Title: The DESIR facility (Decay, Excitation and Storage of Radioactive Ions).

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Abstract: *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.*

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. Nuclear physics as well as fundamental weak-interaction physics and astrophysics questions will be addressed using laser spectroscopy techniques, decay spectroscopy of radioactive species, mass spectrometry and other trap-assisted measurements.

To run such a facility efficiently, parallel operation of the low-energy part and the post-accelerator is required. From experience at other ISOL facilities (e.g, ISOLDE and ISAC) it is stressed that ion beams with a high degree of purity are needed to push experiments towards the limits of stability. The most efficient and universal way of achieving isotopic pure beams is a high-resolution mass separator in combination with element-selective ion sources.

We present a first design for the facility and give a brief description of the beam preparation and beam handling for the ISOL beams. A more extended version of the LOI is available as an appendix.

Scientific case

To date only about 2800 nuclei are known of the 5000 to 7000 theoretically predicted to be bound in their ground state. 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 (e.g. pairing enhancement). For these and many other reasons, it is important and timely to produce and study these new nuclear species.

In this letter of intent we argue for the need of a low-energy beam facility to be coupled with the LINAC driver and a variety of target – ion-sources for the production of exotic beams in different regions of the nuclear chart. Low-energy beams of exotic nuclei allow different types of decay spectroscopy experiments (half lives, masses, decay properties, spins, moments, etc.,) on beams with rather low intensities (as low as only several event per hour depending on the quantity to be measured). Therefore, these are often the first studies possible for a new exotic beam. Other observables, such as radii and weak-interaction correlation parameters), require pure beams of exotic nuclei in rather high intensities (> 10^5/s) to achieve sufficient statistical precision.

(1) Nuclear Structure and Astrophysics Studies

We propose to combine a variety of experimental tools for the study of complementary properties of exotic nuclei to investigate their nuclear structure and its impact on astrophysics scenarios. Shell structure, considered until recently as a robust characteristic of all nuclei, is now recognized as a more local concept. In the shell model, the evolution of single-particle energies plays an important role in determining the effective interactions between valence particles. In weakly bound systems, the spin-orbit force is expected to be weaker and shell gaps arising from this force should disappear. In the region of medium-heavy nuclei, new magic numbers might also appear for nuclei with a large N/Z ratio. The change in orbital ordering is most likely caused by the strongly attractive neutron-proton interaction between spin-orbit partners. For these very asymmetric neutron-rich nuclei, predictions favour a shell closure at N=34 because of the role of the $f_{5/2}$-$f_{7/2}$ interaction. For heavier systems, the $g_{7/2}$ and $h_{9/2}$ orbits are expected to be shifted upwards, disturbing the magic numbers N=82 and 126, respectively. The following experimental techniques will be used to explore the properties of exotic nuclei in neutron-rich regions of the nuclear chart:

- **<u>β-decay spectroscopy:</u>** β-decay to states in the daughter nucleus provides information on the degree of overlap between the neutron and proton states in the parent and daughter nuclei. Observation of γ-radiation from excited states in the daughter nuclei yields invaluable spectroscopic information on the energies and characteristics of its 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 nucleons.

  β-decay is also the first approach to study new **nuclear species along the r-process path** and the **determination of their half-life and decay modes** gives the first information on their structure. These studies can be done with a production rate as low as 0.1-1/s. Exotic nuclei that are far beyond the reach of current accelerator facilities play a role in these astrophysical processes and SPIRAL2 offers the possibility to reach some of the lighter cases along the r-process path.

- **β-delayed particle spectroscopy:** Very high β-decay energies characterize nuclides far from stability for which the daughter nuclei have low nucleon-separation energies. Therefore the **β-decay of exotic nuclei may feed excited states that are unbound with respect to the emission of nucleons or clusters of nucleons**. This decay mode, discovered for βα in 1916 and for βp in the 1960's, has already provided crucial nuclear structure information. The key point is that, if one knows the final state, one can derive the β-feeding to that state and the associated Fermi or Gamow-Teller (GT) matrix elements from the particle spectra. This gives **information on the strong interaction within the nucleus**. Beta-delayed particle emission is now well established and the mechanism governing the decay process is quite well understood. In light nuclei, where the level density is low and the levels are narrow, detailed and very precise information of the nuclear structure can be achieved at very low count rate (about 1/s or less). For heavier nuclei, the width of the individual levels is smaller than their spacing, but the emitted particles from these unbound states are nevertheless hardly resolvable. The structure of the nucleus is best 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. 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.
- **Trap-assisted spectroscopy:** The aim of trap-assisted spectroscopy is to perform decay spectroscopy with ultra pure samples. This is e.g. needed **for high-precision measurements** in weak-interaction studies like the measurements of the half-life and the branching ratios of super-allowed $0^+ \rightarrow 0^+$ β decays to test the conserved vector current hypothesis and to determine the V_{ud} matrix element of the CKM quark mixing matrix (see below). In these measurements, the radioactive samples are accumulated in a Penning trap, purified and finally ejected toward a measurement station. Penning traps can also trap the daughter products and as such offer access to **species otherwise unobtainable from thick targets** (i.e. some refractory elements). Decay Q-values can be determined in this way and hence, binding energies of exotic nuclides.
- **Collinear laser spectroscopy:** Atomic physics and optical techniques have played an important role to study the behaviour of nuclear matter at low excitation energy. Through the observation of the magnetic and electrostatic hyperfine structure in optical spectra as well as the influence of the nuclear charge radii on the isotope shifts between different isotopes of a given element, nuclear moments can be measured. These **nuclear moments (radii, magnetic dipole, electric quadrupole) can be determined in a model independent way and they provide direct information on the nuclear structure** (occupation of single particle orbits, collectivity and deformation, …) as well as a **stringent test for nuclear models**.
  The neutron rich N=50 region towards ^{78}Ni and the N=82 region around ^{132}Sn is of particular interest for astrophysical as well as for nuclear structure reasons. Measurement of the changes in the mean square charge radii can provide clear signatures for changes in the nuclear deformation with increasing N, and in combination with measurements of the matter radii, one can determine the neutron skin thickness for nuclei far from stability. A key element for such studies is germanium, whose isotopes are produced in large quantities in neutron stars.

- **<u>β-NMR on optically polarized beams:</u>** With a collinear laser beam it is possible to polarize nuclear spins. After implantation of the polarized beam in a suitable crystal, the magnetic and quadrupole moment of the nucleus can be measured with high precision using a radiofrequency field. By combining the information deduced from a hyperfine structure measurement using the collinear laser technique (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. It is particularly **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 (e.g. the regions around ^{78}Ni and along the N=50 and N=82 shells). β-NMR measurements yield the **nuclear moments with a precision** of better than 0.1% (for g-factor) and 1% (for Q-moment), thus allowing probing 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.
- **<u>Microwave double resonance in a Paul trap:</u>** High-precision measurements of the hyperfine anomaly allows quantifying the influence of the nuclear magnetic distribution on the hyperfine structure and this allows to study more precisely the effects on parity non-conservation in isotopic series and to better understand the contribution of the neutrons to the nuclear wave function. To study the hyperfine anomaly along a chain of isotopes, the magnetic hyperfine constant needs to be determined with very high precision. In combination with a precision measurement of the nuclear gyromagnetic factor (using for example ß-NMR), the hyperfine anomaly can be directly deduced from the magnetic hyperfine constant. The combination of laser and microwave spectroscopy in a Paul trap (where Doppler effects are reduced) gives the necessary precision of the order of 10^{-9} on the magnetic hyperfine constant and allows reaching the 3rd and 4th order of the hyperfine interaction. Thus higher-order nuclear moments associated with deformations of octupole and hexadecapole character can be investigated in heavy elements. Such studies should be very interesting in the gold isotopes where the hyperfine anomaly can vary between 1 and 10 %.

(2) Studies related to the Standard Model.

- **<u>Determination of fundamental couplings by β-decay:</u>** The searches for deviations from the unitarity condition of the CKM quark-mixing matrix provide very stringent tests of the Standard Model of electroweak interactions, which could point to the presence of new physics. So far, high-precision measurements of super-allowed (Fermi) β-decay properties provide the most precise determination of the V_{ud} matrix element leading to the most stringent unitarity test of the CKM matrix. Pure Fermi 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 for a comparison between the theoretical predictions and experimental results. The relative precision needed for the *ft* values of the β decays to permit a meaningful comparison between theory and experiment is about 10^{-3} – 10^{-4}. This requires the β-decay half-life and the super-allowed branching ratio to be measured with this precision, whereas the β-decay *Q* value requires 10^{-8}. Such a goal has been achieved to date for 13 nuclei and needs to be extended to other nuclei for an improved understanding of the theoretical corrections. New data for lighter nuclei is also of great importance for improved tests 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.

- **Structure of the weak interaction by angular correlation measurements:** The vector and axial-vector structure of weak interactions, discovered 50 years ago in nuclear beta decay, has been imbedded in the Standard Model (SM) where the interaction between leptons and quarks is described by the exchange of charged weak vector bosons. Several extensions to the SM introduce new exchange bosons, which would be manifested by the presence of scalar and tensor interactions in nuclear beta decay. A robust observable for the structure of the weak interaction is the angular correlation between the emitted electron and recoiling nucleus (or the positron and the neutrino). This correlation probes the presence of exotic couplings without assumptions on their discrete space and time transformation properties. Direct and indirect techniques have been implemented to measure the nuclear recoils following beta decay. In particular, experiments using atom traps have recently achieved an unprecedented level of precision, of few parts in 10^{-3} on the correlation coefficient, to search for scalar couplings. The availability of very high intensity radioactive beams enables consideration of new techniques beyond atom and ion traps, in which the angular correlation is determined from the measurement of decays in flight from a very low energy beam with small transverse size. Such techniques require dedicated beam preparation in order to achieve a number of decays of about 1000 per second over the beam volume seen by the detectors.
- **Symmetry tests:** Observables which are odd under the space inversion (parity) or time reversal transformations provide a simple means to search for deviations from maximal parity violation in the weak interaction or for new sources of T (or CP) violation in the strangeness-conserving sector probed by beta-decay experiments. Many scenarios beyond the SM predict the restoration of parity symmetry at some higher energy scale or the presence of new CP-violating phases beyond the standard electroweak CP phase of the CKM matrix. Precision experiments at low energies can often probe energy scales not otherwise accessible and are hence complementary to the searches for new physics performed at the highest possible energies. Significant improvements have been achieved in measurements of the longitudinal and transverse polarizations of beta particles from polarized nuclei and in other correlation parameters in nuclear and neutron decays. A precision level of a few 10^{-3} has been reached on several observables and provided new constraints on the parameter space of SM extensions. New exploratory experiments for parity and time-reversal symmetry tests have been performed using atom traps in which the radioactive atoms were polarized with lasers. Other such tests involve interference effects with the electromagnetic interaction in atoms (PNC) and the search for non-permanent electric dipole moments. In general, the sensitivity to symmetry violations in atoms is strongly enhanced for isotopes with high atomic numbers, which in addition may be radioactive. These experiments require beams or sources of very high intensity and purity as well as the development of polarization techniques.

Methodology

Beam properties *(primary beam, RIB: nature, intensity, time resolution, purity, use of beam tracking detectors etc. - to be specified if possible):*

Primary beams: The DESIR facility will utilize the entire variety of beams that should become available at SPIRAL2. This will require the use of **different production methods and thus different target-ion source stations**. For the neutron-rich nuclei, the deuteron- or neutron-induced fission of ^{238}U on a thick target will be used, while for the studies of intermediate-mass nuclei along the N=Z line (for nuclear structure and weak-interaction studies) fusion-evaporation on a thin target is preferred

Radioactive low-energy beams: After their production, the nuclei of interest must be ionized with a suitable method (surface, plasma or laser ionization). This target-ion source ensemble will be installed on a **high-voltage platform**, which will produce ion beams of a few tens of keV (at least **40 kV** should be considered for the DESIR beams). These ion beams can then be used either at an ISOL facility (DESIR) or they can be accelerated by the CIME cyclotron and be used to induce nuclear reactions.

- Intensity: for the experiments to be conducted at DESIR, beam intensities in a wide range have to be considered: **from a few ions/minute up to 10^7/s** are needed for the different experiments.

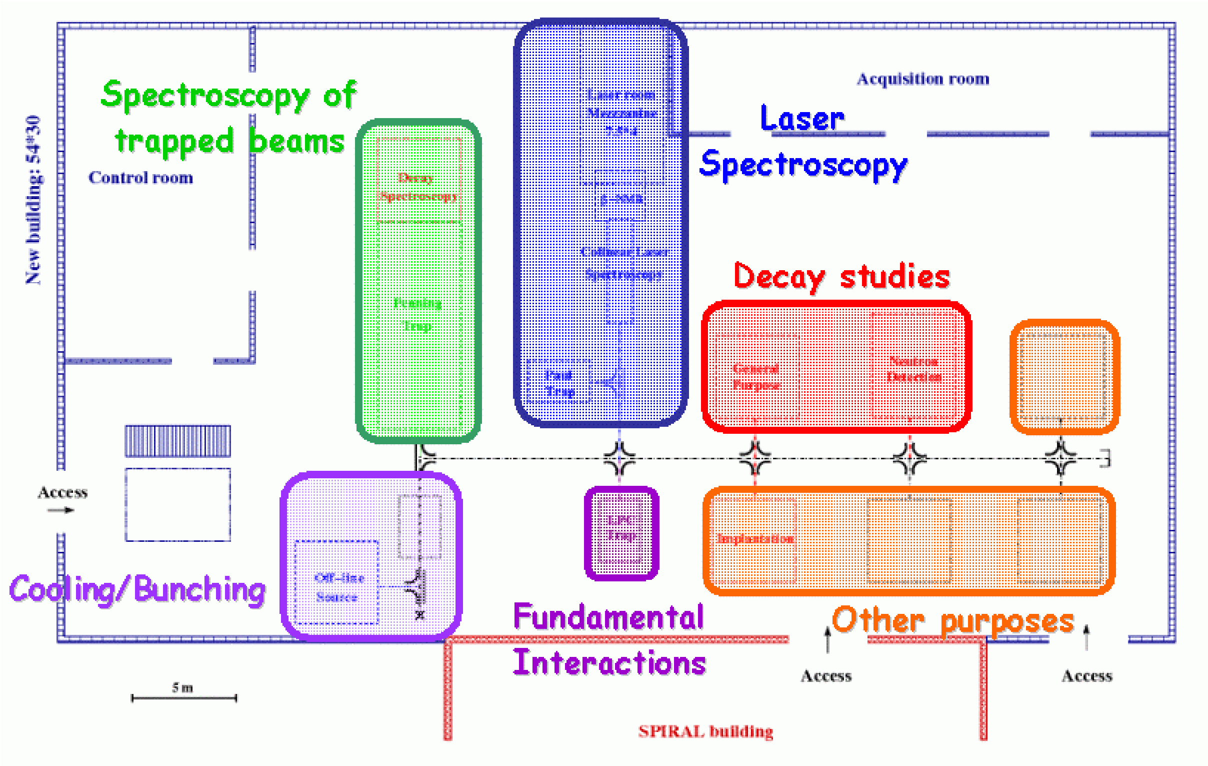
  Purity: beam purity is a major concern for the beams sent into the DESIR beam lines. Most experiments require **high beam purities (some up to 80% or more**). Therefore, in order to keep pace with intensity upgrades, the development of techniques for efficient beam purification will be necessary. Solving the problem of isobaric contamination will play a determinant role in whether experiments with low-energy beams can be performed or not. While **beam purification should be performed in the production area** (in order to transport a minimum of activity and to allow for parallel running and preparation of experiments in the DESIR hall), the low-energy beam preparation is preferably done in the experimental area. We therefore ask for a **high-resolution mass separator with a resolving power of at least 3000.**
- Beam size: a small beam size (order of about a millimeter) is needed for the kinematic reconstruction of multi-particle events and for angular correlation studies.
- Beam manipulation: bunched beams will be provided by an **RFQ cooler** placed in the DESIR hall. Further purification can be obtained by a **Penning trap**, which can also be used for trap-assisted spectroscopy studies.
- Time resolution: we will prepare the time structure of our beam using the RFQ at the entrance of the DESIR hall.
- Off-line source: as many experiments require extensive testing of the experimental set-ups, studies of systematic effects, developments of laser excitation schemes, etc… an off-line source that can provide stable beams of good intensity to all beam lines is planned.

Instrumentation and detectors *(equipment to be constructed or modified):*

In the figure below, a schematic layout of the DESIR facility is shown. 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.

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

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.



Theoretical support *(short description of the necessary calculations and developments):*

This project will certainly benefit from a close collaboration with theory groups. The suggested experiments should provide valuable input for the developments of shell-model interactions to improve the description of the cross-shell interactions across N=50 and N=82.

Preliminary schedule of the process leading to the signature of the Memorandum of Understanding and of the construction of new equipment:

If the present LoI gets a positive answer from the SAC of SPIRAL2, an MoU will be signed by the different members of the collaboration.

Preliminary evaluation of the cost of the equipment to be constructed as well as necessary manpower:

The cost estimates mentioned in the following are only rough estimates 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. Some of these costs need to be included in the SPIRAL2 project costs (or be provided by GANIL), while other items can be provided by the collaboration. This will have to be discussed between the GANIL-SPIRAL2 management board and the DESIR collaboration representatives, if the LoI receives a positive evaluation.

a) The DESIR hall

The DESIR hall is suggested to have a total surface of 1500m^2. A rough estimate of the construction costs including the necessary infrastructure (water, air conditioning, pressurised air, liquid nitrogen, electrical power of about 2MWA etc.) was deduced from the cost 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, magnetic-dipole separator, preceded by a beam cooler to avoid transmission losses that normally result. 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/cooler + 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 (Laser Utilisation for Measurement and Ionization of Exotic Radioactive Nuclei)

The laser installation for the physics experiments requires an equipped laser room of about 20 m^2 preferably on a mezzanine. If this room is also used for the ion source lasers, it must be extended to 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+argon) 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 BESTIOL facility (BEta decay STudies at the SPIRAL2 IsOL facility

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) Fundamental interactions

Fundamental interaction studies will be performed mainly with traps and in-flight decays. These setups require an investment of 350 kEuros for a MOT trap and of 150 kEuros for the in-flight setup. Including the overhead, we estimate a cost of 600 kEuros.

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' price 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 for the start of the DESIR operation; it can be purchased at a later stage.

Appendix: Members of the DESIR collaboration

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