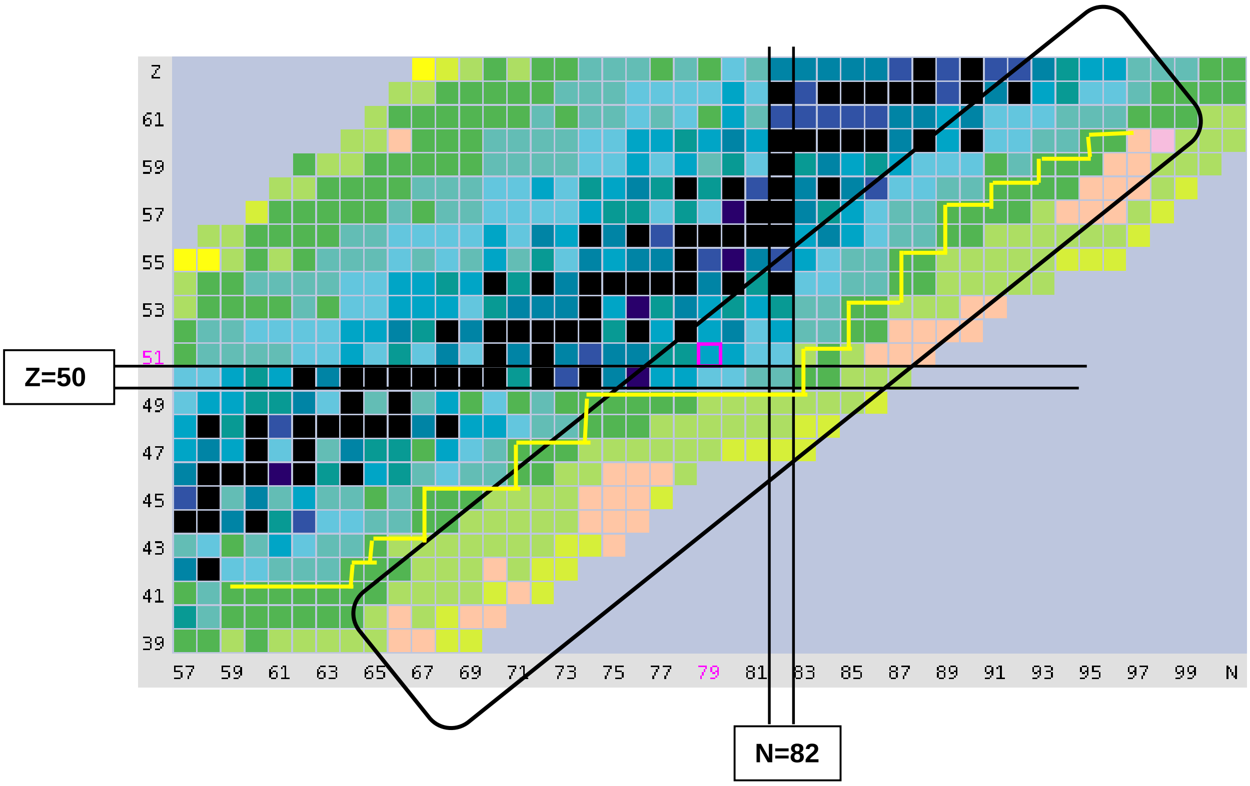

Figure LS-3: Part of the nuclear chart in the neutron-rich region around ^{132}Sn, which will be produced by neutron-induced fission using a converter target. The elements at the right of the yellow line have suitable lifetimes for performing β-NMR measurements.

The physics cases to address:

- study of the **monopole migration of proton and neutron single-particle levels in the neutron-rich region around ^{78}Ni (as a function of N and Z).** Ground state and isomeric state spin assignments are needed for this purpose. They can be obtained indirectly by measuring the nuclear g-factor (as the g-factor is very sensitive to the occupied valence orbit) or directly by a combination of β-NMR and hyperfine structure measurements using collinear spectroscopy.
- nuclear moments are very good **probes to test the nuclear models** which are being developed for these neutron-rich regions, and which need to be tested on their predictive power for more and more exotic cases. Such tests require **systematic studies of the nuclear moments** in a particular region of the nuclear chart, such as the neutron-rich region around magic N=50 approaching ^{78}Ni.
- trends of nuclear moments provide information on the existence (or not) of a shell gap and can be used thus to **probe the persistence of the N=50 shell gap towards ^{78}Ni or of N=82 towards and below ^{132}Sn.**

Possible key experiments:

1) *Ground state spins and moments of the neutron-rich Cu and Ga isotopes (Z=31)*

With respectively 1 and 3 protons above the Z=28 shell, the ground state of these isotopes is expected to be dominated by the $\pi p_{3/2}$ proton orbital. However, for the neutron-rich Cu isotopes, evidence is found that the ground state is dominated by the $\pi f_{5/2}$ proton orbital from N=45 on. For the Ga isotopes, a similar trend is observed, but the inversion is suggested to occur for ^{81}Ga (N=50). The g-factor for both proton configurations is very different ($g_{eff}(\pi p_{3/2}) \sim 1.7$ and $g_{eff}(\pi f_{5/2}) \sim 0.65$) thus one can assign the ground-state configuration unambiguously by measuring it. This is illustrated in the Fig. LS-4, where the calculated g-factors for the lowest 3/2- and 5/2- states in the odd Cu isotopes are presented together with the measured ground-state g-factors up to ^{71}Cu. If indeed the ground state is dominated by the $\pi f_{5/2}$ proton from ^{73}Cu on, this should be clearly visible as a large reduction in its ground state g-factor.

Both elements can be resonantly excited by CW lasers. Suitable transitions for polarizing the beams are available in the atomic case, which is obtained after charge-exchange. While collinear spectroscopy can provide the magnetic moment, the quadrupole moment and the changes in mean square charge radii, the combination with β-NMR will yield unambiguous spin assignments and precision values for the g-factors.

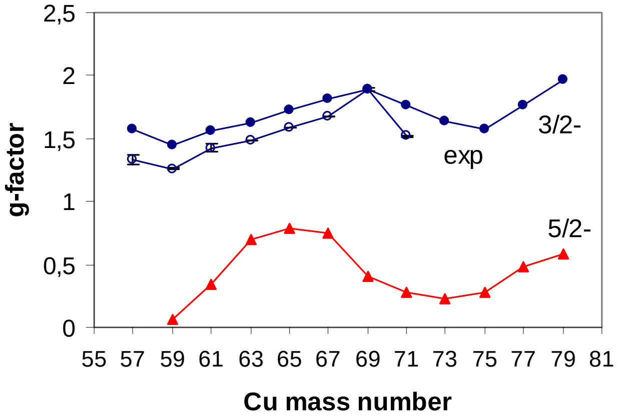

Figure LS-4: Calculated g-factors (full symbols) for the lowest 3/2- (ground state) and 5/2- state in odd Cu isotopes, compared to the experimental ground-state g-factors, in order to illustrate that measuring the ground-state g-factors of the neutron-rich isotopes will reveal the nature of its proton configuration.

2) *Ground state spins of N=49 and N=51 isotones with even proton number*

These nuclei can be studied to verify the persistence of the N=50 shell gap by looking at their ground-state spin and parity: if N=50 is a good shell gap, the N=49 isotones with even proton number will have a $\nu g_{9/2}$ as leading ground state configuration, thus $I^{\pi}=9/2^{+}$ (^{81}Ge, ^{79}Zn, ^{77}Ni). On the other hand, the N=51 isotones are expected to have the odd neutron in the $\nu d_{5/2}$ orbital and thus $I^{\pi}=5/2^{+}$ is expected for their ground-state spin.

Microwave double resonance in a Paul trap: hyperfine anomaly and higher order momenta

In the nucleus, every observable that is related to the neutron wave function is difficult to measure directly because of its zero charge. The hyperfine anomaly is the way to reach this type of parameter since it allows quantifying the influence of the nuclear magnetic distribution on the hyperfine structure. If one has a precise idea of the volume repartition of the magnetism in the nucleus, one can study more precisely the effects on parity non-conservation in isotopic series and better understand the contribution of the neutrons to the nuclear wave function.

At first order in the magnetic hyperfine interaction, the nucleus is represented as a magnetic point charge. However, mainly in heavy elements, the magnetic distribution is extended over the whole nuclear volume. In an isotopic series, this distribution seen by the electron is different from an isotope to another. This is the Bohr-Weisskopf effect that introduces a small perturbation on the magnetic field created by the electron inside the nucleus. This hyperfine anomaly is of the order of some thousandth and can reach some ten percent for mass 200.

This is why the measurement of the hyperfine constants at high precision is of fundamental importance to study the hyperfine anomaly along an isotopic chain and also to reach nuclear deformation of octupole and hexadecapole character. The combination of laser optical pumping and a radiofrequency scan on ions in a Paul trap allows bypassing the Doppler effect and thus getting very high accuracy on the values of the Zeeman transitions. Such studies have already been performed on five europium isotopes and the precision reached on the magnetic hyperfine constant is of the order of 10^{-9}.

If the nuclear gyromagnetic factor is measured using for example ß-NMR or a Penning trap, the measurement of the magnetic hyperfine constant gives directly the hyperfine anomaly. Such studies should be very interesting in the gold isotopes where the hyperfine anomaly can vary between 1 and 10 %. Other elements like europium or cesium have also to be studied.

Finally, in the very heavy elements, octupole and hexadecapole deformations play an important role in the structure of the nucleus. The hyperfine interaction can quantify them model-independently. In a first step, the heavy elements in the actinide region (Rn, Fr, Ra and even Am) will be studied. The measurement of the deformation in the second well would really be a challenge for such experiments.

The beam **requirements for double resonance measurements** on exotic radioactive nuclei are:

- purity of the beam > 50%
- minimum lifetime of the state: 100 ms
- yield: 10 to 10000/s

IV Beta decay studies: The BESTIOL facility (BEta decay STudies at the SPIRAL2 IsOL facility)

To date only 2000 nuclei are known of the 5000 to 7000 theoretically predicted. New facilities are planned aiming to produce new species and increase the intensity of the known ones. Often the key nuclei are either very neutron or proton rich. Such exotic systems permit the isolation and amplification of specific aspects of nucleonic interactions due to the asymmetric neutron proton balance. Exotic nuclei near the drip lines are loosely bound systems which lead to such exotic topologies as halo nuclei and to changes in the nuclear mean field potential even at the so-called magic numbers. Moreover the proximity of the unbound continuum can lead to important changes in residual interactions (pairing enhancement). For these and many other reasons, it is important and timely to produce and study these new nuclear species

The purpose of the SPIRAL2 project is to extend significantly the possibilities of Radioactive Ion Beams (RIB) physics at GANIL. Several domains of research at the limits of stability will be covered in this project. SPIRAL2 is based on a multi-beam driver in order to allow for both ISOL and low-energy in-flight techniques to produce RIB.

In this letter of intent we argue for the need of a low energy beam line for beta decay studies, showing how such β-decay studies can help to characterize the structure of the new systems produced.

Beta-decay studies can be done with very low beam intensity and therefore are often the first study possible for a new exotic beam. The contribution of beta decay in the characterization of new species is crucial as it is only from the beta half-life and its comparison with existing models that one can grasp the richness of the structure of the system. As an example, the half-life of ^{11}Li was twice the expected value for p-shell nuclei, suggesting a mixed character of the ground state.

For cases in which the statistics and the purity are high enough so that a full spectroscopic study can be carried out, the probability of β-decay to states of the associated daughter nucleus provides information on the degree of overlap between the neutron and proton states in the parent and daughter nuclei. When the radioactive decay populates excited states of the daughter nucleus, observation of the radiation associated with their de-excitation yields invaluable spectroscopic information on the energies and characteristics of low-lying excited states. This spectrum of states permits the characterization of the structure of the daughter nucleus concerning its rigidity, deformation and the arrangement of its particles.

The identification of new nuclei often opens novel fields of investigation leading to discoveries. Some well-known examples include:

- Nuclei with halos
- Disappearance of "shells"
- New types of pairing
- New regions of deformation

Extremely neutron-deficient or neutron-rich nuclei are characterized by very high β-decay energies. At the same time, the daughter nuclei have low particle separation energies so that the β-decay may feed excited states that are unbound to emission of nucleons or clusters of nucleons. This mechanism, which occurs for most exotic nuclei, is called β-delayed particle radioactivity. This decay mode, discovered for βα in 1916 and for βp in the sixties, has already provided much information of importance. The key point is that if one knows the final state, from the particle spectra one can derive the beta feeding to that state and the associated Fermi or Gamow-Teller (GT) matrix element that give information on the strong interaction within the nucleus. Beta-delayed particle emission has been established for a very long time now and the mechanism governing the decays is quite well understood. In lighter nuclei, the particle emitting states often have an appreciable fraction of the single-particle strength and hence a large width.

The distribution of the β-strength in the daughter nucleus determines not only the β half-lives and the rates for β-delayed particle emission and fission but also the shape of the emitted electron/positron and antineutrino/neutrino spectra.

Physics topic for β decay studies at DESIR

In what follows, we describe in some detail several other examples in which β-decay studies in exotic systems can provide information of importance in nuclear physics and related fields.

a) Decay studies with halo nuclei

The process of β-delayed deuteron emission is only possible if the S_{2n} value of the decaying nucleus is less than 3 MeV.

$$Q_{\beta^-}(A,Z) - S_d(A,Z+1) = 0.782 + 2.22 - S_{2n}(A,Z) \quad MeV$$

Therefore, this decay process can be particularly useful in studies of the two-neutron halo state. There are very few candidates for this decay mode. But if they exist the decay must be favoured. The reason is that nuclei with very low S_{2n} values develop a halo around the central core. One can assume that the neutron pair is in a ^{1}S-state and decays into a deuteron with a transition probability corresponding to that of a super-allowed beta decay (this will drastically increase the probability to observe this rare event). This decay mode has been observed in the halo nucleus ^{6}He and indirectly in ^{11}Li. It is of great interest to look for it in heavier systems that exhibit a two-neutron halo.

Another interesting problem is to check the GT-distributions of the decay of the halo nucleus compared to that of its core. If halo/core factorisation of the wave function is possible in such exotic nuclei then the GT-distributions of the halo and the core should show similar patterns.

b) Clustering studies in light nuclei

For nuclei such as ^{8}Be, ^{12}C and ^{16}O with A=2N=2Z it has long been known that some of the low-lying states have alpha-particles as relevant degrees of freedom rather than independent protons and neutrons – this is the phenomenon of alpha clustering, one of the many that make the nuclear many-body problem particularly challenging. With the advent of radioactive beams these studies have been extended in recent years to systems consisting of neutrons in molecule-like orbits around alpha particles. This has been most clearly explored in the Be isotopes, indeed mainly at GANIL. The preferred experimental approach towards studying these cluster states has been transfer and break-up reactions at intermediate energies, but beta decay could be an interesting alternative due to its selectivity in the population of states and the firm determination of spins via correlation studies that it permits. As an example, the neutron-rich isotopes of the element Boron can populate states along the chain of Carbon isotopes where molecular states have been proposed. The possibility of studying the corresponding mirror decays adds a further probe of the structure because changing a neutron into a proton in an alpha-particle plus neutron molecular state is expected to be unfavoured, making an enhancement of mirror asymmetry likely.

c) Super-allowed β decays and the standard model of electro-weak interaction

The standard model of the electro-weak interaction can be nicely tested by high-precision measurements of super-allowed Fermi β decays. These transitions are intrinsically simple and can therefore be precisely described by theory. However, as these decays take place in the nuclear medium, corrections are necessary in order to compare the predictions from theory with the high-precision results from experiment.

The relative precision needed for the *ft* value of the β decay, to permit a meaningful comparison between theory and experiment, is about $10^{-3} - 10^{-4}$. To achieve this, the β-decay Q value, the β-decay half-life and the super-allowed branching ratio all have to be measured with this precision. This goal has been achieved to date for 13 nuclei (see Fig. DS-1), ranging from ^{10}C to ^{74}Rb. Nowadays, the limiting factor in the comparison between theory and experiment is the correction required to translate the *ft* value for an individual nucleus to a universal *Ft* value, which is independent of the nuclear medium. Two important components to this correction are i) a radiative correction due, for example, to the interaction of the emitted positron with the charge of the nucleus, and ii) an isospin breaking correction due to nuclear structure:

$$Ft = ft\,(1 + \delta'_R)\,(1 + \delta_{NS} - \delta_c) = K / M_F^2\, G'^2_V$$

Having a universal *Ft* value would confirm the standard model hypothesis of a conservation of the vector current in weak interactions, characterized by a unique weak vector coupling constant G'_V. Comparing the value of G'_V in nuclear beta decay and in the purely leptonic decay of the muon, the V_{ud} matrix element of the Cabbibo-Kobayashi-Maskawa quark mixing matrix can be determined, and the unitarity of the CKM matrix can be addressed.

The term δ_{NS} - δ_c in the above equation for the universal *Ft* value is the dominant source of error in the comparison with theory. It can be tested by measuring new super-allowed β decays for heavier nuclei, where these corrections are predicted to become much more important. However, for heavier nuclei the predictions for these corrections also become more uncertain. This is no longer the case for the heaviest nuclei that can be used for these studies, namely ^{98}In or ^{94}Ag. In these cases, the corrections are again very reliable, as these nuclei are close to doubly-magic ^{100}Sn, making shell-model calculations based on this core of modest dimension and thus quite reliable.

Improved data for lighter nuclei are also of great importance for an improved understanding of the electro-weak interaction. In order to perform high-precision measurements on these nuclei, one needs to produce about 1000 particles per second in rather pure conditions, which should be within reach for the DESIR facility.

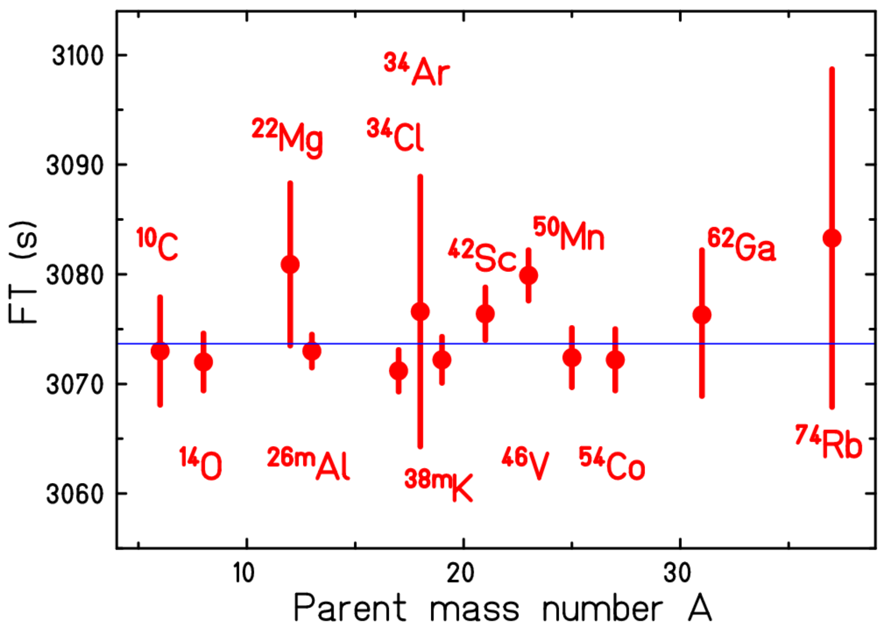

Figure DS-1: Ft value for the thirteen most precisely studied nuclei. These Ft values are deduced from high-precision measurements of the β-decay Q value, of the half-life and of the branching ratios.

d) Cases of astrophysical interest

Elements from iron to uranium found in nature are thought to be mainly synthesized by neutron capture processes, about half by slow neutron captures (s-process) and the other half by the rapid neutron process (r-process). The latter constitutes a theoretical and experimental challenge, since it requires a sequence of neutron capture, β-decay and fission reactions of exotic nuclei that are far beyond the reach of current accelerator facilities.

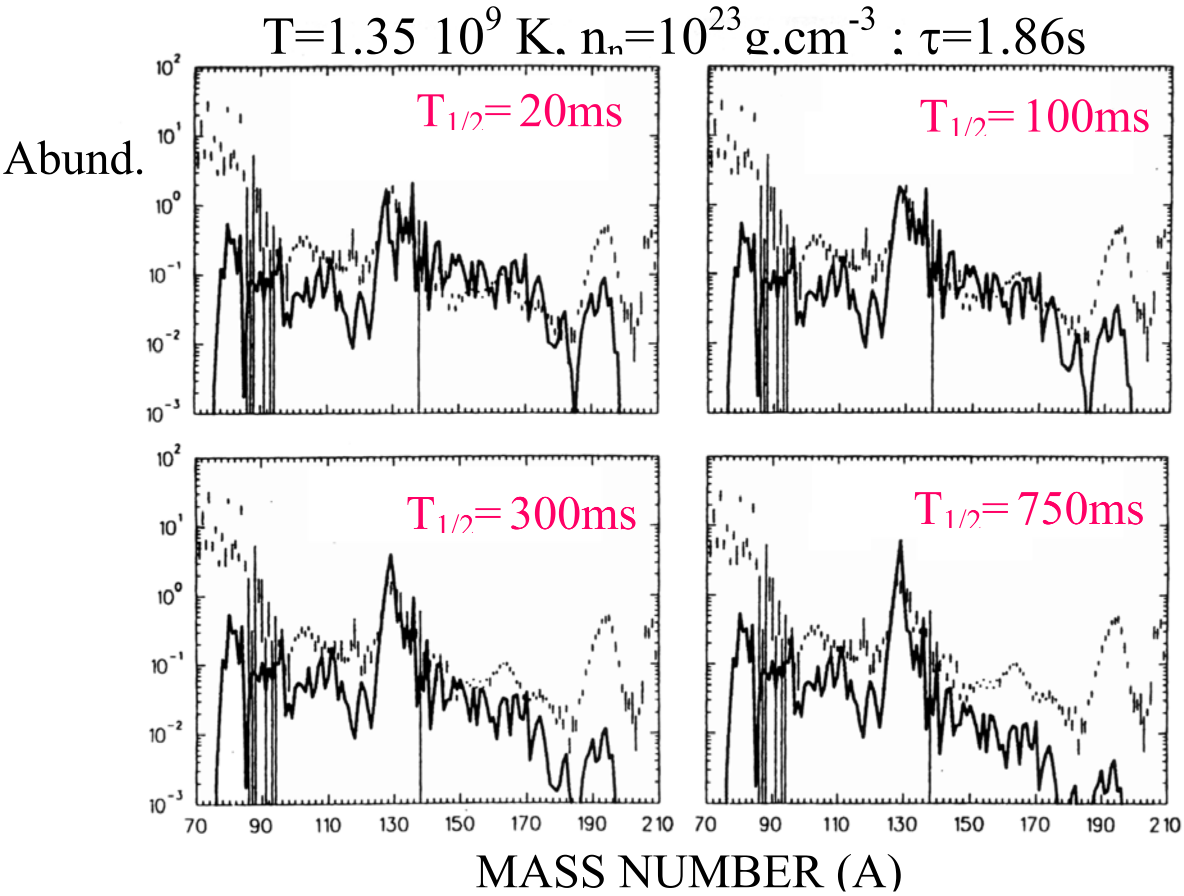

Fig. DS-2 : Influence of the lifetimes values of the nuclei located at the N=82 shell closure on the abundance pattern of the r elements. The solar curve is shown with a dotted line. $T_{1/2}$ has been varied from 20 ms to 750 ms, while the temperature T and the duration of the process □ have been kept constant. For short lifetimes, the nucleosynthesis spans over the whole mass range, while the r peak at A~130 is not clearly seen. For longer lifetimes, the A~130 peak is very sharp, and few heavier nuclei are produced.

The β-decay studies far off stability are important for at least two reasons: first to infer the abundance of the stable nuclei from the time elapsed at the neutron-rich waiting point nuclei, second to constraint the global duration of the r process by summing the lifetimes of all isotopic chains to built the heaviest elements in nature like Th, U and Pu. Determinations of half-live and P_n values are especially important at closed shells. The neutron delayed emission smoothens the r abundance curve, as compared to the even-odd staggering observed in the s abundance curve. As shown in Fig. DS-2, short lifetimes would make the building of r process peaks difficult, but the synthesis of heavier masses easier. At the opposite, long lifetimes would block the process at a given shell closure as the neutron fuel would be exhausted to proceed further. These nuclear structure parameters need to be measured in order to determine whether one r process could produce the overall mass range of elements or if the abundance curve results from a superposition of several processes. If occurring in the high entropy bubble, the r-process should develop with a short dynamical timescale in order to avoid its suppression by the high neutrino flux of the neutrino-driven wind. Hence, a better knowledge of the β-decay rates at the closed-shells (and especially the evolution of the Gamow Teller strength $\nu g_{7/2}$ to $\pi g_{9/2}$) and to what extent shells are quenched would enable to deduce if the r-process could occur in such environments. So far the β-decay of ^{130}Cd has shown that the N=82 is probably quenched. In the case of odd nuclei, low-lying excited states could be thermally excited. This could drastically change the lifetime and/or neutron-captures rates of the nuclei involved in the r process. Therefore energy and spin assignments of low lying states should also be determined.

When the r process path comes closer to stability, after successive neutron-captures and β-decays at major shell closures, the half-life of the nuclei involved becomes longer. If the neutron flux which prevail in the star is large enough, neutron captures could eventually compete with β-decays. The determination of neutron-capture cross sections (σ_n) brings access to the rate of leakage of the r-process towards the next shell closure for a given neutron density value. Beta delayed-neutron studies will help to determine the existence of isolated resonance above the neutron-emission threshold in the daughter nucleus, to be used for the determination of neutron capture cross sections at closed shells.

So far a detailed spectroscopy of only two neutron-magic r progenitors have been obtained, i.e. ^{80}Zn and ^{130}Cd. Some selected key nuclei for β-decay studies for the r process are $^{76\text{-}80}$Ni, $^{80\text{-}84}$Zn, $^{78\text{-}82}$Cu, ^{85}Ga, $^{96\text{-}100}$Kr, $^{108\text{-}112}$Zr, $^{122\text{-}130}$Pd , $^{128\text{-}131}$Ag, $^{131\text{-}134}$Cd and $^{146\text{-}150}$Xe.

e) New magic numbers

Shell structure, considered until recently as a robust characteristic of all nuclei, is now recognized as a more local concept. Recently, several independent measurements from the study of neutron-rich nuclei located near the N=20 and N=28 shell closures have been carried out using different approaches and techniques, starting with ^{31}Na. In the mid-seventies the sd-shell was the focus of much attention, people having forgotten the case of ^{11}Be with spin inversion, when the beta-decay properties of $^{31}Na_{20}$ and $^{32}Mg_{20}$ indicated that they were not semi-magic. This region is called *The Island of Inversion* as the shell-model configurations are strongly rearranged. The extreme value of isospin leads to the disappearance of magicity as the nucleus is able to gain in energy by deformation. The detailed contour of this island depends strongly on the behaviour of the effective single-particle energies.

In the shell model the evolution of single-particle energies plays an important role in determining the effective interactions between valence particles. For instance, β-decay studies of ^{35}Al allowed for the location of the single-particle states in ^{35}Si. This work indicated an erosion of the spin-orbit force far from stability and helped to define the interaction in this region. In this way the SDPF-shell model calculation (Madrid-Strasbourg) predicted that the $p_{3/2}$-$f_{7/2}$ gap decreases as protons are removed, leading to a weakening of the N=28 shell closure. In weakly-bound systems, the spin-orbit force is expected to be weaker and shell gaps arising from this force should disappear, which is the case for N=28. The decrease of the gap, combined with a gain in correlation energy of the 2p-2h configuration, leads to a breakdown of the N=28 closure for $^{44}S_{28}$, $^{42}Si_{28}$ and $^{40}Mg_{28}$. The study of ^{44}S, which included the position of the isomeric state confirmed these predictions. The case of ^{42}Si is more complicated, and it is of interest to look at it further.

In the region of medium-heavy nuclei, new magic numbers might also appear for nuclei with a large N/Z ratio. The change in ordering is most likely caused by the strongly attractive neutron-proton interaction between spin-orbits partners. Predictions favour for these very asymmetric neutron rich nuclei a shell closure at N=34 rather than N=40 (see Fig. DS-3) because of the role of the $0f_{5/2}$-$0f_{7/2}$ interaction. For heavier systems, the $0g_{7/2}$ and $0h_{9/2}$ orbits are expected to be shifted upwards, disturbing the magic numbers N=82 and 126, respectively.

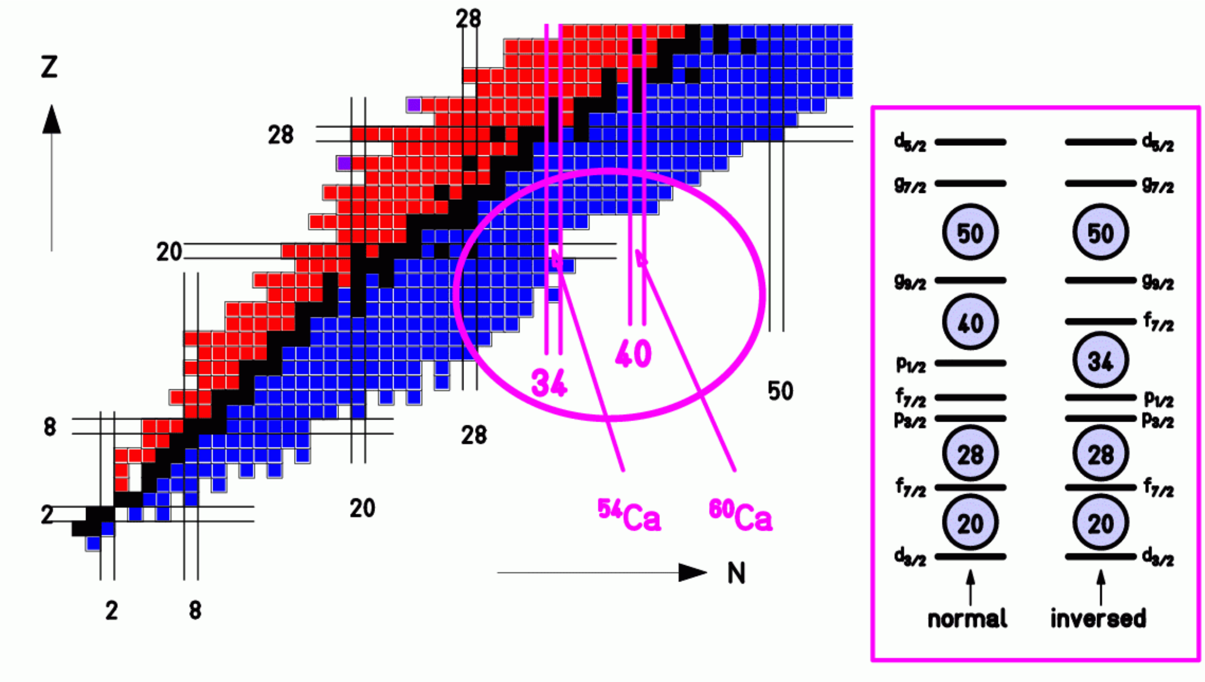

Figure DS-3: Part of the chart of nuclides around N=34 and N=40. Possible shell gap changes far from stability due to the spin-orbit interaction are illustrated on the right.

It is quite obvious that in order to test these predictions, one must reinforce the scarce experimental observations. Nuclei with large N/Z ratios need to be produced, and properly studied by means of spectroscopy techniques. It will be of interest to test these predictions by studying, for instance, $^{110}Zr_{70}$. If the predictions are confirmed, implications on the modelization of the r-process have to be investigated

f) Transition from Order to Chaos

The delayed-particle spectra (see Fig. DS-4) change from a broad distribution for very light nuclei to distant narrow levels when the single-particle strength is highly fragmented to a bell shape distribution for higher Z.

The high energy available for the β-decay of nuclei far from stability not only leads to the possibility of populating states above the threshold for particle emission, but also gives access to nuclear excited levels of extreme complexity. A situation frequently encountered is the separation of the individual levels, *i.e.* their width is smaller than their spacing, which are nevertheless hardly resolvable in experiments. The complexity is such that the most profitable approach is one where the structure of the nucleus is described in terms of local averages and fluctuations around them. These fluctuations in nuclear level widths and spacing can be described by general statistical laws and are characteristic of the phenomenon of deterministic chaos in nuclei. The fluctuations in the spectrum provide an interesting method to determine level densities in exotic nuclei.

For the heavier delayed-particle emitters, the individual levels are narrow, but in the high-energy part of the excitation spectrum where the delayed particle originate, the level density is very high and the structure of the states very complex. For such p, n- or α-emitting states, the best description is obtained in terms of the compound nucleus model.

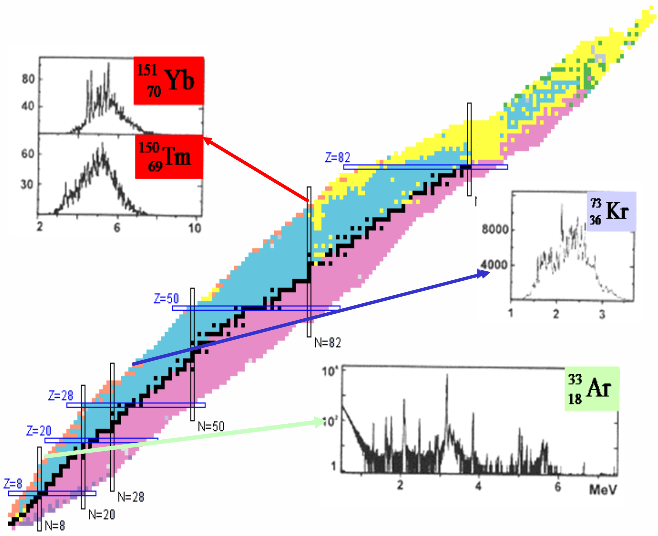

Figure DS-4: Beta-delayed proton spectrum for a light-mass, a medium-mass and a rather heavy nucleus. For light nuclei, the spectrum is dominated by pronounced proton lines, whereas for heavier nuclei a bell-shaped structure governs the spectrum.

Detailed spectroscopy of neutron-deficient nuclei from argon to krypton will be of interest to determine where and how the transition from order to chaos occurs.

g) Shape coexistence, deformation and Gamow-Teller distribution

Nuclear species with equal number of neutrons and protons are very interesting. The N=Z line departs from stability above mass 40, developing along the particle stability border up to ^{100}Sn. Since neutrons and protons in these nuclei occupy the same orbitals, important issues related to properties of the T=0 (np) interaction and the T=1 (pp or nn) interaction can be clarified.

Nuclei with N≈Z and A≈70-80 are particularly interesting in this context. In these nuclei the active neutrons and protons indeed fill the same orbitals. This coupled with their low single-particle level density leads to rapid changes in shape, with the addition or subtraction of only a few nucleons. As a result, mean-field models predict several minima with different shapes in the same nucleus, that is to say shape coexistence phenomena.

Nuclear deformation is a key issue in nuclear structure, the simplest property to visualize but a more difficult one to assess experimentally. There are various methods to measure the deformation of the ground state in unstable nuclei based on the interaction of the electric quadrupole moment of the nucleus with an external field gradient. This method is not applicable to J=0 and ½ nuclei and seldom gives the sign of the quadrupole moment.

Close to the drip lines, the main part of the GT resonance in the daughter nucleus is expected to be located in the Q-beta window. Mean-field calculations predict the GT energy distribution to be sensitive to nuclear ground state deformation. Calculations for even-even nuclei in the A=70 region exhibit strong differences in the total intensity and energy distribution of the GT strength depending of the shape of the parent nucleus.

To determine the GT distribution is not an easy task, as the traditional high resolution technique to detect gamma rays after beta decay fails to detect significant but very fragmented strength at high excitation energy in the daughter nucleus. The method to determine the Gamow-Teller strength distribution, B_{GT}, is total absorption spectroscopy. It has been successfully applied to ^{76}Sr and ^{74}Kr and can be used in other regions of shape coexistence, such as in the Sm or light Pb isotopes

h) Beta-decaying and particle decaying high spin isomers

Long-lived (>100ms) high-spin isomers offer the possibility to study novel and exotic decay modes. These, at least in some cases, will be most-sensitively studied with ~50 keV ISOL beams. DESIR at SPIRAL2 would therefore provide excellent opportunities.

Spin-gap isomers near doubly-magic closed-shell nuclei offer the chance to measure properties of single-particle states in order to test predictions of the nuclear shell model. An example is the nucleus ^{94}Ag, which has been studied at GSI using the ^{58}Ni(^{40}Ca, p3n) reaction. A long-lived spin-21 isomer was found to decay by beta, p, and 2p emission. It was inferred from the 2p-correlations that the long-lived state must also decay through simultaneous two-proton emission, making ^{94}Ag the first nucleus found to exhibit one- as well as two-proton radioactivity. The two-proton emission behavior and the unexpectedly large probability for this decay mechanism were attributed to a very large prolate deformation of the parent state, which facilitates emission of protons either from the same or from opposite ends of the “cigar-like” nucleus. This result needs to be confirmed. In any case, exotic isomer decay modes are expected in the region around doubly-magic ^{100}Sn, which demands further study.

The small number of oblate-shaped nuclei found in nature compared with the much larger number of prolate nuclei is a surprising feature of nuclear structure, which seems to be related to the importance of the nuclear spin-orbit interaction. Furthermore, with increasing angular momentum, the collective rotation of an oblate shape about an axis perpendicular to its axis of symmetry will not be favoured in comparison with the prolate case. Therefore, the prediction of “giant backbending”, with collective oblate rotation becoming favoured at $I \approx 26\hbar$ in the case of ^{180}Hf, was unexpected. However, an explanation is possible in terms of rotation-alignment effects. Despite theoretical confirmation, experimental evidence remains elusive. This is because, at lower angular momentum, the phenomenon is restricted to neutron-rich $A \approx 180$-190 nuclides. The transition from prolate to oblate shapes as a function of increasing spin is predicted to be associated with shape isomerism. It will present a striking and sudden structural change, quite unlike anything yet observed. This region is optimal due to the mutual reinforcing of proton and neutron shell structures, with both Fermi levels being high in their respective shells. Calculations suggest that the 1-ms isomeric state in ^{190}W, which feeds into the ground-state rotational band at $I^{\pi} = (10^{+})$, is a good candidate for this study. In addition, prolate non-collective angular momentum is generated by multi-quasiparticle excitations in this mass region, and long-lived beta-decaying high-spin isomers are expected, competing with the collective oblate mode. Furthermore, the possibility of neutron decay from the multi-quasiparticle isomers has also been discussed. Therefore, more detailed investigations of neutron-rich nuclei in the mass 180-190 region should uncover some novel aspects of nuclear structure.

i) Test of isospin symmetry combined with charge exchange reactions

In the core-collapse stage of type II supernova, weak-interaction processes involving pf-shell nuclei play an important role. Therefore, studies of electron capture and the decay caused by charged-current processes are of great astrophysical interest. The charged-current processes are dominated by Fermi and Gamow-Teller transitions, but information on the important GT transitions are very limited. The B(GT) values obtained for some far from stability pf-shell nuclei such as ^{46}Cr, ^{50}Fe, ^{54}Ni and ^{58}Zn are based on a few low-lying states and therefore have large ambiguities. In fact beta feeding of highly excited states is difficult to measure as the phase space factor decreases with the excitation energy.

While charge-exchange reactions, such as (p,n), (n,p), (d,^{2}He) or (^{3}He,t) can access GT transitions at higher excitation energies, they cannot provide absolute B(GT) values by themselves. Assuming isospin symmetry in the T=1 isobars and the following relation for the β-decay half-life

$$(1/T_{1/2}) = (1/t_F) + \sum_{i=GT} (1/t_i)$$

one can deduce absolute B(GT) values for the T_z = 1 nuclei from the (^{3}He,t) reaction. Therefore, the half-life is determined with the neutron-deficient T_z = -1 nucleus, which is then used to normalise the B(GT) value of the neutron-rich nucleus. This has been done for the T=1, A=50 system and can be applied also to the T = 2 systems where the accurate total and partial half-life measurement of exotic T_Z = -2 nuclei can be done at the low-energy beam line at SPIRAL2.

j) Beta-delayed charged-particle emission

The main characteristic of beta decay far from stability is the number of decay channels open. This is due to the quadratic increase of the isobaric mass differences and the reduction in the separation energies for emitting nucleons or clusters of nucleons when going away from the valley of stability. In a two-body break-up, as after the beta decay of ^{8}Li and ^{8}B, the complete decay dynamics can be determined by measuring just the single-alpha spectrum. Many attempts have been made to explain the three-body break-up mechanism, even though only singles spectra were observed experimentally. But to do so, one needs to introduce model assumptions. In complete kinematics measurements, these assumptions can be checked.

The break-up of nuclear states into more than two fragments has attracted much attention. Different techniques, mainly β-decay spectroscopy, nuclear reactions or Coulomb excitation, have been used to populate excited states. The main interest in β-delayed multi-particle emission is that the mechanism is not fully determined by energy and momentum conservation. In three-body break-up there are three binary subsystems and each subsystem has resonances controlling the break-up. The break-up process is determined by the width of the resonances, the height of the barrier, and the structure within the decaying state that can single out a certain channel.

The elusive character of two-proton radioactivity has also attracted much interest, especially concerning the two-proton emission from excited states populated by beta decay or by reactions. Here the proposed mechanisms are (see Fig. DS-5): 1) sequential decay, 2) ^{2}He = di-proton like, highly correlated emission, and 3) three-body direct or democratic break-up. The experimental signatures of the individual proton distributions in the three cases are very different.

The sequential 3-body break-up reduces to two binary decays and is fully described by R-matrix formalism, which depends on the barrier penetrability and the reduced width. For the case of broad resonances, the decay amplitude is described in a set of hyper-spherical harmonics functions that fully describe the final state of the three particles. The decay occurs through the resonances so fast that the third particle is still felt by the other two. Detailed spectroscopic studies have been carried out for ^{31}Ar, ^{12}C and the A=9 isobars. New cases related to cluster structures such as ^{13}O and others are of great interest.

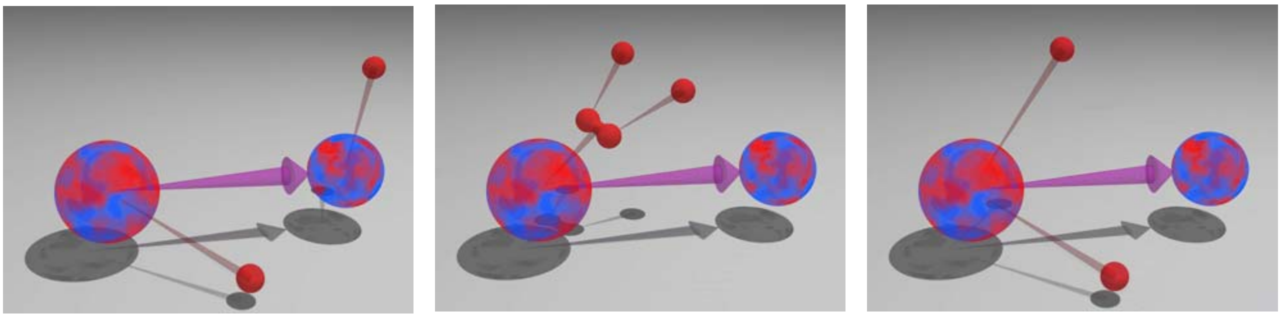

Figure DS-5: Schematic representation of the different possibilities of two-proton emission (from left to right): sequential emission, ^{2}He emission, and three-body decay.

Instrumentation

In order to perform the above mentioned decay studies, new or upgraded instrumentation is needed. In the following, we discuss the different devices necessary to perform the experiments proposed.

- A **4π charged particle device**, aiming for high segmentation and large angular coverage is needed for the rare exotic species. A silicon cube consisting of 6 DSSSD-E telescopes has already been realized and a silicon ball including time-of-flight for the identification of the different charged particles was also proposed, indicating that the detection of charged particles and the measurements of their angular correlations are well under control and equipment and solutions seem to exist in the different groups.

- A good scheme for **neutron detection** is very important and it is an issue clearly not resolved. Different schemes for neutron detection based on time of flight such as TONNERRE or more versatile and with higher granularity like DEMON exit, but the detection of low-energy neutrons, relevant for many physics cases, some of great astrophysical relevance, is far from being solved. R & D is needed to propose a new neutron detection scheme. In addition, when going far into the neutron-rich middle-mass nuclei region, the level density increases and higher energy resolution as well as discrimination of neutrons and γ rays are needed.

- The **detection of γ rays** is a *must* in spectroscopy studies. In decay studies of exotic nuclei, the multiplicity is not an issue. Therefore, it was proposed to have 4-6 robust segmented HPGe detectors of the clover or cluster type. When going far from stability, these measurements should be combined with the detection of neutrons or charged particles.

- Isomer studies are very important in the middle mass region and therefore half-life measurements in the picosecond and nanosecond range are very important. This will require in addition to the proposed HPGe detectors, a **fast timing set-up** as e.g. the presently used BaF_2 detector assemblies or the newly developed $La_3Br(Ce)$ crystals.

- Due to the high efficiency of **total absorption γ spectrometers**, such a set-up is considered to be very useful to determine the Gamow-Teller strength distribution in nuclei with high level densities.

- Experiments at the limits of the feasibility are characterized by:
  - many electronics channels
  - low intensities and short half-lives

  Therefore, a pool of **digital electronics** will certainly be desirable for high-quality set-ups.

- Decay experiments are very often conducted with a **tape station** in order to transport the activity or to remove long-lived contaminants. Such a tape station should be fast to handle the very short half-lives expected for exotic nuclei (< 100 ms).

The development of instrumentation should be conducted as far as possible together with the EURISOL DS and FAIR-NUSTAR collaborations.

V Symmetry tests and Fundamental Interactions

The most general description of the weak interaction at the nuclear level involves four types of Lorentz invariants associated with the vector (V), scalar (S), axial-vector (A) and tensor (T) type interactions. Each of these can in addition be even or odd with respect to the discrete transformations of space and time inversion. The predominantly Vector, Axial-vector character of the weak interaction, with maximal parity violation, is embedded into the Standard Model by allowing only the charged vector bosons, $W^{\pm}$, to couple only with left-handed fermion doublets. Furthermore, CP-violation has been observed so far only in the decays of K and B mesons and all observations can be accounted for by the CP-violating phase resulting from the three generations quark mixing matrix. Assuming that the CPT theorem holds, the effects of the weak standard model CP-violation are too small to induce any effect on T-violating observables or properties involving only the light u and d quarks.

The manifestation of right-handed or time reversal violating Vector and Axial interactions, or of exotic Scalar or Tensor interactions, can be probed by measuring several correlation terms resulting from combinations of the kinematical vectors (spins and momenta) of the particles involved in the β decay process. The coefficients driving these correlations can also probe the properties of the interactions with respect to space and time transformations. Pure Fermi transitions are sensitive to V and S interactions, whereas pure Gamow-Teller transitions are sensitive to A and T. For well selected transitions, the correlation coefficients are, to first order, independent from nuclear matrix elements. The comparison of precision correlation measurements with the unambiguous predictions made within the Standard Model provides then a very sensitive means to probe the presence of new physics.

Especially important for such measurements are the nuclei near the N=Z line for which nuclear structure effects are generally under control. In fast transitions (with log ft < 5.5), small recoil effects can be also taken into account and corrected for. Radiative corrections are only important at the 10^{-4} level and lower, which is well below the present level of precision

(0.1% to 1%) of correlation measurements in nuclear β decay. The super-allowed pure Fermi transitions (Sec. IVc) are also very sensitive to probe left-handed scalar interactions.

Magneto-optical atom traps have recently proven to be a very sensitive tool for high-precision correlation measurements. Several developments with ion traps should culminate in the near future at comparable sensitivity levels. The performance of ion traps will ultimately be limited by the trap capacities which are generally dominated by space charge effects. The availability of new exotic beams with higher intensities and purities enables to consider alternative setups for correlation measurements where the ion trap limitations could be reduced or circumvented. The use of atom and ion traps for measurements with polarized samples has resulted in several proofs of principles but has not been fully explored so far.

Right-handed Vector and Axial-Vector interactions

Searches for deviations from maximal parity violation can probe specific scenarios of new physics where the parity symmetry is restored at some higher energy scale due to the exchange of new right-handed bosons. The search for mechanisms inducing the seemingly maximal violation of parity can be most directly probed in precision measurements of pseudo-scalar quantities like the β asymmetry parameter of electrons emitted from polarized nuclei, A, or the β particle longitudinal polarization, P_L, or a combination of these. Relative measurements comparing the longitudinal polarization of positrons emitted along two opposite directions relative to the nuclear spin (the so-called polarization asymmetry correlation) provide so far the most stringent tests of maximal parity violation in nuclear β decay. In such relative measurements, the uncertainties associated with the degree of nuclear polarization or with the analyzing power of the β polarimeter are strongly reduced. Two such measurements have been carried out, in ^{12}N and ^{107}In decays, and the measured quantities have reached a precision level of few parts in 10^{-3}. All measurements so far are consistent with the Standard Model predictions. In the simplest scenarios, the mass scale probed by these experiments is in the range 300-350 GeV/c^2 but in others they provide complementary constraints to those obtained from direct searches performed at colliders (Fig. FI-1) or from precision measurements in pure leptonic decays.

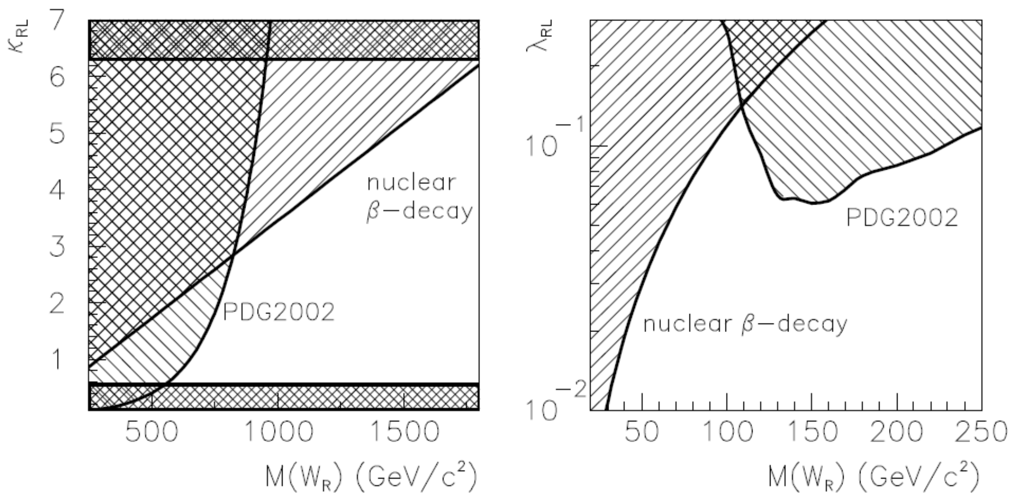

Fig. FI-1. Exclusion plots on parameters of generalized left-right symmetric extensions of the standard model as a function of the mass of a hypothetical right-handed boson. The excluded areas show the complementarity between results from nuclear β decay experiments and those from high-energy physics.

Pure GT transitions or super-allowed mixed transitions are best suited for precision measurements of the β emission asymmetry parameter in the decay of polarized nuclei. In both cases, a relative precision below 0.2 % is required to produce competitive results. Relative asymmetry measurements can be carried out in decays like ^{21}Na, ^{32}P or ^{35}Ar, where the two main decays proceed by a pure GT and by a mixed transition. The identification of the decay to the excited state requires the measurement of the subsequent γ ray. The proof of principle to measure the asymmetry parameter in the decay of polarized ^{82}Rb in a magneto-optical trap has recently been demonstrated and new methods to produce and monitor the nuclear polarization are being developed.

Further progress can be expected from efforts in the production of highly-polarized, high-intensity and high-purity samples combined with advanced β-particle detection and polarimetry techniques. Any new effort in β decay to reach a precision level corresponding to a mass scale in the range between 500 GeV/c^2 and 1 TeV/c^2 is considered as highly valuable.

Exotic Scalar and Tensor interactions

All correlation coefficients in nuclear β decay are sensitive to the presence of S and T contributions. The β-neutrino angular correlation coefficient, a, plays a special role as it is the only one sensitive to all possible interaction types, whatever their properties with respect to space and time inversion transformations. This coefficient has been measured in the past for several transitions (Fig. FI-2) and the results provided the experimental foundation establishing the V-A nature of the weak interaction.

The present constraints on the amplitudes of the Scalar and Tensor contributions relative to the Vector and Axial ones are at the level of 0.07 and 0.09, respectively (90% CL). Further improvements require a relative experimental precision below 1% on the angular correlation coefficient.

Atom and ion traps provide ideal environments for measurements where the direct detection of the recoiling ions is needed. The radioactive sources maintained in a trap can be produced with high purity and the matter-free surrounding further reduces effects associated with electron scattering relative to experiments using targets. Unprecedented precision has recently been achieved in measurements with magneto-optical atom traps (MOT) in ^{38}K and ^{21}Na. The first one produced the most stringent constraints on scalar couplings and the second is at variance with the Standard Model prediction (see Fig. FI-2). Efficient atom traps are limited to alkaline and earth-alkaline elements but have the advantage that the nuclei can be laser polarized. Paul and Penning traps allow the confinement of any element but their combination with polarization techniques is not straightforward. In addition, the capacity of ion traps is ultimately fixed by space charge effects which limit the number of ions in the trap. The further increase in the intensity of exotic beams could be exploited for angular correlation measurements by considering new setups where the β particle and recoiling ion are measured in coincidence from decays in flight with a very low energy beam.

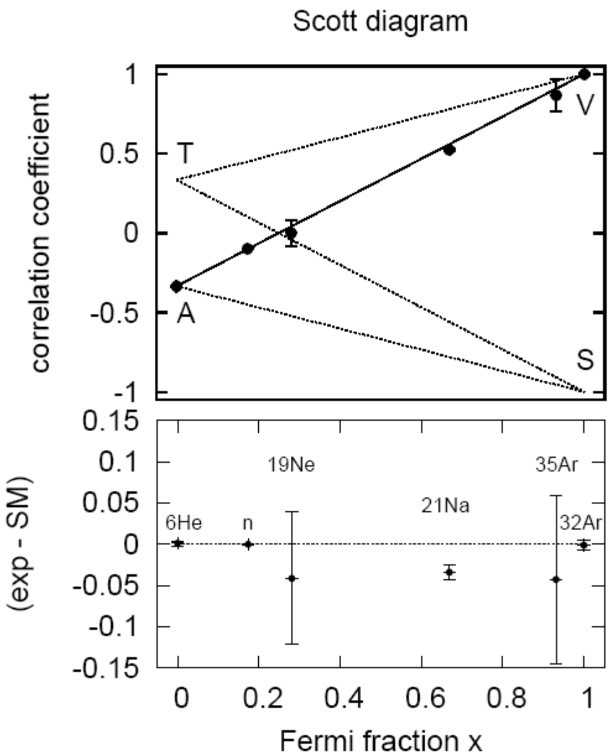

Fig. FI-2. The Scott diagram presents the sensitivity of the angular correlation coefficient to the different types of interactions as a function of the so-called Fermi fraction. This fraction measures the relative contributions of the Vector and Axial-vector interaction in a transition.

Search for new sources of T (or CP) violation

The violation of the CP symmetry observed in *K*- and *B*-meson decays is incorporated in the Standard Model by the quark mixing mechanism. This electro-weak CP-violation is too weak to explain the excess of baryons over anti-baryons observed in the universe. Assuming CPT invariance, this excess provides then a hint for the existence of a new unknown source of T-violation. The Standard Model predictions for T-violating effects originating from the quark mixing scheme for systems built up of *u* and *d* quarks are by more than 6 orders of magnitude lower than the experimental accuracies presently accessible. Because the standard contributions to time reversal violating observables are so strongly suppressed, any sign for the presence of time reversal violation at the present level of precision would be the signature of a new source of time reversal violation. Such sources are introduced by many scenarios of physics beyond the Standard Model.

a) Triple correlations measurements

In nuclear β decay, T-violating effects can be searched for by the presence of a possible imaginary part in the different couplings (V, A, S and T). Direct searches for time reversal violation in β decay require the measurement of terms including an odd number of spin and/or momentum vectors and are therefore rather difficult. Only two such correlations have been measured so far, driven by the *D* and *R* coefficients. The determination of *D* requires the measurement of the momenta of the β particle and of the neutrino emitted mutually perpendicular to the nuclear polarization. The determination of *R* needs the measurement of the transverse polarization of the β particles emitted perpendicularly to the nuclear polarization. Final-state effects, which might mimic a time reversal violating signal, are typically of the order of 10^{-4}.

In nuclear β decay, the D correlation was only measured in the decay of ^{19}Ne and the result has reached the limit imposed by final-state effects. Two measurements of the R correlation were carried out in nuclear β decay, in ^{19}Ne in ^{8}Li. The precision achieved with ^{8}Li is at the 2×10^{-3} level and provides the best constraints on an imaginary component of a tensor type interaction (Fig. FI-3).

New triple correlation measurements in transitions where the final-state effects are smaller than in the cases considered so far are highly valuable. For the D correlation, a T = 1/2 mirror nucleus should be selected to be sensitive to the phase between the axial and vector couplings. For the R correlation, a candidate with a fast pure GT transition is required to improve the limits on a time reversal violating tensor interaction.

b) Electric dipole moments

A very sensitive observable to search for new mechanisms of CP violation at low energies is the permanent electric dipole moment (EDM) of particles. In this context, the EDM of the neutron has played a crucial role, as its upper limit has been improved by about 7 orders of magnitude over the past 50 years. In specific scenarios of new physics, like in Super Symmetric extensions to the standard model, the limits on the EDM of the neutron and of the electron provide complementary constraints on new CP violating phases which appear in such models.

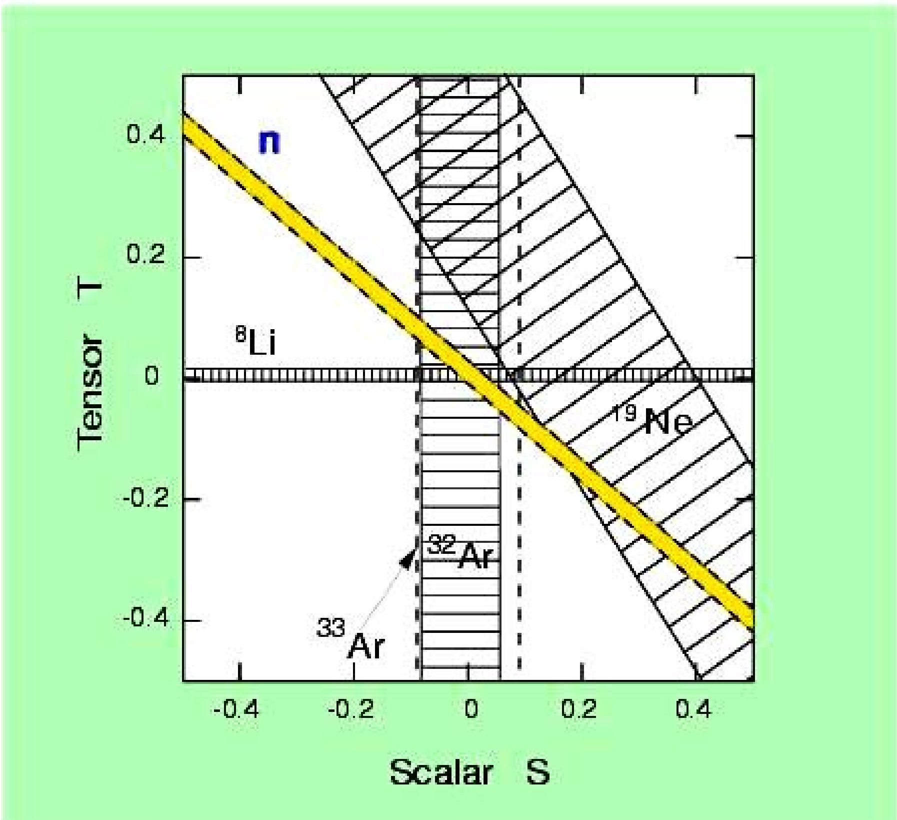

Fig. FI-3. Exclusion plots on possible imaginary parts of scalar and tensor couplings obtained from nuclear β decay. The inclined band shows the constraints to be obtained from a measurement of the R coefficient in neutron decay with a precision of 0.5%.

New ideas in the search for EDM of particles have recently been proposed where radioactive nuclear species could play an important role. A first concept considers the possibility to measure the EDM of nuclei with β emitters confined in a small-size storage ring. The signal of the spin precession is detected by measuring the decay electrons, similar to experiments measuring the g-factor of the muon in storage rings. Another concept considers exploiting the sensitivity increase in EDM searches with atoms, where large enhancements are offered by systems with high atomic numbers, like Radium. Such experiments need a high production yield of the suitable isotopes with good selectivity along with the development of dedicated confinement precision tools.

VI Beam Requirements & Instrumentation

The beam requirements necessary to carry out the above-mentioned decay and laser spectroscopy studies at DESIR are outlined in the following.

- **Beam purity and a small beam size** (down to about a millimeter). Interesting research topics were proposed on the proton-rich and on the neutron-rich side of the valley of stability that cannot be realized without these conditions. For the kinematic reconstruction of the multi-particle event, a point-like source is crucial.

- **Magnetic selectivity beyond the proposed schemes of about m/Δm = 250**. Therefore, a **separator** with a resolution of at least 3000 is requested. The separator should be placed outside the DESIR hall to be able to profit of the full space of the hall for experiments and to allow for working in parallel with one experiment setting up, while another experiment takes data. One should bear in mind that the cases of interest often have low production rates and therefore the radioactivity level is much reduced.

- **A large variety of different beams**. One of the limiting factors of SPIRAL is the small number of different beams available and the large time delays needed for the development of new beams. Therefore, **more than one production-target – ion-source station** is required to ensure flexible schedules and an interesting experimental program.

- The physics program should not be limited to fission products. **Fusion-evaporation reactions** should be included from the beginning to produce proton-rich nuclei for DESIR and other installations.

- The possibility of **pulsed and stored beams** by means of an RFQ cooler should be provided.

- **Radioactive isotopes** as source material (e.g. ^{56}Ni) should be considered.

VII General layout of the DESIR facility

The DESIR facility is meant to be the ISOL facility of SPIRAL and SPIRAL2. Therefore, DESIR should be installed such that beams from SPIRAL and SPIRAL2 can be delivered to the different set-ups of DESIR. The installation proposed for DESIR is shown in access for instrumentation.

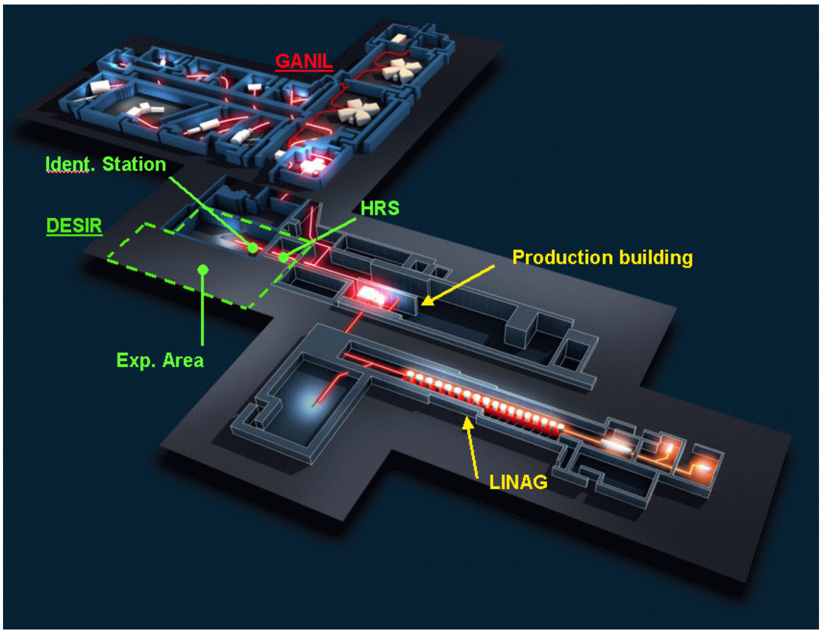

Figure DE-1: General layout of the GANIL-SPIRAL2 complex and the proposed location of the DESIR facility.

The layout of the facility as proposed below is largely inspired by the ISOLDE facility of CERN. The space requirements are derived from existing set-ups at ISOLDE and elsewhere. The basic idea is that the high-resolution mass separator (HRS) proposed above is installed either in the beam-production building or at underground level. Two schemes should be possible: i) the low-energy beams from the SPIRAL2 target – ion-source ensemble are mass-selected by the separator and can then be delivered to all experimental stations in the DESIR hall. ii) The mass separator can be by-passed and the full beam (most likely with a limitation in intensity) can be delivered to DESIR.

A preliminary design of the DESIR experimental hall is shown in Fig. DE-2. The beam arrives from underground, where the high-resolution separator and an identification station will be installed, in the “Cooling / Bunching” section and can then be transported to all experimental set-ups. In addition to radioactive beams from SPIRAL and SPIRAL2, stable ISOL beams will be produced by an off-line source. This will allow for testing experimental equipment before taking beam and therefore to make optimum use of the beam time.

For the moment, set-ups to perform trap-assisted decay spectroscopy, laser spectroscopy, fundamental interaction studies and decay studies are foreseen. In addition, space is provided for other installations. The overall size of the DESIR building is about 1500 m^2. This includes a control room and a data acquisition room. For power supplies, vacuum systems and other equipment, a basement of about 500 m^2 should be provided.

VIII Cost estimates for the different parts of DESIR

The cost estimates mentioned in the following are only rough estimates based on new equipment. They are meant to give an order of magnitude of the investment necessary to construct the DESIR facility as proposed here. A more detailed estimate is foreseen for the end of 2006, after a preliminary design study is performed.

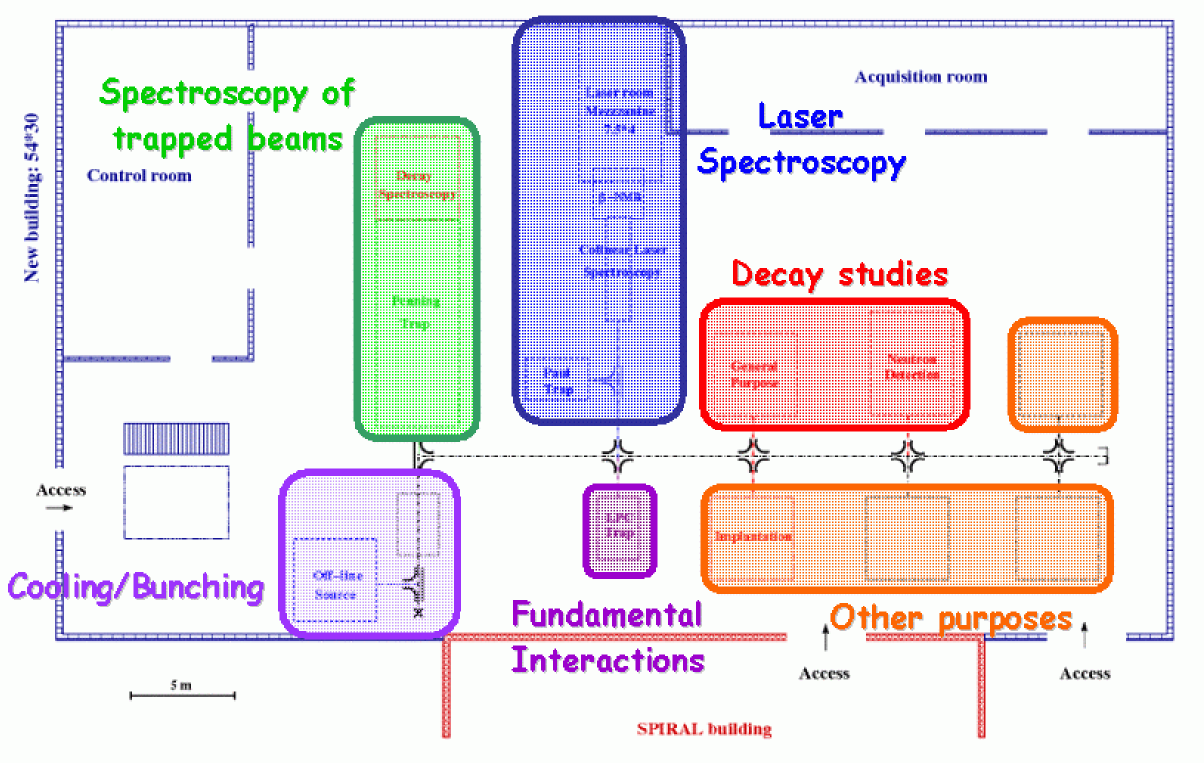

Figure DE-2: General layout of the DESIR experimental hall as proposed in the present work. The beam arrives in the DESIR hall in the 'Cooling/Bunching' section at the position of the 'x' and can then be transported to all experimental stations. In addition to the radioactive beams from SPIRAL and SPIRAL2, an off-line source will be installed to allow for testing and preparation of experimental set-ups.

a) The DESIR hall

The DESIR hall has a total surface of 1500 m^2. A rough estimate of the construction costs including the necessary infrastructure (water, electrical power of about 2MWA, air conditioning, pressurised air, liquid nitrogen, etc.) can be deduced from the costs of the ISOLDE hall extension at CERN and the AIFIRA building at the CENBG in Bordeaux. For both constructions, the costs were about 2 kEuros per square meter. This yields a cost estimate of 3 MEuros. About 1 MEuro should be foreseen for the basement of the building and another 1 MEuros for a crane of the hall. Including an overhead of 20%, this gives a total cost estimate of 6 MEuros for the DESIR building.

b) The high-resolution separator

The high-resolution mass separator will be a two-stage, two-dipole separator. From studies e.g. in the frame of EURISOL, the following estimates are possible:

- RFQ cooler 150 kEuros
- two magnets including power supplies and NMR probes 400 kEuros
- pumps, beam lines between magnets, diagnostics, electrostatic lenses 130 kEuros
- 20% overhead 136 kEuros

The total costs for the separator are therefore about 816 kEuros.

c) The beam-handling system

The beam-handling devices consist of an off-line ion source, an RFQ buncher, a switchyard and a preparation Penning trap. In addition, an in-trap decay detection system is foreseen.

- off-line source 60 kEuros
- RFQ buncher + switchyard 650 kEuros
- preparation Penning trap 460 kEuros (260 kE for magnet)
- in-trap decay detection 195 kEuros
- 20 % overhead 275 kEuros

The total cost for this part is therefore about 1640 kEuros.

d) The LUMIERE installation

For the physics, the laser installation requires an equipped laser room of about 20 m^2 generally on a mezzanine. If this room is also used for the laser ion source it has to be extended at about 35 m^2. The lasers for the 3 LUMIERE physics cases can be a high-resolution dye laser (Ring type) pumped by a 20 W argon laser.

In the experimental hall, two lines have to be installed: one for the laser spectroscopy / ß-NMR and the other with high vacuum (10^{-9}) for the Paul trap.

- laser room with infrastructure 150 kEuros
- two lasers (dye+Ar) 180 kEuros
- collinear spectroscopy installation: charge exchange cell, beam line (electrostatic elements, diagnostic, power supply), vacuum, electronics, detection 170 kEuros
- ß-NMR set-up: RF, cooling system, telescope, vacuum, magnet 160 kEuros
- Paul trap set-up: Paul trap, RF, beam line (diagnostic, retardation lens), cryogenic pumping 150 kEuros
- 20% overhead 162 kEuros

The total cost for the LUMIERE facility is therefore 972 kEuros.

e) The β-decay set-ups

The detection systems envisioned for β-decay studies include four robust Germanium clover detectors (1.2 MEuros). Due to the fact that these detectors will only work with stopped beams, no high segmentation is necessary. The associated electronics has a cost of about 25 kEuros.

For a fast timing set-up, four fast scintillators and their electronics have to be purchased. The costs are estimated to be of the order of 34 kEuros.

A 4π charged-particle set-up is proposed. Such a set-up consists of 6 double-sided silicon strip detectors associated with 6 standard large-size silicon detectors. The costs for the detectors are about 48 kEuros, the electronics with pre-amplifiers, amplifiers, timing electronics and data acquisition modules is estimated to cost 120 kEuros.

Another important set-up will be the neutron detection device. A very rough estimate can be based on estimates made for the FP5 EURISOL report a few years ago. For a multi-element array, based on thin cylindrical liquid scintillator modules, which should be able to discriminate neutrons and γ rays, have a variable geometry and be able to detect 2 neutrons at low relative momenta or small angular separation, the cost is of order 400 kEuros for a 100 element array.

This yields a total cost estimate for the DESIR β-decay studies of about 2160 kEuros, which includes an overhead of 20%.

f) Traps and detectors for fundamental interaction studies

The costs of the trapping systems strongly rely on the quality of the low-energy beams. In many cases, the trapping systems comprise two traps, one for preparation and a second for measurement. We assume here that the beam preparation achieved up-stream by the beam handling is sufficient to avoid the use of specific additional preparation traps. The cost of a Magneto-Optical Trap is dominated by the cost of the associated lasers and optical system. An estimate of 350 kEuros refers to a moderate cost system. For the detectors and associated electronics of an in-flight decay setup, the total cost is about 150 kEuros.

This yields a total cost estimate of about 600 kEuros for this topic, including an overhead of 20%.

g) The low-energy beam lines

To bring the beam from the exit of the target – ion-source system to the different DESIR installations, we count about 100m of low-energy beam lines. The “standard” prize for this type of beam lines at GANIL (including pumping, focussing etc.) is 36 kEuros per meter. Therefore, a total of 3.6 MEuros has to be provided for the beam lines.

h) Summary

The total costs for the DESIR facility amount to about 16 MEuros. To some extent, instrumentation exists already and can possibly be recovered (e.g. β-decay instrumentation exists in different laboratories, laser spectroscopy instrumentation exists at COMPLIS and ALTO, etc.). This possibility is not included in the present cost estimates. Therefore, the present estimates are only meant to give cost boundaries. In addition, not all material is needed from the beginning of the DESIR operation, but can be purchased at a later stage.

IX Conclusion

The DESIR facility will allow for a wide range of studies of nuclear structure physics, of astrophysics, of fundamental interactions, and, not described here, of topics of “non-nuclear” physics. The wide range of radioactive species, which will be available from SPIRAL and

SPIRAL2, will make DESIR a unique installation. Such a facility can and should be operational from day one of SPIRAL2 operation.

X The DESIR collaboration

Spokes-person: Bertram Blank (CENBG)
GANIL correspondant: Jean-Charles Thomas (GANIL)

Chairpersons:

- β-decay studies: Maria José Garcià Borge (CSIC Madrid)
- laser spectroscopy: François Leblanc (IPN Orsay)
  Gerda Neyens (KU Leuven)
  Paul Campbell (University of Manchester)
- atom and ion traps: Dave Lunney (CSNSM)
  Oscar Naviliat-Cuncic (LPC-Caen)
  Frank Herfurth (GSI)

Members:

Lynda Achouri, LPC Caen
Alejandro Algora, MTA Atomiki and CSIC Valencia
Jean-Claude Angélique, LPC Caen
Alain Astier, CSNSM Orsay
Georges Audi, CSNSM Orsay
Juha Äystö, University of Jyväskylä
Dimiter Balabanski, INRNE Sofia
Emmanuel Balanzat, CIRIL Caen
Gilles Ban, LPC Caen
Bertram Blank, CENBG Bordeaux
Klaus Blaum, University Mainz
Maria Jose Garcia Borge, CSIC Madrid
Dorel Bucurescu, NIPNE Bucarest
Apostol Buta, NIPNE Bucarest
Paul Campbell, University of Manchester
Grégory Canchel, CENBG Bordeaux
Daniel Cano Ott, CIEMAT Madrid
Joakim Cederkall, ISOLDE-CERN
Fatima Dayras, CSNSM Orsay
Giacomo de Angelis, INFN Legnaro
Pierre Delahaye, ISOLDE-CERN
Jean-Pierre Delaroche, CEA Bruyères-le-Chatel
Frank Delaunay, LPC Caen
Isabelle Deloncle, CSNSM Orsay
François de Oliveira Santos, GANIL Caen
Philippe Dessagne, IPHC Strasbourg
Gilbert Dûchene, IPHC Strasburg
Cédric Dossat, DAPNIA Saclay
Dominique Durand, LPC Caen
Serge Franchoo, IPN Orsay
Xavier Fléchard, LPC Caen

Kieran Flanagan, University Leuven
Carole Gaulard, CSNSM Orsay
Bill Gelletly, University of Surrey
Georgi Georgiev, CSNSM Orsay
Omar Gianfrancesco, CSNSM Orsay
Jérôme Giovinazzo, CENBG Bordeaux
Stéphane Grévy, GANIL Caen
Héloïse Goutte, CEA Bruyères-le-Chatel
Paul-Henri Heenen, University of Brussels
Frank Herfurth, GSI Darmstadt
Jussi Huikari, CENBG Bordeaux
Fadi Ibrahim, IPN Orsay
Ari Jokinen, University Jyväskylä
Andrea Jungclaus, University Madrid
Klaus Jungmann, KVI Gronningen
Swaminathan Kailas, BARC Mumbai
Jürgen Kluge, GSI Darmstadt
Magdalena Kowalska, University Mainz
François Le Blanc, IPN Orsay
Roy Lemmon, CCLRC Daresbury
Marek Lewitowicz, GANIL Caen
Etienne Liénard, LPC Caen
David Lunney, CSNSM Orsay
Miguel Marques, LPC Caen
Ismael Martel, Universidad de Huelva
Iolanda Matea, CENBG Bordeaux
Enrique Minaya-Ramirez, CSNSM Orsay
Iain Moore, University of Jyväskylä
Oscar Naviliat-Cunic, LPC Caen
Florin Negoita, NIPNE Bucarest
Gerda Neyens, University Leuven
C.J.G. Onderwater, KVI Groningen
Nigel Orr, LPC Caen
Dan Pantelica, NIPNE Bucarest
Sophie Péru-Desenfants, CEA Bruyères-le-Chatel
Stephane Pietri, University of Surrey
Natalie Pillet, CEA Bruyères-le-Chatel
Zsolt Podolyak, University of Surrey
Marie-Genevieve Porquet, CSNSM Orsay
Wolfgang Quint, GSI Darmstadt
Paul-Gerhard Reinhard, University of Erlangen
Ernst Roeckl, GSI Darmstadt
Daniel Rodriguez, Universidad de Huelva
Brian Roeder, LPC Caen
Bertra Rubio, CSIC Valencia
Lutz Schweikhard, University Greifswald
Nathal Severijns, University Leuven
Aradhana Shrivastava, BARC Mumbai
Cosimo Signorini, INFN Padova
Gary Simpson, LPSC Grenoble
John Simpson, CCLRC Daresbury

Olivier Sorlin, GANIL Caen
Krunoslav Subotic, University Belgrade
Olof Tengblad, CSIC Madrid
Catherine Thibault, CSNSM Orsay
Jean-Charles Thomas, GANIL Caen
Dragan Toprek, University Belgrade
Piet van Duppen, University Leuven
David Verney, IPN Orsay
Phil Walker, University Surrey
Christine Weber, University Jyväskylä
L. Willmann, KVI Gronningen
Hans Wilschut, KVI Gronningen
Martin Winkler, GSI Darmstadt
Nicolae Victor Zamfir, NIPNE Bucarest