# High-resolution Gamma-ray Spectroscopy at SPIRAL2

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***Corresponding convener for each specific physics case:***

- D. Rudolph, Lund University, Sweden (Proton drip-line studies and *N*=*Z* nuclei)
- A. Gadea, Laboratori Nazionali di Legnaro (Neutron-rich nuclei)
- A. Görgen, CEA Saclay (Nuclear shapes and high-spin spectroscopy)
- S. Leoni, INFN Milano (Collective modes in the continuum)
- G. Georgiev, CSNSM Orsay (Nuclear electromagnetic moments)
- P. Greenlees, University of Jyväskylä (Spectroscopy of the heaviest elements)

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***Collaboration***:
Here we give a *list of collaborating institutes* (see next page) with participants in at least one of the specific activities and both in the experimental and the theoretical domain. A complete list of participating scientists and laboratories is given in the individual sections.

***Introduction:***
This Letter of Intent is presented by the GANIL user community interested in performing *high-resolution gamma-ray spectroscopy* experiments using both radioactive and high-intensity stable beams from the SPIRAL2 facility. It comprises several distinct science cases aiming at different properties of nuclei and/or different regions of the nuclear chart. Since an important overlap exists between the collaborations pursuing the different science cases, and since the principal experimental equipment is identical, e.g. the large germanium spectrometers EXOGAM and AGATA, a common document is presented with a summary of the general physics case and a description of the principal instrumentation and methods, followed by individual Letters of Intend related to each science case. Individual collaborations are listed in the corresponding sections.

This document is the result of a series of workshops held over the last few years. It has been edited by the conveners of these workshops and coordinated by the chairpersons of the steering committees of the AGATA and EXOGAM collaborations. A formal decision on the final structure of the collaboration and the spokesperson(s) will be taken in due time.

***<u>List of collaborating institutes:</u>***

University of Ankara, Ankara, Turkey
Argonne National Laboratory, Argonne, Illinois, USA
Lawrence Berkeley National Laboratory, Berkeley, California, USA
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Natl. Inst. of Physics and Nucl. Engineering, Bucharest, Romania
Université Libre de Bruxelles, Belgium
CEA/DIF/DPTA/PN, Bruyères le Châtel, France
GANIL, Caen, France
Panjab University, Chandigarh, India
Niels Bohr Institute, Univ. of Copenhagen, Denmark
GSI Darmstadt, Germany
Inst. of Nuclear Research, ATOMKI, Debrecen, Hungary
Daresbury Laboratory, Daresbury, United Kingdom
CERN, Geneva, Switzerland
LPSC, IN2P3-CNRS, Grenoble, France
University of Surrey, Guildford, United Kingdom
University of Jyväskylä, Finland
IKP University of Köln, Köln, Germany
Saha Institute of Nuclear Physics, Kolkata, India
Niewodniczański Institute of Physics & IFJ PAN, Krakow, Poland
University of Liverpool, UK
INFN-Laboratori Nazionali di Legnaro, Legnaro, Italy
IKS, KU Leuven, Leuven, Belgium
Lund University, Lund, Sweden
IPN Lyon, IN2P3-CNRS, Lyon, France
University of Manchester, United Kingdom
Michigan State University, East lansing, USA
Universidad Autónoma de Madrid, Madrid, Spain
University of Milano and INFN, Milano, Italy
Tata Institute of Fundamental Research, Mumbai, India
Dipartimento di Scienze Fisiche, University of Napoli and INFN, Napoli, Italy
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KTH, Royal Institute of Technology, Stockholm, Sweden
IPHC, IN2P3-CNRS, and University Louis Pasteur, Strasbourg, France
Universita di Torino and INFN, Sezione di Torino, Italy
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University of York, York, United Kingdom
University of Warsaw, Warsaw, Poland

## Scientific case

High-resolution gamma-ray spectroscopy is a major tool to understand the structure of atomic nuclei. It is used to explore many different facets of nuclear structure and many different experimental techniques are required to study these. We have thus decided to divide the science case into several major topics which are outlined below. Further details can be found in the corresponding sections following the general part.

***Proton drip-line studies and N=Z nuclei***

Neutron-deficient nuclei at or sometimes even beyond the proton drip line were studied extensively in the past decades. A large amount of data has been accumulated even for high-spin states using fusion-evaporation reactions with stable beam and target combinations. This has led (and still leads) to the acquisition of considerable knowledge on these nuclei and associated physics. However, it is clear that deeper and more fundamental questions arise from the available information, such as: Do we understand pairing in the isospin $T=0$ and $T=1$ channels? Which (nuclear?) effects break isospin symmetry? Can we follow the demise of isospin for heavy $N$~$Z$ nuclei or nuclei with a large proton excess? Are there exotic shapes and decay modes and, related, where exactly is the proton drip line? Do proton skins or even halos exist? Are there 'Islands of Inversion' on the neutron-deficient side of the chart of the nuclides? In addition to these nuclear physics questions, there is considerable interest from nuclear astrophysics (*rp* process) and weak interaction (CVC conservation and unitarity of the CKM matrix) associated with medium-heavy $N \leq Z$ nuclei.

All these open questions demand more detailed γ-spectroscopic studies of neutron-deficient nuclei, employing both high-intensity stable and radioactive beams at energies around the Coulomb barrier. In view of the extremely small production rates for the nuclei of interest a unique and efficient event-by-event identification is needed, using either (proton- or super-allowed β-decay) tagging techniques of the nuclei in the focal plane of a spectrometer and/or a measurement of the evaporated light-charged particles and neutrons. Alternatively, Coulomb excitation and transfer experiments could be employed directly on the radioactive nucleus in order to measure other nuclear properties (electromagnetic moments, spectroscopic factors, etc).

***Neutron-rich nuclei***

Extending the knowledge of nuclear properties towards neutron-rich nuclei is of fundamental importance for the understanding of nuclear structure and nuclear models at large values of isospin, the latter of which has been largely derived from the properties of nuclei observed close to stability. Significant changes of the shell structure are predicted for neutron-rich nuclei, and to investigate the evolution of the shell structure is one of the key objectives of SPIRAL-2. Open questions include: the evolution of the nuclear effective interactions in the monopole and multipole terms, the quenching of the known shell gaps and development of new ones, the evolution of the nuclear collectivity (onset of deformation in light n-rich nuclei), the shape phase transitions (dynamical symmetries) and the onset of exotic shapes. These experimental open questions can be studied by exploring the nuclear spectrum of excited states up to medium-high angular momentum and by direct measurement of transition probabilities.

Neutron-rich nuclei are much more difficult to access than their proton-rich counterparts. In particular it is difficult to access states with spins exceeding those populated in beta decay or through fragmentation or fission reactions. Multi-nucleon transfer and deep-inelastic reactions performed at energies 10-20% above the Coulomb barrier are well suited to populate states up to spin 20 ħ in neutron-rich nuclei. The production cross-section generally follows the N/Z equilibration line. Deep-inelastic reactions with intense neutron-rich beams from SPIRAL-2 on $^{238}$U targets permit to reach neutron-rich nuclei well beyond the scope of experiments with stable beams. The nuclei of interest are generally produced with small cross sections and have to be distinguished from a very large background from other reaction channels (including fission). The required selectivity can be reached by coupling an efficient γ-ray spectrometer (AGATA or EXOGAM) to a large-acceptance magnetic spectrometer (VAMOS). The spectrometer is rotated at the grazing angle in order to detect the recoiling fragments, which are uniquely identified in Z and A. The measurement of the recoil velocity can be used to further improve Doppler correction. In this way the γ-rays are uniquely assigned to unknown nuclei and additional selectivity is achieved by analysing γ-γ coincidence data.

***Nuclear shapes and high-spin spectroscopy***

The shape of an atomic nucleus is a fundamental property which is governed by a delicate interplay of the macroscopic liquid-drop properties of nuclear matter and microscopic shell effects. The nuclear shell structure is drastically altered as one moves from spherical nuclei to regions of high deformation. Rotation adds a further dimension to the nuclear many-body problem. Studying the evolution of nuclear shapes and shape coexistence, collective modes such as rotations and vibrations, and the measurement of nuclear moments gives important insight into the nuclear structure and is often a critical test for theoretical models. Many fundamental questions related to nuclear shapes and the breaking of spherical symmetry are not well understood: Why are prolate shapes so much more abundant than oblate shapes? What leads to axial symmetry breaking and what are the consequences of triaxiality for the three-dimensional rotation of nuclei (wobbling, chirality)? New high-rank symmetries corresponding to tetrahedral and octahedral shapes are predicted for certain nuclei far from stability that remain to be discovered experimentally. Phenomena at the extremes of deformation are very sensitive to details of the nuclear force.

Fusion-evaporation reactions with neutron-rich beams from SPIRAL2 give access for the first time to high-spin states in moderately neutron-rich nuclei and will further push the experimental spin limit into a new regime where new phenomena are expected to occur, for example hyperdeformation, the Jacobi shape transition, the termination of collective rotation, and the total quenching of pairing correlations. In order to understand the elementary excitations in nuclei far from stability, the spin degree of freedom in nuclei further from stability needs to be investigated. Appropriate tools for such studies are multiple Coulomb excitation, and transfer and deep inelastic reactions. New collective modes are expected in exotic nuclei with large neutron excess. Projectile Coulomb excitation experiments with radioactive beams at energies below the Coulomb barrier are an ideal tool to investigate collective excitations in exotic nuclei and yield access to quadrupole moments and the nuclear shapes involved.

***Collective Modes in the Continuum***

Collective modes are a powerful tool to investigate nuclear shapes and their evolution, the influence of thermal environments on low-lying modes, and the elastic response of nuclear matter. Because these properties are expected to change when going away from the valley of stability, the study of collective modes in exotic nuclei will provide new insight into the structure of these nuclei and the nuclear many-body problem in general. Selective γ-spectroscopy measurements are essential to carry out such investigations. The employment of high-intensity neutron-rich beams from SPIRAL2 will allow studying vibrational and rotational collective phenomena at finite temperature, making use of both inelastic scattering and fusion-evaporation reactions. In particular, we plan to investigate the properties of *giant resonance states* in exotic systems, such as Giant Quadrupole Resonances (GQR) and Giant Dipole Resonances (GDR). The GDR built on specific nuclear shapes and deformations are interesting both for nuclear structure at finite temperature and for the understanding of dynamical modes in fusion reactions. In particular, they provide information on the damping mechanisms of collective modes, on the charge equilibration time, and on the symmetry energy of the nuclear matter at densities lower than the saturation value. In addition, the study of *warm rotational motion*, namely of the nuclear rotation at moderate excitation energies above yrast (U≈ 2-4 MeV), both in normal deformed and super deformed configurations, will provide valuable information on the disappearance of quantum numbers with temperature, namely on the onset of the chaotic regime in the atomic nucleus.

***Nuclear electromagnetic moments***

Significant changes in the nuclear shell structure away from the valley of β-stability have been observed experimentally during the last years, showing that new nuclear features are to be expected at extreme isospin. The measurement of electromagnetic nuclear moments, with their sensitivity both to the single-particle and collective properties of the nuclear wave function, is an indispensable tool for the nuclear structure investigations of exotic nuclei. The **magnetic dipole** moments are very sensitive probes to the valence nucleons and are one of the first rigid tests of the nuclear models. The **electric quadrupole** moments, being a fingerprint of the distribution of the electric charges in the nucleus, give insight into the nuclear deformation and the developments of exotic shapes. The **static electromagnetic moments** give precise information on a particular nuclear state and the composition of its wave function, while the dynamic moments (**transition probabilities**) depend on both nuclear states involved and reveal the interrelations between different structures in the nucleus. We intend to study static electromagnetic moments using perturbed angular distributions and correlations, transient fields, and β-NMR after tilted-foils polarization. Furthermore we plan to measure transition probabilities via lifetime and Coulomb excitation techniques, the latter being sensitive to static quadrupole moments.

***Spectroscopy of the heaviest elements***

The spectroscopy of transfermium elements is part of the heavy-element programme. The physics case and the required instrumentation are described in the Letter of Intent "From Actinides to Superheavy Elements with SPIRAL2: Reaction dynamics and structure" (P. Greenlees et al.).

## Methodology

***Instrumentation and detectors***:

In this section we describe the detectors which are common for many of the high-resolution spectroscopy experiments. Further details on specific instruments can be found in the different annexes. The experimental programme described above is feasible by combining very efficient gamma-ray spectrometers like **AGATA** or **EXOGAM II** with powerful separators such as **VAMOS** or **S$^3$** and several ancillary devices to measure light-charged particles, neutrons etc.

***AGATA***

The ***"Advanced GAmma Tracking Array"*** (**AGATA**) is a major breakthrough in instrumenttation for gamma-ray spectroscopy. The first 4π γ-ray spectrometer solely built from Germanium (Ge) detectors is based on the novel technique of gamma-ray tracking which makes use of position-sensitive 36-fold segmented, encapsulated Ge crystals, digital electronics, on-line pulse-shape analysis and gamma-ray tracking algorithms and full parallel readout. It is capable of measuring γ radiation in a very large energy range (from a few tens of keV up to 10 MeV and more), with the largest possible efficiency and with a very good spectral response. AGATA is several orders of magnitude more powerful than current γ–ray spectrometers.

It is planned to install AGATA at GANIL for campaigns with minimum durations of one year. Three different locations are considered for the installation of AGATA, serving the specific needs of the different experimental programs: in G1 coupled to VAMOS, in G2 coupled to an array of neutron detectors or stand alone, and at the secondary target point of the new $S^3$ separator in the LINAG experimental area. The full AGATA spectrometer comprises 180 germanium crystals and its construction is expected to be completed by 2016. About half of the detectors are expected to be available in 2012. The spectrometer is modular and can be used in different configurations. The first choice for its installation is in G1 with up to 45 triple modules (3π configuration) coupled to VAMOS. Various ancillary detectors can be implemented for additional selectivity and reaction product identification, such as a CsI multi-detector for light charged particles or highly pixelised silicon detectors for Coulomb excitation experiments. Experiments to study nuclei at the highest spins involve very large γ-ray multiplicities and require the full AGATA spectrometer in 4π geometry. In this configuration AGATA will be installed in the G2 experimental area. In G2 it is also possible to couple AGATA in a 2π or 3π configuration to a neutron array or a conversion-electron spectrometer. The option to install AGATA, e.g. in a 2π configuration, at the secondary target point of the $S^3$ separator-spectrometer should be considered for the layout of the new experimental area to be constructed at the LINAG.

AGATA will be installed with a dedicated infrastructure by the AGATA collaboration. Some GANIL infrastructure items will have to be adapted:

- the mechanical support of the holding frame will have to fit to the experimental area ($S^3$, VAMOS, G2) and the beam-line design fit with AGATA,
- the electrical power (120 kVA in the experimental area, 200 kVA in the acquisition area) and the digitiser cooling water (750 l/min),
- the liquid nitrogen delivery (~1600 l/day)

***EXOGAM2***

EXOGAM is an array of HPGe detectors designed to exploit radioactive beams from SPIRAL. The original design (see http://www.ganil.fr/exogam/) consists of 16 large segmented Ge clover detectors surrounded by a modular Compton suppression shield. The signals from the clover detectors (core and segments) as well as from the Compton suppression shields are processed presently using VXI electronics.

The EXOGAM clover detectors have an electric segmentation, which improves the Doppler correction of the gamma-ray energies. This is achieved with pulse-shape analysis (PSA) and the localization of the first interaction point, which is possible with significantly better resolution than the size of the individual segments (2 cm at the front face). An EXOGAM clover detector has been scanned at the University of Liverpool, and it has been shown that the PSA results in a position resolution of about 5 mm. The radial position is extracted from the rise time of the net-charge signal in a segment, while the induced mirror charges in the neighbouring segments give the azimuthal angle. In order to exploit the possibility of performing PSA it will be necessary to develop a digital electronics system for EXOGAM, which will analyze the rise time of the preamplifier signals and derive the useful information online.

With the new demand from the physics cases and in particular to guarantee the efficient use of the radioactive beams from SPIRAL2, there is a need for using higher counting rates and avoiding the common dead-time mode with EXOGAM. Furthermore it is difficult to maintain in the long term the existing VXI electronics. Therefore it is time to think about a new phase of EXOGAM, called thereafter EXOGAM2, which in particular considers a complete redesign of the electronics, the purchase of two additional clover detectors, and the modification of infrastructure items. As the AGATA spectrometer will only be installed at GANIL during periods of about one year, there is a clear demand for a high-performance gamma-ray array outside these campaigns.

**Electronics and data acquisition:**
EXOGAM2 should fulfil the following requirements:

- Localisation of the first interaction using PSA on the core and segment signals. This requires digital electronics and signal processing.
- Higher counting rate capability. Today, a limitation arises from the analogue electronics, and eventually preamplifiers, leading to a maximum rate of about 10 kHz. Using digital electronics, rates of 50 kHz can be easily archived. This aspect is of particular importance when EXOGAM will be coupled to the AGATA demonstrator, thus avoiding a situation where the combined performance would be limited by the Exogam capabilities. A collaboration with the ADONIS team (CEA/DRT/LIST) on numerical methods is ongoing.
- The Compton suppression shields have to be included in the fully digital system.
- Energy, time and localisation have to be processed on-line and the system should be able to produce events.
- The system has to be compatible with the AGATA demonstrator and ancillary detectors (existing and foreseen). EXOGAM2 has to provide a multiplicity signal to ancillary detectors and should be able to be triggered, or at least filtered, by external detectors. More precisely :
    - With the AGATA demonstrator, the system has to be compatible with the global trigger system (GTS) of AGATA. It should be able to produce time-stamped data and should use the AGATA clock.
    - EXOGAM2 has to be compatible with the Ganil clock system (CENTRUM and future GAMER modules).
- The system has to be fully remote controlled and provide diagnostic tools since access to the experimental hall will be prohibited with Spiral II beams. This includes the electronics, but also the HV system and LN2 filling … Reliability should be therefore a priority in the EXOGAM2 design. If possible, electronics and DAQ should be located outside the experimental hall.
- Clover detectors are intensively used in the different experimental areas of Ganil (D6, G3 …), but there is no dedicated electronics attached to the detectors. This means it is often not possible to use the Compton suppression shields. The new electronics (at least the front-end) should be therefore easily installed in different places.

***Ancillary detectors***

Gamma spectrometers are usually used with ancillary detectors such as **charged particle arrays, neutron detectors, scintillator arrays for high-energy γ rays, or recoil spectrometer and separators.** Many ancillary detectors have already been used with EXOGAM, but need to be adapted to take into account the larger intensity of the SPIRAL2 radioactive beams. A number of ancillary detectors will be available for AGATA. Some of them exist already, others are planned or under construction. Developments, simulations, electronics and the DAQ of ancillary detectors for AGATA are coordinated by the "Ancillary detectors working group" of the AGATA collaboration. The development and installation of such detectors is usually under the responsibility of the owners. Some specific requirements for the ancillary detectors are described in the LoI's describing the individual physics cases and will not be detailed in this section. The list includes:

- ***Charged-particle arrays***

  For high-intensity stable beams the key challenge is the charged-particle rates to be sustained by the device. For the highest numbers, i.e., $10^{12}$ pps, a total of some 3000 detector elements are needed. One suitable starting point is the TRACE project pursued at LNL, Italy. In the case of reactions induced by radioactive ion beams, efficiency is the dominating issue, while keeping in mind particle-spectroscopy. Another possible solution could be a DIAMANT type CsI array which has already been used with EXOGAM and radioactive beams from SPIRAL. An increased granularity and the option of including DSSD detectors at forward angles must be studied. Coulomb excitation experiments require highly segmented annular silicon detectors, which also need to sustain high count rates from the intense SPIRAL2 beams. Due to the large number of channels, the use of ASIC electronics will be considered.

- ***Neutron array***

  For channel selection in fusion-evaporation reactions the use of neutron detectors at forward angles is essential, often in combination with charged-particle selection (or veto). High granularity and efficiency are important. The ability to determine the energy of the neutron interaction as well as (the usual) time of flight will help in elimination of neutron scattering contamination. Thus, we consider that it is essential to investigate new neutron detection methods – such as use of deuterated liquid scintillators, solid plastic scintillators etc. Experiments at an early stage, however, can use the existing neutron detector arrays such as the Euroball Neutron Wall, which should be maintained and made available at GANIL.

- ***Scintillator array for high energy γ-rays***

  A part of the planned program needs, in addition to AGATA, the use of efficient high-energy γ ray detectors, such as large-volume scintillators. Experiments aiming at studying the GDR decay at finite temperature using a combination of germanium and scintillator detectors were successfully performed within the Euroball collaboration. They showed the importance of exclusive measurements to select particular shapes and configurations. Presently, various possibilities for an ancillary detector based on large-volume scintillators are under study, the simplest one being the use of the HECTOR or similar existing arrays. The design and constructions of a detector made from new scintillator materials has been initiated and is subject to a separate letter of intent ("High-energy γ rays as a probe of hot nuclei and reaction mechanisms", A. Maj et al.). The modularity and the flexibility of the new design will allow the coupling of such a scintillator array to different instrumentations described above.

- ***Recoil spectrometer and separators***

Due to the high gamma-ray background from the decay of the radioactive beam, it will be important in many to identify the reaction product event by event in Z and A. This can be achieved by using a spectrometer with high transmission and the appropriate focal-plane detection systems. The versatile VAMOS spectrometer with its high angular and momentum acceptance and transmission efficiency remains the primary instrument for this purpose. The study of transfermium and very neutron-deficient nuclei requires alpha- or proton-tagging techniques, for which a focal-plane detection system is currently being developed (MUSETT). The $S^3$ separator spectrometer in combination with rotating or cooled (thin) production targets allows the in-flight production of radioactive beams, which for example can be used for Coulomb excitation on a secondary target. Details are described in the LoI for the $S^3$ separator spectrometer.

***Beam properties***:

All different types of beams produced by SPIRAL2 will be useful for this research program:

- very intense stable heavy-ion beams (from $10^{11}$ to $10^{14}$ pps) provided by the LINAG accelerator ($^{48,40}$Ca, $^{58}$Ni, …)
- neutron-rich radioactive beams of, e.g., Kr, Sn, Xe, Nd, …
- neutron-deficient radioactive beams with $T_z \leq 0$, e.g., $^{18}$Ne, $^{34}$Ar, $^{56}$Ni, $^{58}$Cu, $^{72}$Kr, …

Usually with the highest possible intensity; from $10^3$ pps are needed for Coulomb excitation measurements while $>10^8$ pps are required for fusion-evaporation reactions. The requested beam energy covers a range from 3-5 MeV/A to 10-15 MeV/A.

Detailed specifications of the beam properties are given in the individual LoI's. Here, only a few general considerations are summarized:

- In many cases **beam purity** is of highest concern and impurities should not exceed the 1% level.
- **High quality of the radioactive beams** (emittance, halo, …) is very important in order to use position-sensitive detectors around the target point for the high-resolution gamma-ray spectroscopy and the coincidence with the particles.
- **Good timing properties** (below 1ns) are needed for all experiments using "fast" ancillary detectors, e.g. for neutrons.
- Experiments with radioactive beams usually require **stable beams to set up the detectors** under clean conditions (higher intensity, less background).
- **Source development for CIME** is needed in order to deliver stable isotopes of all elements that are available as radioactive beams from SPIRAL-2.
- **Parallel beam delivery via the new direct beam line from CIME to G1 and G2** would also greatly benefit from such source development.

***Targets:***

***RIB production target:***

In addition to the $UC_x$ target for the production of fission-fragment beams, we fully support the construction of a second target station to produce the RIB in heavy-ion and light-ion induced reactions on other target materials using the ISOL technique, in particular to produce neutron-deficient and intense light-ion beams.

***Secondary targets:***
In most cases the secondary targets will be metallic foils of typically 0.5-1 mg/cm$^2$ thickness. A well-equipped laboratory for the manufacturing of such targets and at least one well-trained and experienced technician are of high importance.

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

- **AGATA**

A MoU for the construction of AGATA is currently being prepared and should be signed by the end of the so-called demonstrator phase (2007). A first installation of AGATA, e.g. in a 2π configuration could be foreseen in 2012 for at least one year for experiments using high intensity stable beam and/or radioactive beams. A second campaign with AGATA in a 3π configuration coupled to VAMOS could be foreseen in 2015 for radioactive beam experiments. Further installations are envisaged for the 4π configuration at G2. In all cases, ancillary devices will be coupled to AGATA (see above).

- **EXOGAM II**

Discussions on the upgrade of the EXOGAM spectrometer as described above have only very recently started in the collaboration.

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

- **AGATA**

The construction costs for the full AGATA array (~50M€) will be requested from the member states of the collaboration and from the EU. According to EU representatives AGATA would qualify for an EU contribution within the FP7 programme financing the construction of new infrastructures if requested through GANIL as SPIRAL2 host laboratory.

Additional infrastructure costs to host the full array are estimated to be about 250 k€ at the first installation and about 150 k€ for any following installation.

For all experiments, GANIL provides a technical support during the installation and the experiment itself. This support is provided by a Department of 45 persons: the STP “Support Technique pour la Physique”. To day, there are two persons (1 engineer, 1 technician) working full time for the EXOGAM detector assisted by the electronics and the data acquisition groups. Those teams should be adapted and trained to the specificities of the AGATA array at GANIL.

# Proton Drip-Line Studies and *N*~*Z* Nuclei


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***Abstract:***

This Letter of Intent summarizes the physics cases and associated instrumentation for in-beam nuclear structure studies of neutron deficient nuclei based on high-resolution γ-ray spectroscopy techniques using the prospected capabilities of SPIRAL2 and the high-intensity stable-beam accelerator, LINAG.

***Scientific case:***

**Physics of Nuclei on and Around the Line of N=Z: Some Challenges Ahead**

Unlike neutron-rich nuclei, neutron-deficient nuclei at or sometimes even beyond the proton drip line have been studied extensively in the past decades. On the one hand, this led (and still leads) to a considerable knowledge on these nuclei and associated physics. On the other hand, deeper and more fundamental questions arise from the available information, such as: Do we understand neutron-proton pairing and its influence in the isospin $T=0$ and $T=1$ channels? Which (nuclear?) effects break isospin symmetry? Can we follow the demise of isospin for heavy $N\sim Z$ nuclei or nuclei with a large proton excess? Are there exotic shapes and decay modes and, related, where exactly is the proton drip line? Do proton skins or even halos exist? Are there 'Islands of Inversion' on the neutron-deficient side of the chart of the nuclides? In addition to these nuclear physics questions, there is considerable interest from nuclear astrophysics (*rp*-process) and weak interaction (CVC conservation and unitarity of the CKM matrix) associated with medium heavy $N \leq Z$ nuclei. Some of these topics are expanded upon below, and in the following section, we discuss how some of the selected areas for study might be studied using SPIRAL2.

Isospin symmetry, a concept most relevant for nuclei with $N\sim Z$, is a consequence of the assumption that nuclear forces are independent of charge. Even though this symmetry is broken to a certain extent by the strong interaction, in a significant way by the weak interaction and, most significantly, by the electromagnetic interaction, the isospin formalism remains an extremely powerful tool to understand the structure of nuclei. The isospin symmetry breaking terms of the nuclear hamiltonian should lead to each nuclear state having, in addition to its main component of isospin $T$, minor components of differing isospin. The breaking of the isospin symmetry by the Coulomb force increases with $Z$ and for a given mass it is maximum for $N=Z$ nuclei. The study of the heavier nuclei with $N \approx Z$ is thus of fundamental interest.

Nuclei at the $N=Z$ line are unusually tightly bound, requiring an additional so-called Wigner term in nuclear mass formulas that specifically deals with $N=Z$ nuclei. Generally, an increase in the nuclear binding energy may be the consequence of additional correlations, for example, pairing. While pairing correlations between identical nucleons are by now well understood, those due to the combined effect of pairing in the $T=0$ and $T=1$ channels are more complex, and it can be shown that they lead to an $\alpha$-type clustering effect, *i.e.* a quartetting rather than a pairing effect, which gives rise to the extra binding energy of $N=Z$ nuclei. At present, the evolution of the Wigner energy with mass is unknown and it is not clear if some effect will remain at mass numbers approaching $A=100$ or whether the effect will completely disappear.

Correlations between pairs of particles are of fundamental importance in all fields of physics. Superconductivity in solids is a well-known and well-understood phenomenon arising from the interaction between pairs of electrons moving in opposite directions. The superconducting state that is realized in certain materials can be expressed as a freely moving (non-interacting) collection of such strongly correlated "Cooper pairs" and described with Bardeen-Cooper-Schrieffer (BCS) theory. Not as well known as the Cooper pairs in condensed-matter physics, but equally fundamental, is the pairing effect in nuclear physics, which results from a coupling of neutrons and protons in pairs and gives rise to nuclear superfluidity. Also here strong correlations involving Cooper pairs arise. In the nuclear domain, the strongest interactions involve nucleon pairs that are close in space, reflecting the fact that the nucleon-

nucleon force has a range that is small compared to the size of the nucleus. In addition, a unique feature of nuclei is that they consist of a combination of two fermionic fluids (neutrons and protons) and as a consequence, the nucleons can form four types of Cooper pairs, each of which can be in a state of relative orbital angular momentum zero and hence well correlated in space. As a consequence of spin-isospin symmetry, the neutron-neutron (*nn*), neutron-proton (*np*) or proton-proton (*pp*) pairs are characterized by the quantum numbers of total spin ($S$) and isospin ($T$). To date, only the nuclear superfluid phases associated with Cooper pairs of like nucleons (nn or pp) have been observed. Whether there also exists strong deuteron-like isoscalar ($T$=0) correlations, remains an open question. For neutron-deficient nuclei, approaching the double spherical shell closure at $N$=$Z$=50, neutrons and protons occupy very similar orbitals, and there is therefore a large spatial overlap of the wave functions describing them. In addition, there are a sufficient number of valence particles to create a correlated state which, according to theoretical predictions, may give rise to special effects of *np* pairing which are very different from the normal pairing effects observed closer to stability. In fact, theoretical calculations suggest that *np* isoscalar pairing in such cases may compete effectively, or perhaps even dominate over, the isovector pairing modes which includes not only like-particle but also *np*-isovector pairing. The search for this new phase of nuclear matter and the study of its manifestations represents one of the most significant challenges in nuclear structure physics for the upcoming years.

Another interesting aspect of heavy mirror nuclei is the possibility to search for exotic matter distributions in the nucleus, *i.e.* to test theoretical predictions for proton skins, by means of Coulomb energy differences of isobaric analogue states since the Coulomb repulsion between the protons in the nucleus is directly related to their spatial distributions. Studies of $N$~$Z$ systems in the $A$~80 region of nuclei may also shed light on dynamical symmetries in nuclei, one of the key contemporary topics. For example, the neutron deficient $^{76,78}$Sr and $^{78,80}$Zr nuclei have been found as promising candidates to explore X(5) symmetry.

## Selected Physics Questions and Approaches with SPIRAL2

In this section we list key physics questions to be addressed via in-beam γ-ray spectroscopy and outline the experimental schemes while focusing on new approaches that may be utilised at GANIL. The tables at the end of this section list specific key reactions, with estimates of required intensities of both radioactive and stable beams.

### 1 Spectroscopy at Large Isospin and Exotic Particle Decays.

This programme involves the study of the breakdown of isospin symmetry, resulting from, for example, Coulomb distortion of analogue wave functions, low or even negative proton binding in neutron-deficient analogue states or through the existence of isospin non-conserving part of the nuclear interaction. For light nuclei ($A$<60), detailed spectroscopy (for instance including high-precision lifetimes) should be envisaged, whilst for heavier nuclei ($A$=70-100), new physics comes from spectroscopy of a few low-lying excited states. Since much of new experimental work is taking place at or beyond the proton drip line, the possibility of excited states having considerable charged-particle decay widths in competition to γ-ray emission has always to be considered. This field of research has already been established in its own right in the $^{56}$Ni region, combining nuclear structure with more general studies of quantum tunnelling. Additionally, a search for ground-state proton emitters below $^{100}$Sn can be pursued, providing a stringent test of nuclear models. $^{89}$Rh is a good candidate for such a search.

For heavier nuclei around *A*=70-80, a region of shape-coexistence develops that continues to prove a rich testing ground of the leading nuclear models. In this region, examination of energy differences between *T*=1 isobaric analogue states can be used to shed light on structure effects at low excitation energy. To do this, examination of all three members of the multiplet is required, although to date the $T_z$=-1 nuclei, such as $^{74}$Sr and $^{78}$Zr are inaccessible at current facilities. Also differences in the electromagnetic transition matrix elements can be used as experimental signature of the isospin-violating force. An example is measurement of *E1* amplitudes in mirror nuclei which allow the investigation of isospin-mixing contributions. Here the isovector part of the Coulomb potential is responsible for breaking the symmetry, since it has opposite signs in pairs of mirror nuclei, but in this case it will also mix together states of equal isospin.

**Approach:** This programme generally requires the development of intense $^{18}$Ne, $^{34}$Ar, $^{56}$Ni and $^{58}$Cu beams, which, when used with *N*=*Z* targets, allow access to a range of neutron-deficient nuclei of interest. Essential for this programme is the availability of reaction channel-selection devices including a charged-particle array, a high efficiency neutron array and – in particular – a recoil separator capable of *Z* and *A* identification using reactions in normal kinematics with radioactive beams. Combined $\gamma$ and charged-particle spectroscopy calls for a dedicated high-granularity charged-particle array. A search for ground state proton emitters below *Z*=50 will also require implantation detectors at the focal plane of a spectrometer and will be employed for decay spectroscopy and for recoil-decay tagging (RDT) studies in conjunction with an efficient Ge detector array at the target position. A limitation will be the lifetimes of the nuclei of interest relative to the flight time in the spectrometer. Table 1 shows some typical reactions that could be employed to pursue this programme.

In addition to the use of radioactive beams, high intensity stable beams at carefully tuned energies close to the Coulomb barrier can be used to populate states of interest in exotic nuclei through, for example, 2n evaporation channels – see Table 2. Like the stable-beam studies described in section 4 below, this is most easily achieved with development of the stable-beam line from CIME to G1 and G2 to deliver high-intensity beams to the experimental facilities dedicated to in-beam spectroscopy. Neutron detection is essential, and use of a charged-particle veto device could also be envisaged.

## 2 Isospin *T*=0 *np*-Pairing.

One of the key questions in contemporary nuclear physics is the existence, or otherwise, of a *T*=0 pairing condensate near the ground state. Spectroscopy of low-lying states in heavy odd-odd *N*=*Z* nuclei yields crucial information on this. The *T*=0 phase is also more resistant to the Coriolis effect, and *T*=0 correlations can prevail at high spin in *N*=*Z* nuclei. More generally, medium- to high spin states beyond *N*=*Z*=40 $^{80}$Zr are not currently accessible, but can be studied with SPIRAL2 beams of sufficient intensity. Table 1 shows some of the typical reactions that can be employed to probe these states in *N*=*Z* nuclei. Low spin states in odd-odd *N*=*Z* nuclei also have the potential to yield crucial information on T=0 pairing. Indeed, it is predicted that *T*=0 *np* pairing starts to become important for *N*=*Z* nuclei heavier than *A*=80.

**Approach**: For studies near the ground state, historically, two-nucleon (2N) transfer or removal has been the way to study the pairing field in nuclei, for example, via ($^3$He,*p*) reactions and exploring low-lying states. It is suggested that comparing the transfer of *np*-pairs with *nn*- or *pp*-pairs is the only direct way to address the (non-)existence of isospin *T*=0 pairing fields in *N*=*Z* nuclei near the ground states. Prominent candidates are beams of $^{56}$Ni, $^{58}$Cu, $^{64}$Ge, or $^{72}$Kr and required are a recoil spectrometer of VAMOS or PRISMA type, and charged-particle arrays such as TIARA, possibly neutron detectors.

The study of low-spin states in $N$=$Z$ odd-odd nuclei such as $^{94}$Ag or $^{90}$Rh (see Table 1) and the search for isoscalar *np*-pairing effects for medium- to high spin states in $N$=$Z$ nuclei can also be addressed through application of more intense $^{34}$Ar, $^{56}$Ni, and $^{58}$Cu beams. Efficient channel selection devices as mentioned above (section 1) are essential for this programme. With high intensity stable beams it will be possible to investigate (i) the yrast structure of the heavy even-even $N$=$Z$ nuclei up to high spins, and (ii) the deformation of such nuclei in the region of the band crossing. An example is the even-even nucleus $^{92}$Pd with $N$=$Z$=46, where one expects an excited structure which reflects the enforced $T$=0 *np* pairing through the appearance of more collective excitations with respect to the heavier Pd isotopes.

## 3 Coulomb Excitation of Low-lying Collective States in $N$~$Z$ Nuclei at $A$≈70.

The question of shape co-existence and collectivity near the ground state in the $A$=70-80 region is one of much interest. Key questions are, for example, measurements of $B(E2)$ strengths in $^{76}$Sr, $^{80}$Zr, and $^{84}$Mo and the determination of the sign of the quadrupole moment in nuclei such as $^{68}$Se and $^{72}$Kr. For lighter nuclei, determinations of the $B(E2)$ in sets of $T$=1 triplets (or more exotic isobaric multiplets) have the potential to shed new light on isospin mixing in $N$=$Z$ systems.

**Approach**: For lighter nuclei, direct Coulomb excitation of SPIRAL2 ISOL beams can be considered. However, for heavier nuclei - and especially for chemically difficult elements such as Se, Sr, Zr - the ISOL approach is limited. It is proposed to use the high intensity LINAG beams ($^{58}$Ni or $^{40}$Ca) to produce separated beams of the nuclei of interest, which can then be Coulomb excited at the focal plane of the separator, following $A$ and, possibly, $Z$ identification. See Table 2 for typical reactions. Experience from REX-ISOLDE suggests that $10^4$ pps of the nuclide of interest would be sufficient, and this can be achieved with the proposed high intensity LINAG beams.

## 4 Single-Particle States Around $^{100}$Sn.

The structure of nuclei around $^{100}$Sn remains one of the key questions in nuclear structure physics. For a variety of nuclear structure and nuclear astrophysics reasons it is essential to establish the single-particle states in $^{99}$In and $^{101}$Sn. In particular the identification of excited states in the latter calls for a flagship experimental programme with reactions induced by both stable and radioactive ion beams.

**Approach:** One idea is to use a beam of stable $^{58}$Ni of up to $5\times10^{12}$ pps intensity – possibly starting from an upgraded beam from the current GANIL facility. $^{101}$Sn could be populated through a three-neutron evaporation channel – see Table 3. For this reaction to be feasible the reaction would have to be performed very close to the Coulomb barrier to keep the total reaction rate manageable for the γ-array. This also requires accurate tuning of the beam energy. In the second approach, ISOL beams from SPIRAL2 of $^{56}$Ni, $^{57}$Ni, or $^{58}$Cu can be considered. With $^{57}$Ni, the loss in beam intensity is compensated by better neutron detection efficiency for the two-neutron channel and higher production cross-section of $^{101}$Sn. With $^{56}$Ni, the 2α1n channel is an alternative, although a beam intensity of $>10^8$ pps is required. $^{56}$Ni at an intensity of $10^8$ pps or better opens up a wide range of nuclei in the region, including $^{100}$In, $^{97}$Cd, $^{105}$Te. With a $^{58}$Cu beam one could aim at $^{99}$In. This programme requires a dedicated neutron array coupled to either an active charged-particle array as outlined above, or a highly efficient charged-particle veto device in case of pure neutron-evaporation channels.

## 5. Large Deformation in Ground States of Exotic Rare-Earth Nuclei

Mapping the understanding of large deformation away from closed shells is an important aspect of nuclear structure physics. Adding protons above $Z$ = 50 while removing neutrons from $N$ = 82 produces a major region of deformation in the ground-states of light rare-earth nuclei. This has been predicted in several theoretical approaches near the proton drip-line, and experiments have succeeded in studying nuclei approaching, but not yet reaching, the peak of this deformation . Maximal ground-state deformation in this mass region is predicted with $\beta$ ~ 0.40. This value of deformation is the same as that deduced for superdeformed cerium and neodymium isotopes as well as the one known for the core of the mass $A$=80 region, namely $N$=$Z$=38 $^{76}$Sr. Since these light rare-earth nuclei are near the $N$=$Z$ and proton drip line, they also relate to competing proton- and $\gamma$-ray emission issues discussed earlier.

**Approach:** The use of relatively intense radioactive beams will open up this exotic region of nuclei and allow the study of nuclei around the peak of this systematic feature. For $\gamma$-spectroscopy studies at medium spin in these nuclei near the proton drip-line, fusion-evaporation reactions will be used with neutron-deficient radioactive beams – for example $^{72,74}$Kr beams with intensity greater than $10^7$ pps on $^{58}$Ni targets. As with other fusion evaporation studies of neutron-deficient nuclei described in sections 1 and 2, a recoil separator would need to be used, as well one of the proposed charged-particle arrays and the neutron detectors (see below).

TABLE 1. Selected key reactions using radioactive beams.

| Reaction | Beam Int. (pps) | Physics Area (see above) |
|---|---|---|
| $^{18}Ne+^{24}Mg \rightarrow$ $^{37}Ca+\alpha n$<br>$^{35}K+\alpha p2n$ | $>1\times10^9$ | 1 |
| $^{34}Ar+^{40}Ca \rightarrow$ $^{69}Br+\alpha p$<br>$^{72}Rb+pn$<br>$^{71}Kr+2pn$ | $>1\times10^8$ | 1,2 |
| 2N transfer; $^{56}$Ni, $^{58}$Cu, $^{64}$Ge, $^{72}$Kr | > 1 x $10^5$ | 2 |
| $^{56}Ni+^{40}Ca\rightarrow^{88}Ru+2\alpha$ | $>1\times10^8$ | 2, 3 |
| $^{56}Ni+^{28}Si\rightarrow^{79}Zr+\alpha n$ | $>1\times10^8$ | 1, 2, 3 |
| $^{34}Ar+^{58}Ni \rightarrow$ $^{88}Ru+2p2n$<br>$^{89}Rh+p2n$<br>$^{90}Rh+pn$ | $>1\times10^8$ | 1,2 |
| $^{56}Ni+^{40}Ca\rightarrow^{94}Ag+pn$ | $>1\times10^8$ | 2 |
| $^{58}Cu+^{46}Ti\rightarrow^{99}In+\alpha n$ | $>1\times10^8$ | 4 |
| $^{56}Ni+^{54}Fe\rightarrow^{101}Sn+2\alpha n$ | $>1\times10^8$ | 4 |
| $^{57}Ni+^{46}Ti\rightarrow^{101}Sn+2n$ | $>1\times10^9$ | 4 |
| $^{72}Kr+^{58}Ni\rightarrow^{124}Nd+\alpha 2p$ | $>1\times10^7$ | 5 |

TABLE 2. Selected key reactions with stable beams to produce separated secondary beams.

| Reaction | Beam Int. (pps) | Physics Area (see above) |
|---|---|---|
| $^{58}Ni+^{24}Mg\rightarrow^{80}Zr+2n$ | $>1\times10^{12}$ | 1, 3 |
| $^{40}Ca+^{40}Ca\rightarrow^{78}Zr+2n$ | $>1\times10^{12}$ | 1, 3 |

TABLE 3. Selected key reaction for a stable-beam in-beam study.

| Reaction | Beam Int. (pps) | Physics Area (see above) |
|---|---|---|
| $^{58}Ni+^{46}Ti\rightarrow^{101}Sn+3n$ | $\sim1\times10^{12}$ | 4 |
| $^{40}Ca+^{40}Ca\rightarrow^{78}Zr+2n$ | $\sim1\times10^{12}$ | 1 |
| $^{36}Ar+^{40}Ca\rightarrow^{74}Sr+2n$ | $\sim1\times10^{12}$ | 1 |
| $^{40}Ca+^{58}Ni\rightarrow^{92}Pd+\alpha2n$ | $\sim1\times10^{12}$ | 2 |

## ***Methodology:***

### ***Beam properties***

The species and intensities of the stable and radioactive beams of interest for the prospected program on nuclei at or beyond the proton drip line are given in Tables 1 to 3 in the previous section. It is worth mentioning that in particular for the stable $^{58}$Ni and radioactive $^{56}$Ni and $^{58}$Cu beams, a staged intensity profile is envisaged: The present $^{58}$Ni beam intensities may already now allow for first approaches of $^{101}$Sn, while higher beam intensities indicated for SPIRAL2 will enable the studies outline in subsections 1 and/or 3 above to be pursued. Similarly, the first low-intensity beams of $^{56}$Ni and $^{58}$Cu will allow for the 2N transfer studies, while at a later stage higher yields and better quality beams are required for the fusion-evaporation experiments.

In general, for all studies indicated above good beam quality is of importance, i.e., the energy resolution should be better than 1% and the emittance should be on the same level (about 5π mm mrad) as presently available beams at Coulomb barrier energies (3-5 MeV/u). This aids both beam suppression in the separator devices and is essential for high-resolution in-beam particle-γ coincidence spectroscopy. For studies with the highest intensities, a "wobbling" system may be required in conjunction with a rotating target.

The **purity** of the radioactive beams used for fusion-evaporation reactions aiming at the most exotic nuclei is **vital** – this especially concerns isobaric contamination of, for example, beams of $^{56}$Ni with potential fractions of $^{56}$Co. Such contaminations must be less than 1%.

### ***Target(s)***

The development of rotating or cooled target system is required for the highest beam intensities of LINAG. The in-beam (secondary) targets are typically 0.2-0.6 mg/cm$^2$ thick and **not radioactive** but of isotopically highly enriched (>99.9%) material. A target laboratory at GANIL to prepare these thin, preferably self-supporting targets of, for example $^{12}$C, $^{24}$Mg, $^{28}$Si, $^{40}$Ca, $^{46}$Ti, $^{54}$Fe, timely for an experiment is requested.

***Instrumentation and detectors***

For the experimental programmes described above, the following detector systems need to be available or developed. We assume the presence of a high efficiency and high granularity γ-ray array – such as an upgrade of EXOGAM and, eventually, AGATA. Thus we concentrate here on ancillary devices. Some of these will be "generic" in the sense that they will be used in other areas of in-beam γ-ray spectroscopy and others (such as the separators) have some specific requirements, but should also be developed and built together with other subgroups. In addition, the list is not intended to be exhaustive, rather it is the intention to outline the basic requirements for this area of research. Instruments not mentioned include, for example, a plunger device for lifetime measurements or a prompt electron spectrometer to be sensitive to potential low-lying $0^+ \rightarrow 0^+$ transitions.

**1. Charged Particle Arrays.**

Three solutions are presented here. Firstly, for high-intensity stable beams the challenge is the charged-particle rate to be sustained by the device. For the highest numbers, i.e., a beam of $10^{12}$ pps, a total of some 3000 detector elements are needed. One suitable starting point is the TRACE project pursued at LNL, Italy.

TRACE is a project aiming to develop a new ancillary charged-particle detector to be coupled with large Ge arrays and, in particular, with AGATA. It uses modern Si-detector technology and is focussed on the detection of light charged particles produced in fusion evaporation reactions. The Doppler correction is obtained by trajectory reconstruction, following detection of the emitted charged particles. Large coverage (90%), reduced dead areas, good energy resolution (50 keV for 5.5 MeV α-particles), wide energy range (keV-20 MeV for protons, 80 MeV for α-particles), high counting rate capabilities, and sufficient segmentation for angular resolution (2°÷6°) are the key attributes of TRACE. It will use pulse shape analysis for a number of channels of the order of 7000.

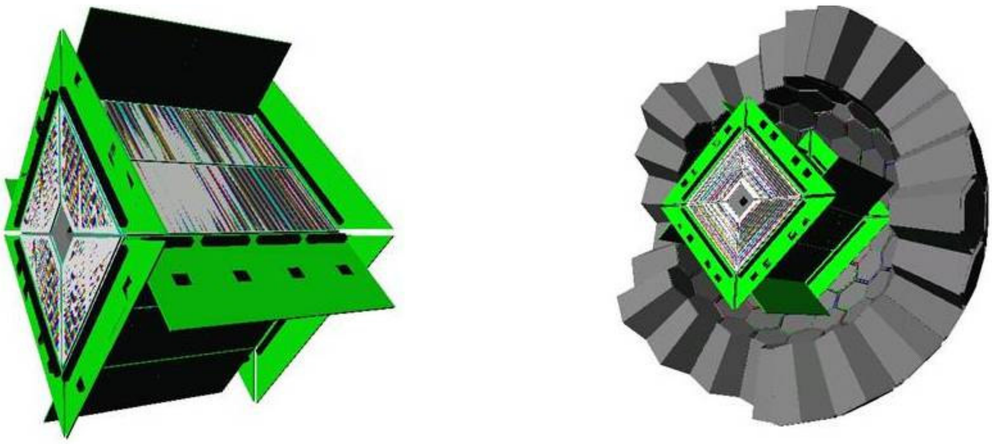

Fig. 1: TRACE square configuration

Secondly, for the case of reactions induced by radioactive ion beams, efficiency is the dominating issue, while keeping in mind particle-spectroscopy. A possible solution could be a DIAMANT type CsI array of somewhat higher granularity and the option of including DSSD detectors at forward angles.

Finally, for Coulomb excitation experiments in the focal plane of recoil spectrometers upgrades of existing set-ups used at REX-ISOLDE or GANIL are envisaged.

## 2. Charged-Particle Veto Detector.

For studies of very neutron-deficient nuclei produced in fusion-evaporation reactions, detection of charged particles, in addition to detection of neutrons, is absolutely necessary. In special situations, when very interesting neutron deficient nuclides are produced by the emission of only neutrons from the compound nucleus (e.g. $^{101}$Sn), a specialised highly efficient charged particle veto detector may be more suitable than a multipurpose proton and α-particle detection system. For such a purpose, a plastic scintillator veto detector CUP has been constructed and used in a EUROBALL experiment [M. Palacz *et al.*, Nucl. Instr. Meth. A550 (2005) 414]. Proton and α-particle efficiencies of 80 and 63% were measured, respectively.

Simulations indicate that proton and α-particle efficiency of about 90% and 70% can be achieved with a similar veto device, if the two main identified problems, namely the delta-electron background and the electronic dead time, are properly addressed. Possibilities of electrostatic screening of the scintillator in order to reduce the influence of delta electrons should be investigated, and electronics optimised for the minimum dead time should be constructed or purchased. These developments should also enable use of the detector with high intensity pulsed beams, up to $10^{12}$ pps, and with the fusion-evaporation reaction rate up to 5 MHz.

Note that increasing proton efficiency from 80 to 90% halves the probability of a proton escaping, and hence reduces the background from proton emission reaction channels in vetoed γ-ray spectra by a factor of $2^n$, where $n$ is the number of protons emitted from the compound nucleus. At the same time, with the proton efficiency of 90%, and mean proton multiplicity equal to three, the dead time of 0.1% increases the background twofold.

## 3. Neutron Array.

In combination with efficient charged-particle detection (or veto), a powerful neutron detector array is needed as an ancillary detector for γ-ray spectroscopy experiments using both intense stable beams as well as radioactive ion beams at SPIRAL2. The goal is to develop and build an array with the highest possible neutron detection efficiency, excellent discrimination of neutrons and γ rays, and a very small neutron-scattering probability. These properties are necessary in order to achieve a clean and efficient identification of the rare neutron-deficient nuclides produced in reactions in which two or more neutrons are emitted.

The neutron detector array should cover a solid angle of up to 50% and have a large granularity. In addition to using standard liquid scintillators, most commonly used in fast-neutron detectors, we consider it essential to investigate new detector materials, with better response functions and better energy resolution for detection of neutrons. A good determination of the energy deposited in each neutron detector in combination with a high detector granularity can be used to significantly reduce the discrimination between genuine multiple-neutron events and neutron scattering. New detector materials which will be investigated are, for example, deuterated liquid scintillators and solid plastic scintillators with neutron-γ pulse-shape properties,

Digital electronics, using a fast sampling ADC, will be used for direct digitization of the detector signal. The electronics hardware will either be commercial (if available) or developed within the community. Efficient pulse-shape algorithms for discrimination of neutrons and γ rays, neutron scattering reduction, pile-up rejection etc, will be developed and investigated. A good discrimination of neutrons and γ rays is very important in particular in experiments using radioactive ion beams, which mostly give rise to an increased background of γ rays.

A neutron detector working group is required for the necessary R&D work. Working groups with very similar goals already exist within the NUSTAR HISPEC/DESPEC and the EURISOL projects. The present plan is therefore to merge these groups into one common group, with sub-groups working on the specific aspects at each accelerator facility.

It should also be mentioned that SPIRAL2 experiments at an early stage can use existing neutron detector arrays such as the Neutron Wall built for EUROBALL.

## 4. Recoil Separators.

For experiments with both high intensity stable beams and radioactive beams, a zero degree mass spectrometer with high transmission is essential for studies of very neutron-deficient nuclei.

For high-intensity stable beams from LINAG, a high rigidity separator – with excellent beam rejection properties – must be developed to enable the clean separation of beams to be used for reactions at the focal plane (cf. reactions in Table 2). This separator should provide the ability to cleanly identify the mass *A* and proton number *Z* of the recoil. The $S^3$ spectrometer is designed to perform spectroscopy (in-beam or decay spectroscopy) of exotic fragments created using high-intensity LINAG beams. A γ array could be placed around the final spectrometer focal plane to enable Coulomb excitation of exotic neutron-deficient nuclei such as $^{80}Zr$.

As discussed above, a separator for fusion and transfer reactions with radioactive ISOL beams is also essential, and also here the ability to cleanly identify *A* and *Z* of the recoil is vital. As discussed in the previous section, VAMOS in its present or upgraded configuration is suited for this purpose.

The charge *Z* of the recoil in such separators is usually determined by energy loss in an ionisation chamber, although for many reactions the recoil energy of the nucleus is insufficient to obtain effective *Z*-separation. This suggests a new approach – the ”re-acceleration” or “boost” of the recoils at the focal plane of the mass separator to around 2 MeV/u. As well as providing sufficient energy for *Z*-separation in an energy-loss detector, this could also help with Coulomb excitation at the focal plane for the stable-beam induced reactions (Table 2). One could envisage an RF cavity plus Wien filter at the focal plane – followed by an ionisation chamber to enable full isotope identification. For the stable-beam induced reactions, this could then be followed by a secondary reaction target for Coulomb excitation.

If “only” aiming at unique event-by-event identification of the recoils in the focal plane, proton- or (superallowed) β-decay tagging techniques are an alternative to the energy-loss technique. This would require a focal plane spectrometer, the requirements for which would be essentially identical to the one discussed in the LoI “From Actinides to SHE: Reaction Dynamics and Structure Studies”.

## 5. Plunger Device

For lifetime experiments in the picosecond region a new coincidence plunger device is needed.

***Theoretical support:***

There are a number of European theory groups active and interested in the description of neutron-deficient *N~Z* nuclei at or beyond the proton drip-line. The topics include the development of basic shell-model theory and the inclusion of unbound states, the influence of different isospin pairing channels in algebraic and mean field models, isospin symmetry effects at high angular momentum, self-regulated two-dimensional quantum tunneling processes, or relations to astrophysical processes.

P. van Isacker and M. Ploszajczak, GANIL, Caen, France
J. Dobaczewski and W. Satula, University of Warsaw, Warsaw, Poland
R. Wyss, Royal Institute of Technology, Stockholm, Sweden
I. Ragnarsson and S. Åberg, Lund University, Lund, Sweden
E. Caurier, F. Nowacki, A. Poves, and A.P. Zuker, Madrid-Strasbourg Shell-Model Group
K. Langanke and G. Martinez-Pinedo, GSI, Darmstadt, Germany

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

The key equipment needs specific to the projects outlined are covered below.

For prompt in-beam spectroscopy the **EXOGAM2** and **AGATA** arrays are essential, the upgrade and implementation of which (respectively) are discussed in the covering Letter of Intent "High-Resolution Gamma-ray Spectroscopy at SPIRAL2". The programme will also make use of (upgrades of) existing equipment at GANIL – e.g. VAMOS. In addition, equipment and developments described in other Letters of Intent are envisaged to be utilized in the programme of research. This includes the **Stable beam separator - the $S^3$ spectrometer** (see the $S^3$ Letter of Intent) and potentially the tagging (focal plane) spectrometer described in the Letter of Intent "From Actinides to SHE: reaction dynamics and structure studies".

**Post-separator Booster:** Over the next 12-24 months, a feasibility study will be launched (York) to pursue the concept of the booster for use at various facilities (including SPIRAL2).

**Charged-particle array No. 1: TRACE.** The construction of the ancillary detector TRACE will be done in the framework of the AGATA collaboration and the time schedule and MoU of will be defined in this context.

**Charged-particle array No. 2: CsI+DSSD**

| | |
|---|---|
| **Manpower:** | 1 PostDoc and 1 PhD, 50% of 3 years each |
| **~250 CsI detector modules:** | ~ 25 kEuro (alternatively DIAMANT) |
| **CD-type DSSD** for ~ five years operation: | ~ 18 kEuro |
| **~250 CsI preamplifiers** with boards: | ~ 10 kEuro (alternatively existing/new ASICs) |
| **~300 Si preamplifiers** with boards: | ~ 12 kEuro (alternatively existing/new ASICs) |
| **Contingencies** (cables, connectors, mechanics, etc.): | ~ 10 kEuro |

**Main electronics**: ASIC solutions based on NUSTAR/SPIRAL2 collaborations.

**<u>Charged-particle veto detector: CUP upgrade</u>**:

**Manpower**: 1 year PostDoc
**Material cost (electronics, scintillators, hardware)**: 30 kEuro
**Running cost**: 2 kEuro per 1 week experiment
(scintillators deteriorate and must be regularly replaced)
**Source of funding**: application to the Polish Ministry of Science will be submitted

**Laboratories involved**: Heavy Ion Laboratory - Warsaw University, Uppsala University

**<u>Neutron detector array:</u>**

**Investment costs:** 1 MEURO
**Manpower R&D** (postdoc, PhD student): 2 man-years
**Manpower construction** (engineers): 4 man-years

**Source of funding**: Partial funding will applied for from the Swedish Research Council

**Laboratories involved (partial list):**
Uppsala University, Uppsala, Sweden
Heavy Ion Laboratory, Warsaw University, Warsaw, Poland
Royal Institute of Technology, Stockholm, Sweden
Ankara University, Ankara, Turkey

**<u>Plunger Device:</u>**

**Manpower** 2 man-years
**Laboratory involved** INRNE Sofia

# High resolution spectroscopy of neutron-rich nuclei with AGATA coupled to a large-acceptance Magnetic Spectrometer using SPIRAL2 and LINAG beams at the Coulomb barrier energy

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***Abstract:***
High resolution spectroscopy of neutron-rich nuclear species plays a mayor role on the understanding of the nuclear structure at large isospin values. Among the open questions are of special interest the evolution of the nuclear effective interactions, in the monopole and multipole terms, the quenching of the known shell gaps and development of new ones, the evolutions of the nuclear collectivity (onset of deformation in light neutron-rich nuclei, shape coexistence, etc..), the shape phase transitions as the dynamical symmetries at the critical point and the onset of exotic shapes. These experimental open questions can be studied by exploring the nuclear spectrum up to medium-high angular momentum and by direct measurement of transition probabilities. This Letter of Intent summarizes the physics cases and associated instrumentation for in-beam nuclear-structure studies of neutron-rich nuclei based on high-resolution $\gamma$-ray spectroscopy techniques using the capabilities of SPIRAL2 both for high-intensity beams of stable ions and the radioactive beams.

***Scientific case:***
The range of unstable nuclei accessible with the next generation radioactive beam facilities will open new possibilities to search for new nuclear phenomena. When going far away from the valley of stability mean field and residual interactions are likely to be modified due to the uneven occupancies of protons and neutrons. For nuclei close to the drip line discrete states will come close in energy to the continuum and their coupling will modify the residual interactions. Between the region of known nuclei and the neutron drip line lays an extensive zone where structural evolution, new types of correlations and collectivity are expected to occur. The use of nuclear reactions close to the Coulomb barrier makes it possible to progress toward the drip lines and to study the structure of the atomic nucleus in a largely unexplored region. In the following paragraphs are discussed several examples of physics cases which use a gamma-ray array associated to an efficient magnetic spectrometer as a tool.

- Evolution of the nuclear effective interaction: Monopole and tensor interaction. Possible contributions of the multipole term. Evolution of “known” shell gaps towards the neutron drip-line (quenching and appearance of new magic numbers).

The total number of nucleons and the N/Z ratio of neutrons to protons are critical ingredients in determining the properties of a nucleus from a given effective interaction. For nuclei close to the drip line, the alteration of the size and increased diffuseness of the nuclear potential modifies the average field experienced by a single nucleon. For large neutron excess this softening of the Woods-Saxon shape of the neutron potential is expected to cause a reduction of the spin-orbit interaction and therefore a migration of the high-*l* orbitals with a large impact on the shell structure of nuclei far from stability.
A different scenario has been recently suggested, where the evolution of the shell structure in going from stable to exotic nuclei can be related to the effect of the tensor part of the nucleon-nucleon interaction. The tensor-force, one of the most direct manifestations of the meson-exchange origin of the nucleon-nucleon interaction, is responsible of the strong attraction between a proton and a neutron in “spin-flip” partner orbits. Very recently this mechanism has also been extended to orbitals with different orbital angular momenta. In this context it is expected that orbitals with anti-parallel spin configuration attract each other whereas orbitals with parallel spin configuration repel each other. In most cases both configurations coexist, leading to a competition between the attraction among orbitals with anti-parallel spins and repulsion between orbitals with parallel spins.

Those effects become particularly visible when moving away from the valley of stability. In such cases removing nucleons from one of the spin-orbit partners significantly modifies the proton-neutron interaction, which in turn, affects the effective single-particle energies, hence the shell structure.
The modification of the shell structure induced by this mechanism has been recently discussed in various mass regions of the nuclear chart. In such a context neutron-rich nuclei close to the shell gaps are particularly interesting since, when compared with the shell model prediction, they allow searching for anomalies in the shell structure. It is predicted, for example, that the Z=28 gap for protons in the pf-shell becomes smaller when moving from $^{68}$Ni to $^{78}$Ni as a consequence of the attraction between the proton $f_{5/2}$ and the neutron $g_{9/2}$ orbits and the repulsion between the proton $f_{7/2}$ and the neutron $g_{9/2}$ configurations. The same argument also predicts a weakening of the N=50 shell gap when approaching the $^{78}$Ni nucleus due to the attraction between the neutron $g_{9/2}$ and $d_{5/2}$ configurations with the proton $f_{5/2}$ state and the repulsion between the neutron $g_{7/2}$ with the proton $f_{5/2}$ state. Properties inconsistent with shell closure have been found in several neutron-rich systems around shell-model magic numbers like $^{30}$Ne or $^{32}$Mg at N=20 for instance.
In the last decade a few cases of "local" shell closures have been identified, it is the case of N=40 for the Ni isotopes, in the 90's, and more recently a new shell closure at N=32 has been identified for Ca isotopes. The presence of N=32 shell gap has been explained by Otsuka and collaborators as coming from the strong spin-flip proton-neutron monopole interaction between the $\pi f7/2$ and the $\nu f5/2$ orbitals. This shell closure gets progressively weaker, in Ti and Cr isotopes, as Z increases. The presence of such shell closures in an isotopic chain opens new areas where the shell model approach can play a major role.
We intend to study the evolution or breakdown of shell gaps, resulting from the combined effects of the spin-isospin tensor interaction and of the density dependent terms of the nuclear force on single-particle states. Of particular interest are the mass regions close to magic numbers far from stability like Z=28, N=50 or Z=50, N=82.

- Evolution of the collectivity: onset of collective modes, such as rotation in neutron-rich light and medium –mass nuclei or new collective modes related to the neutron skin.

Little is known about deformed states in light neutron-rich nuclei. Shell model calculations (LSSM) predict a large deformation $\beta_2$ =0.3 for the neutron rich S and Ar isotopes close to N=28. These isotopes can not be populated in fusion-evaporation reactions with stable beams, but are accessible via multi-nucleon transfer or deep inelastic reactions, using intense beams of stable neutron-rich isotopes from Ca and Cl. Recent Hartree-Fock-Bogoliubov (HFB) calculations with the Gogny force predict the existence of states with large deformation in the Mg and Si neutron-rich isotopes. In particular for the $^{32-34}$Mg and $^{36-38}$Si nuclei, the estimated deformation is very large. Skyrme–Hartree–Fock calculations predict super-deformed bands ($\beta_2$ =0.6) in extreme neutron-rich Sulfur isotopes as $^{48}$S and $^{50}$S. High-spin studies in these nuclei populated in multi-nucleon transfer or deep-inelastic reactions can tell us whether this collectivity results in the development of rotational bands

Collective dipole excitations are among the most easily accessible observables to probe the isospin-dependent part of the effective nucleon-nucleon interaction. The existence of a halo or skin of neutrons in neutron-rich nuclei far from stability is expected to give rise to a new kind of dipole mode in which the excess of neutrons oscillates with respect to the more strongly bound core. See LOI : Collective Modes in the Continuum by S. Leoni et al. This programme might require, in addition to the setup based on Ge detectors, the use of an array of detectors

for high-energy gamma rays. A possibility could be offered by an array of Lantanum Bromide scintillators (LaBr3).
Another interesting question that can be explored by use of multi-nucleon transfer reactions is the problem of pairing. The ground states of the majority of nuclei close to the stability line are very well described in terms of superfluid condensates, in which the pairs of nucleons form Cooper pairs. Correlations due to pairing, core polarisation or clustering are crucial in weakly bound systems. In nuclei with a large neutron excess a neutron skin may be formed, providing different conditions for the neutron correlation. For example, a transition from the normal BCS pairing to the Bose-Einstein condensation may take place. At a density of 1/5 of the normal nuclear density formation of di-neutron clusters is predicted. By use of multi-nucleon transfer reactions the existence of such clusterisation can be tested. Formation of neutron skin may affect also the deep inelastic process itself, and may allow for an enhanced neutron flow between the touching systems. Coupling of the neutrons in the skin to the core may be different from that in normal nuclei, and may affect the collective behaviour of the valence nucleons. This case becomes important at relatively low spin, since in high spin phenomena the intruder high spin orbitals are well localised in the nuclear interior even if they are weakly bound. Study of nuclei with a substantial neutron skin via deep inelastic processes may reveal such a phenomenon.

- Shape phase transitions in nuclei: Dynamical symmetries at the critical point, including in moderately light neutron-rich nuclei. New Nuclear symmetries: chirality and the tetrahedral and octahedral symmetries.

The phase structure of quantum many-body systems has been in recent years a subject of great experimental and theoretical interest. Recently F. Iachello and collaborators have shown that algebraic nuclear models based on dynamical symmetries are powerful tools for the description of the complex quantum system that is the atomic nucleus. From the point of view of these models, the symmetries observed in nuclei are the image of symmetries in the Hamiltonian and therefore in the nuclear interactions.
For certain specific forms of its Hamiltonian, an algebraic model exhibits dynamical symmetries, which constitute the phases of the system. Critical point symmetries have been introduced by F. Iachello for describing nuclear systems undergoing a quantum phase transition. Such symmetries, called E(5) and X(5), correspond to phase transitions when going from the vibrational – U(5) - to the γ-soft – O(6) – limit or from the rotational - SU(3) - limit to the vibrational one – U(5) – respectively. In principle, due to the characteristic of these phase transitions, it is not expected to find these structures in light or medium mass nuclei. From this limitation might be excluded the nuclei with a very large isospin asymmetry, for example very n-rich nuclei. In such case, the excess of neutrons might provide sufficient collective degrees of freedom to the system to undergo the phase transitions. A neutron-rich region to explore is the vicinity of $^{58}$Cr (Z=24, N=34).
Recently a new quantum phase transition has been introduced concerning systems undergoing a shape transition from axial to triaxial deformation. This new Y(5) symmetry corresponds to a phase transition in the triaxiality variable (γ-angle). Of particular interest are the study of the conditions under which proton-neutron triaxial deformation may occur and the nature of the transition to such structure. Such studies require the experimental investigation of triaxial structure as progressively more neutron rich nuclei become accessible. Nuclei in the N=90 mass region, around Gd and Ce, are expected to display X5 symmetry (spherical to prolate axial phase transition) and the $^{170}$Er nucleus Y5 symmetry (spherical to γ-soft).

Chiral symmetry has also been suggested to be present in nuclear systems. This symmetry, as well as the wobbling collective mode, is associated with triaxial shapes. They are very rare and the identification of nuclei exhibiting them and their spin range will contribute large to the understanding of the mechanism developing these collective modes.
S. Frauendorf and collaborators pointed out that in well-deformed triaxial odd-odd nuclei, with angular momentum components along all three axes, chiral doublet bands can occur. Chiral symmetry can be identified on the bases of the energy degeneracy of the levels. A recent test of such symmetry based on the measurement of absolute-transition matrix elements has shown that chirality does not appear in mass A=130. Of high interest is to check the existence of chirality in the neutron-rich A=106 mass region. Neutron-rich nuclei with A = 99-113 show a smooth evolution from axial symmetry to maximum triaxiality in Rh isotopes. In the mass range A=106 to 113 nuclei with almost complete level energy degeneracy have been found. Since these nuclei exhibit evidence for triaxial shapes, it has been suggested an interpretation as chiral bands.

The tetrahedral/octahedral symmetric nuclei are predicted around the following magic closures: {Z,N} = {32,40,56,64,70,90,132-136}. A set of good candidates ranging over three mass regions A~80, A~150 and A~220 has been identified. The majority of these nuclei are either proton rich or neutron-rich which corresponds to the realm of Spiral and mainly Spiral2. Among them, the Zirconium isotopes are particularly interesting because two islands of tetrahedral shapes are predicted at both extremes of the N/Z ratio: center around $^{80}$Zr and $^{110}$Zr.
Clearly $^{110}$Zr will be extremely difficult to reach experimentally in good conditions of production; one could expect to scan the more accessible zirconium isotopes to determine the boundaries of both islands for intermediate N/Z ratio. This result would be extremely important for the theory.

- Exotic clustering in neutron-rich light nuclei.

The occurrence of nuclear molecules in reactions induced by alpha-like nuclei ($^{12}$C, $^{16}$O, $^{20}$Ne, $^{24}$Mg and $^{28}$Si) in terms of alpha-clustering is now well accepted. Experimental signatures of the Bose-Einstein condensation of alpha clusters in the atomic nucleus have also been reported. As a Consequence, similar exotic cluster states in n-rich light nuclei close to the proton driplines have been recently investigated. Reactions induced by $^{6}$He, a nucleus with a Borromean structure with two weakly bound neutrons and an alpha-particle core, are well suited. Adding more particles to this loosely-bound extended object will produce nuclei in states that resemble a molecular configuration in a manner extremely similar to the exchange of electrons in covalently bound atomic molecules. The existence of molecular-like structures has still to be demonstrated in heavier non alpha-like di-nuclear systems. From molecular models, such as the one based upon Antisymmetrized Molecular Dynamics (AMD), for instance, it is anticipated that very neutron-rich C or Ne isotopes as projectiles might be the best suited for the search of very exotic molecular configurations (like the "nuclear water" predicted by the extension of the well-known Ikeda diagram). The study with 6,8He, 15,16C, 11Be and 23,25Ne nuclei of the process by which the cloud of valence neutrons is exchanged between the clusters cores should provide an insight into the possible structures at the drip-line also. Similarly to systems induced by alpha-like nuclei for which superdeformed and hyperdeformed shapes have been found to decay via a ternary fission mode with detectable probability, experiments at Spiral2 with neutron-rich projectiles will permit to study more deeply the ternary fission on the whole chart of nuclei.

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***Methodology:***

The available reaction mechanisms that allow, starting from a stable or neutron-rich radioactive beam to produce more neutron-rich nuclei, without resorting to fission, are multinucleon-transfer, deep-inelastic collisions and incomplete fusion. Fusion evaporation, even with neutron-rich targets, very seldom allows to populate neutron-rich nuclei far away from stability. The use of the incomplete fusion reactions with relatively light beams, or targets in case of inverse reactions, has proved to be useful mechanism to populate neutron-rich nuclei a few nucleons away from the initial reaction partners.

This LoI is mainly devoted to the use of multinucleon-transfer reactions and deep-inelastic collisions to study the structure of neutron-rich nuclei far from stability, with the radioactive beams delivered at SPIRAL2 at energies close to the Coulomb barrier. The use of high-intensity stable beams from LINAG is also foreseen.
Recent cross-section measurements and calculations, for selected multinucleon-transfer reactions with neutron-rich targets, have shown the potentiality of this reaction mechanism to populate neutron-rich nuclei with sizeable cross-section values.
It is well known that quasi-elastic reaction channels at energies close to the coulomb barrier takes a sizeable fraction of the total reaction cross-section. Recently it has been shown that the multi-nucleon transfer mechanism with stable neutron-rich nuclei populates moderately neutron-rich nuclei far from stability with cross-sections ranging from hundreds of μb to several mb [1]. Part of this cross-section is coming for an unexpected enhancement of the proton-stripping cross-sections, probably due to pairing effects [2].
In order to know the cross-section of the nuclei populated in quasi-elastic transfer reactions, it is possible to resort to a semi-classical approach with the code GRAZING [3], developed by A.Winther, G.Pollarolo and collaborators.
The following experimental examples illustrate this technique:

1. The study of the nuclear structure in the $^{78}$Ni region. It has been suggested that the evidence of a shell-gap quenching at N=50 is best observed at large angular momentum, where the contribution of the neutrons (excited to orbitals above the N=50 gap) to the wave function might be consistent [4]. The $^{78}$Ni nucleus can be populated by two-neutron transfer with a $^{76}$Ni radioactive beam (~$10^6$ pps) and a heavy target (the use of medium-mass targets yields very small cross-sections), as shown in Fig.1. Using a $^{238}$U target, the integral cross-section is of the order of 10mb, with a maximum differential cross-section of $d\sigma/d\Omega \approx 10$ mb/sr This cross-section implies approximately few hundred AGATA(3π)-VAMOS coincidences in the high-spin spectrum of $^{78}$Ni, after a week of beam time. In addition quasi-elastic transfer reactions can be used to obtain information in single-particle hole states in the vicinity of N=50 and on pair correlation in weakly-bound nuclei. The multinucleon-transfer reaction with a $^{80}$Zn beam (see Fig.2) has almost two orders of magnitude lower cross-section for the population of $^{78}$Ni, but it has high cross-sections to study the $^{81}$Zn and $^{82}$Zn isotopes, where the evolution of the monopole interaction (N=51) and the evolution of the collectivity towards the Z=28 shell closure, in N=52, can be investigated respectively.

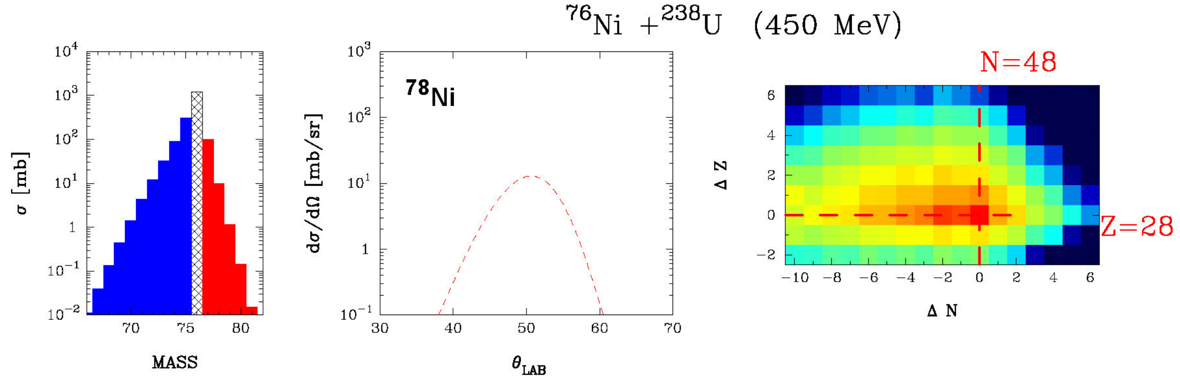


Figure 1. Cross-section calculations for the production of neutron-rich Ni isotopes, with a $^{76}$Ni unstable beam on a $^{238}$U targets, performed with the code GRAZING [3] by G.Pollarolo. In The differential cross-section plot, the dashed line represents the two-neutron pickup channel.

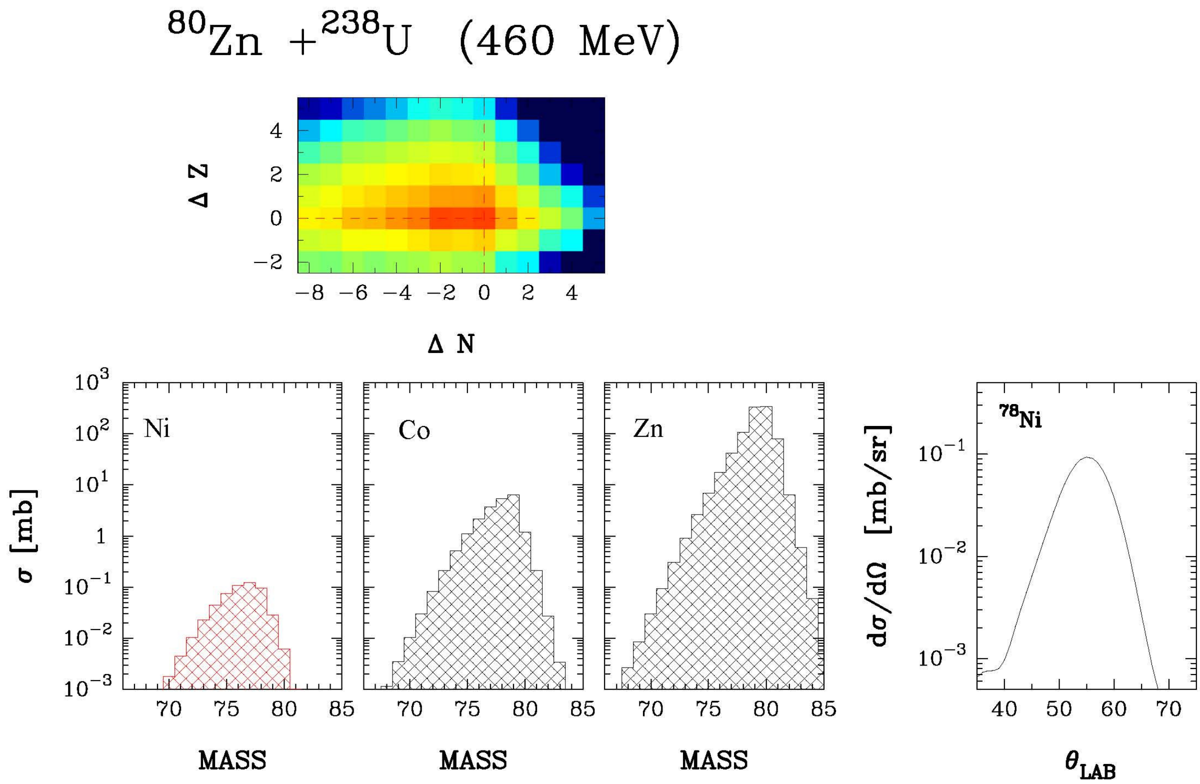


Figure 2. Cross-section calculations for the production of neutron-rich Ni,Co and Zn isotopes, with a $^{80}$Zn unstable beam on a $^{238}$U targets, performed with the code GRAZING [3] by G.Pollarolo. In The differential cross-section plot, the dash line represents the two-proton stripping channel ($^{76}$Ni) . Among the nuclei of interest produced, with large cross-sections, in this reaction are the N=51 $^{81}$Zn and the N=52 $^{82}$Zn.

2. Proton-rich Kr isotopes show low-lying shape coexistence in the vicinity of N=Z [5]. Extreme neutron-rich Kr isotopes present similar characteristics, for isotopes with N>50. Going towards neutron-rich species, the deformation slowly increases up to values of $\beta_2$ from 0.3 to 0.4 for both oblate and prolate shapes [6]. The calculated

separation energy, between both minima, is of the order of few hundred keV for the ground state and it decreases and even inverts for very neutron-rich Kr isotopes. With the intense SPIRAL2 $^{94-96}$Kr beams ($10^9$-$10^{10}$ pps) and $^{238}$U targets, taking into account the sizeable cross-sections of about 1 – 10 mb (see Fig. 3), nuclei such as $^{96}$Kr, $^{98}$Kr can be easily reached up to medium angular momentum, allowing to explore the shape coexistence in this mass region.

3. The medium-high spin structure of the neutron-rich Sn isotopes can be explored with multinucleon-transfer processes at SPIRAL2 with Sn beams on a $^{238}$U target. As an example, in Fig.3 it is shown the production cross-section of the nucleus $^{136}$Sn, the four-neutron valence nucleus respect of the doubly magic $^{132}$Sn, starting from a $^{134}$Sn SPIRAL2 beam. The physics case in this region can be focused on the onset of collectivity in Sn isotopes with a neutron number beyond N=82, which is expected in $^{136}$Sn, and the measurements of transition probabilities in the Sn isotopes. In this context, usually a large value of B(E2) is a fingerprint of collectivity, and near a shell closure the collectivity vanishes and therefore low B(E2)s are expected. However, it is known since long that in case of $^{208}$Pb the $2^+$ energy becomes large accompanied by an enhancement of B(E2) as well. The same behaviour is predicted and preliminary measured in $^{132}$Sn. After the sudden increase of the B(E2) value for the doubly-magic nucleus, the B(E2) drops again and is only expected to increase again with the onset of collectivity at N≥86[7].
   In the last years, a consistent progress has been made accessing nuclei far from stability in the vicinity of the double magic $^{132}$Sn, by using large gamma arrays and spontaneous or induced fission of several Actinides. Recently, new data has emerged on both the neutron [8] and proton [9] single particle states, together with the information on the neutron hole states [10], respect to the $^{132}$Sn core. Limited information exists regarding the proton hole states in the region.
   Nuclear structure information is more complete for nuclei above the Z=50 shell closure (for instance, Sb and Te isotopes), and is scarce for the In and Cd isotopes, which are much more difficult to produce, Kautzsch and collaborators [11] have obtained some spectroscopic information on $^{126,128}$Cd, which have two proton and two or four neutron holes, respectively, in the $^{132}$Sn core. Although this information is still rather scarce, it seems to indicate that these nuclei possess some degree of collectivity. The conclusion is that nuclei close to the $^{132}$Sn core are well described by the shell model, but there are indications that nuclei with a few valence particles acquire collective properties. It is therefore of interest to investigate the N>84 nuclei in the region in order to test the limits of the shell model.

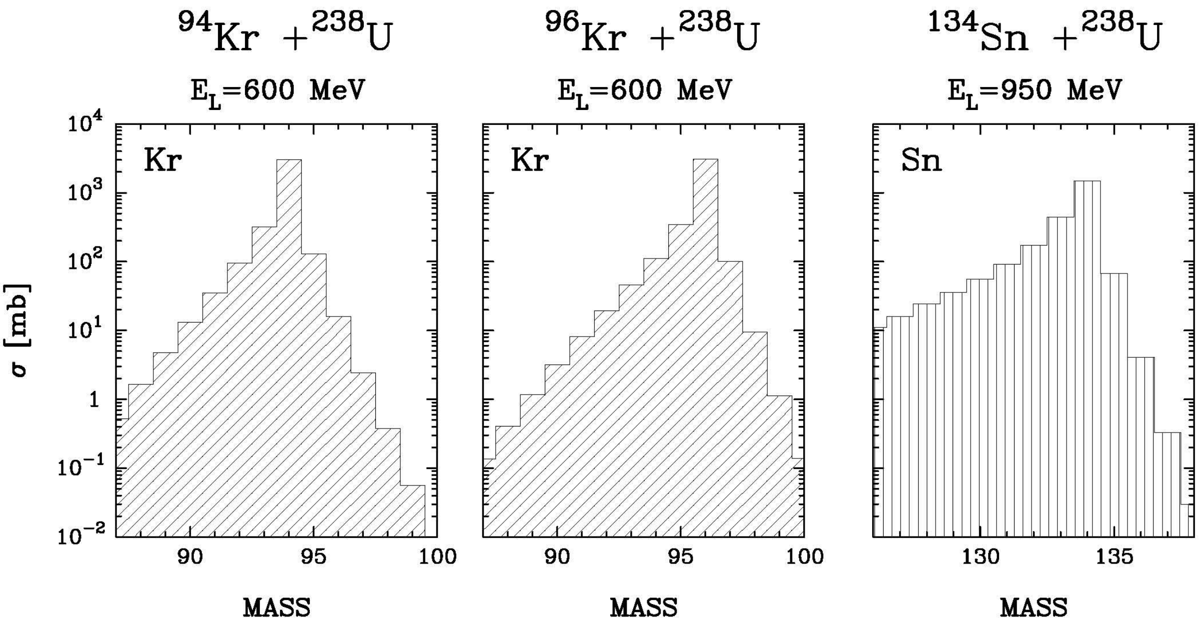


Figure 3. Examples of cross-section calculations for the production of neutron-rich Kr and Sn isotopes, with SPIRAL2 beams on a 238U targets, performed with the code GRAZING [3] by G.Pollarolo.

4. As it has been already mentioned in the scientific case, the tetrahedral and octahedral symmetry structures will be easily accessible making use of the radioactive neutron-rich beams at SPIRAL2. Some candidates of interest are the neutron-rich Zr isotopes. These nuclei can be populated with the help of fusion-evaporation or incomplete fusion reactions in inverse kinematics, using the heaviest Kr beams that will be available at SPIRAL2. Multinucleon-transfer reactions are another alternative to the study of neutron-rich Zr isotopes. The former reactions will populate the states of interest, i.e. states at relatively high excitation energy and low spin.
   In the mass 80 region, 88Ge is an ideal case that can be populated via deep-inelastic reactions with a 92Kr beam on a 238U target (4 proton stripping channel). AGATA coupled with VAMOS, would be the ideal setup to study these nuclei.
   More information and references about tetrahedral/octahedral symmetric nuclei are given in the general High-resolution Gamma-ray Spectroscopy LOI.

Concerning lifetime measurements, the well known DSAM and RDDS techniques can be used in incomplete fusion reactions and in the case of neutron-rich nuclei produced in binary reactions, the following techniques might be considered:

A) The Recoil Distance Doppler Shift (RDDS) method in conjunction with the gamma-ray array AGATA and a large-acceptance magnetic spectrometer.
   Recently an experiment using the differential plunger method with the CLARA-PRISMA setup has allowed to measure lifetimes in the $^{64}$Ni region, using the reaction $^{64}$Ni(400MeV) + $^{208}$Pb. In order to cover from 1-10ps lifetime range, various fixed distances, ranging from 30 μm to 300 μm were used in this experiment. Figure 4 shows the RDDS gamma-ray spectra obtained after gating at different velocity ranges.
   One of the limitations of the RDDS method is the determination of the feeding history of an excited level after the reaction. If the parameters describing the feeding history are not

well determined, as could happen if we deal with doublets, one can get unrealistic lifetimes. The RDDS method coupled to a magnetic spectrometer might solve this problem since one can gate at different recoil energies and look at the different feeding intensities of the excited states. As can be seen in Fig. 4, the relative intensities of the gamma rays coming from the de-excitation of the states in $^{64}$Ni depends on the velocity range (Q-value) selected from the recoils.

Another possibility to measure lifetimes of neutron-rich nuclei produced in binary reactions with the RDDS method is the use of a heavy-ion ancillary detector. The beam-like and target-like fragments produced in multi-nucleon transfer reactions or deep-inelastic reactions will fly through a degrader foil in the plunger device and eventually will be detected in a heavy-ion detector that can distinguish between beam-like and target-like fragments via means of time of flight, so the recoils can be identify and the kinematics of the reaction can be reconstructed, thus a RDDS spectra can be obtained and analysed for the nuclei of interest. The heavy-ion detector has to have high position resolution to determine the reaction kinematics, a possible solution could be a 4π DANTE-like detector (see addendum), where the binary fragments will be measure in coincidence.

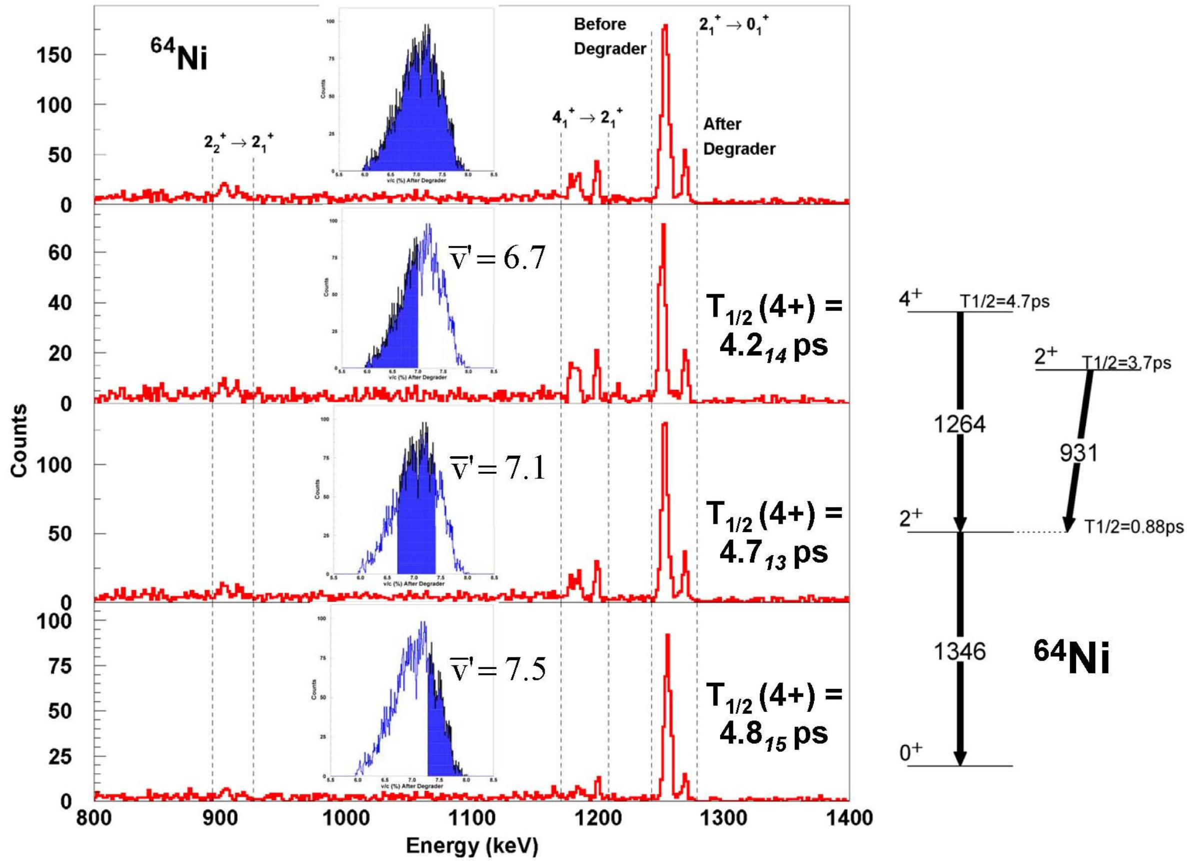


Figure 4. RDDS spectrum from the CLARA array gated at different velocity ranges. (right) Partial level scheme of 64Ni

B) The second technique was developed for the Kraków Recoil Filter Detector (RFD) and it covers the lifetime range between tenths to hundreds of fentoseconds. The technique, with similarities with the DSAM, is based on the fact that in a relatively thick target, the straggling of the ions produce a wrong Doppler corrected component in the spectrum.

This component is only present if the emission is done within the transition time of the reaction products through the target. The technique requires an accurate position sensitive detector to determine the trajectory of the products as well as the measurement with different target thicknesses to cover the aforementioned range.

C) DSAM technique. In the case of the differential plunger a mass spectrometer is required to define the direction of the selected binary product. For DSAM measurements a high-granularity detector for heavy ion able to determine the particle kinematics is needed. Here the recoiling direction of the stopped fragment will be determined through the measurement of the complementary product. An identification will be provided by $\gamma$-gating on the complementary fragment. In a high efficiency $\gamma$-ray detector array is needed.

In conclusion, the use of multinucleon-transfer and deep inelastic collisions, to perform in-beam spectroscopy of very exotic products, will be possible with the use of new set-ups consisting on the coupling of efficient arrays of Ge detectors (AGATA) to large acceptance magnetic spectrometers.
The interest in studying the above mentioned phenomena present in neutron-rich medium mass or heavy nuclei very far from stability, requires radioactive neutron-rich beams as well as high intensity stable beams, that will be available at SPIRAL2. The development of new set-ups combining AGATA with large-acceptance magnetic spectrometers and ancillary instruments is of paramount importance.

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***Beam properties***

In general, for all studies indicated above, good beam quality is of importance, i.e., the energy resolution should be better than 1% and the emittance should be on the same level (about 5π mm mrad) as for presently available beams at Coulomb barrier energies (3-5 MeV/u). Good timing properties of the beam are also required for the lifetime measurements. For studies with the highest intensities, a “wobbling” system may be required in conjunction with a rotating target. High purity radioactive beams are not required if a large acceptance spectrometer is used to detect the reaction products. For setups including only ancillary devices detecting the product trajectory, the purity of the radioactive beams used for multinucleon-transfer and deep-inelastic reactions aiming at the most exotic nuclei is very important. Such contaminations must be less than 3%.
Required beams:

- Neutron-rich radioactive beams from SPIRAL2. Intensity $\geq 10^6$ pps (see selected examples in TABLE 1)
- High intensity stable beams from LINAG (see selected examples in TABLE 2)

TABLE 1. Selected key reactions using radioactive beams.

| Reaction | Beam Int. (pps) | Physics Area |
|---|---|---|
| $^{84}Se+^{238}U \rightarrow ^{80}Zn + FF$<br>$^{84}Se+^{238}U \rightarrow ^{78}Ni + FF$ | $> 2\times10^9$ | **Shell evolution** |
| $^{94}Kr+^{238}U\rightarrow^{78}Ni+FF$ | $>6\times10^9$ | **Shell evolution** |
| $^{92}Kr+^{238}U \rightarrow ^{88}Ge + FF$ | > 2 x $10^{10}$ | **Exotic shapes** |
| $^{94}Kr+^{208}Pb \rightarrow ^{96}Kr+^{206}Pb$ | $>6\times10^9$ | **Shape coexistence** |
| $^{98}Sr+^{238}U \rightarrow ^{104}Zr + FF$ | > 5 x $10^8$ | **Exotic shapes** |
| $^{140}Xe+^{208}Pb\rightarrow^{142}Xe+^{206}Pb$ | $>1\times10^8$ | **Shell evolution** |
| $^{132}Sn+^{208}Pb\rightarrow^{134}Sn+^{206}Pb$ | $>1\times10^9$ | **Shell evolution** |

TABLE 2. Selected key reaction for a stable-beam in-beam study.

| Reaction | Beam Int. (pps) | Physics Area (see above) |
|---|---|---|
| $^{150}Nd+^{197}Au\rightarrow^{148}Ce+^{199}Tl$ | $>1\times10^{14}$ | **Nuclear symmetries** |
| $^{110}Pd+^{197}Au\rightarrow^{106}Mo+^{201}Bi$ | $>1\times10^{14}$ | **Nuclear symmetries** |
| $^{64}Ni+^{238}U\rightarrow^{62}Cr+FF$ | $>1\times10^{14}$ | **Shell evolution** |
| $^{82}Se+^{238}U\rightarrow^{80}Zn+FF$ | $>1\times10^{14}$ | **Shell evolution** |
| $^{86}kr+^{238}U\rightarrow^{80}Zn+FF$ | $>1\times10^{14}$ | **Shell evolution** |
| $^{124}Sn+^{208}Pb\rightarrow^{120}Pd+FF$<br>$^{124}Sn+^{238}U\rightarrow^{122}Pd+FF$ | $>1\times10^{14}$ | **Shell evolution** |

***Target(s)***

Production target UCx standard SPIRAL2 target. The in-beam (secondary) targets are typically 0.2-1.0 mg/cm2 thin. $^{208}$Pb, $^{238}$U and possibly $^{248}$Cm, $^{250}$Cm $^{244}$Pu or $^{252}$Cf radioactive targets required. Rotating or cooled target systems are required for the highest beam intensities of LINAG.

***Instrumentation and detectors***

**Basic instrumentation for spectroscopy studies with quasi-elastic and deep-inelastic reactions:**

In order to study neutron-rich nuclei via quasi-elastic and deep-inelastic reactions, set-ups combining an efficient γ-array such as AGATA with large-acceptance magnetic spectrometers, such as PRISMA or VAMOS, are required (see Fig.5). For experiments with both high-intensity stable-beams and radioactive beams, a mass spectrometer with high transmission and the possibility of being positioned at the grazing angle is essential. Since the location for the radioactive nuclear beams and for the high-intensity beams of stable elements are different one should consider two dedicated devices. The separator should have the capability to cleanly identify the mass A and proton number Z of the recoil. In some cases the recoiling energy could be insufficient to obtain effective Z-separation. As suggested in other letters of intent a possible solution could be the "re-acceleration" or "boost" of the recoils at the focal plane of the mass separator. One could envisage an RF cavity plus Wien filter at the focal plane – followed by an ionisation chamber to enable full isotope identification. The requirements for the spectrometer itself are also very similar to the one discussed in the LoI dealing with "Spectroscopy of Transfermium Elements" .

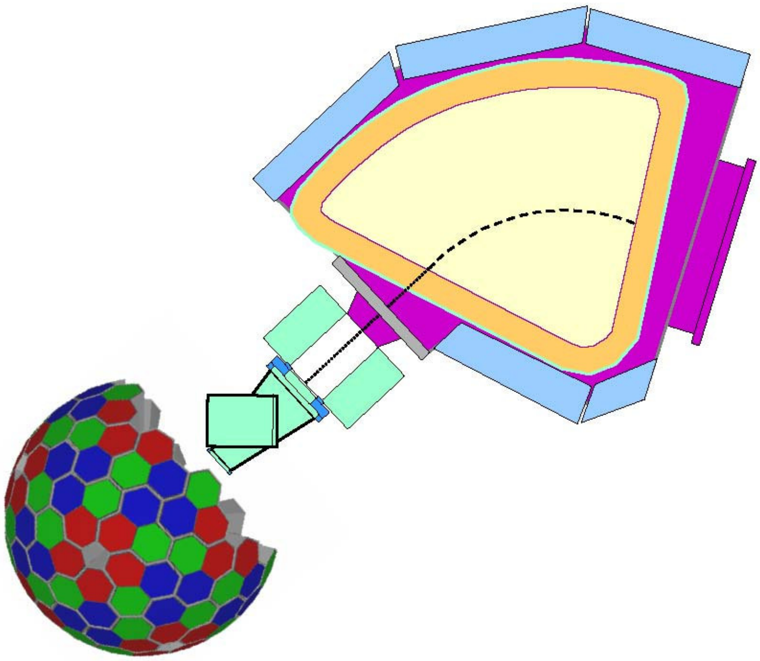

**Figure 5. Scheme of the coupling of AGATA-3π with a large-acceptance magnetic spectrometer**

**Ancillary devices:**

As it has been already mentioned, the basic setup necessary to study the structure of very exotic neutron-rich nuclei, via quasi-elastic and deep-inelastic reactions, consist basically of an efficient γ-array as AGATA or EXOGAM2 with large-acceptance magnetic spectrometers. However considering the binary nature of the reaction, the fact that most of the studies to be done at SPIRAL2 will be in direct kinematics and the limited angular coverage of the magnetic spectrometers, a large fraction all the recoils that are out of the limited acceptance of the spectrometer do not contribute to the γ-recoil coincidence. In order to improve the detection efficiency, a heavy ion detector with high positional sensitivity and large solid angle coverage is required.

In the past such detectors based on PPAC arrays have been built for EUROBALL and GAMMASPHERE. In the case of the PRISMA spectrometer gas-filled detectors are excluded at the target position and a system based on micro-channel plate (MCP) detectors has been build at LNL. The DANTE array (Detector Array for multi-Nucleon Transfer Ejectiles) allows detecting the recoils at the grazing angle outside the acceptance of PRISMA and consequently recovering those events, making possible the Doppler correction.

A similar solution could also be envisaged at SPIRAL2, in the framework of the AGATA collaboration, we propose the development of a new ancillary MCP array, based in the DANTE (INFN-FLNR Dubna) technology. Since the AGATA specifications foresee an inner space with ~23 cm radius, placing the MCP detectors at an average distance of 20 cm from the target, it is expected and angular resolution of ~0.3$^{o}$ with the position resolution of 1 mm reached at DANTE.

The larger inner space will also allowed to have a START-STOP structure in the MCP array with 15 cm between the detectors and, therefore, with TOF's of the order of 10ns. With the time resolution of 130 ps measured at Dante, it would be possible to identify the target-like or beam-like nature of the reaction products, and in some cases, to have a rough estimate of the fragment mass. For DSAM measurements a detector with ΔE-E response for Z identification would be preferred. It could be based on plastic scintillators or monolithic Si detectors.

***Theoretical support:***

Several theory groups are active in the description of neutron-rich nuclei. The topics include the development of shell-model theory and the inclusion of unbound states, the influence of different pairing channels in algebraic and mean-field models, theory of the Shape phase transitions: dynamical symmetries at the critical point, development of relativistic mean-field and relativistic QRPA models and relationship to astrophysical processes.

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B.A.Brown et al., Michigan State University, USA
J.Dudek et al., IPHC and University Louis Pasteur, Strasbourg, France
S. Frauendorf et al., University of Notre Dame, Indiana, USA
J.L.Egido, L.M.Robledo et al., Universidad Autónoma de Madrid, Spain

L.S.Geng, J.Meng et al., Peking University, Beijing , China
D.Vretenar et al., University of Zagreb, Croatia
P.Ring et al., University of Munich, Germany
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K.Langanke, G. Martínez-Pinedo et al., GSI, Darmstadt, Germany

Developments are also necessary in the theory of the reaction mechanisms to understand the process and perform cross-sections predictions. Some groups working on multi-nucleon transfer reactionsand deep-inelastic collisions theory are:

G.Pollarolo et al., INFN and University of Torino, Italy
M.Veselsky et al., Institute of Physics, Bratislava, Slovakia

***Preliminary schedule of the construction of new equipment:***

The construction of the DANTE like ancillary detector will be done in the framework of the AGATA collaboration and the time schedule and MoU of will be defined in this context.

***ADDENDUM***

## The Heavy-ion MCP-based Ancillary Detector DANTE

INFN-Laboratori Nazionali di Legnaro, INFN-and University of Milan, INFN-and University of Padova, FLNR Dubna

**Abstract.**
The CLARA-PRISMA setup is a powerful tool for spectroscopic studies of neutron-rich nuclei produced in multi-nucleon transfer and deep-inelastic reactions. It combines the large acceptance spectrometer PRISMA with the γ-ray array CLARA. At present, the ancillary heavy-ion detector DANTE, based on Micro-Channel Plates to be installed at the CLARA-PRISMA setup, is being constructed at LNL. DANTE will open the possibility of measuring γ-γ Doppler-corrected coincidences for the events outside the acceptance of PRISMA. In this presentation, it is described the heavy-ion detector DANTE, as well as the performances of the first prototype.

**Introduction**
Neutron-rich nuclei are of particular interest since the neutron excess leads to interesting phenomena, such as modified shell structure and exotic collectivity. These nuclei are difficult to produce, particularly in high-spin states, since they are not reachable by fusion-evaporation reaction or incomplete fusion. However, multi-nucleon transfer and deep-inelastic reactions, if combined with high efficiency γ-ray arrays and ancillary detectors to identify the reaction products, are an ideal mechanism to populate and study neutron-rich nuclei at high spin, in spite of the low cross-section. The γ-ray array CLARA [1] coupled to the large acceptance magnetic spectrometer PRISMA [2] allows the study of moderately neutron-rich nuclei populated at medium-high spin via multi-nucleon transfer [3] and deep-inelastic reactions [4]. The setup provides correlations between the in-beam prompt γ rays detected in CLARA with the reaction products analysed by PRISMA, which are univocally identified in atomic number *Z* and mass *A*. Nevertheless, all the CLARA events correlated with reaction products, which are outside the PRISMA acceptance, are lost during the analysis, since a Doppler correction is not feasible, and therefore those events do not contribute to the gated γ-γ coincidence matrices. In order to recover those events, the DANTE array is being built at LNL. This detector will allow to reconstruct kinematically event by event and to perform the Doppler correction of the prompt γ rays detected in CLARA.

**The DANTE Array**
DANTE (Detector Array for multi-Nucleon Transfer Ejectiles) is a heavy-ion position-sensitive ancillary array based on Micro-Channel Plates (MCP) that will be installed in the reaction chamber of the CLARA-PRISMA setup. The first prototypes of the DANTE array have been built and tested. They present a configuration very similar to that of the start detector of the PRISMA spectrometer [5] and of the CORSET-type detector [6]. Each detector consists of a mylar foil, at the entrance, for electron production, followed by two Micro-Channel-Plates (MCP), of dimensions 40×60 $mm^2$, mounted in Chevron configuration. The position-sensitive anode consists of two orthogonal delay lines made of copper wires with a diameter of 100 μm, which are placed in such a way that a tin-coated copper wire alternates with an isolated copper wire. These wires are connected to a low-noise differential preamplifier, in order to minimize the influence of fast signals from the MCP and are wound

around a frame of two Plexiglas rods. The rods present different diameters in each direction *X* and *Y*, in order to keep them insulated from each other and both of them from the steel reflection plate for electrons. The delay line is attached to the printed circuit board where the preamplifiers are mounted. Figure 1 (left) shows a lateral photograph of a MCP prototype. The *X* and *Y* positions are obtained from the difference in arrival time of the signal at one end of the corresponding delay line with respect to a reference time signal. The reference time signal is derived from the second MCP through a capacitor. The rise time of the fast time signals is around 2-3 ns. The position and time resolution of the first DANTE prototype was measured placing an α source of $^{241}$Am in front of the detector. The position resolution was measured to be better that 1 mm. Figure 2 shows a two dimensional *X-Y* spectrum obtained placing a mask with narrow slits (1 mm) in front of the MCP entrance surface. The time resolution was extracted from a Time-Of-Flight (TOF) measurement. A small CORSET type detector [6], providing the start signal, was placed between the α source and the DANTE prototype at around 15 cm, which provided the stop signal. The time resolution was measured in this configuration to be around 130 ps. The final design of the DANTE array aims at maximizing the detection efficiency for the reaction products in combination with the γ-γ coincidences measured with the CLARA array. As a consequence, the MCP detectors will be placed around the grazing angle, where the cross-section is largest. Figure 1 (right) shows the configuration of DANTE at 90° within the reaction chamber of CLARA. The arrangement of the detectors in the array will be flexible in order to place them at the grazing angle of the various reactions of interest.

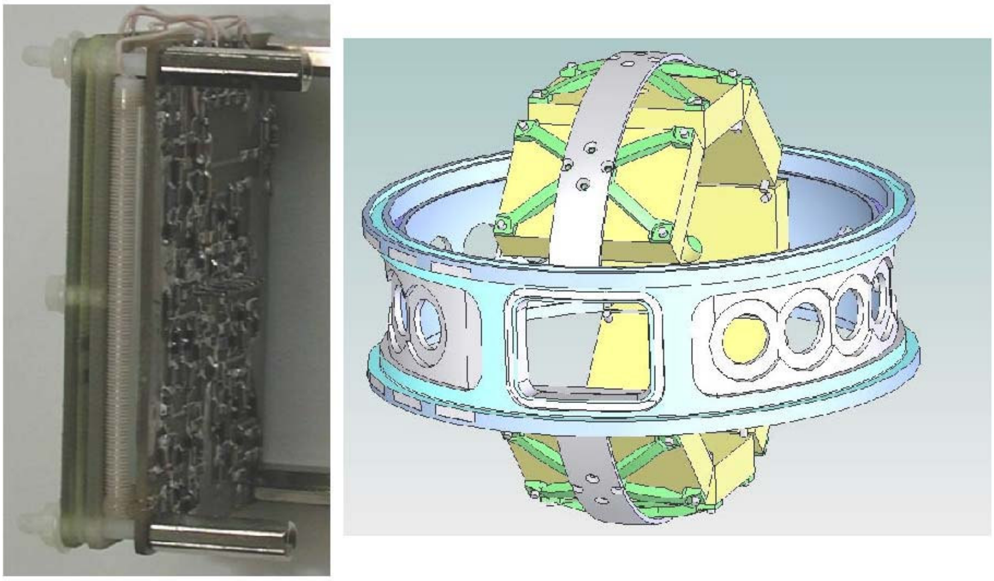

**FIGURE 1.** View of one of the MCP prototypes of the DANTE array to be installed at the CLARAPRISMA setup at LNL (left). Design of the DANTE array at a configuration angle of $90^o$ (right).

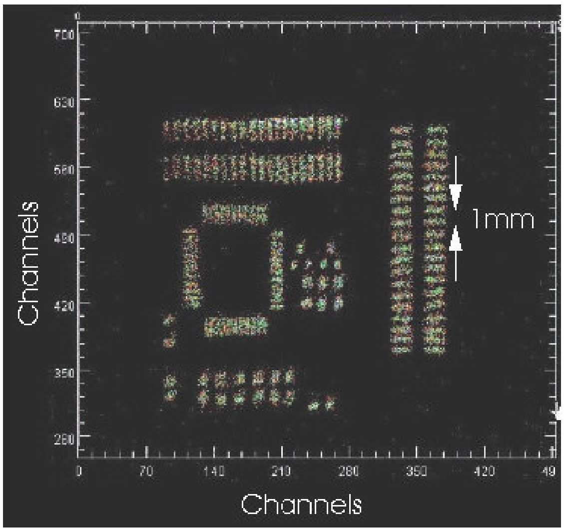


**FIGURE 2.** Two-dimensional *X-Y* spectrum obtained from the MCP prototype detector where a suitable mask was placed in front; the test was performed with an α source.

**Results**
In order to assess the in-beam performance of the DANTE array, an analysis using the start detector of PRISMA [5], as if it were one detector of the DANTE array, has been made. The results obtained with the start detector of PRISMA represent, in good approximation, the expected in-beam performance of the DANTE array, since both detectors are based on the same physics principle (MCP based) and they will be placed under the same experimental conditions.

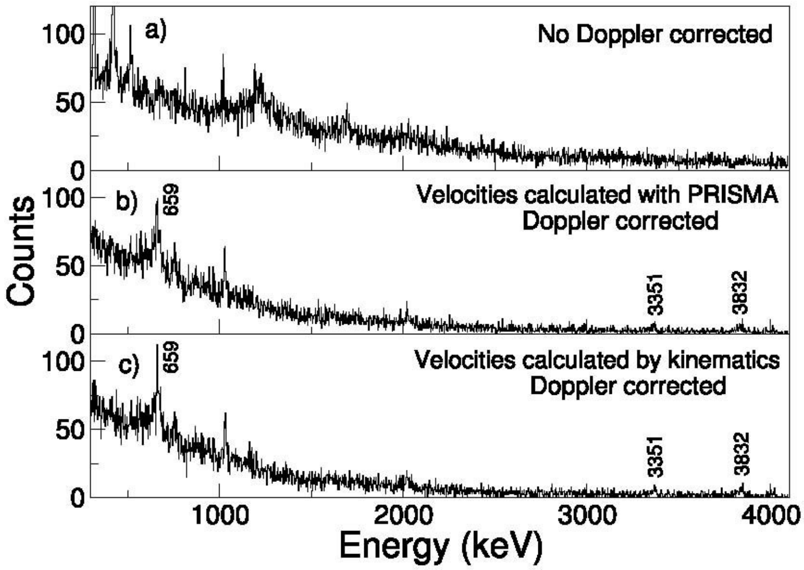


**FIGURE 3.** Gamma-ray spectra for the reaction 238U + 48Ca at *Elab* = 330 MeV. (a) Raw γ-ray spectra, uncorrected (b) Doppler corrected γ-ray spectra for the beam-like fragments using the velocities measured by PRISMA. (c) Doppler corrected γ-ray spectra for the beam-like fragments using the kinematics measured with the start detector of PRISMA.

Figure 3 shows γ-ray spectra from the reaction $^{238}U$ + $^{48}Ca$ at *Elab* = 330 MeV, where the only difference between them is the way the Doppler correction has been performed. Figure 3 a) shows the raw γ-ray spectra, where no Doppler correction has been performed. Figure 3 b) shows the Doppler corrected γ-ray spectra for beam-like fragments, where the velocities of the recoils, used to perform the Doppler correction, are the ones measured by PRISMA event by event. The energy resolution of the 3351 and 3832 keV transitions is approximately 0.8%. Finally, figure 3 c) shows the Doppler corrected γ-ray spectra for beam-like fragments, in this case the velocities of the recoils have been calculated taking into account the kinematics of the reaction. The energy resolution of the 3351, and 3832 keV transitions is approximately 1.0%. In the case of the DANTE array, the velocities will be calculated from the position interaction of the recoils, considering the kinematics of the reaction. Therefore, the γ-ray spectra shown in figure 3 c) present the expected spectra from the DANTE array.

Figure 4 shows Doppler corrected γ-ray spectra for beam-like fragments from the reaction $^{238}U$ + $^{82}Se$ at *Elab* = 505 MeV. They are in coincidence with the 1080 keV transition (4+→2+) from $^{82}Se$. The transition observed at 654 keV in figure 4, corresponds to the 2+→0+ transition of $^{82}Se$. The Doppler correction in figure 4 a) uses the measured velocities of PRISMA, and therefore the γ rays are in coincidence with the recoils analysed by PRISMA. While figure 4 b) shows the Doppler corrected events using the kinematics measured with the start detector of PRISMA, and therefore these events are not necessarily in coincidence with the recoils analysed by PRISMA. It can be noted that in the latter case the statistics of the (2+→0+) transition of 82Se at 654 keV, has increased by a factor of five.

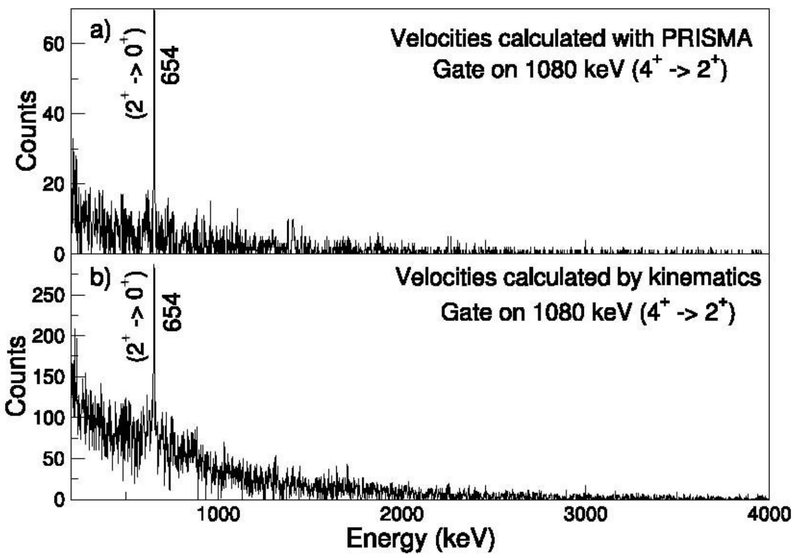


**FIGURE 4.** Doppler corrected γ-ray spectra for beam-like fragments from the reaction $^{238}U$ + $^{82}Se$ at *Elab* = 505 MeV. (a) Doppler correction performed using the velocities measured with PRISMA. (b) Doppler correction performed using the kinematics measured with the start detector of PRISMA.

**Summary**

DANTE is a heavy-ion position-sensitive ancillary array, based on Micro-Channel Plates, developed primarily for the use in conjunction with the CLARA-PRISMA setup. This ancillary detector will allow measuring γ-γ Doppler-corrected coincidences, for the events outside the acceptance of PRISMA. It presents a position resolution of 1 mm while the time-of-flight difference is measured with 130 ps resolution. The in-beam performance has been assessed, using the start detector of PRISMA as if it were a DANTE detector. It has been observed that the energy resolution after Doppler correction, where the velocities have been calculated taking into account the kinematics of the reaction is comparable to the one given when the velocities are measured event-by-event with PRISMA. In addition, the statistics of the (2+→0+) transition of $^{82}$Se at 654 keV is a factor of five higher, when the start detector is used as a DANTE detector, since the efficiency of PRISMA is not considered.

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## Nuclear shapes and high-spin spectroscopy

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***Scientific case:***

The shape of an atomic nucleus is a fundamental property which is governed by a delicate interplay of the macroscopic liquid-drop properties of nuclear matter and microscopic shell effects. Nucleons occupying shape-driving orbitals polarize the nucleus, and the deformed configurations are often stabilized by rotation. Different orbitals can give rise to different types of deformation (prolate, oblate, octupole etc.), resulting in a coexistence of different shapes in the same nucleus. The quadrupole moment, which is accessible experimentally through Coulomb excitation and lifetime measurements, probes the deformation and collective behaviour of nuclei. Magnetic nuclear moments are sensitive to the orbitals occupied by the valence particles (or holes) and are thus a sensitive probe of the nucleon configuration and nuclear structure. Both quantities can be directly compared with theoretical predictions, thus providing an excellent tool to test their validity. The experimental techniques to measure nuclear electromagnetic moments are detailed in the section "Nuclear electromagnetic moments".

The study of exotic shapes and nuclear structure at high angular momentum has been limited to proton-rich nuclei in the past because it relies on the use of fusion-evaporation reactions to populate the high-spin states. The use of intense neutron-rich radioactive beams will give access for the first time to states of very high spin in stable and moderately neutron-rich nuclei. Such systems have an increased stability against fission due to a higher fission barrier, so that SPIRAL-2 will not only extend the region of nuclei accessible for high-spin studies, but will also open up a new regime of ultra-high spin above 70 ħ. Pushing the experimental spin limit has always led to the observation of new phenomena in the past and has a strong potential for new physics. To find the limits of angular momentum that a nucleus can sustain is a fundamental question in nuclear structure physics. This region delineates the transition from collective rotation to non-collective states, where rotational bands terminate and the core underneath the valence nucleons is broken. It is also an open question whether it comes to a total quenching of the nuclear pair field at such extreme angular momenta (nuclear Meissner effect) or whether the finite nature of nuclei preserves the dynamical pairing correlations.

It is at the extreme values of spin well above 60 ħ where exotic shapes such as hyperdeformation are expected to occur. The observation of hyperdeformation at high spin would be a major achievement in the field of nuclear physics. A key experiment would be the investigation of extreme shapes around $^{114}$Cd in the fusion-evaporation reaction $^{26}$Mg($^{94}$Kr,6n), where both proton and neutron (N+3) *hyperintruder* orbitals are expected to be occupied, and which can hold more angular momentum than $^{108}$Cd, the heaviest cadmium isotope that can be reached with stable heavy-ion beams and in which structures with extreme deformation were observed. A first glimpse of extremely deformed, possibly hyperdeformed structures was recently observed in form of narrow ridge structures in barium and xenon isotopes following the reaction $^{64}$Ni+$^{64}$Ni→$^{128}$Ba*. A compound system with 14 additional neutrons can be produced with the intense $^{94}$Kr beam from SPIRAL-2 in the reaction $^{94}$Kr+$^{48}$Ca→$^{142}$Ba*, pushing the angular-momentum limit significantly and enhancing the chances to populate structures with extreme deformation.

The evolution of the superdeformation phenomenon with isospin requires further elucidation. For example, various theoretical approaches reproduce well the observed moments of inertia of the yrast superdeformed bands in $^{194}$Pb and $^{196}$Pb, but fail to do so for $^{198}$Pb. A possible explanation could be that pairing correlations play a stronger role in this region when increasing the neutron number and are probably governed by a power of the (N-Z)/A factor. Another possibility is that the simultaneous presence of high-*j* proton and high-*j* neutron alignments generates a residual proton-neutron interaction which could play a role in the particle-hole channel. Data on more neutron-rich Pb nuclei are needed in order to understand this phenomenon. Neutron-rich radioactive beams such as $^{132}$Sn or $^{142}$Xe can be used to populate superdeformed states in heavier Pb isotopes towards $^{208}$Pb.

The evolution of nuclear shapes with spin depends critically on the macroscopic aspects of nuclear dynamics. It is well known that rotating classical fluids undergo a dramatic transition from a near spherical oblate to a very deformed triaxial shape. The observation of this Jacobi shape transition in nuclei would give important insight into the physics of rotating finite quantum fluids and the nuclear structure at the extremes of angular momentum. Favourable macroscopic liquid-drop properties, manifested in the Jacobi shape transition, are presumed to be a prerequisite for the population of hyperdeformed shapes. The A~100-120 region is also from this point of view the most promising. Experimental signatures for the Jacobi transition are the splitting of the GDR and a “giant backbending” of the moment of inertia. Collective excitations at high temperatures are discussed in the part “Collective modes in the continuum”.

Another kind of giant backbending is predicted to be arising from a rotation-induced transition from prolate collective rotation to oblate collective rotation. This is predicted to occur in the neutron-rich A~180-190 region, and results from reinforcing neutron and proton alignments for oblate shapes. Despite the consistency of different theoretical descriptions, the phenomenon remains elusive experimentally, due to its favoured occurrence only in nuclei on the neutron-rich side of stability. Since collective oblate rotation is hardly observed in any nuclei, its experimental identification as the yrast structure is an important objective. SPIRAL-2 will give excellent opportunities to uncover the favoured oblate mode, using neutron-rich tin and xenon beams on $^{48}$Ca and $^{50}$Ti targets, making final nuclei such as $^{180}$Hf and $^{184}$W at high spin. Giant backbending is predicted to occur at I~20 in these nuclides, tantalisingly out of reach with current stable-beam techniques. In the same n-rich A~180-190 region, prolate non-collective states (high-K states) are predicted to compete with oblate collective rotation, and to form long-lived, high-spin isomers. Such high-K isomers help elucidating the properties and positions of single-particle levels and hence gain access to the shell properties of these nuclei.

While the study of nuclei at extreme values of angular momentum is limited to nuclei near stability, it is important to explore the spin degree of freedom also for exotic nuclei further away from stability. Coulomb excitation experiments and spectroscopy after fragmentation reactions often give information about the first excited state in nuclei far from stability, which allows investigating the evolution of the shell structure. However, to understand the elementary excitations such as rotation, vibration, pairing, single-particle excitations, and the influence of the weak binding, more spectroscopic information is needed than only the first excited state. From this point of view all states above the first $2^+$ state can be considered “high spin”. New forms of collective excitations are expected in very neutron-rich nuclei due to the decoupling of the motion of neutrons and protons. The rotational spectrum will be sensitive to a change in neutron pairing when the Fermi level approaches zero. While fusion-evaporation is the primary tool to populate high-spin states, other techniques are better adapted to study low- and medium-spin states in nuclei further away from stability. These include (multiple) Coulomb excitation, transfer reactions in inverse kinematics, and deep inelastic reactions.

Excitations around closed-shell nuclei play a key role in understanding the microscopic origin of collective motion. Highly deformed structures have been observed and interpreted as multi particle-hole excitations around $^{40}Ca$ and $^{56}Ni$. These cases provide the opportunity to study highly collective states in the framework of both the nuclear shell model and mean-field approaches, and they may form a bridge to resonant molecular and cluster states in light nuclei. For heavier nuclei it will be possible to study excitations around $^{208}Pb$ using fusion-evaporation reactions with $^{132}Sn$ and $^{142}Xe$ beams from SPIRAL-2, while nuclei in the vicinity of $^{132}Sn$ and $^{78}Ni$ can only be reached in transfer reactions, e.g. involving $^{136}Te$ or $^{81}Ga$ beams.

New types of symmetries like tetrahedral and octahedral shapes are predicted by mean-field models in many areas of the nuclear chart. A possible first indication of tetrahedral symmetry has been found recently in rare-earth nuclei in a new evaluation of old experimental data from the 1980s. The peculiar branching ratios observed for the low-spin members of a negative-parity band in $^{156}Gd$ were not understood at that time, but can be interpreted as a signature for tetrahedral symmetry. The exotic-symmetry states are predicted to lie relatively low above the ground state (between 0.5 - 2.0 MeV), but to be well separated from the quadrupole-deformed ground state by a barrier of several MeV. Experiments to further investigate the phenomenon in this accessible region of the chart are under way. Large tetrahedral or octahedral shell gaps are predicted for {Z,N} = {32,40,56,64,70,90,132-136} with good candidates for the new symmetries in the A≈80, 150, and 220 mass regions. The majority of these nuclei are either proton rich or neutron rich which corresponds to the realm of SPIRAL and mainly SPIRAL2. Among them, the zirconium isotopes are particularly interesting because two islands of tetrahedral shapes are predicted at both extremes of the N/Z ratio around $^{80}Zr$ and $^{110}Zr$. Even though these nuclei are difficult to reach experimentally, the systematic study of the chain of Zr isotopes could give insight into the development of the tetrahedral shell gaps. Heavy Zr isotopes can be reached in fusion-evaporation reactions with neutron-rich krypton beams from SPIRAL2 on $^{9}Be$ targets, which are well suited to populate nuclei at relatively high excitation energy and low spin. The production and handling of the secondary Be targets would require a safety assessment. The gamma spectrometer AGATA or EXOGAM would be used coupled to VAMOS in order to identify the reaction products. In the case of the proton rich isotopes, a light charge particles array is needed.

It was only recently that experiments gave firm experimental evidence for the breaking of axial symmetry in nuclei. A stable triaxiality in nuclei can manifest itself in a chiral symmetry breaking or in a new type of collective excitation called “wobbling”. The latter is so far only known in two odd-mass Lu isotopes, and more examples are needed to fully understand these new phenomena. Studying nuclei without axial symmetry is important to better understand three-dimensional rotation of nuclei. Many of the regions that are predicted to be candidates for these new symmetries cannot be reached with stable beams, but will become accessible with neutron-rich radioactive beams from SPIRAL2.

***Beams and targets:***

Coulomb excitation measurements are possible even with relatively low beam intensities of $>10^3$ pps and are therefore suited for nuclei far from stability. Beam purity is important in such measurements. If contaminants cannot be avoided, it is important to know the exact beam composition, if possible through event-by-event identification of the projectiles. Multiple Coulomb excitation and reorientation measurements require at least $10^4$-$10^5$ pps for systems with high collectivity, otherwise even more. A very large emittance or beam haloes and satellites can be problematic.

Fusion-evaporation reactions require much higher beam intensities of at least $10^8$ pps. For fission-fragment beams such intensities will only be reached for selected species. Examples of beams that can populate neutron-rich compound nuclei at high angular momentum include $^{94}$Kr, $^{94}$Sr, $^{132}$Sn, and $^{142}$Xe. Even though light-ion beams cannot populate the highest spins, they are often the only means to populate nuclei either near or beyond the N=Z line or near stability at intermediate spins. Intense light-ion beams can be produced in proton, neutron, or deuteron-induced reactions with high cross sections, either using the ISOL technique or, in case of long-lived isotopes, in batch mode, using dedicated target stations.

For the study of isomeric states beam pulsing techniques should be developed ranging from ns to µs. Tagging on isomeric states is furthermore an efficient tool to select the structures of interest from a large background.

We support the development of a rotating or cooled target system for in-flight production of the RIB with heavy ions in inverse kinematics. The secondary target, e.g. for Coulomb excitation, would then be located behind the separator stage of S$^3$. Technical details for this development are described in the S$^3$ letter of intent.[1] Example reactions are $^{12}$C($^{58}$Ni,2n)$^{68}$Se or $^{24}$Mg($^{58}$Ni,2n)$^{80}$Zn. This development has strong synergies with the heavy-element program.[2]

***Instrumentation and detectors***:
Nuclear spectroscopy at high spin involves large γ-ray multiplicities and requires a γ-ray spectrometer with high efficiency, resolution, and granularity. The ideal instrument for such studies is the **AGATA** spectrometer comprising as many detector modules as possible and available. Since AGATA will also be installed at other laboratories, experiments have to be organized in campaigns. Most experiments require the coupling of the γ-ray spectrometer to other detection systems such as charged-particle detectors, a recoil separator with focal-plane detection system, or neutron detectors. The coupling of AGATA (e.g. in a 3π configuration) to **VAMOS** will be essential for many experiments. The required space for AGATA and its electronics and infrastructure in G1 needs to be carefully evaluated. While G1 is the first choice for the location of AGATA, space does not permit the coupling to neutron detectors or the operation in the full 4π configuration. Thus the operation of AGATA in G2 should be also considered.

The coupling of AGATA to the new **S$^3$** separator would result in a very powerful tool for high-spin experiments due to the unique beam intensities of the LINAG and the unmatched count-rate capabilities of the AGATA spectrometer. The space and infrastructure requirements of AGATA should therefore be considered in the layout of the new experimental area of the S$^3$ separator.

**EXOGAM** is well adapted for experiments involving low and medium γ-ray multiplicities and will remain to be an essential tool for γ-ray spectroscopy at GANIL, in particular at times when AGATA is not available. The equipment with fully digital electronics should have high priority in order to keep EXOGAM competitive.
For experiments with radioactive beams it is of particular importance to distinguish the reactions under study (fusion-evaporation, Coulomb excitation, transfer) from the high

[1] "S$^3$: Super Separator Spectrometer" (A. Villari, A. Drouart et al.)
[2] "From Actinides to Superheavy Elements with SPIRAL2: Reaction dynamics and structure" (P. Greenlees et al.).

background. In addition to using VAMOS to identify the reaction products, various "smaller" equipments can serve this purpose and should be available at GANIL. These include:

- A compact **CsI multi-detector** of $4\pi$ geometry for light charged particles such as DIAMANT to be used inside AGATA or EXOGAM.
- Highly pixelized **silicon detectors** and silicon telescopes for heavy ions and light charged particles.
- Large liquid scintillator detectors for neutrons. The **neutron wall** currently hosted by GANIL should be maintained and made available for campaigns.

Transitions between states of different shape can have strong electric monopole components. Low-lying $0^+$ states in even-even nuclei are an indication for shape coexistence and their E0 decay to the ground state is very sensitive to the details of the wave functions and the deformations involved. Since E0 transitions are non-radiative, **conversion-electron spectroscopy** is an important tool to study shape coexistence and the decay of structures based on exotic shapes. The possibilities of performing in-beam conversion-electron spectroscopy, ideally in coincidence with $\gamma$ rays, should be investigated and an initiative to construct a CE spectrometer should be launched as soon as possible (see also LoI "Spectroscopy of Transfermium Elements").

Lifetime measurements of excited states allow determining the transition matrix elements and are a sensitive probe of the nuclear structure. Various experimental methods have been developed (see LoI on nuclear moments). The measurement of lifetimes in the picosecond range with the recoil-distance Doppler shift technique requires a so-called **plunger**. The construction of a plunger dedicated to GANIL should be initiated. It should be well adapted both for a use together with VAMOS (differential plunger) and stand-alone.

***Theoretical support***:
For medium and heavy nuclei, shape coexistence phenomena at low spin appear often for mid-shell nuclei with too many active particles in too many shells to be described by the interacting shell model. The microscopic methods of choice to describe these nuclei are based on configuration mixing of self-consistent mean-field states in the framework of global energy density functional methods. First applications have demonstrated the power of the methods and even the possibility to perform global calculations extending over a large range of nuclei. One of the advantages of these methods is that their results can still be interpreted in the intuitive picture of deformed shapes and shells. Qualitative agreement with the existing experimental data has been obtained for some series of isotopes (in particular the neutron deficient Kr and Pb isotopes) but a more quantitative agreement will require some substantial improvements of the methods (new symmetry breaking) and of the effective interactions. More dramatically, these microscopic models still fail to describe some other series of isotopes, like the Zr, from the proton rich to neutron rich ones. Detailed data on spectra, up to spins high enough to have a decreased effect of configuration mixings, are necessary to adjust the balance between prolate, spherical and oblates shapes. More data up to high spin states will also be necessary to improve the description of dynamical pairing correlations.

Considering the A=170-190 deformed region, and shifting away from the stability line toward a neutron-rich direction raises the neutron Fermi level toward the largest magic number N=126, in the medium and heavy nuclear systems. Just below the N=126 shell gap, many high-Omega states originating from high-j intruder orbitals (such as i13/2) are present. If the Fermi level is placed amongst these states, these nuclei may have substantial triaxial deformation at low spin, due to the shell effect. Rotation of a triaxial nucleus is an interesting research theme in terms of three-dimensional rotation. A lack of axial symmetry allows a triaxial rotor to rotate around any of the principal axes of the mass quadrupole moment. Under these circumstances, many types of multi-dimensional nuclear rotation have been intensively studied at present, such as chiral rotation, wobbling motion and tilted rotation.

Using the self-consistent 3D-cranked HFB method (3d-CHFB) and the generator coordinate method (GCM), we would like to investigate various types of nuclear rotation induced by the triaxial deformation in the neutron-rich region. Our particular interest is the following: (i) Coupling between high-K and low-K states through the wobbling mode, (ii) Quantum fluctuation effects of high-K and the role of tilted rotation, (iii) Transitions from 1D rotation to 2D, and/or 2D to 3D at high spin. In this research, dynamical effects in nuclear many-body systems are studied from a quantum mechanical point of view.

# Collective Modes in the Continuum

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**_Scientific case:_**
With the advent of high intensity neutron-rich beams, nuclear structure at the limit of excitation energies, angular momentum and N/Z ratio will be investigated in details through selective $\gamma$ spectroscopy measurements. In particular, it will be possible to study vibrational and rotational collective modes in exotic systems, employing both inelastic scattering and fusion evaporation reactions. In the following sections we present selected physics cases which can be addressed by the combined use of high intensity SPIRAL2 beams and of a large spectrometer such as AGATA and its ancillary (in particular large volume scintillator detectors for high-energy γ-rays). A table of key reactions will also be given at the end.

### 1- Inelastic scattering: Giant Quadrupole Resonances and high-lying states

Inelastic scattering reactions of high intensity exotic beams will allow investigating in detail Giant Quadrupole Resonance (GQR) states and high-lying states around the particle threshold.

The study of the GQR, a collective vibration where both the shape and the nucleon distribution change, will provide direct information about the bulk properties of nuclear matter and of the effective N-N interaction. The GQR is not expected to show a strong fragmentation and/or a downwards shift of the strength as the neutron number increases, but a stronger admixture between the isoscalar (IS, where n and p move together) and the isovector (IV, characterised by a separated motion of p and n) components is predicted.
Inelastic scattering of heavy ions at few tens of MeV/A can excite giant resonance states with an angular distribution which is not characteristic of the multipolarity of the mode but with an

enhanced cross section in comparison with p and α scattering. By investigating the γ-decay channel, both the multipolarity of the excitation and the microscopic structure of the state can be inferred. At present, the γ-decay of the GQR has been studied in few systems only [1], requiring very exclusive measurements of the total decay energy, which has to be equal to the energy of the inelastically scattered particles. In exotic systems, such as $^{132}$Sn and heavy Zr isotopes, the GQR could be studied in inverse kinematics, namely by measuring the excitation modes of the projectile at bombarding energies between 10 and 20 MeV/A, for which the yield of the GDR excitation is negligible compared with the excitation of other resonance states.

Inelastic scattering of neutron-rich beams from SPIRAL2 can also be used to investigate high-lying low-spin states in exotic systems. Among the most interesting states are the double-phonon states $2^+ \otimes 3^-$ and the high-lying electric dipole states around the particle threshold, which in neutron rich nuclei are expected to have a sizable strength (pygmy states). Good candidates for such studies could be neutron-rich Ba, Ce, Nd and Sn isotopes, whose stable nuclei have been studied by (γ,γ′) reactions [2].

**2- Giant Dipole Resonances at Finite Temperature: shapes and deformation**

Fusion evaporation reactions with high intensity neutron-rich beams will allow us to populate exotic compound nuclei, transferring more initial angular momentum compared to the use of stable beams. This will be crucial in high-spin discrete spectroscopy studies (which are the subject of another letter of intent[3], aiming, for example, at the search for hyperdeformed structures and extreme shape changes), but also in the study of the Giant Dipole Resonance (GDR) at finite temperature.

Giant Dipole Resonances can in fact be used to investigate the so-called Jacobi shape transition, a nuclear shape change at high angular momenta from oblate to triaxial and very elongated prolate. This transition has been predicted to appear in many nuclei in the liquid drop regime [3], and it is considered to be a gateway to hyperdeformed shapes. One of the principal signatures for the Jacobi transition is the splitting of the Giant Dipole Resonance strength function [4], together with the "giant back-bend" observed in the rotational frequency of the E2 bump as a function of angular momentum, at the highest spins [5]. In addition, a preferential feeding of the highly deformed structures in residual nuclei by the GDR low-energy component has been predicted and also experimentally observed in the case of the superdeformed $^{143}$Eu nucleus (see Figure 1 a)) [6].
Liquid drop calculations predict a very wide Jacobi spin window (from 60ℏ up to almost 100ℏ) for the $^{120}$Cd compound nucleus (see Figura 1 b) and c)), which can be produced at very high angular momenta in inverse kinematics by the SPIRAL2 reaction $^{94}$Kr on $^{26}$Mg. Other nuclei will be within reach by the use of radioactive beams, such as $^{98}$Mo (produced by $^{68}$Ni + $^{30}$Si), $^{71}$Zn (produced by $^{23}$N + $^{48}$Ca), together with some other cases which can be studied with high intensity stabe beams from LINAG, such as $^{98}$Cd (produced by $^{40}$Ca+$^{58}$Ni) and $^{44}$Ti (produced by $^{12}$C+$^{32}$S).

The investigation of the Jacobi shape transition at high spins with GDR and charged particles is the subject of another letter of intent[4]. In the present LOI we instead propose to couple

[3] Nuclear Shapes and High-spin spectroscopy (A. Görgen et al.)
[4] High-energy γ-rays as a probe of hot nuclei and reaction mechanisms (A. Maj et al.)

AGATA to high-energy γ-ray detectors, in order to study the correlations between the low-energy component of the splitted GDR strength function and the superdeformed (or hyperdeformed) structures in residual nuclei.

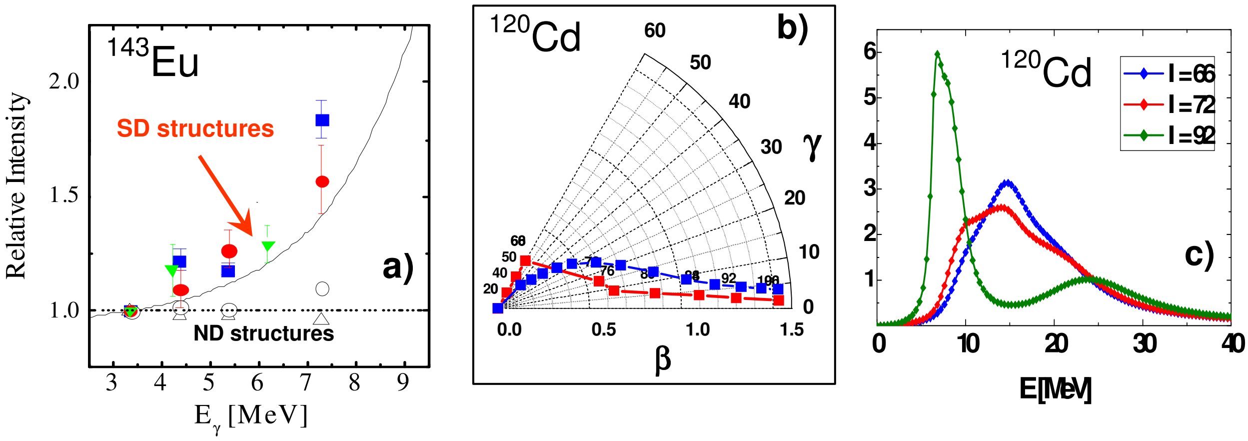


**Figure 1**: Panel a): In the nucleus $^{143}$Eu, the relative intensity of the superdeformed (SD) structures (filled symbols) is found to increase when a coincidence with high-energy γ-rays from the GDR resonance is requested. This is not observed in the case of the normal deformed (ND) structures (open symbols) [6]. Panel b) and c) show predictions for the Jacobi shape transition in hot $^{120}$Cd. In particular, panel b) shows the evolution of the equilibrium (red) and average deformation (blue) with angular momentum, while in panel c) the GDR strength functions for I=66, 72 and 92 are given.

### 3 - The Prompt Dipole Mode and the Reaction Dynamics

Giant Dipole Resonances will also be investigated in pre-equilibrium fusion reactions. In particular, reactions with very different values of the N/Z of the target and projectile are characterized by the presence of the so-called dynamical mode, which consists in pre-equilibrium dipole radiation emitted by the fusing system [7]. This topic is particularly interesting because it provides information on the charge equilibration time and on the symmetry energy of the nuclear matter at densities lower than the saturation value (see also the LOI for SPIRAL2 of V. Baran et al.). In addition, it represents a cooling mechanism to be exploited in the formation of superheavy elements with N~162, in hot fusion reactions.

This emission of the prompt dipole radiation is characterised by a low energy centroid, ~10 MeV, and can be isolated from the contribution of the GDR emitted after the equilibration of the system by comparing the E1 yield of two different reactions leading to the same compound nucleus, at the same excitation energy and spin: one (symmetric) employing target and projectile with similar N/Z and one (asymmetric) with projectile and target with very different N/Z.

The yield of the prompt dipole radiation is expected to increase by more than an order of magnitude making use of more and more N/Z asymmetric systems, such as the ones which will be within reach by the use of radioactive neutron-rich beams. In addition, by employing radioactive beams we will able to perform a systematic study of the phenomenon, as the same composite system can be formed by using many more target-projectile combinations than can be achieved with stable encounters. As an example, by producing the same compound nucleus $^{172}Yb$ with different projectile-target combinations (such as $^{132}Sn+^{40}Ca$, $^{77}Ni+^{95}Mo$, $^{140}Xe+^{32}S$, $^{94}Kr+^{78}Se$) one expects to observe an increase in the prompt dipole yield of more than an order of magnitude, as compared to stable projectile and target combinations, such as $^{48}Ca+^{124}Sn$ (see Figure 2).

Within this topic, at the onset of this mechanism it becomes important to measure simultaneously with high resolution and accuracy the distribution of residual nuclei with discrete spectroscopy. At higher temperature, set ups measuring neutron and charged particle spectra are instead crucial and for this we refer to LOI of A. Maj et al. (*High-energy γ-rays as a probe of ho nuclei and reaction mechanisms*).

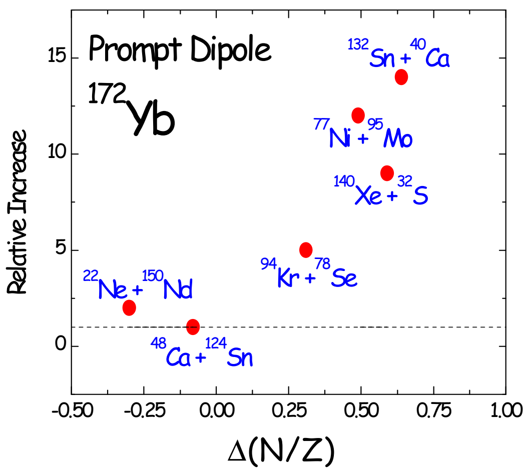


Figure 2: The yield of the GDR emission in pre-equilibrium fusion reactions leading to the compound nucleus $^{172}Yb$ is expected to increase significantly with the N/Z asymmetry of the projectile-target system. In the figure, the increase is calculated according to the model of ref. [8], and it is shown relative to the value obtained for the most symmetric case $^{48}Ca+^{124}Sn$.

### 4 - Collective rotation at finite temperature: order-to-chaos transition and superdeformation

The study of the *warm* rotational motion, namely of the nuclear rotation at moderate excitation energies above yrast (U≈ 2-4 MeV), plays a crucial role in the understanding of the properties of the nuclear system beyond the mean field description. It, in fact, provides relevant information on the two-body residual interaction responsible for the band mixing process [9].

Close to the ground state, the low-lying excited states are characterized by good intrinsic quantum numbers and consequently their decays are governed by selection rules. At higher energies, the level density and level mixing increase very much, therefore the concept of quantum numbers is broken. The disappearance of the quantum numbers characteristic of the intrinsic configurations is a signature of the quantum chaos, which in the atomic nucleus is found to be fully reached at the level of neutron resonance states (~6-8 MeV of thermal energy). Therefore, in the warm region, lying in between the regular g.s. regime and the chaotic region, there must be a transition from order to chaos. This is where the rotational motion is *damped*, namely the mean-field bands become strongly mixed, giving rise to a rotational E2 γ-decay fragmented over many final states. The width of the associated B(E2) strength function is defined as the rotational damping width $\Gamma_{rot}$ and it carries information on the properties of the nuclear systems at finite temperature.

The use of radioactive ion beams will allow to test the strong dependence of the damping width on spin and excitation energy [10], which has been experimentally verified only in a limited region of angular momenta [11]. This will provide a better understanding of the order-to-chaos transition and also the possibility to observe exotic effects associated with chaos, such as motional narrowing. In addition, variation of the damping width with neutron number will be studied, giving information on shell structure effects at finite temperature, as shown in Figure 3 a). In this respects, key reactions will be $^{132}$Sn on $^{48}$Ca (allowing to populate $^{176}$Yb up to 76$\hbar$, with an average excitation energy almost 1 MeV higher than achievable with stable beams), and $^{74}$Kr on $^{58}$Ni (which will populate the proton rich nucleus $^{128}$Nd, after the evaporation of 4 protons, allowing to study rotational damping as a function of the excitation energy).

We also plan to study the onset of chaos in terms of vanishing of selection rules on specific quantum numbers, such as K, the projection of the angular momentum on the symmetry axis [12]. Neutron rich Hf isotopes, for example, offer the possibility of investigating the warm rotating motion in both low-K and high-K configurations, and they will be within rich by the use of neutron rich beams of SPIRAL2. A possible reaction will be $^{136}$Te on $^{48}$Ca, allowing to populate $^{180,182}$Hf nuclei.

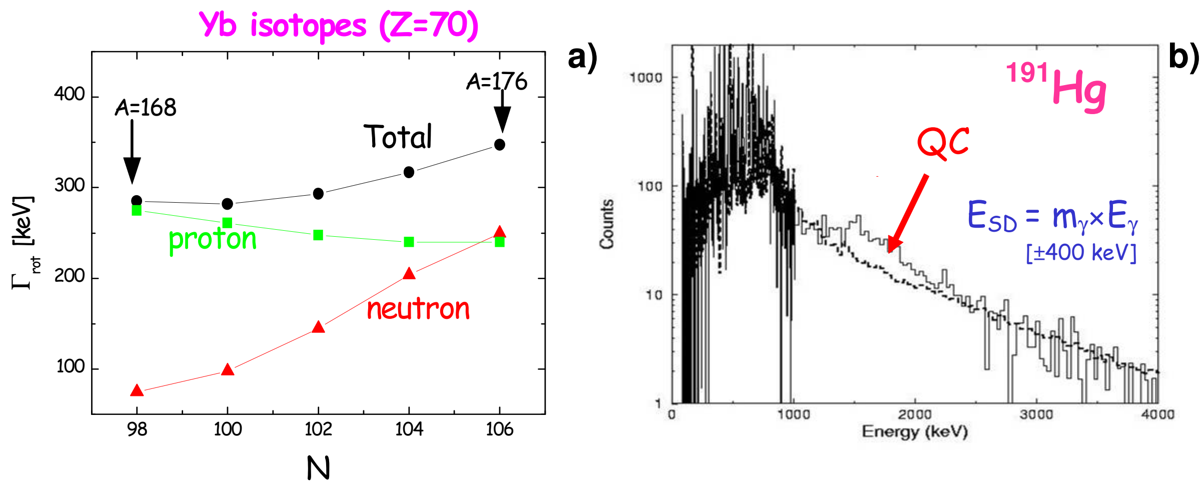


**Figure 3.** Shell effects on rotational damping are shown in panel a): in Yb isotopes the rotational damping width $\Gamma_{rot}$ (circles) increases ≈ 25% from A=168 to A=176, mostly due to neutron shell effects. The calculations [10] are performed at spin I=40$\hbar$ and thermal energy U≈2 MeV. Panel b) shows the experimental study of the quasi-continuum decay-out in the superdeformed nucleus $^{191}$Hg: from the comparison between spectra gated on ND (dotted line) and SD (solid line) transitions in $^{191}$Hg, the quasi-continuum distribution originating from the decay-out of the SD band is evidenced [13].

In the case of superdeformed (SD) nuclei, the use of exotic neutron rich beams will generally allow to better populate SD states, due to the ability of the nucleus to sustain larger angular momenta. In particular, the mass regions A≈190 and A≈110 will offer the possibility to investigate in details the properties of largely elongated shapes.

In the mass region A≈190, the study of the quasi-continuum decay-out spectrum in heavy Hg isotopes will provide an experimental estimate of the excitation energy of the SD band as a function of the A mass number (see Figure 3 b)), making it possible to test the predictive power of mean-fields theories [14]. Key reactions will be $^{152,154}$Nd beam on $^{48}$Ca target, which will populate $^{196,198}$Hg isotopes up to spin 60$\hbar$.

In addition, the study of largely elongated shapes in exotic systems will also give the opportunity to investigate the SD rotational quasi-continuum up to the highest spins, including the possibility to observe the occurrence of spectacular effects such as the ergodic/compound bands: a non-fragmented rotational decay between practically chaotic states [15]. This phenomenon is predicted to occur especially in heavy nuclei and highly deformed shapes, as for example neutron-rich Hg isotopes or Cd isotopes (A≈110). In the latter case, extremely large/hyperdeformed shapes are expected to be found going towards neutron rich systems [16], such as $^{114}$Cd which can be produced by the SPIRAL2 reaction $^{94}$Kr on $^{26}$Mg.

A precursor of the ergodic regime has been recently observed in excited SD bands of $^{194}$Hg [17] and theoretical predictions show that SD nuclei around $^{192}$Hg, in particular, are expected to exhibit this property [18]. This might be related to a special feature of the SD well of Hg nuclei, namely the presence of numerous high-K orbitals around the Fermi level. A fundamental question that needs to be addressed is whether SD shapes and high-K orbitals are necessary for ergodic-like flow, or whether the latter is only necessary. Therefore, the role of the K quantum number on nuclear ergodicity should be also investigated, and this could be done by studying, for example, the feeding of high-K states in normal deformed nuclei. Good candidates for these studies are the neutron rich Hf isotopes, already mentioned before.

TABLE 1. Selected key reactions using radioactive beams

| Reaction | Beam Energy (MeV/A) | Beam Int. (pps) | Physics Area (see above) |
|---|---|---|---|
| $^{132}Sn+^{40}Ca$<br>$^{140}Xe+^{32}S \rightarrow ^{172}Yb$<br>$^{94}Kr+^{78}Se$ | 4 - 6 | $\geq 1\times10^{9}$ | 2 |
| $^{94}Kr+^{26}Mg \rightarrow ^{120}Cd$<br>$^{68}Ni+^{30}Si \rightarrow ^{98}Mo$ | 9.4<br>7.4 | $\approx 1\times10^{10}$<br>$>10^{8}$ | 2 |
| $^{132}Sn+^{48}Ca \rightarrow ^{176}Yb+4n$ | 4.2 | $\geq 1\times10^{9}$ | 3 |
| $^{74}Kr+^{58}Ni \rightarrow ^{128}Nd+4p$ | 4.4 | $\geq 1\times10^{6}$ | 3 |
| $^{136}Nd+^{48}Ca \rightarrow ^{180}Hf+4n$ | 5 | $\geq 1\times10^{9}$ | 3 |
| $^{152,154}Nd+^{48}Ca \rightarrow ^{196,198}Hg+4n$ | 5 | $\geq 1\times10^{9}$ | 3 |
| $^{94}Kr+^{26}Mg \rightarrow ^{114}Cd+6n$ | 5 | $\geq 1\times10^{9}$ | 3 |

TABLE 2. Selected key reactions using LINAG beams

| Reaction | Beam Energy (MeV/A) | Beam Int. (pps) | Physics Area (see above) |
|---|---|---|---|
| $^{40}Ca+^{58}Ni \rightarrow ^{98}Cd$ | 6.3 | $>1\times10^{12}$ | 2 |
| $^{12}C+^{32}S \rightarrow ^{44}Ti$ | 14 | $>1\times10^{12}$ | 2 |

***Beams and targets***

A selection of a number of radioactive and stable beams required for the research program on collective modes employing fusion evaporation reactions is given in Table 1 and 2, together with estimates for the beam energies and intensities.

In addition, high intensity neutron rich beams of Sn and Zr (at 10-20 MeV/A) are foreseen in order to investigate in detail the properties of Giant Quadrupole Resonance states, as discussed in section 1. High intensity neutron rich Sn, Ba, Nd and Ce beams at ~10 MeV/A are also requested for the study of high-lying states around the particle threshold, which can be reached through inelastic scattering of the projectiles. We are aware that these energies might be a bit too high for the GANIL facility, but this scientific case could be a motivation for a SPIRAL2 extension towards higher energy in a second phase.

***Instrumentation and detectors***:

The study of the collective modes in the continuum with exclusive measurements requires a γ-ray spectrometer with high efficiency, resolution, and granularity. The ideal instrument for such studies is the AGATA spectrometer comprising as many detector modules as possible and available. In some specific cases the coupling to scintillators and other ancillaries is foreseen. Since in many cases we are interested in transitions of 5-15 MeV we are investigating in detail the AGATA response in this energy interval. In addition we are working on a new procedure, based on pulse shape and tracking, to improve the time resolution of the Germanium. This is crucial for neutron discrimination.

The coupling of the AGATA spectrometers to an array of large scintillator detectors for high-energy γ-rays is part of the planned program, as previously done within the EUROBALL collaboration. This will allow toperform exclusive measurements in which giant resonance states are studied in specific nuclear shapes and configurations. At present, the simplest solution for an ancillary based on large volume scintillators is the use of detectors already existing in Europe, as for example the HECTOR array.

***Theoretical support***:

Several theoretical groups in Europe, Japan and US are active and interested in the theoretical study of collective modes, both in terms of vibrations and rotations, such as the theory group in Milano, Orsay, Strasbourg, Copenhagen and Niigata. In particular, part of the proposed program on giant resonances will be carried out in strong contact with the theory groups of Milano (P.F. Bortignon, G. Colò) and Orsay (E. Khan) who have developed models based on Random Phase Approximation (RPA) calculations. The inclusion of pairing and temperature degrees of freedom in these microscopic models will allow a strong interplay with experiments such as pairing critical temperature determination, or the decay of gaint pairing vibrations. The Milano group will also take care of the informatic tools. For the study of the warm rotation, shell model calculations at finite temperature have been developed, together with simulation models of the γ-decay flow (T. Døssing, M. Matsuo and E. Vigezzi). In all cases, extensions to more exotic systems are foreseen, in order to interpret the nuclear structure far from stability.

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# Nuclear Electromagnetic Moments at SPIRAL2

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***Scientific case:***

Nuclear magnetic moments are sensitive to the orbits occupied by the valence particles (or holes) and can thus be used to test the configuration purity. The quadrupole moment probes the deformation and collective behaviour of nuclei both at low and high excitation energy. Generally speaking, the magnetic moments are sensitive to 1p-1h excitations across a magic shell gap, whereas quadrupole moments are sensitive to quadrupole, particle-core coupling interactions (2p-2h excitations). Both quantities can be directly compared with theoretical predictions, thus providing an excellent tool to probe nuclear models. This plays an important role in understanding the basic ingredients needed to explain the changes in the nuclear shell structure of nuclei far from stability.

**Proton radioactivity and electromagnetic moments of proton-emitting states**
Experimentally, the proton drip line has been fully mapped up to Z=30 and, in a fragmentary way, for odd-Z nuclei up to Z=91. Decay by direct proton emission, which occurs for drip-line nuclei, provides the opportunity to study the structure of unbound systems even beyond the drip line. The phenomenon of ground-state proton radioactivity is determined by a delicate interplay between the nuclear attraction and the Coulomb and centrifugal terms of the

effective potential. Although the highest-lying protons occupy states with positive energy, they still experience the Coulomb and centrifugal barriers. Ground state proton emission is thus dictated by quantum-mechanical tunnelling. The emitted proton is characterized by a discrete value of the energy and a resonance width or its inverse, the half-life.

A theoretical description of spherical proton emitters is relatively simple, but accurate models for proton decay rates from deformed nuclei have been developed only very recently. Even the most realistic calculations, however, are not based on a fully microscopic and self-consistent description of proton unstable nuclei. It is still not possible, for instance, to predict within the same theoretical framework which nuclei are likely to be proton emitters, and to calculate the respective decay rates. Below Z=50, proton decay from the ground state has not been observed experimentally, but some excited proton-emitting states have been identified with long half-lives in $^{53}$Co and $^{94}$Ag and in nuclei near the doubly magic $^{56}$Ni. In the last of these cases, the decaying states are highly deformed whereas the final states are almost spherical. The pronounced difference between the wave functions of the parent and daughter nuclei strongly hinders the decay. Such a process cannot be described within a simple single-particle framework and, therefore, presents a serious challenge for the modeling of proton emission. In $^{54}$Ni and $^{94}$Ag the proton emitting states are long-lived isomers. Studies of the g factors and the quadrupole moments of such states will enhance the development of theoretical models. Further candidates for long-lived proton-unbound isomers are probably $^{95m}$Ag ($37/2^+$) and $^{98m}$Cd ($12^+$), which were recently identified by γ-ray spectroscopy, or have been predicted to occur in $^{96}$Cd ($16^+$), $^{97}$Cd ($25/2^+$) and $^{100}$Sn ($6^+$). At present, only the *g* factor and the quadrupole moment of the proton-emitting isomer in $^{54}$Ni are within reach, but the development of more intense exotic beams will enhance such studies.

**Electromagnetic moments of neutron-rich isotopes**

The properties of neutron-rich isotopes, in particular the doubly closed shell nuclei $^{48}$Ca (Z=20, N=28), $^{78}$Ni (Z=28, N=50), $^{132}$Sn (Z=50, N=82) and their nearest neighbours are of considerable nuclear-structure and astrophysical interest, some of them being candidates for waiting points in the astrophysical r-process. In this context, the study of their electromagnetic moments provides a unique opportunity to tune the nuclear models.

With increasing proton/neutron excess one expects modifications of the nuclear mean-field potentials, which in turn modify the position of the single-particle levels. Since in some cases the neutron-proton interaction is strong, the neutron potential depends not only on the neutron but also on the proton number. Overall one observes a gradual migration of single-particle levels, which may even cross within one major shell.

This effect was observed recently in the case of neutron-rich copper isotopes located one particle away from the singly-magic $^{68}$Ni. Due to the coupling between the valence proton and the additional pairs of neutrons filling the $1g_{9/2}$ orbital, the excitation energy of the $1f_{5/2}$ proton orbital decreases from 1.214 MeV to 0.166 MeV when moving from $^{69}$Cu to $^{73}$Cu. This so-called "monopole migration" phenomenon may induce an inversion of the $1f_{5/2}$ and $2p_{3/2}$ proton orbitals in $^{77}$Cu or $^{79}$Cu. Such a migration may have major consequences for the size of the magic gaps, and therefore on the modification of the known magic numbers for nuclei far from stability. At present the migration of single-particle levels is the subject of intensive investigation. Around $^{132}$Sn, for example, some energy levels are known in $^{133}$Sn, $^{131}$Sn, $^{133}$Sb and $^{131}$In, which make it possible to determine the separation in energy between the $g_{7/2}$ and $g_{9/2}$ proton orbits, or the $h_{9/2}$ and $h_{11/2}$ neutron orbits. Nuclear *g* factors are a sensitive tool to probe such effects since they provide information on occupation numbers.

The spectroscopic information on $^{78}$Ni and its neighbours is rather poor to date. The half-life of $^{78}$Ni was measured following the fragmentation of relativistic beams of stable isotopes. Isomeric states are expected to exist in this region. Studies of their electromagnetic moments will allow detailed knowledge of the nuclear wave functions and the onset of deformation. At present *g* factors of isomeric states built on the $\nu g_{9/2}$ orbit are studied in the vicinity of $^{68}$Ni.

At present much more spectroscopic information exists on $^{132}$Sn and its nearest neighbours. However, studies of electromagnetic moments in this region are rather limited, especially when the doubly-magic $^{132}$Sn is approached. One of the future tasks for experimenters will be to gain information on the electromagnetic moments of the nearest neighbours of $^{78}$Ni, to go beyond the neutron shell closures at N=50 and N=82, and to search for neutron-radioactive isomers and eventually measure their *g* factors. The latter phenomenon, which has not been observed to date, has been predicted to occur, e.g., in $^{63}$Ti (Z=22) as a $\{\pi(1f_{7/2}{}^{2})_{6+}\otimes\nu(1g_{9/2})\}_{21/2+}$ configuration with a half-life of 4 s, and in $^{67}$Fe(Z=26) as a $\{\pi(1f_{7/2}{}^{-2})_{6+}\otimes\nu(1g_{9/2})\}_{19/2+}$ configuration with a half-life of 50 µs.

**Single-particle properties and many-body effects**

Apart from the migration of pure single-particle levels, which results from modifications of the mean fields when the number of nucleons varies, other physical phenomena may influence the single-particle shell structure of nuclei, as well. The most spectacular are those related to deformation effects, whereby open-shell nuclei exhibit single-particle levels characteristic of nucleons moving in a deformed mean field. This can be understood as a strong coupling, mostly of a quadrupole character, between the individual particles and the core formed by all the other nucleons. Studies of nuclear quadrupole moments allow probing of nuclear deformation and in this way provide a tool to investigate collective phenomena in atomic nuclei.

**Intruder states**

In a deformed mean field, the energies of high-*j* orbitals depend very strongly on the deformation, and such single-particle orbitals may fairly easily cross the spherical gap of a magic nucleus. Therefore, by exciting particles across the magic gap, and into these deformation-driving states, one obtains deformed intruder configurations that are observed in various regions of the nuclear chart. In most of the cases such states are isomeric and measurements of their electromagnetic moments are possible.

The intruder configurations are very interesting from the point of view of measuring the sizes of magic gaps. However, they can provide useful information about the single-particle structure only after careful analysis of the many-body aspects of the problem and an important observable in this case is the nuclear quadrupole moment. The energies of such intruder configurations depend not only on the "initial" positions of high-*j* orbitals at spherical shapes, but also on the strength of the quadrupole-quadrupole component of the nuclear interaction as well as its monopole components (e.g. pairing) that act towards restoring the spherical symmetry. Moreover, these many-body configurations can easily mix with the ground-state magic configurations thus perturbing the magicity of certain nuclei. Altogether, the study of intruder states requires a comprehensive approach which can potentially provide invaluable information on nuclei near magicity. The evolution of nuclear properties measured along extended isotopic chains, will be particularly important in improving theoretical descriptions.

**Nuclear shapes and shape coexistence**

Nuclei with closed proton and neutron shells are always spherical in their ground state. In nuclei with partially filled shells the valence nucleons polarize the nucleus to a deformed mass distribution. The shape of a nucleus is not directly observable. The closest measurable quantities are the expectation values of the electric multipole moments, i.e. for the distribution of the protons in the nucleus. These are accessible in favorable cases via Coulomb excitation measurements. Information on the nuclear shape is often derived from rotational properties and in particular from electromagnetic transition probabilities. The nuclear shape does not only vary with proton and neutron number, but can also vary within the same nucleus, since the nucleons can occupy different orbitals polarizing the nucleus in different ways. Spectacular examples for coexisting shapes in the same nucleus are superdeformed nuclei, even though the normal- and superdeformed states differ significantly in excitation energy. Sometimes shape-coexisting states are found within a narrow energy range, for example in the neutron-deficient lead isotopes, where spherical, prolate and oblate shapes differ by less than 1 MeV, or the krypton isotopes near the $N=Z$ line, where the coexistence of prolate and oblate shapes has been proven recently at SPIRAL. The wave functions of shape-coexisting states of the same spin and parity can mix if they are energetically close, and low-lying excited $0^+$ states corresponding to a shape different to that of the ground state (in even-even nuclei) can have long lifetimes (*shape isomers*). The situation is different when deformed collective and non-collective states coexist. Such high-K states preserve their identity up to relatively high excitation energies which implies that these states do not mix with the other states around and below them, and they are also often isomeric.

Very abrupt changes from oblate to very deformed prolate ground-state shapes are predicted in the region around the fission fragments with mass A≈100, for example in the Sr and Zr isotopes with N=60. These nuclei will be abundantly produced at SPIRAL2, and detailed measurements of the static and transitional quadrupole moments with Coulomb excitation will allow understanding the shape transition and coexistence in this region. Other key experiments on the neutron-rich side of the valley of stability concern the development of collectivity around $^{132}$Sn and towards $^{78}$Ni.

On the proton-rich side, the various production schemes of SPIRAL2 permits extending the study of nuclear shapes and shape coexistence to higher masses and to go closer to or even beyond the N=Z line, for example by in-flight production of the exotic nuclei followed by Coulomb excitation. A more detailed description of the physics of nuclear shapes and shape coexistence can be found in the Letter of Intent “Nuclear shapes and high-spin spectroscopy”.

**Structure of heavy and superheavy nuclei**

It is clear that the studies of synthesis must be accompanied by studies of the nuclear structure and reaction mechanisms, in order to understand the physics of superheavy nuclei in a complete and coherent way. Current devices make it possible to study the structure of the superheavy elements, and to understand how it influences their stability, i.e. to know their shapes and their decay times. The trends of these variables for individual elements can be expected to vary according to the number of neutrons. A particularly interesting aspect for such studies is to investigate the *g* factors of shape isomers in the transactinides and of intruder isomers in superheavy isotopes (see also the LoI “From actinides to superheavy elements with SPIRAL2: reaction dynamics and structure”). The former study will allow the levels in the second minimum to be fixed, which will be a first direct investigation of the shell structure of superdeformed nuclei. The latter measurements will be a direct test of the shell model for superheavy isotopes.

The high-intensity stable-isotope beams delivered by SPIRAL2 will allow us to extend the spectroscopy to a wider range of nuclei in terms of neutron number and higher Z. This is necessary to explore and to understand the trends in the single particle levels that ultimately indicate the onset of the long sought shell gap.

Some further points both on the physics motivation of nuclear moment measurements and on the regions of the nuclear structure studies where they can be applied can be found in the LoI on "High-resolution γ-ray spectroscopy" - "Nuclear Shapes and High-Spin Spectroscopy".

***Methodology:***

Due to the large variety of techniques for nuclear moment measurements we present them here grouped around two main subjects, namely, transition probability determination and measurements of static electromagnetic moments. Short description of these techniques will be introduced. Specific beam-, target- and equipment requirements will be presented in parallel for each of the techniques where appropriate.
Although some subjects of nuclear moment measurements are already covered in other Letters of Intent (see e.g. LoI of DESIR) here we will try to focus our discussion mainly on experiments that require γ-ray detection systems and/or necessitate the use of post-accelerated beams. The here presented techniques, having similar bases with those presented in the LoI of DESIR, should be considered as complementary ones and by no means in competition.

**Transition probabilities**

- ***Coulomb Excitation***

Nuclear excitation by the time-dependent electromagnetic field acting between colliding nuclei is called Coulomb excitation. Contributions from the nuclear force can be excluded for bombarding energies well below the Coulomb barrier. This so-called safe Coulomb excitation has to be distinguished from Coulomb excitation at intermediate energy (typically around 50·A MeV), where nuclear contributions are minimized by the selection of small scattering angles, i.e. large impact parameters. The excitation probability is a direct measure of the electromagnetic matrix elements connecting collective states. In the case of intermediate energy, the interaction time is very short and only the first excited state is populated, allowing the measurement of the B(E2;0+→2+) value for even-even nuclei. At safe energies higher-lying states can be populated in multiple steps. While the excitation probability depends to first order only on the transitional matrix elements, the second order reorientation effect is also sensitive to the diagonal matrix elements and therefore to the static quadrupole moments including their signs. The availability of high-quality radioactive beams around the Coulomb barrier allows determining static quadrupole moments of short-lived excited states for the first time. In order to exploit the reorientation effect, the differential cross section has to be measured as a function of scattering angle and/or atomic number of the target. The electromagnetic matrix elements are determined by comparing the measured γ-ray yields to Coulomb excitation calculations. In favorable cases this results in a complete set of both transitional and diagonal matrix elements for the states populated. Reorientation measurements with weak radioactive beams are difficult due to the limited statistics.

Complementary lifetime measurements to determine the transition strengths in an independent way are helpful to determine static quadrupole moments in such cases.

Additionally to the standard application of the Coulomb excitation techniques on even-even nuclei some recent results from REX-ISOLDE (e.g. experiment IS435) have shown their power for the study of odd-mass and odd-odd-nuclei. The specific selectivity of the Coulomb excitation mechanism can not only be used for the determination of the transition probability connecting two states but also in order to populate them. In several cases new levels, not observed up to now in any other studies, have been populated. The existence of more than one β-decaying state is often observed especially in odd-odd nuclei. Having the possibility to obtain isomerically pure beams of those states gives the unique possibility to investigate particular structures in the same nucleus. Therefore, we would like to stress the necessity to investigate the possibility of producing **isomeric beams** at SPIRAL2

While beam intensities of a few thousand ions per second are sufficient to measure transition rates, a reorientation measurement requires at least $10^5$ pps. Beam contaminants are problematic and the exact beam composition has to be known. A highly segmented double-sided silicon detector is placed typically a few centimeters downstream from the target in order to measure the scattered particles. The excitation probabilities are determined from the γ-ray yields measured with an efficient germanium detector array such as EXOGAM. The technique is well established for stable beams and has been successfully applied with weak radioactive beams from SPIRAL 1.

- ***Lifetime measurements***

An alternative way to determine transition rates between excited states are lifetime measurements. Transition rates of relatively long-lived states with lifetimes above ~10 ps can be directly measured using detectors based on fast scintillator materials like $BaF_2$ or the newly appearing $LaBr_3$. Most excited states, however, have shorter lifetimes. In these cases Doppler-shift techniques can be employed. Lifetimes down to ~1 ps can be measured with the Recoil-Distance Doppler Shift (RDDS) method. The excited states are populated in a thin target and the recoils are stopped after a certain distance of some μm. The distance is adjusted and controlled with a so-called *plunger* apparatus. If the flight time is of the order of the lifetime of the state of interest, the transition depopulating the state will consist of a Doppler shifted and a stopped component. Varying the distance changes the intensity ratio of the two components and allows extracting the lifetime. The technique is primarily used with fusion-evaporation reactions, but other reaction types are not excluded. Stopping of the radioactive beam near the target will, however, not be feasible in most of the cases because of the background radiation from the beta decay. The problem can be avoided by replacing the stopper with a degrader foil, so that two components corresponding to different recoil velocities are observed. This differential technique has furthermore the advantage that the recoils can be identified in a spectrometer such as VAMOS. Germanium detectors from EXOGAM and/or AGATA should be placed at backward and, if possible, forward angles, where the Doppler effect is largest. The construction of a plunger device dedicated to GANIL and compatible with VAMOS should be initiated. Even shorter lifetimes of a few hundred femtoseconds can be measured using the Doppler Shift Attenuation Method (DSAM), where the Doppler shifts of the transitions are compared with modeled velocity profiles of the recoils in the target material and/or a target backing. As for the RDDS method, the radioactive beam should not be stopped, which makes the application of DSAM more difficult but not impossible. Such experiments require an efficient and granular germanium detector array such as AGATA.

## Static Electromagnetic Moment Measurements

A common point for any of the here presented techniques for static nuclear moment measurements is that they require an ensemble of initially spin-oriented nuclei that is interacting with an external electromagnetic field in which it is immersed. Therefore some of the key points in these measurements concern the way to obtain a sufficient degree of nuclear orientation or sufficiently high external field, which should allow a measurable modification of the initial nuclear orientation within the life-time of the nuclear state. This inevitably brings the necessity to apply different techniques for the specific ranges of the lifetimes of the investigated states.

- ***Transient Fields and Recoil-in-Vacuum***

The Transient Field (TF) and the Recoil-in-Vacuum (RIV) techniques are using the very strong magnetic fields, produced either in medium (ferromagnetic materials) or of the atomic electrons around the nucleus, in order to give an access to nuclear moment measurements of extremely short lived states (~1 ps). We plan to use these methods in order to measure nuclear states produced mainly after the Coulomb excitation of post-accelerated beams at SPIRAL 2.

In the transient field technique the 1s electrons of the ions of interest are polarized during their passage through a ferromagnetic target layer via spin exchange interactions with the polarized electrons of the ferromagnetic host. The hyperfine interaction between the nuclear spin, aligned due to the reaction kinematics, and the oriented electron spin leads to a precession of the nuclear spin about a fixed axis (given by the direction of the external magnetic field) and thus to an observable *rotation of the angular distribution* of the γ-rays emitted in the decay of the state. This technique has been applied since many years in stable beam experiments. A particularly successful version of this technique, namely its application to excited states populated in Coulomb excitation in inverse kinematics at beam energies of a few MeV/u, has been developed in recent years by the group of Prof. Speidel at the University of Bonn. Although so far it has mainly been applied to stable ion beams a first test of its application to radioactive beams has been performed last year at REX-ISOLDE and the measurement of the first $2^+$ g-factor in $^{138}$Xe using the transient field technique will follow this year. The results from the first application of the TF technique on nuclear states produced at intermediate energy Coulomb excitation at MSU, USA have shown that considerably higher magnetic fields are to be expected at these energies. This can have an additional positive impact on the TF measurements using the post-acceleration of CIME cyclotron at SPIRAL2 since energies well above the Coulomb barrier can be reached for a large variety of species.

The second technique of choice for the measurement of magnetic moments of short-lived excited states is the recoil-in-vacuum (RIV) method. Here, the nuclei in the excited state of interest populated for example by Coulomb excitation leave the target and recoil into vacuum. In this case the electron spins are randomly oriented and the hyperfine interaction between them and the aligned nuclear spin leads to a precession of the nuclear spin about random axes. The net effect in this case is the observation of an *attenuation of the angular distribution* of the subsequently emitted gamma-rays. This technique has been successfully applied for the first time recently in a radioactive beam experiment at Oak Ridge to measure the g factor of the first excited $2^+$ state in $^{134}$Te.

For both the TF and RIV techniques it is very important that stable beams with the same characteristics (chemical element, energies, etc.) are available for proper calibration. Therefore an installation of an **ion source for CIME, able to produce the whole variety of elements available at SPIRAL 2** is of very high importance.

- ***Time Integral- and Time Differential Perturbed Angular Correlations and Distributions***

The Time-Dependent- and Time Integral Perturbed Angular Correlations and Distributions (TIPAC and TDPAD) are general techniques usually used in order to gain access to the nuclear moment measurements of excited states in the lifetime range of tens-of-picoseconds to a few micro-seconds. The basis of these techniques is the application of a magnetic field that induces a Larmor precession of the nuclear spin-ensemble. Subsequently, (depending on the life-time of the state under study, its g factor, and the applied field) this can be observed either as a partial- (time-integral technique) or multiple- (time-differential techniques) rotations within the life-time of the state. If the applied magnetic field is determined, then the gyromagnetic factor of the studied state can be derived. The time-integral techniques are usually applied to shorter-lifetime states and the time-differential ones are more suitable for the longer-lived (isomeric) ones.

- ***Time-integral techniques (~10 ps – few ns lifetimes)***

No initial spin-orientation is necessary for the angular correlation measurements. The rotation of the spin ensemble is determined via the detection of γ-rays in a cascade and the initial space-orientation is determined by the detection of the direction of the γ-transition populating the state under investigation. This brings the necessity of higher beam intensities compared to the angular distribution variant of the method. To produce a rotation large enough to be measured (at least a few tens of mSr) static hyperfine fields are used, which are experienced after implantation into a magnetised ferromagnetic host. These fields vary in strength but are typically between a few and 100 Tesla. If the lifetime of the state is known then a magnetic moment can be extracted from the measured rotation of angular correlations.

One of the probably most suitable ways to populate the nuclear states to investigate via TIPAC is the β-decay, since it gives access to the most intense beams. Its drawback, the population or relatively low-energy- and low-spin states from the mother nucleus, can be avoided using some other production mechanisms. Several reactions with radioactive beams like e.g. transfer- and incomplete fusion reactions are known to produce substantial alignment. The deep-inelastic reactions are thought to be suitable too. This gives a wide range of methods to access low-to-intermediate spin states in very neutron-rich rare nuclei. **Further R&D studies** in order to allow the application of different production mechanisms for magnetic moment studies are indispensable.

- ***Time-differential techniques (few ns – few μs lifetimes)***

An essential point for the Time Differential Perturbed Angular Distribution (TDPAD) measurements is the initial spin-orientation in which the nuclear states are produced since this determines the level of sensitivity of the method and the lower limit of the necessary beam intensity. As mentioned above several reaction mechanisms are known or thought to produce a substantial nuclear alignment. However, further work is necessary in order to better understand the mechanism via which this orientation is obtained in order to gain some better control over it and eventually increase it via e.g. particle-γ correlations.

Another very important point in the application of the TDPAD is the determination of the t=0 for the time-differential measurements. This is usually done via a pulsing of the beam. The natural beam pulsing of the CIME cyclotron (~10 MHz) is a very good starting point and its period is well sufficient for isomeric states having half-lives bellow 50 ns. For the longer-lived isomers it is necessary to find a way for a **beam pulsing on a μs scale** without any substantial loss of the beam intensity.

- ***Tilted Foils***

In the β-NMR method, widely used for the nuclear moment measurements of the ground states of unstable nuclei, the nuclei are polarized using various possible mechanisms such as reaction polarization, optical pumping and low-temperature orientation. The resulting asymmetric distribution of the emitted β-particles is monitored in the presence of an external static magnetic field and a perturbing rf field. The particular method chosen for polarizing a given nucleus depends mostly upon properties such as life times and atomic structure.

In the case of tilted foil (TF) geometry, atomic polarization is initially induced in ionic electrons by a surface interaction upon the exit of an ion from a thin foil, tilted at an oblique angle with respect to the ionic beam direction. The atomic polarization (in the direction n **x** V - where n is the unit vector perpendicular to the outgoing surface of the foil and v is the ion velocity vector) is transferred to the nucleus via the hyperfine interaction. The nuclear polarization thus induced can be enhanced, especially for high-spin states, by the use of several foils spaced sufficiently as to allow a significant nuclear precession around the total angular momentum in the flight time between successive foils. As a consequence, for short-lived nuclei in the ms range, or for elements not readily amenable to laser techniques, the tilted foil method has a broad potential when combined with the β-NMR technique that stems from its "Universality" even if the TF induced polarizations may be not very high.

Previous experience with the application of the TF technique on a High-Voltage (HV) platform at ISOLDE has demonstrated its feasibility as well as the extreme experimental difficulties caused by the use of a HV platform. SPIRAL2 with the possibilities of CIME to post-accelerate a variety of radioactive nuclei at quite low energies (1 – 2 MeV/u) will be an ideal place for these types of studies.

For the successful application of a TF measurement beam intensities of the order of $10^3$ p/s or, depending on the case, even lower are sufficient. Since this technique is based on the interaction of the ions with the surface of the foils it is expected that the highest degree of polarization can be obtained at beam energies from a fraction of a MeV/u up to 1-2 MeV/u. With the present LoI we would like to stress **the necessity to further investigate possibilities to obtain low-energy post-accelerated radioactive beams after CIME** at SPIRAL2.

***Target(s)***:

Most of the techniques for nuclear moment measurements require the stopping of the beam, or at least of the reaction products, in the target/host material. This might appear in contradiction with the necessity to avoid the presence of any fraction of the radioactive beam close to the detection point in order to avoid the high background form its β-decay. Therefore it is essential to **develop techniques for very precise control of the target thickness**. In this sense the use of gas targets or targets in which at least a part of them consists of a gas material and which thickness can be easier controlled via a modification of the gas pressure is something to be developed.

For the application of the transfer reactions in order to populate the states of interest it is very important that different deuterated materials are investigated as possible targets and hosts.

We find that it is a must that well equipped **target laboratory** with knowledgeable and well trained target-makers is established at SPIRAL2.

***Instrumentation and detectors***:

Most of the techniques presented here are based on the detection of γ-rays originating from the decay of excited states. Therefore, we strongly support the presence of **AGATA** at SPIRAL2 as well as the upgrade of **EXOGAM** proposed in the Letter of Intent "High-resolution γ-ray spectroscopy". Due to the requirements of the techniques described above, germanium detectors are needed at specific angles with respect to the beam axis. Any detection setup that does ***not*** have a 4π-coverage should therefore allow the positioning of detectors at these specific angles.

We are additionally considering the construction of a new **plunger device** for SPIRAL2. A compact magnet should be included in the center of the setup for most of the experiments envisaged. The possibility to implement a liquid Helium cold finger as well as an "oven" for the target holder will allow reaching and controlling any specific temperature in the range between 4 K and few hundreds of Kelvin.

Another option for the γ-ray detection which we envisage is related to the use of a **4π scintillator array** with very good energy resolution (~ 2 – 3 %) and excellent time resolution (~ 1 ns or bellow). For many of the techniques described in the present LoI (e.g. most of the cases related to isomeric state measurements) such an array can cover most of our needs. Therefore we strongly support the LoI on "High-energy γ-rays as a probe of hot nuclei and reaction mechanisms" by A. May et. al.

***Theoretical support***:

Magnetic dipole and electric quadrupole moments are very sensitive to all types of correlations: pairing type, as well as collective ones. Comparisons between experimental values and theoretical ones from mean-field calculations (Hartree-Fock-Bogoliubov) and beyond mean-field calculations (Generator Coordinate Method with the Gaussian Overlap Approximation or exact configuration mixing calculations including symmetry restorations) will allow us to analyze the effect of long range correlations on single-particle states. Indeed, such observables will serve to i) challenge our microscopic predictions based on Gogny or Skyrme forces, and ii) possibly suggest new tracks for improving our present models.

$B(E2)(0^+ \rightarrow 2^+)$ reduced transition probabilities in even-even nuclei are of key importance for testing the effective force through collective models predictions based on Generator Coordinate Method. Extended measurements in neutron-rich nuclei will probe collective properties far from stability.

The shell-model, combined with pertinent effective interactions allows us within a defined model space to mount exact calculations of a many-body system. As such one can study nuclear spectra starting with a free nucleon-nucleon interaction and/or three-body interactions. A discrepancy with experiment can then be used to improve both our approximations to a model space and our many-body formalism. Magnetic moments and E2 transitions are extremely good tests of both collective and single-particle properties of a many-body wave function. Within a shell-model picture one can easily extract this information from the obtained many-body wave function.

Of interest to this particular project is the development of improved effective two-body interactions for the shell-model, based on both a G-matrix renormalization and a no-core renormalization of the free nucleon-nucleon force. Higher-order many-body terms not included in the renormalization of the free force will be included using both the Coupled-Cluster approach and the resummation of the Parquet type of diagrams. Furthermore, the inclusion of three-body forces, in addition to effective three-body terms generated by the two-body force, will be included in our shell-model studies. As such, we will be able to tell how much a three-body force influences the properties of these nuclei.