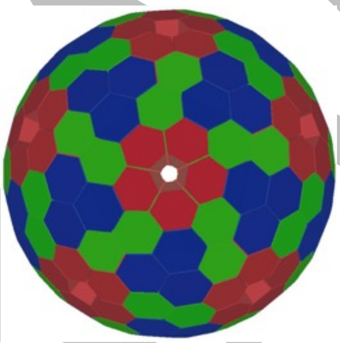
AGATA

Advanced Gamma Tracking Array

Physics Case

Phase 2 (2021-2030)



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(List to be completed)

AGATA White Paper – Draft Version 2019.05.24

Executive Summary

The properties of the nucleus, being a many-body quantum system, arise from the combined action of the strong and electromagnetic forces acting between the elementary particles that are its basic constituents. Establishing how the complex nuclear behaviors emerge from the fundamental laws of quantum chromodynamics is one the goals of modern nuclear physics. In order to reach this goal, one attempts to push atomic nuclei to the extremes: those of the isospin (neutron-to-proton ratio N/Z), mass (A), temperature (E*), angular momentum (I) or density of the nuclear matter. This implies studying various regions of the Segré chart in diverse experimental conditions, which requires, in turn, to make use of the variety of existing accelerator facilities so that the applied reaction mechanism provides the best experimental sensitivity to key observables.

One of the most sensitive probes used in nuclear physics studies is the electromagnetic radiation. In most applications High Purity Germanium (HPGe) detectors, which currently hold the record in terms of energy resolution, are by far the most powerful. Tracking arrays based on HPGe crystals mark a major advance in the development of gamma-ray detector devices, as they can withstand higher counting rates, provide unprecedented Doppler-correction capabilities and enhanced polarization sensitivity. Compared to conventional arrays based on Compton-suppressed HPGe detectors gains of up to 3 orders of magnitude in the sensitivity to weak decay paths are expected.

This document describes the physics opportunities with the Advanced Gamma Tracking Array (AGATA), a truly universal high-resolution spectrometer, capable of measuring gamma rays from a few tenths of keV to beyond 10 MeV, with unprecedented efficiency, excellent position resolution for individual gamma-ray interactions and with very high count-rate capability.

According to the recommendations in the latest long-range plan from NuPECC[1] "AGATA represents the state-of-the-art in γ-ray spectroscopy and is an essential precision tool underpinning a broad programme of studies in nuclear structure, nuclear astrophysics and nuclear reactions. AGATA will be exploited at all European large-scale radioactive and stable beam facilities and in the long-term must be fully completed in full 60 detector unit geometry in order to realise the envisaged scientific programme."

As described in this document AGATA will make essential contributions to many of the most pertinent questions that modern nuclear structure physics is facing such as

- How does the nuclear chart emerge from the underlying fundamental interactions?
- How do the simple patterns and symmetries present in nuclear structure emerge from the complex properties of the nucleon-nucleon forces?
- How do nuclear shapes evolve across the nuclear landscape?
- How does nuclear structure change with temperature and angular momentum?

This White Paper describes the new physics opportunities for which the use of AGATA will be pivotal: The study of shell evolution, understanding the microscopic origin of nuclear deformation and the interplay between single-particle and collective degrees of freedom, the search for exotic and extreme shapes (in particular nuclear hyperdeformation), establishing shape coexistence and shape transitions, and understanding the underlying mechanisms, testing theoretical predictions for neutron and proton skins, probing the nature of pair correlations and investigating how angular momentum is generated, measuring the degree of isospin-symmetry breaking, finding fingerprints of chaos in nuclei, etc.

[1] NUPECC Long Range Plan 2017, www.nupecc.org/

Introduction

Nuclear structure studies far from stability are entering into a high-precision era with increased intensities and purity of radioactive ion beams and new methods to produce exotic nuclei using stable beams. High-resolution γ-ray spectroscopy is the only method capable of unravelling the complex structure of excited states and has therefore always played a prominent role in the understanding of nuclear structure. In order to focus on essential observables to validate and guide the theoretical developments improved efficiency and sensitivity of the instruments are mandatory. This has led to a continuous improvement of the instrumentation, from the multi-detector High-Purity Germanium (HPGe) arrays of the 1990s (e.g. EUROBALL), through the first arrays consisting of segmented HPGe detectors (e.g., MINIBALL, EXOGAM), to the development of AGATA, the Advanced Gamma Tracking Array, a 4π spectrometer solely built from position-sensitive HPGe detectors.

AGATA is a truly universal high-resolution spectrometer, capable of measuring γ rays from a few tenths of keV to beyond 10 MeV, with unprecedented efficiency, excellent position resolution for individual γ-ray interactions and very high count-rate capability. These features will allow AGATA to be operated in such diverse environments such as the relativistic beams from the FAIR/SUPER-FRS facility, the second-generation high-intensity ISOL facilities (HIE-ISOLDE, SPES, SPIRAL2) and the high-intensity stable beam facilities at GANIL, JYFL, and LNL. AGATA started as an R&D project in the late 1990s and the AGATA demonstrator became operational in 2009. Steadily growing over the years the AGATA array has been in constant use for experiments. Currently a coverage of approximately 1π has been achieved. Exciting new results were obtained in campaigns at LNL (2009-12), GSI (2013-14) and GANIL (since 2015). This success led to the recommendation in the latest NuPECC Long-Range Plan that “the timely completion of the full AGATA spectrometer and the provision of adequate support and maintenance are of the highest importance to address the exciting science programme at both the stable and radioactive beam facilities.”

This White Paper describes the new physics opportunities opened up by AGATA. In the first part various physics cases are described for which the use of AGATA will be pivotal: the study of shell evolution, understanding the microscopic origin of nuclear deformation and the interplay between single-particle and collective degrees of freedom, the search for exotic and extreme shapes (in

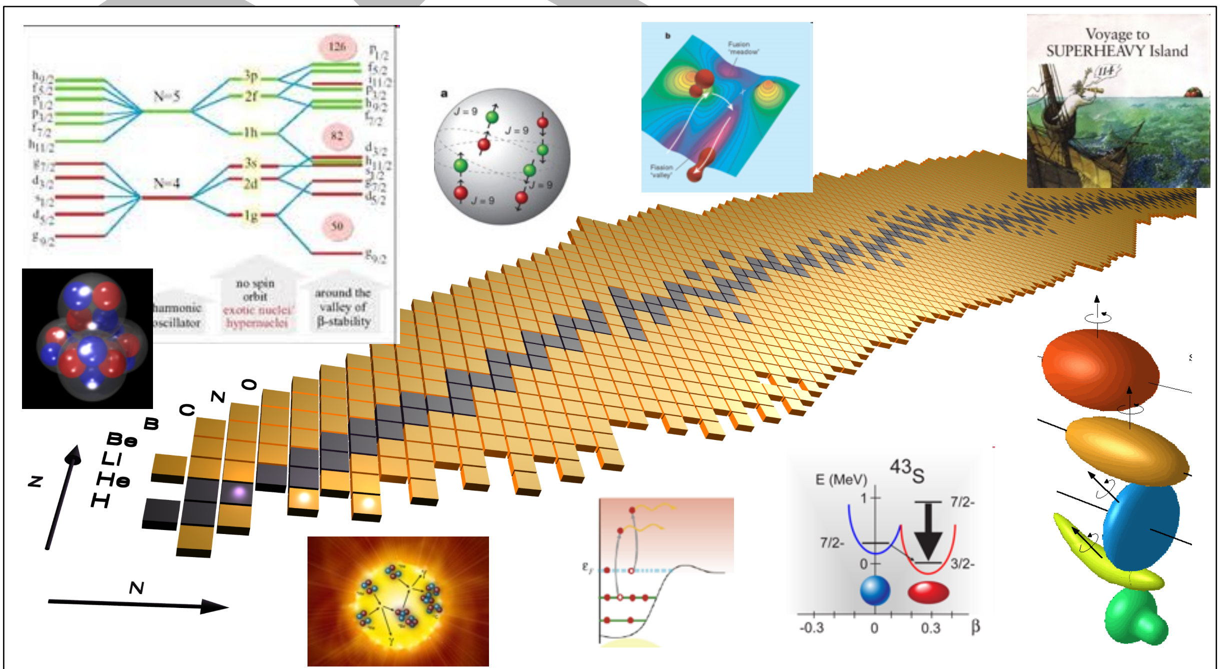

Figure 1: Nuclear Landscape showing some of the properties currently being studied using high-resolution spectroscopy (see text for details).

particular nuclear hyperdeformation), establishing shape coexistence and shape transitions, and understanding the underlying mechanisms, testing theoretical predictions for neutron and proton skins, probing the nature of pair correlations and investigating how angular momentum is generated, measuring the degree of isospin-symmetry breaking, finding fingerprints of chaos in nuclei, etc. In the following sections more detailed physics cases and simulations of experimental investigations are described that will profit from the unique capabilities of AGATA combined with specific advantages of the host laboratories.

The Nuclear Shell Structure and its Evolution

In the vicinity of the valley of stability "magic" numbers are well established for nuclides, with (Z,N) = 2, 8, 20, 28, 50, 82 and 126. For these particle numbers, the single-particle shells are filled, i.e., these shells are closed and the corresponding nuclei are called singly- or doubly-magic. The properties of the nearest neighbours of doubly-magic nuclei are of fundamental importance for the understanding of nuclear structure. With the new RIB facilities under construction in Europe, the most exotic of these doubly-magic nuclei will come within reach of detailed spectroscopic studies, namely ^{56}Ni and ^{78}Ni (Z=20 and N=28 and 50, respectively), ^{100}Sn and ^{132}Sn (Z=50 and N=50 and 82, respectively).

The evolution of shell structure in neutron-rich nuclei is intimately related to the nature of the spin and isospin dependence of the in-medium nucleon-nucleon interaction. There are two main mechanisms predicted to drive shell evolution in nuclei: the monopole migration and shell quenching due to a softening of the potential shape by excessive neutrons. There is firm evidence in light and medium-heavy nuclei that the neutron shells erode (e.g. the N=8, 20, 28 shell gaps give way to new magic numbers at for example N=14, 32, 34,…, and the expected semi-magic nuclei, e.g. ^{32}Mg, ^{42}Si, become deformed and lead to so-called islands of inversion). It will be very important to explore this evolution in heavier nuclei, e.g. to search for such islands below ^{78}Ni and ^{132}Sn, where the spin-orbit interaction is more pronounced.

The size of a shell gap and the identification of the corresponding mechanism responsible for its change can be inferred in some cases from the observation of low-lying core-breaking states, or (in even-even nuclei) 0^+ deformed states resulting from the balance between particle excitation and correlation energy. Isomers, which are often challenging to identify experimentally, are possibly associated with this phenomenon.

In contrast with stable and near stable nuclei, where a strong proton-neutron interaction is a key ingredient in inducing deformation of the whole nucleus, decoupling between the valence neutrons and the proton core may occur in very neutron-rich nuclei. Decoupling or strong polarisation effects in nuclei can be searched for by measuring the evolution of the electric quadrupole transition strength, B(E2), along singly-magic isotopic chains.

Experiments with AGATA will lead to breakthrough studies related to the above properties by combining the specific strength of different facilities with the most advantageous reaction mechanisms and observables: knock-out and relativistic Coulomb excitation at FAIR, Coulomb excitation and transfer reactions at the ISOL facilities, and also spectroscopic studies using fusion, fission or deep-inelastic reactions at stable beam facilities. For nuclei, which possess or lack only one nucleon in otherwise empty or filled shells, the energies of single-particle and single-hole states can be extracted, which are important empirical parameters in any microscopic description of nuclear properties of atomic nuclei. Nuclei with two particles outside a doubly-magic core bring the most direct information on the correlations between pairs of nucleons occupying orbitals close to the Fermi surface. Even-even nuclei provide the effective interaction between like nucleons, while the odd-odd isotopes give access to the proton-neutron (πν) two-body matrix elements. All this information will become accessible with AGATA in hitherto unknown territories.

The interplay between single-particle excitations and collective responses of the nucleus (phonons in particular) generates a multifaceted scenario of nuclear excitations, which can be studied in their simplest form in systems composed of one valence particle and a doubly magic core. These types of coupling between nucleons and phonons are major sources of partial occupancies of nucleonic orbitals and constitute the doorway to more complex excitations, all the way up to damping phenomena in Giant Resonances. Among a number of very interesting cases, the spectroscopy of one/two-valence-particle/hole systems with respect to the doubly-magic ^{132}Sn core, is probably the most accessible for European ISOL facilities, where intense and pure ^{132}Sn-like beams will be available.

The coupling of the AGATA array with a recoil spectrometer and light charged-particle detection devices will allow very selective studies of these neutron-rich systems populated by transfer reactions. The excellent performance of AGATA regarding angular distribution and polarisation measurements with AGATA will allow firm spin and parity assignment of the excited states. An

Nuclear Structure around doubly closed-shell nuclei

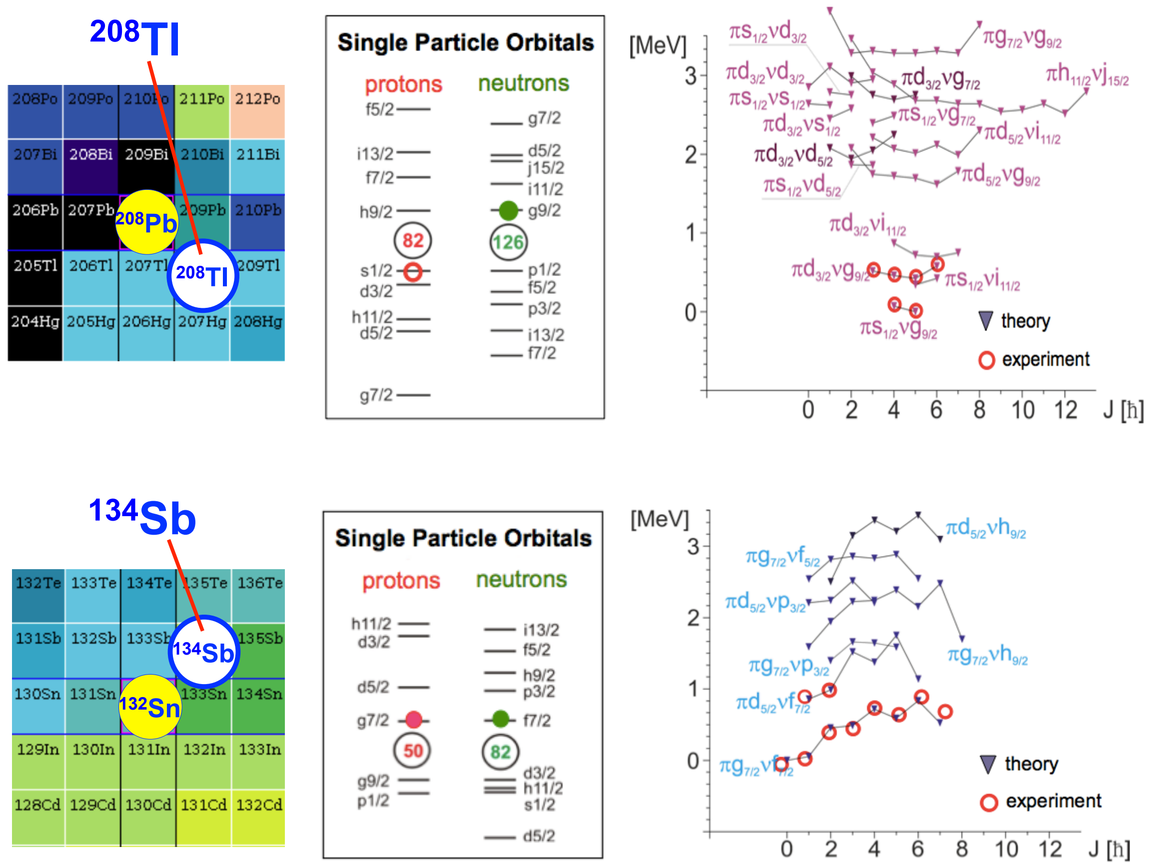

Figure 2: Direct information on the proton-neutron interaction can be obtained from odd-odd nuclei around double shell closures, by studying, e.g., multiplets arising from correlations between valence particles. Of special interest are nuclei like i) ^{134}Sb, located north-east of ^{132}Sn, with one proton valence particle and one neutron valence particle, and ii) the one proton hole-one neutron particle nucleus ^{208}Tl, situated south-east of ^{208}Pb. (Right) Predictions for the multiplets (up to 3.5 MeV excitation energy) in ^{134}Sb (negative parity) and ^{208}Tl(positive parity) obtained from shell-model calculations using a realistic interaction. In both cases the experimental information is rather scarce, and only members of the lowest-lying multiplets are known. Higher lying states belonging to other multiplets and being characterised by a more significant configuration mixing, can be established with AGATA, which will allow testing their diagonal and off-diagonal matrix elements and those of the proton-neutron interaction.

assessment of their collectivity using lifetime measurements, leading to a complete characterisation of the properties of the states.

Light Exotic Nuclei and Clusterisation Phenomena

Weakly-bound systems provide a sensitive test of the nuclear force, and the neighbourhood of the drip-lines offers unique opportunities to extend our understanding of this interaction. Light nuclei are a test bench for the most advanced theory approaches and play a key role in nuclear astrophysics. Recent developments in ab-initio many-body methods allow their application to light exotic nuclei in order to perform dedicated tests of nuclear interactions and to determine what input is required to best constrain nuclear forces. In turn, detailed experimental observations will shed light on the question as to which higher-order terms of the nuclear interaction (3-body, etc.) are essential for a correct description of nuclear properties in this mass region.

On the proton-rich side of the valley of stability, the instability against spontaneous proton emission is masked by the Coulomb barrier, allowing these nuclei to have “measurable” lifetimes (μs or longer) and their excited states to decay by γ-ray emission. Therefore, these nuclei are the ideal laboratory to study “particle-unbound” states using γ rays, but also the competition between charged-particle and γ-ray emission.

On the neutron-rich side, phenomena of clusterisation are emerging; near threshold states are of paramount importance in astrophysics (e.g. the Hoyle state in ^{12}C) and continuum states have a large impact on the structure of the nucleus. From the theoretical point of view, these necessitate merging of structure and reaction descriptions.

Electromagnetic (EM) decays are the most sensitive probe of the wave functions. Studying bound states of exotic nuclei, e.g. ^{20}O, will provide precision tests of the nuclear interaction. AGATA will also allow studying EM decays from unbound states (e.g. resonances) with typical decay branches of 10^{-3} – 10^{-5}. The latter constitute an almost unexplored territory, ideal for investigations with AGATA coupled to light charged-particle detectors, using intense stable beams. For example, reactions such as ^{6,7}Li on ^{9}Be, ^{12,13}C, ^{6,7}Li and ^{10,11}B targets, will lead, after a single proton evaporation, to the population of unbound states in ^{13}B, ^{15}C, ^{17,19}O and ^{16,17}N.

Shape coexistence

The shape of an atomic nucleus is governed by the interplay of macroscopic, liquid-drop-like properties of the nuclear matter and microscopic shell effects. While closed-shell nuclei always exhibit spherical shapes in their ground states, nucleons residing in open shells tend to deform the mass distribution, with quadrupole deformation being the most important degree of freedom. The shape of a nuclear state depends on the details of the microscopic wave function, and thus it may change, not only as a function of the number of nucleons, but it may also vary from one state to another within the same nucleus, which is known as shape coexistence. Establishing shape coexistence is challenging and requires highly-refined experimental techniques, however provides one of the most demanding and stringent tests of modern nuclear theories and models. It is for this reason that studies of this phenomenon are at the forefront of nuclear structure research.

Typically, shape coexistence arises when the nuclear potential energy surface (PES) in the deformation space exhibits minima associated with different shapes. When the energy barrier separating such minima is sufficiently high, it may lead to the appearance of shape isomer-like structures, like the well-known fission isomers in the actinides. Striking manifestations of shape coexistence can also be found in nuclei on the shores of the islands of inversion, as well as open-shell nuclei where rapid shape changes occur. Very neutron-rich nuclei exhibit a neutron skin, which may assume a different shape (i.e. deform more easily than the core), leading to an enhancement of the isovector components in EM decays. Correspondingly, unusual shape-coexistence phenomena may be observed, whereby the isovector shapes will co-exist with the isoscalar ones. Such effects are abundantly predicted for small-amplitude vibrational states. However, the same arguments also apply for all kinds of low-lying collective excitations, which should probably be described by novel types of collective models that take the isospin degrees-of-freedom explicitly into account.

Shape coexistence and shape isomers

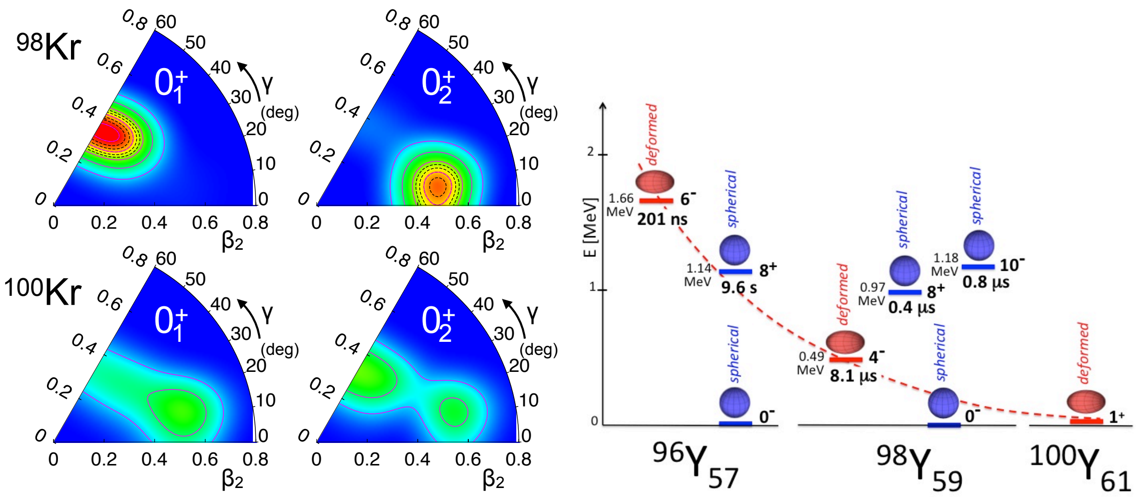

Figure 3: Shape coexistence occurs when different microscopic configurations correspond to similar binding energies, as illustrated by the example of neutron-rich krypton isotopes (left). Low-energy Coulomb excitation is an ideal tool to pin down their structure. These different configurations may appear as long-lived shape isomers, as observed e. g., in the Y isotopes (right). To reach such states, (sub-barrier) transfer reactions can be employed. Besides its high efficiency, the unprecedented position resolution of AGATA is needed to counteract the Doppler broadening, and its high-rate capability will ensure high throughput despite possible occurrence of intense contaminations in radioactive ion beam experiments.

Experiments with AGATA will create a multitude of opportunities to study the evolution of nuclear shapes and shape coexistence: Coulomb-excitation studies with stable and radioactive beams will allow identification of different shapes by measuring quadrupole moments of short-lived excited states and determining deformation parameters, in particular of 0^+ states, from quadrupole shape invariants. Direct determination of very weak, retarded γ-decay branches between different configurations will provide insight into the microscopic origin of nuclear deformation, which can be analysed on the basis of, e.g., the most sophisticated shell model calculations. Complementary information will be obtained by following the evolution of the nuclear shape along isotopic chains. One of the key regions for this type of investigation is the neutron-rich nuclei with Z = 36-40, near N = 60, where the most dramatic shape change in the nuclear chart has been observed, with typical characteristics of a quantum-phase transition. This phenomenon has strong impact on the r-process nucleosynthesis path. Ideal cases are the Y/Sr chains, in particular ^{96,97}Y and ^{96,97}Sr, which could be studied by Coulomb excitation or cluster transfer reactions.

Higher-order nuclear deformation

Octupole collectivity is the most prominent exotic deformation in nuclei and most pronounced just above the magic numbers of protons and neutrons. In doubly-magic nuclei such as ^{132}Sn and ^{208}Pb, the first-excited 3^- state is at a comparable energy with the first-excited 2^+ state. Quadrupole vibrations are invoked to explain the 2^+_1 state in these nuclei and octupole vibrations, by analogy, are responsible for the 3^-_1 state. Since there is no coupling between these two vibrational modes at low energy, a very weak *E1* transition between them is observed. In quadrupole-octupole deformed systems, a strong coupling between the two degrees of freedom gives rise to enhanced *E1* transitions, and large *B(E3)* values of the order of 30-80 W.u. are also observed, as e.g. in ^{224,226}Ra. Studying the transitional region between these two modes, i.e. octupole-vibrational nuclei at and near doubly-magic nuclei and octupole-deformed nuclei to the north-east of these, will shed light on the evolution of octupole collectivity. Of particular importance are the energies of negative-parity states in transitional nuclei and the $B(E3; 0^+_1 \rightarrow 3^-_1)$ transition strength, proportional to the square of the octupole moment, Q_3.

Outside of nuclear physics, experiments hoping to measure non-zero Electric Dipole Moments (EDMs) are using octupole-deformed nuclei as a probe. In odd-mass systems with a significant octupole moment, Q_3, an up to three-orders of magnitude increase in the Schiff moment is expected over the current best limit in ^{199}Hg. It is this *nuclear* Schiff moment that gives rise to the EDM in the atomic system and any observation of a non-zero EDM would require new physics beyond the standard model. Nuclear physics input to the calculation and interpretation of the Schiff moment needs to come from theory and experiment, with the energy difference between parity-doublets in odd-mass nuclei currently being the biggest unknown. Direct measurements of Q_3 in odd-mass nuclei are also desirable, though a simpler measurement of this quantity in the neighbouring even-mass isotopes can already guide the theoretical calculations.

Octupole deformed and Tetrahedral nuclei

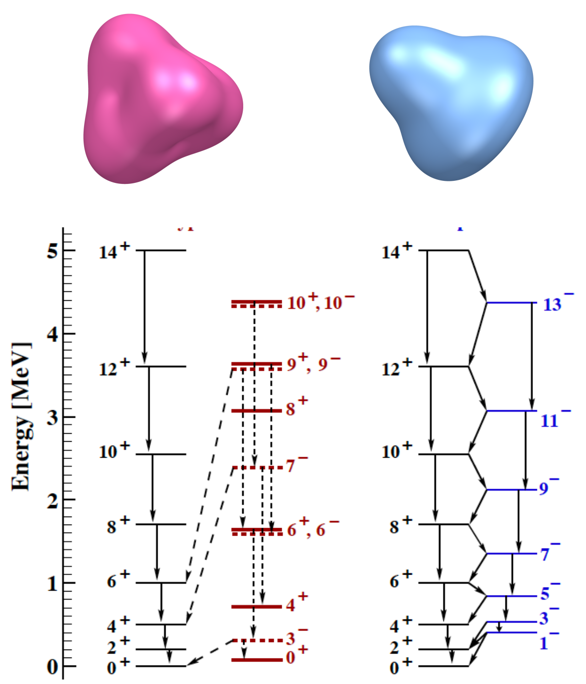

Figure 4: Schematic illustration comparing the characteristic level schemes of an octupole deformed nucleus (right) with staggered levels of opposite parity and decaying via enhanced E1 and E2 transitions and a tetrahedral nucleus (left) with characteristic parity doublets (at spins 6, 9, 10) and decaying predominantly through E3 transitions. While rigid octupole shapes have been observed in certain mass regions, the existence of tetrahedral nuclei still needs to be rigorously established. AGATA is the ideal tool to look for these unusual decay properties.

The research on new exotic nuclear symmetries includes the search for tetrahedral and octahedral symmetries and the underlying nuclear deformation. Some of the intriguing new phenomena predicted to accompany tetrahedral symmetry are 4-fold degeneracies of the nucleonic orbitals (rather than the usual 2-fold spin-up/spin-down Kramers degeneracy) or 16-fold degeneracies of the particle-hole exited states and 32-fold degeneracies of the 2-particle 2-hole excited states. New classes of isomeric configurations could also be expected, producing possibly new waiting-point nuclei, important for the astrophysical modelling of the stellar processes.

The unusual electromagnetic signals from those very special configurations are expected to be very weak and specific analysis techniques have to be introduced, where the application of AGATA will be particularly important. In the exact tetrahedral and octahedral symmetry limit, nuclei would not exhibit either E2 nor E1 transitions. However, exact symmetries are never really present in nuclei due to different symmetry-breaking processes, such as zero-point motion around the corresponding minimum in the quadrupole deformation surface as well as Coriolis coupling of the high-j orbitals. Consequently, AGATA will be essential in detecting the weak E2 and E1 signals originating from the configurations with partially broken symmetries. Similarly, the enhanced E3 transitions between specific states along the tetrahedral bands can be searched for. Such structures are predicted in stable nuclei (for example ^{96}Zr and ^{152}Sm) as well as in exotic isotopes (^{104}Zr).

Isospin Symmetry Studies

Isospin symmetry is based on the fact that (i) protons and neutrons are (almost) identical particles, and (ii) that nuclear forces are nearly charge independent. Although it is known that isospin symmetry is broken to a small extent by the strong interaction, in a more significant way by the weak interaction and, most significantly, by the electromagnetic interaction, the isospin formalism, characterising nuclear states by the isotopic spin ("isospin") quantum number T, remains an extremely powerful tool to understand the structure of nuclei.

The concept of isospin symmetry is most clearly established in so-called "mirror nuclei", nuclei of the same mass, for which the number of protons and neutrons is exchanged, resulting in their structure being very similar. More generally, isobaric nuclei (with the same mass number A) have

High resolution γ-ray spectroscopy along the N=Z line.

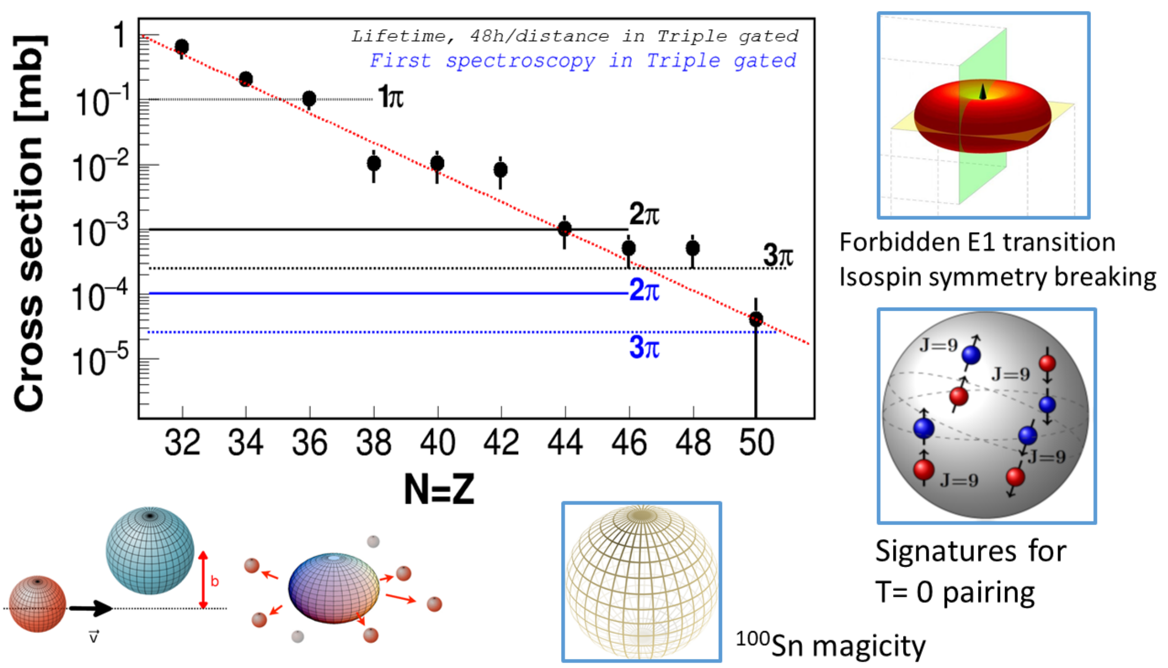

Figure 5: The development of the AGATA array towards 4π will allow reaching more and more exotic N=Z nuclei. AGATA coupled to 1π neutron detector and a charged-particle array will allow spectroscopy towards doubly-magic ^{100}Sn, to determine transition probabilities by lifetime measurement of ^{96}Cd and angular distribution and polarization measurements of ^{92}Ru. The figure illustrates the estimated limits for a plunger lifetime measurement (black, 48hours per distance) and first spectroscopy (blue, 14 days) as a function of the solid angle covered by AGATA. Beam intensities of 10pnA (for ^{50}Cr, ^{58}Ni and ^{40}Ca) and a medium γ-ray multiplicity are considered. The cross sections are taken from B. Blank et al, NIM B416 (2018) 41–49 and experiments at GANIL.

corresponding levels, which can be grouped into multiplets of states of common isospin. However, 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 a different isospin. The amount of isospin mixing, as derived from experiment, can be understood as a measure of the magnitude of the symmetry violation. The breaking of the isospin symmetry by the Coulomb force increases with Z and for a given mass it is at its maximum for N=Z nuclei. The study of the heavier nuclei with N≈Z is thus of fundamental interest. The isospin symmetry breaking can also be studied by looking at the isospin mixing of the nuclear states. Isospin mixing can be directly accessed by measuring the isospin forbidden ($\Delta T=0$) E1 transitions in N=Z nuclei,making use of the following rules:

- E1 transitions between states of equal isospin are forbidden in N=Z nuclei
- B(E1) values between corresponding states in mirror nuclei should be equal
- Mirror γ-ray transitions of any multipolarity with $\Delta T=1$ should have equal reduced strength
- The reduced matrix elements of E2 γ-ray transitions between analogue states of an isobaric multiplet should vary linearly with isospin projection N-Z, with a slope given by the isovector effective charge.

In particular, the last rule has not been investigate to any extent in nuclei beyond the fp shell

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. Level differences have been measured as a function of angular momentum in these nuclei. When data for T=1 bands in N=Z odd-odd nuclei and in the more exotic T_z=-1 members of the multiplets, e.g. those with N=Z-2, became available, it was realised that the perturbative inclusion of the Coulomb interaction among protons (with charge-invariant model wave functions) was not sufficient to explain the measured energy differences. In order to reproduce the experimental data, an isospin non-conserving term has been introduced in the shell-model effective interaction. This term has the form of an additional phenomenological (monopole and quadrupole) pairing term in the energy difference formulae, but its deeper origin still has to be clarified.

High-Spin States, Extreme Deformation and Giant Collective Modes

When a deformed nucleus rotates, the energy of the "intruder" states (from higher-lying major shells) is significantly affected by the rotational frequency. This gives rise to characteristic particle configurations on which many rotational bands are built. The study of rotational band properties may be used to establish these configurations and hence determine the shell energies in nuclei far from stability. Moreover, in the de-excitation of an intruder state along a rotational band by the emission of γ rays, the nucleus may at some point become unstable against neutron emission, leading to appearance of the novel phenomenon of a γ-delayed neutron emission. An analogous proton emission has already been observed in proton-rich nuclei. However, on the neutron-rich side, the particle emission is faster, because it is not hindered by the Coulomb barrier. Such measurements would immediately give information on the position of the intruder state within the sequence of single-particle levels. By studying high-spin states, K-isomers, and rotational bands in exotic nuclei it will also be possible to pin down the properties and positions of single-particle levels and hence gain access to the shell properties of these nuclei.

The existence of extremely deformed or hyper-deformed (HD) nuclear shapes (with R~3:1) is predicted at very high spins, enabling to study the influence of particular orbitals at the limit of nuclear fission. Related studies include, for example, the connection between these extremely deformed structures in cold nuclei and the "Jacobi shape transition" at sufficiently high temperatures. Particularly, the investigation of the role played by the low-energy component of the giant dipole resonance in the feeding of SD and HD states, may become feasible with AGATA. These studies will most strongly benefit from the unprecedented efficiency of AGATA for high-fold γ^n coincidences, which is expected to be hundred times larger for 4-fold and higher coincidences than that of the EUROBALL array. In addition, experiments to establish the high-energy linking transitions will also profit from the improved Doppler correction and higher efficiency at energies of 4 MeV and above, where we expect another gain of an order of magnitude. Finally, these studies require the availability of high-intensity stable ion beams to reach ultra high-spin states in exotic nuclei, or intense neutron-rich RIBs, which are expected to populate states of even higher angular momentum due to the increase in the fission barrier with neutron number.

Non-axial nuclear shapes, and in particular triaxial configurations, may give rise to appearance of chirality effects. Chirality arises when a physical object cannot be superposed with its mirror image via continuous movement (e.g. human left and right hands or a triplet of vectors). The role of chirality

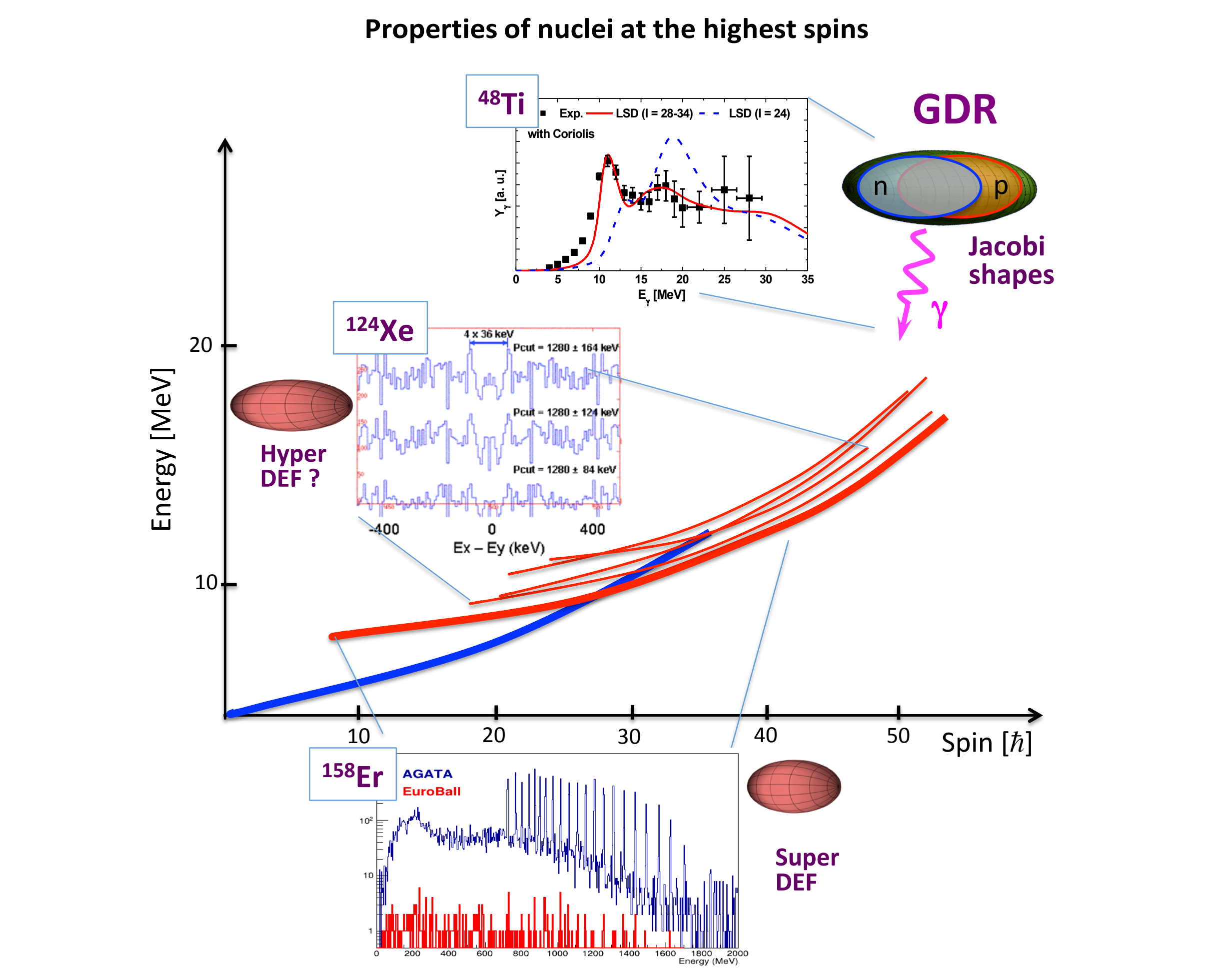

Figure 6: Illustration of nuclear properties at the highest spins: Population of highly elongated structures in cold nuclei (e.g. the lowest-energy super-deformed band in ^{151}Tb) and in warm rotating nuclei (e.g. the possibly hyper-deformed ridge structures in ^{124}Xe) via the decay of the low-energy component of the Giant Dipole Resonance (GDR) built on a hot rotating nucleus possessing a very elongated Jacobi shape (e.g. in ^{48}Ti). The presented data are selected examples of studies performed with the EUROBALL array. AGATA in its 4π configuration, andmaking use of high-fold γ^n coincidences, will exceed significantly the performance of EUROBALL and therefore enable in-depth studies of these processes.

in nuclear structure can be studied in specific odd-odd nuclei, where the three vectors needed to pose the chirality problem are the two individual angular momenta of the odd proton, j_p, and the odd neutron, j_n, together with the collective-rotation vector R, all the three aligned with three different axes. In principle, such a triplet of distinct vectors in the nuclear microscopic mean-field theory generates no dynamical (i.e. impacting the nuclear state energies) distinctions. It implies that a nucleus rotating `from the left to the right' or `from the right to the left' should present strictly identical energy relations. Experimental observation of non-identical rotational sequences is a sign of mechanisms going beyond the mean field and the scale of the symmetry breaking provides an important input for the more advanced modelling and ideas about the spontaneous symmetry breaking. While effects of chirality have been observed in the excitation energy spectra of certain odd-odd nuclei, their spectroscopy is extremely complicated and further detailed investigations are needed to fully understand the influence of chirality.

Pygmy Resonance Excitations

The presence of dipole strength at low excitation energy has been often associated to the possible existence of a new collective mode: the Pygmy Dipole Resonance (PDR). The PDR is associated with the oscillation of a neutron skin against the core. This mode is located below the well-known Giant Dipole Resonance (GDR); it is present in many isotopes with a considerable neutron excess and carries a few percent of the isovector energy-weighted sum rule (EWSR). Its presence has also been established for stable nuclei with a large neutron excess, like ^{208}Pb, but it is expected to be more pronounced in nuclei further from stability. The PDR strength is connected to the properties of the neutron skin, which in turn are used to constrain the equation of state of neutron-rich nuclear matter. Finally, the PDR strength plays a role in the r-process nucleosynthesis.

Pygmy and Giant Dipole Resonance Excitations

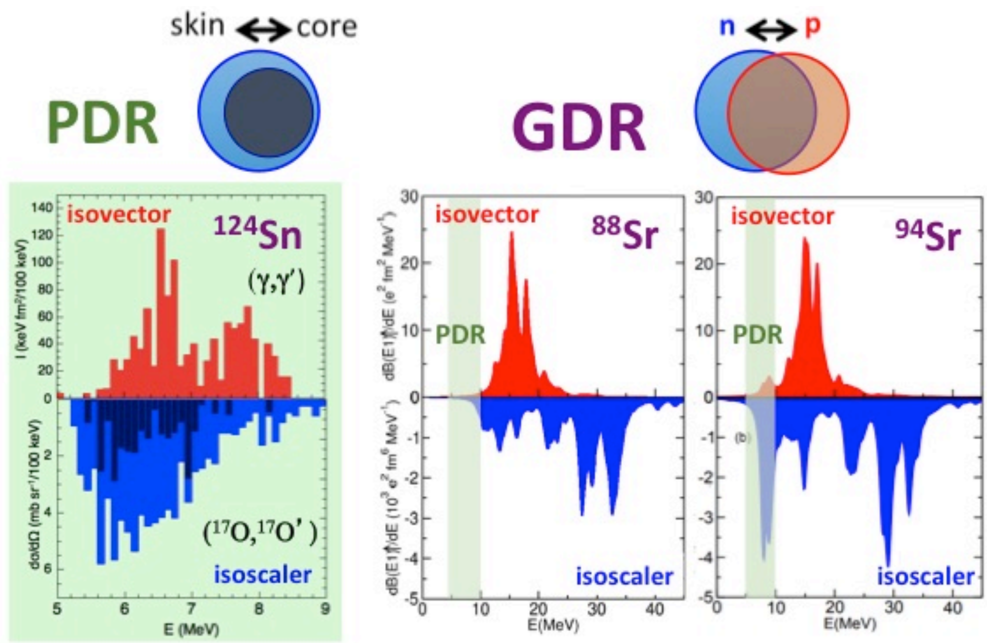

Figure 7: (Left) Photon decay of the PDR in ^{124}Sn following photon scattering at TU Darmstadt (top) and heavy ion inelastic scattering (bottom), as measured with the AGATA Demonstrator array at LNL (L. Pellegri et al, Phys. Lett. B 738 (2014) 519). Random Phase Approximation calculations of the strength distributions are shown for stable ^{88}Sr (middle) and unstable ^{94}Sr (right) and for isovector (top) and isoscalar (bottom) responses. A clear increase is seen in the 5-10 MeV energy region (marked in green) for the PDR in ^{94}Sr. AGATA will allow to extend these studies to unstable nuclei using RIBs.

The presence of a neutron or proton skin also affects excitations of other multipolarities. In particular, a concentration of low-energy electric quadrupole strength, located much below the Isoscalar Giant Quadrupole Resonance (ISGQR), was identified as a new mode of nuclear excitation named Pygmy Quadrupole Resonance (PQR).

Experiments to study or search for these resonances with AGATA would be performed with RIBs (both at Coulomb barrier and relativistic energies), using inelastic scattering reactions, e.g. (α, α’) and (p, p’), in inverse kinematics. Their strong discovery potential is based on the (i) excellent efficiency up to very high γ-ray energies and the excellent position resolution required to correct for the expected strong Doppler effects.

Very Heavy and Superheavy Elements

Understanding the synthesis of super heavy elements (SHE) must go hand in hand with studying the nuclear structure of very heavy elements (VHE) with Z≈100, and the reaction mechanisms leading to their production. The production cross-sections of these transfermium nuclides are sufficiently high to carry out detailed spectroscopy studies. The objectives are:

- to study the collectivity of the nuclei through lifetime measurements, in particular the deformation around the islands of large deformation (^{254}No and ^{270}Hs)
- to determine the properties of the responsible single-particle configurations, in particular in odd-mass nuclei
- to study the role of K-isomerism with respect to their lifetimes and to the disintegration probability through α decay vs. spontaneous fission compared with those of the ground state
- to estimate the fission barriers

Solar abundances and the fission process

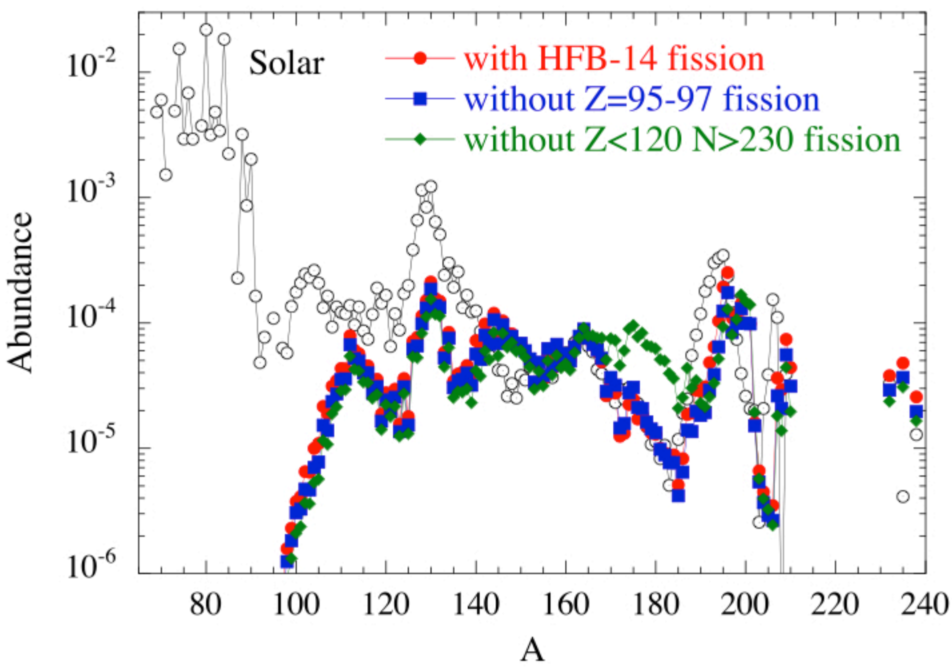

Figure 8: Solar abundances compared with final r-process abundances in ejected matter from a 1.35-135 solar mass neutron star merger calculated with HFB-14 fission barriers (red symbols), assuming Z=95-97 and N>184 nuclei are not affected by fission (blue symbols) and assuming Z<120 and N>230 nuclei do not undergo fission (green symbols) (reproduced from I. Petermann et al., Eur. Phys. J A (2012) 48).

All these studies will tremendously profit from the availability of AGATA in conjunction with a high-rejection particle spectrometer. The high count-rate capabilities are necessary in order to accept high beam intensities to counterbalance the low cross sections. The high efficiency and excellent energy resolution will allow γ-γ coincidence spectroscopy for the first time and in this way to disentangle the level schemes of odd-mass nuclei or those built on K-isomers. Finally, the excellent position resolution will facilitate lifetime measurements using Doppler-shift techniques and the determination of level spins and parities using angular correlation and (linear) polarisation measurements, respectively.

Spectroscopic Studies for Nuclear Astrophysics

Reactions involving radioactive nuclei play a key role in nuclear astrophysics, particularly in explosive scenarios such as X-ray bursts, novae and supernovae. Unfortunately, many of the reactions of interest cannot be measured directly owing to the low intensities of radioactive beams or lack of radioactive targets. An important indirect approach is, therefore, to employ transfer reactions, such as *(d,p)*, to populate the key astrophysical resonances in order to obtain information on their most important spectroscopic properties (e.g. energies, spin-parity values and spectroscopic factors), so that the reaction rate can be determined. Since these states typically exist in regions of large level density, identifying them from detecting charged particles alone is often impossible. Consequently, the use of a high-resolution γ-ray spectrometer has become mandatory in recent studies in order to simultaneously measure the excitation energy of the state of interest and detecting the γ radiation emitted from this state. As the reaction products travel with the initial beam energy (~10 MeV/u), large Doppler effects occur, making a position-sensitive γ-ray spectrometer mandatory to provide the ultra-high resolution required to perform precision spectroscopy measurements with radioactive ion beams. Compared with current arrays, such as MINIBALL (HIE-ISOLDE) or EXOGAM (GANIL), AGATA will provide in addition full γ-ray tracking, improving efficiency and spectrum quality, and a large interior space to host ancillary detectors for particle detection.

The heavy elements beyond the Ni-Fe region are believed to be synthesized in nature through the rapid neutron-capture process, or r-process, expected to take place in violent stellar events, such as neutron-star mergers or possibly core-collapse supernovae. It has been demonstrated that even elements with $Z \approx 100$ and above (with $N \approx 170$-220) could be produced in the r-process, in particular for "cold" conditions (i.e. $T \approx 0.1$ GK). Preliminary calculations of (n,γ) reaction rates for fermium nuclei (see Figure 8), with and without the M1 scissors mode in the γ-strength function (γ-SF), have been performed showing a significant impact on the astrophysical rates, also for nuclei that are accessible in the laboratory by means of fusion-evaporation experiments. Moreover, an enhancement of the reduced average γ-decay probability would boost the γ-decay channel relative to fission with subsequent consequences for the survival of heavy nuclei produced in heavy-ion reactions. Such detailed studies in nuclei produced with tiny cross sections require a γ-ray spectrometer providing not only the highest resolution and efficiency, but also capable of measuring angular correlations and linear polarisation, which are intrinsic properties of AGATA.

Finally, fission of very neutron-rich very heavy nuclei is a key ingredient for modelling the r-process nucleosynthesis since it determines the final r-process abundance distribution (see Figure 8). Whether or not $Z>110$ elements are produced in the r-process and can be found in cosmic rays or terrestrial matter also depends on the fission properties of these nuclei. AGATA in its final 4π configuration used in calorimetric mode will allow the fission barrier to be determined much more precisely than the presently used combination of Ge and scintillator arrays.

AGATA at the FAIR/Super-FRS facility

FAIR is the only facility worldwide that will deliver high-intensity radioactive ion beams (RIBs), in either the ground or an isomeric state, covering the entire chart of nuclides and with high energies up to 1500 MeV/u. These beams are produced in projectile fragmentation and fission reactions, separated and identified in the Super-Fragment Separator (Super-FRS) and directed onto a secondary target. FAIR is therefore a unique place to perform experiments, which take advantage of

- highest energy/velocity of the RIBs (beyond 1 GeV/u)
- RIB of all elements up to U
- isotopically pure secondary beams
- electron-free beams (fully stripped)
- isomeric beams (down to ns lifetimes)

The AGATA tracking array offers not only a high γ-ray efficiency and an excellent peak-to-total ratio, two properties which combined lead to a high sensitivity, but furthermore it features an unprecedented position resolution due to its fine segmentation combined with pulse-shape analysis techniques. It is in particular this excellent position resolution, allowing for an accurate Doppler correction of the energies of γ rays emitted by nuclei moving with velocities reaching 50-80% of the speed of light, which will enable, for the first time, to take full advantage of the available high-energy RIBs. The drastically improved energy resolution, in comparison to the previous γ-ray arrays at GSI (RISING, PreSpec), as well as γ-ray spectrometers based on scintillators currently used at competing laboratories, e.g. DALI2+ at RIKEN, increases the sensitivity for, and in some cases even enables for the first time:

- studies of excited states in very exotic species, which can be produced only with very low rates of a few particles per second
- investigation of non-yrast states at excitation energies of up to 30 MeV
- studies of odd nuclei
- studies of excitations built on isomeric states
- lifetime measurements through Doppler-shift techniques
- analysis of γ–γ coincidences for elaboration of complex excitation schemes

To populate excited states in the nuclei of interest, the high-energy RIBs impinge on stable solid or liquid targets, which due to the high energy of the beams can be very thick. High-Z targets allow for electromagnetic excitations (Coulomb excitations) while reactions mediated by the strong nuclear force, such as inelastic scattering and knockout reactions, dominate when the heavy RIBs hit low-Z targets (H, He, Be, C etc.). The different and often complementary characteristics of these reactions enable a broad range of physics topics. Independent on the reaction mechanism used to populate the excited state of interest, the accurate determination of the γ-ray emission angle enabled by the superb position resolution of AGATA permits the development of a variety of new experimental techniques, which take advantage of the Doppler effect to determine excited-state lifetimes. Such direct and model-independent lifetime measurements constitute a very valuable complement to other experimental techniques.

AGATA will be located in the low-energy branch of the Super-FRS in front of the low-energy buncher/spectrometer (see Figure 1). In the following, the main characteristics of the different techniques, which will be employed with AGATA at FAIR, will be discussed, and typical physics cases mentioned.

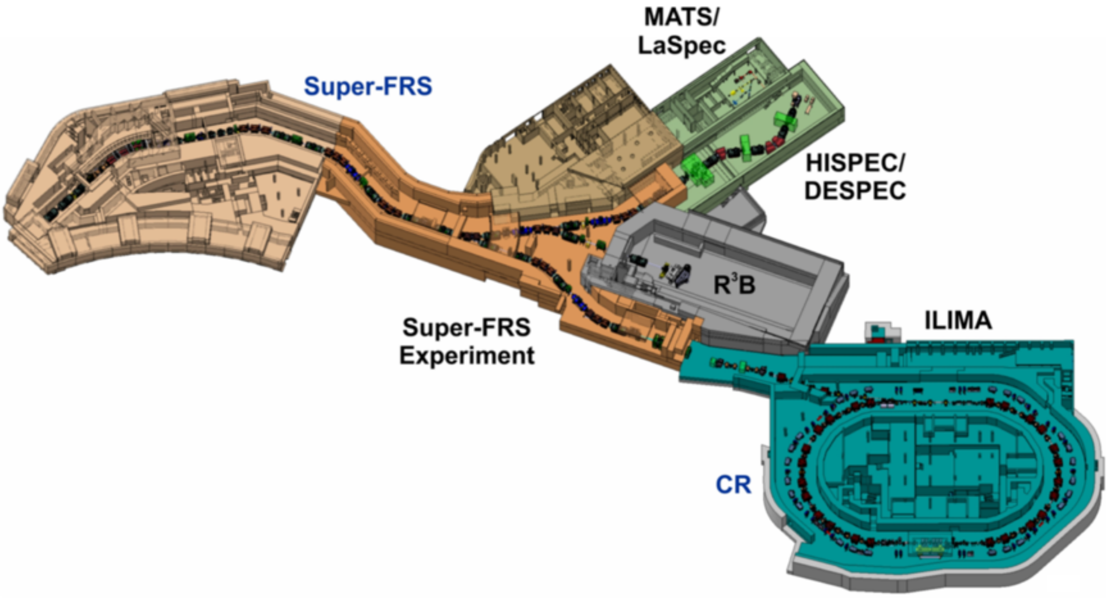

Figure 1: The Super-FRS spectrometer at the FAIR facility. AGATA will be at the heart of the HISPEC experiment located in the low-energy branch in front of the low-energy buncher/spectrometer.

1. Coulomb excitation to probe the electromagnetic response of exotic nuclei

At relativistic beam energies electromagnetic excitation occurs only as one-step process due to the very short interaction time. Consequently, only low-spin states can be excited with reasonable cross section via the absorption of virtual photons of multipolarity E1, M1, E2 or E3. In contrast, no such limitation exists with respect to the excitation energy. While the cross section for the excitation of low-lying 2^+ states rapidly drops with increasing beam energy, so that for the Coulomb excitation of yrast states usually energies not higher than 150 MeV/u are chosen, the excitation probability increases with beam energy for higher-lying states (e.g. 10-15 MeV). This makes FAIR a unique place to measure transition probabilities from the ground and isomeric states to low-lying excited states in heavy nuclei, as well as to study Giant and Pygmy resonances, i.e. collective states at excitation energies from roughly 8 to 30 MeV.

Using the technique of Coulomb excitation at energies around 150 MeV/u both the single-particle structure as well as the evolution of quadrupole and octupole collectivity in the regions around the doubly-magic nuclei ^{132}Sn and ^{208}Pb can be studied. Similarly, in regions of rapidly changing nuclear shapes and shape coexistence, for example around Z=70-76 or N=60, information about the shape of the nuclei can be obtained, which cannot be reached at ISOL facilities and which will contribute to the refinement of different theoretical models very far from stability. In these mass regions long-lived isomeric states are also known to exist and their Coulomb excitation can provide information about the isomers themselves and the structures built on them. To study the Coulomb excitation of isomeric states, the prompt radiation will be detected in the AGATA array accompanied by ancillary detectors around the secondary target position. Additional Ge detectors, for example the DEGAS array, will be placed at the final focal plane of the magnetic separator to register the γ radiation either from long-lived isomeric states or following beta or alpha decay.

More than 50 years ago Axel and Brink formulated the hypothesis that the Giant Dipole Resonance can be built on any excited state, not only the ground state. This hypothesis is commonly used in astrophysical applications and in the studies of hot nuclei, although a firm experimental proof of its validity is still missing. Recently the Axel-Brink hypothesis was generalised by extending it to the Pygmy Dipole Resonance [Mar17]. At FAIR the validity of the original and extended Axel-Brink hypotheses can be tested using relativistic Coulomb excitation to study the GDR and PDR built on both the ground and long-lived isomeric states of unstable nuclei. To study the GDR built on an excited isomeric state, the energy of the secondary beam has to be sufficiently high (ca. 1 GeV/u), so that the virtual photon spectrum covers the full GDR region, i.e. up to 25 MeV. The GDR strength in the 10-20 MeV energy region will be measured by the AGATA array positioned at the secondary target position, while DEGAS will serve to distinguish the excitations built on the ground and isomeric states by measuring the γ rays emitted in the decay of the isomeric state at the final focal plane. The measurement of excitation cross sections for the inelastic scattering on low-Z and high-Z targets allows the separation of the isoscalar and isovector contributions. A helium target (either liquid helium or an active helium gas target) is the best choice to probe the isoscalar component of the excitation, while a gold target serves as dominant isovector probe. Long isotopic chains of semi-magic nuclei such as neutron-rich Ni, Sn or Pb isotopes are perfect candidates for this type of studies. Since in neutron-rich nuclei the nature and distribution of E1 strength yields valuable information about the properties of the neutron matter, its study with AGATA at FAIR will contribute to answering some of the paramount open questions in nuclear physics, namely the origin of the elements and the understanding of the nuclear Equation of State.

2. Knockout reactions and inelastic nuclear scattering

Inelastic scattering is a powerful tool to populate excited states of exotic nuclei and, combined with electromagnetic excitation, to disentangle the contributions from proton and neutron excitations. The use of a (liquid) hydrogen target, being the lightest of all stable targets, combined with a vertex tracker allows an increase in the luminosity, while keeping the outstanding Doppler-correction capabilities of the AGATA spectrometer.

Knockout or other nucleon-removal reactions on light targets, on the other hand, can be used to investigate single-particle structure of excited states in exotic nuclei via the determination of their spectroscopic factors. In the analysis of such experiments, nuclear structure models and eikonal reaction theory are intimately connected. The direct nature of the knockout process also gives a highly selective method for the population, and even the identification, of specific states of interest in exotic species, especially when coupled to a shell-model calculation of spectroscopic strength. The removal of a correlated pair of protons or neutrons gives access to even more exotic species as compared to one-nucleon knockout reactions, while still offering manageable cross sections [Dav13], determined by the two-particle overlap wave functions. Two-proton knockout on the neutron-rich side and two-neutron removal on the proton-rich side are known to be direct, one-step processes, and again can be highly selective. In addition, the two-particle removal process can yield high spins through knockout of correlated pairs from an orbital *j* coupled to maximum spin 2*j*-1. A particularly interesting possibility, especially suited to experiments at FAIR, is the possibility of performing knockout reactions on isomeric beams. For example, knockout of a correlated $g_{9/2}$ neutron pair from known high-spin isomers in nuclei below ^{100}Sn ([Hin12], as seen e.g. in [Baz08] and [Gor97]) will allow studying excited states of N=Z nuclei up to highest spins. As this powerful technique has never been used before, an abundant case, as for example the 14^+ isomer in ^{94}Pd, would be investigated in the first instance.

In general, the importance of the unprecedented position resolution and, as a consequence, of the drastically improved energy resolution of AGATA in comparison with non-segmented Ge or scintillator arrays, increases with the line density in the spectra. For example, in the region around doubly-magic ^{132}Sn, which is important for simulations of the *r* process of nuclear synthesis, one-nucleon knockout from the closed N=82 neutron and Z=50 proton cores populates a variety of excited states leading to complex γ-ray spectra with a high line density (see Figure 2). Only with the excellent energy resolution and efficiency provided by AGATA, γ–γ coincidence relations can be used to establish the level schemes of the populated nuclei. This enable the study of the evolution of the shell gaps as a function of proton and neutron number, challenging modern large-scale shell model calculations.

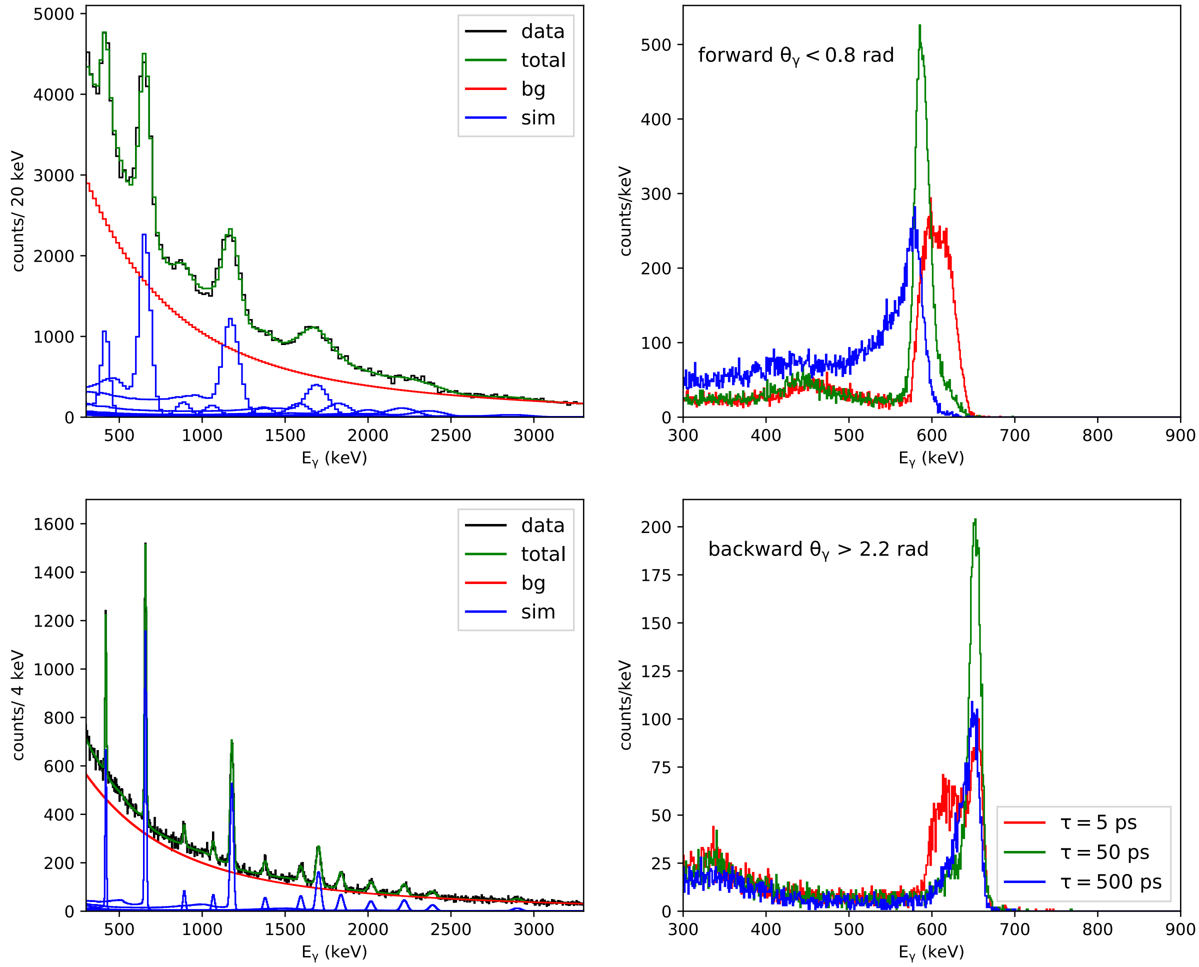

Figure 2: (Top left) Experimental gamma-ray spectrum of ^{135}Te measured with the DALI2 spectrometer following the one-neutron knockout from ^{136}Te projectiles at 165 MeV/u on a carbon target at RIKEN and simulated spectrum (bottom) assuming the same reaction parameters and background shape but using AGATA for γ-ray detection. (Right) Simulated line shapes of the 618-keV 2^+-0^+ transition in ^{132}Cd emitted following Coulomb excitation at an energy of 150 MeV/u on a gold target assuming a 2^+ lifetime of 5 ps (red), 50 ps (green) and 500 ps (blue).

A particular challenge is the study of the region south-east of ^{132}Sn, which is crossed by the *r*-process path, but is difficult to access experimentally. So far the γ decay from excited states has only been observed in ^{132}In following β-delayed neutron emission, and in ^{132}Cd following the two-proton knockout reaction. First information on electromagnetic properties in this quadrant could be obtained with AGATA at FAIR from a direct lifetime measurement of the 2^+ state in ^{132}Cd. Such a measurement, in combination with the existing experimental information for ^{136}Te, would provide valuable information about neutron pairing beyond N=82 as a function of neutron excess. Such direct lifetime measurements only become feasible with the high energy resolution of AGATA, which allows detecting variations of the line shapes due to (i) the velocity change during the slowing-down of the ions in the target and (ii) the change of the emission position after the ions have left the target. Both these processes serve as a clock and thus allow determination of the excited state lifetime from a careful comparison to simulated line shapes (see Figure 2). However, detectors under both forward and backward angles, and ideally are nearly 4pi coverage, are needed in cases where neither the lifetime nor the energy of the state is known.

References:

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AGATA at the GANIL/SPIRAL facility

The physics opportunities with AGATA at the GANIL facility span the fields of nuclear structure, nuclear dynamics and nuclear astrophysics using heavy-ion beam collisions. In the time period 2021-2030, the main strengths of GANIL for in-beam high-resolution γ-ray spectroscopy are the availability of high-intensity stable beams from C to U at energies ranging from the Coulomb barrier to the intermediate regime (50-100 MeV/A) delivered by the cyclotron complex, the possibility to use radioactive beams from the LISE fragment separator at intermediate energies, and post-accelerated radioactive ion beams at the Coulomb barrier from the SPIRAL1 ISOL facility. The preferred first location of the AGATA 4π system at GANIL is in the current experimental halls, either at the target position of the VAMOS++ spectrometer, coupled to the NEDA-DIAMANT setup or at the focal plane of the LISE fragment separator as indicated by the green arrows in Figure 1. In the long term, even more interesting opportunities will be opened by the possible post-acceleration of heavy elements produced by fusion-evaporation and selected in a gas-cell system at the low-energy branch of the new S^3 spectrometer or by fission fragments from SPIRAL2 Phase 2.

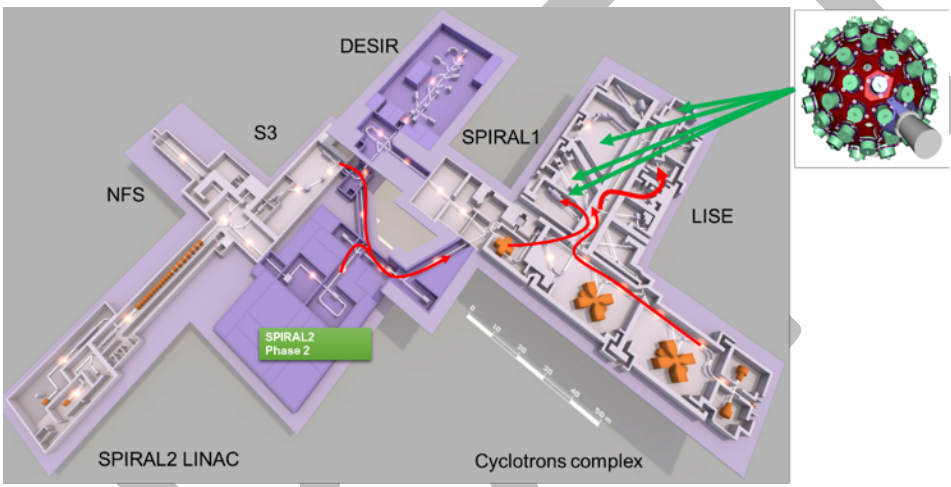

Figure 1: Possible locations for AGATA 4π at GANIL making use of both stable and radioactive beams.

GANIL and its user community offer a wide range of complementary detectors such as magnetic spectrometers or separators (VAMOS++ VAMOS-GFS, LISE), charged-particle detectors for tagging (DIAMANT, MUSETT) and spectroscopy (MUST2, GRIT), neutron detectors (NEDA, NWALL, DEMON), γ-ray scintillators for fast-timing measurements (FATIMA) or high-energy γ-ray spectrometers (PARIS). With the VAMOS magnetic spectrometer it is possible to identify and reconstruct the kinematics of heavy ions in binary collisions up to Z~60 and A~200. With VAMOS in the gas-filled mode fusion-evaporation residues can be separated from the beam- and target-like projectiles and be tagged by their characteristic radioactive decays using the MUSETT detector array. The NEDA neutron detector array and DIAMANT charged-particle detector system allow tagging of residues from fusion-evaporation or transfer reactions by their neutron-proton-alpha evaporation. With GRIT the kinematics of light particles can be reconstructed after few-nucleon transfers. This rich variety of detectors makes it possible to investigate the structure of nuclei ranging from light to heavy species and from neutron deficient to neutron rich. . In addition, nuclear reaction mechanisms can be studied using exotic nuclei in different energy regimes.

With AGATA at GANIL a large variety of physics questions can be addressed, such as

- Search for the contribution of the three-body interaction to the nuclear force,
- Coupling to the continuum for weakly bound nuclei,
- Evolution of the shell structure far from stability in medium-mass and heavy elements,

- Isospin symmetry breaking in N~Z nuclei,
- Clusterisation effects in nuclear matter and the origin of nuclear deformation,
- Proton-neutron pairing,
- Nuclear structure inputs for nuclear astrophysics models
- Studies of the giant collective modes

1. Study of shell evolution with ISOL beams, effect of the p-n interaction

A fascinating subject of nuclear structure research concerns neutron-rich and proton-rich nuclei far from stability, where significant changes of the shell structure are predicted. Those can be inferred, for example, from measurements of spectroscopic factors for single-neutron transfer reactions such as (d,p) in inverse kinematics at energies below and around the Coulomb barrier. The neutron-rich and neutron-deficient RIBs delivered by GANIL will allow the extension of the knowledge of spectroscopic factors and improve their precision for different mass regions, from light to medium mass nuclei.

The reduced electromagnetic transition strengths, e.g., B(E2) values, are sensitive to the proton contribution to the excitation. Knowledge of the excitation energies of low-lying collective states and transition strengths between them can be obtained from Coulomb excitation or nuclear lifetime measurements following nucleon transfer reactions. Such experiments can be performed with very low beam intensities (down to 1000 atoms/s) and require highly efficient γ-ray spectrometers with high position sensitivity. AGATA combined with state-of-the-art light charged-particle arrays will make experiments aimed at determining the contributions of protons and neutrons to specific nuclear excitations possible. As an example, the availability of a ^{56}Ni post-accelerated beam at >10^3 pps will allow an extensive experimental program on this doubly-magic nucleus using Coulomb excitation and direct transfer reactions with ^{2,3}H, or ^{3}He targets to be carried out: including 1n and 2n transfer to probe the N=28 neutron shell closure, 2p transfer to probe the Z=28 proton shell closure, and ^{2}H transfer to study pairing. Such a set of transfer reaction data would be unique. A large set of transition probabilities, spectroscopic factors and spectroscopic quadrupole moments in yrast and non-yrast states in ^{56}Ni and neighbouring isotopes will shed new light on nucleonic correlations in this mass region. Using lighter elements, between He and Ca, direct reactions and charged-particle and γ–ray spectroscopy will allow probing low-lying bound states and their coupling to the continuum. In-beam spectroscopy of post-accelerated beams of $^{6\text{-}8}$He, $^{8\text{-}9}$Li, ^{11}Be, ^{15}C, $^{16\text{-}18}$N, $^{23\text{-}25}$Ne and $^{25\text{-}26}$Na could be performed using the combination of GRIT for detecting charged particles, AGATA for γ rays and a zero-degree spectrometer as VAMOS-GFS.

2. Structure of heavy and superheavy nuclei

The most powerful detection devices available are needed to further our understanding of the structure of the superheavy elements, and to understand how it influences their stability [Ack17]. The trends of lifetimes and other key observables for individual elements can be expected to vary according to the number of neutrons. Various methods (α-, γ-, and electron spectroscopy, Coulomb excitation, ion trapping) give access to their characteristic properties (spin, parity, excited states, quadrupole moments, fission barriers, masses). Fusion-evaporation cross sections decrease rapidly when going towards the heaviest elements Obviously, coupling AGATA with a zero-degree separator (i.e. VAMOS used as gas-filled separator, VAMOS-GFS) is mandatory. The benefits of AGATA will be the gain in total statistics (high counting rate capability and efficiency), and, as a consequence, the gain in γ-γ coincidence statistics, which is mandatory for studying odd nuclei or 2qp states in even-even nuclei. γ-γ coincidences are also valuable for lifetime measurements using the plunger technique. In this mass region, the use of a differential plunger is only possible if the nuclei of interest are produced in inverse kinematics, which requires heavy-ion beams, that are unique at GANIL, and VAMOS-GFS. Since internal electron conversion is large for these nuclei (due to the large

Z), prompt electron spectroscopy would be of great benefit. The proposed experiments include the in-beam spectroscopy of nuclei as close as possible to the doubly-magic deformed ^{270}Hs and the first lifetime measurement in a transfermium element in the rotational ground-state band of ^{254}No. Figure 2 shows the expected limit in prompt γ-ray spectroscopy as a function of the AGATA solid angle coverage and transfermium masses. Approaching ^{270}Hs would be possible with the 3π AGATA system coupled to VAMOS GFS.

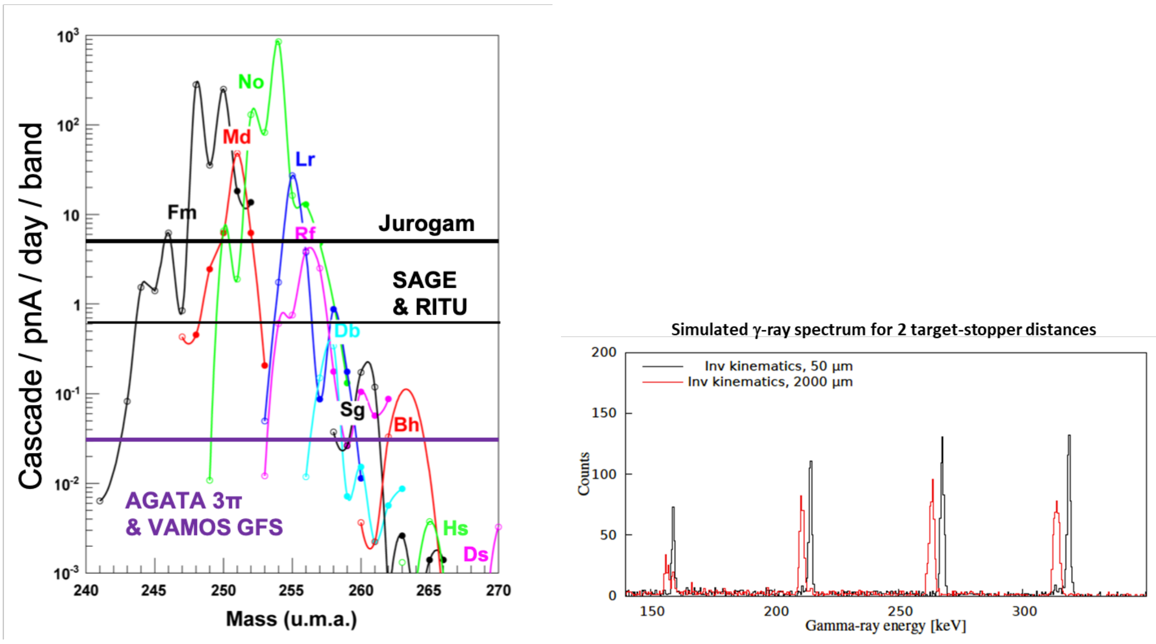

Figure 2: (Left) Sensitivity limit of AGATA for spectroscopy experiments on very heavy and super-heavy elements. (Right) Simulated AGATA response function of a plunger lifetime measurement of ^{254}No using inverse kinematic (^{208}Pb + ^{48}Ca) for two target-to-degrader distances. Thanks to the high quality of the Doppler correction in AGATA, lifetimes in states above the 6^+ could be measured.

As shown in Figure 2 the very first lifetime measurement in a transfermium nucleus could be performed making use of the specific capabilities of AGATA and the ^{208}Pb beam from GANIL. Finally, entry distribution (E*,I) measurements of very heavy nuclei could be performed using the AGATA 4π array [Hen14]. These allow the measurement of fission barriers on the condition that the neutron separation energy is larger than the saddle point. Such measurements are also important to understand the reaction mechanisms leading to the production of these very rare nuclei and, by comparing experiment with theory, will provide a better modelling of the processes involved. It may also be possible to compare the entry distributions for a given nucleus produced in standard fusion-evaporation and in multi-nucleon transfer reactions. This, together with cross-section measurements would certainly give a better handle on the reaction process.

3. Isospin symmetry studies

Isospin symmetry is a consequence of the assumption that nuclear forces are independent of charge. The symmetry is characterised by the isotopic spin (“isospin”) quantum number T. The concept of isospin symmetry is expressed most clearly in the nuclei with conjugate neutron and proton numbers known as “mirror nuclei”, having a very similar structure [Len18]. The breaking of the isospin symmetry by the Coulomb force increases with Z and for a given mass it is at a maximum for N=Z nuclei. Consequently, studies of the heaviest possible nuclei with N≈Z are of fundamental interest. In-beam spectroscopy of the ^{75}Sr/^{75}Rb or ^{79}Zr/^{79}Y are mirror pairs are examples that are accessible with

AGATA at GANIL. For less exotic nuclei, electromagnetic properties of the corresponding states in mirror nuclei are a powerful tool to test isospin symmetry. Here, lifetime measurements in A=71 or A=67 nuclei are ideal cases. These could be performed using plunger techniques following fusion-evaporation reactions or multi-nucleon transfer. The isospin symmetry breaking can be also studied by observing the isospin mixing of nuclear states. In fact, every nuclear state is expected to contain, in addition to the main component of isospin T, minor components of different isospin. Isospin mixing can be directly accessed by measuring the isospin forbidden (ΔT=0) E1 transitions in N=Z nuclei. Lifetime measurements of excited states de-exciting through E1 transitions in heavy N=Z nuclei would allow a direct determination of the isospin mixing. Such detailed spectroscopic information combining measurements of angular distributions, γ-ray polarization and lifetimes was obtained for the N=Z case of ^{64}Ge [Far03]. Similar studies in ^{68}Se and ^{72}Kr would be of great importance.

4. Pairing modes

Correlations between pairs of particles (so-called pairing) have a fundamental importance in all fields of physics involving multi-particle systems. In the nuclear domain, the strongest interactions involve nucleon pairs that are close in space, reflecting the fact that the range of the nucleon-nucleon force is small compared with the size of the nucleus. A wealth of experimental evidence has been accumulated over the years supporting the existence of neutron-neutron and proton-proton pairs [Ced11, War06]. For very exotic nuclei, pair correlations can no longer be treated as a small residual interaction, since their effect is of the same order of magnitude as the binding energy of outer nucleons generated by the remaining part of the nuclear potential. The T=0 pairing mode, in which the intrinsic spins of nucleons are aligned, is forbidden by the Pauli principle for like-particle pairs, unlike for neutron-proton pairs. Obtaining information on neutron-proton (np) correlations in nuclei is a long-standing ambition in nuclear physics. For N=Z nuclei, isoscalar np pairing (S=1, T=0) may become significant. Several manifestations of such an isoscalar superfluid state could be tested experimentally. Transfer reactions such as (^{3}He,p) or (p,^{3}He) are ideal probes for these studies in the same way as (p,t) and (t,p) for neutron-neutron pairing [Isa05]. Indeed, systematics of cross-section measurements for np transfer to the J=1$^+$,T=0 and to the J=0$^+$, T=1 states along the N=Z line from one closed shell to the next can be considered an ideal probe to investigate this possible new type of pairing collectivity. This can be measured by means of (^{3}He,p) reactions. Because of the experimental difficulties in studying intermediate-mass N = Z nuclei, the existing information is mostly limited to sd-shell nuclei, with very scarce data available above the fp-shell nuclei. ^{58}Cu is one of the best candidates accessible experimentally as it is the only odd-odd nucleus in this region to have a J=1$^+$,T=0 ground state (all others having J=0$^+$,T=1). The high-j orbitals should favour the development of collectivity and particularly of a superfluid state. Studies towards even heavier nuclei, e.g. ^{72}Kr and ideally ^{92}Pd would be of utmost importance. Therefore, the key physics cases for AGATA at GANIL would be to study the ^{72}Kr (^{3}He,p)^{74}Rb and ^{56}Ni(^{3}He,p)^{58}Cu reactions using SPIRAL1 beams.

An alternative approach to probe the nature of pair correlations in proton-rich nuclei is to study the level structure of N=Z nuclei at moderate to high angular momenta. The Coriolis effect acting on the paired nucleons in a deformed rotating nucleus, which drives them to align their intrinsic angular momenta along the collective rotational axis, is selective with respect to the residual interaction. In the case of normal T=1, S=0 pairing the Coriolis effect leads to breaking the nucleonic pairs, which produces discontinuities (backbending) in the rotational behaviour. In contrast, in the case of strong T=0, S=1 (i.e. deuteron-like) correlations the np pairs are already spin-aligned and the Coriolis force is not expected to perturb the system as violently. Consequently, significant differences in the rotational behaviour are expected depending on whether a deformed nucleus is dominated by isovector (T=1) or isoscalar (T=0) pair correlations. Such phenomena can be probed experimentally using fusion-evaporation reactions and γ-ray spectroscopy by observing heavy N≈Z nuclei in excited states up to moderate spins. The presence of T=0 pairing may slightly enlarge the pair gap at low spins producing a systematic shift in the rotational crossing frequency of the backbending effect in N=Z nuclei as compared with neighbouring nuclei. This idea, first suggested for ^{72}Kr, has been explored in the medium-spin region of N=Z nuclei with A=70-80. Evidence for the shift of the crossing frequency is, however, not yet conclusive, since possible shape changes precluded a precise determination of the band-crossing frequencies. Therefore, new experimental data on heavier N=Z systems, which are less prone to shape changes, are needed. A complete study of yrast states up to moderate angular momentum in these N=Z nuclei (^{88}Ru, ^{90}Rh, ^{92}Pd, ^{94}Ag, ^{96}Cd and ^{98}In) is a major goal requiring the full performance of the AGATA tracking spectrometer.

5. Nuclear Astrophysics

Nuclear astrophysics studies will benefit from a highly efficient γ-ray tracking detector array such as AGATA. For example, the reaction rates in stars can be strongly influenced by the nuclear properties of the involved nuclei, thus affecting the abundance of the chemical elements. Thermonuclear H and He capture reactions are the most important, hydrogen and helium being about 99% of the baryonic matter in the Universe, and having the lowest Coulomb barriers. Some key processes are also influenced by the structure of light nuclei, such as Li, Be, B, C, O, In particular, near-threshold resonances, such as those in ^{12}C (the famous "Hoyle state") and in ^{16}O can exhibit a pronounced cluster structure that alters the reaction rates. Knowing electromagnetic decays from unbound states would represent a big step forward. However, γ-decay branching ratios are of the order of 10^{-3} or lower. This means that direct measurements at the relevant energies (usually of the order of hundreds of keV) are strongly hindered by the extremely low cross section as well as by the background from cosmic rays and natural radioactivity. In particular, the ^{12}C(α,γ)^{16}O key reaction is of paramount importance in the advanced burning of a massive star, but the reaction rate is still rather uncertain. As a consequence, the uncertainty on the C/O ratio that governs the final fate of the star is quite large.

A typical measurement with a high intensity beam (μA) of light ions delivered onto a solid target would strongly benefit from the use of a tracking detector like AGATA surrounding the target. These studies can be extended to reactions populating more exotic species near the proton and neutron driplines provided by the SPIRAL1 facility that may play a role in explosive scenarios, such as ^{10,11,15,16}C, ^{12,13,16,17}N or ^{14,15,19,20}O, whose decay properties and structure are mostly unknown. Even less exotic C, N and O isotopes are of great interest for understanding the isotopic composition observed in giant stars of various masses. For these studies, reactions between light/medium nuclei, such as ^{12,13,14}C on ^{9,10}Be or ^{10,11}B can be used.

6. Nuclear structure at the highest spins

The phenomenon of nuclear super-deformation (SD), from the quantum nuclear-structure theory view point, is a manifestation of unitary symmetries in nuclei and, more precisely, the so-called pseudo-SU(3) symmetry. Based on this concept, SD bands were predicted in many mass regions before their experimental discovery. Today, more than 200 SD bands are established in full agreement with the theoretical predictions. Hyper-deformed structures are also predicted, but have not yet been found experimentally due to the lack of resolving power of the previous-generation γ-ray spectrometers. At moderate nuclear deformation, several other topics, such as the nuclear pairing phase transition, the structure beyond the termination of rotational bands, when all single-particle spins are fully aligned, and nuclear triaxiality and chirality, deserve more in-depth studies.

The population of these very to extremely elongated nuclear shapes is a very delicate process, which seems to be related to the presence of the nuclear Jacobi shape transition at high temperature in the compound nucleus and to the associated low-energy component of the Coriolis splitting of the GDR. Precise state-of-the-art theoretical predictions enable the determination of the spin feeding window of these structures, which will allow optimisation of the experiments searching for the HD structures. Such studies will bring information as to how specific single-nucleonic shell structures stabilise the nuclear matter on the way to fission.

In most cases of known SD bands, the decay towards lower-lying structures is not established experimentally, which means that the excitation energies, spins and parities of the SD states are not known, which in turn severally hampers the comparison with theoretical models. Another amazing observation is the so-called `identical band phenomenon', where the γ-ray energies of SD bands in neighbouring nuclei differing in mass are identical within 1 keV. The mechanism manifests itself through the vanishing of the differences between the kinematical moments of inertia of two different nuclei, a feature which is all but intuitive. Finally, certain SD configurations are also predicted to correspond to non-axial shapes, manifesting molecular symmetries.

Phase transitions are among the most fascinating collective phenomena which engage significant subsets of nucleons in the system. They lead “all of the sudden” to “jumping” from one phase to another, e.g. from the nuclear superfluid phase, in which the nuclear moment of inertia is about 50% of the rigid-body value, to the “normal” phase, in which the moment of inertia takes its rigid body value. This transition may be induced by increasing collective rotation or, alternatively, the nuclear temperature. What are the mechanisms which initiate these transitions? Why aligning one pair in a given nucleus can lead to the complete disappearance of superfluidity whereas a similar pair in another nucleus leaves the moment of inertia at 80% of the rigid-body value? Despite the success of some theoretical approaches, the deep understanding of the phenomenon is going beyond the existing models.

The shape instabilities or deformation softness may give rise to a dramatic shape and structure evolution with increasing spin manifested as disappearance of the nuclear rotational collectivity known as band termination. The nuclear motion at angular momenta in the vicinity of the critical spins of a Jacobi transition assumes a character of a dramatic shape instability. Indeed, the shape can oscillate between strongly oblate and prolate with elongations exceeding those observed for super-deformation, while the excitation energy changes only by a few hundred keV. Such dramatic shape transitions at no energy cost are accompanied by virtually dozens of individual nucleonic level crossings corresponding to equally dramatic intrinsic structure rearrangements. Given that various orbitals, which participate in these level crossings, have dramatically different nodal structures (spatial distributions of the particles) and the fact that all of them are accompanied by virtually negligible energy changes indicates new states of matter and/or phase transitions, similar to those intensively studied in condensed-matter physics.

In all physics cases presented in this section, the highest γ-ray detection efficiency is mandatory, as provided by the 4π AGATA array. Only in this case the necessary sensitivity can be achieved by exploiting very high-fold γ^n coincidences. In addition, the tracking properties will allow to retain the best possible energy resolution and optimise the peak-to-background ratio, both of which are also important to maximise the sensitivity.

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AGATA at the HIE-ISOLDE facility

The Isotope mass Separator On-Line Device (ISOLDE) facility at CERN has a unique expertise worldwide in production of low-energy purified exotic beams. The radionuclides, spanning a vast area of the nuclear chart, are produced by high-intensity 1.4-GeV proton beam impinging on specially developed thick targets. The selective ionisation, extraction and separation techniques have been refined over the 50 years of the continuous operation of the facility. In total, over 1300 isotopes of more than 70 elements have been delivered by ISOLDE.

Commissioned in October 2015 and subsequently upgraded, the new linear accelerator HIE-ISOLDE will bring the final energy of post-accelerated radioactive beams of up to 10 MeV/A. In addition, the new developments aiming at delivering more intense and pure beams are under way. Such beam energies provide an important increase of multi-step Coulomb-excitation cross section and allow for nucleon transfer reactions on all radioactive nuclei produced at ISOLDE, up to A>200. The combination of the outstanding variety and quality of beams available at HIE-ISOLDE with unparalleled efficiency and energy resolution of AGATA enables broadening the scope of physics questions that can be addressed via detailed and precise studies at the heart of the most important regions of the nuclear chart.

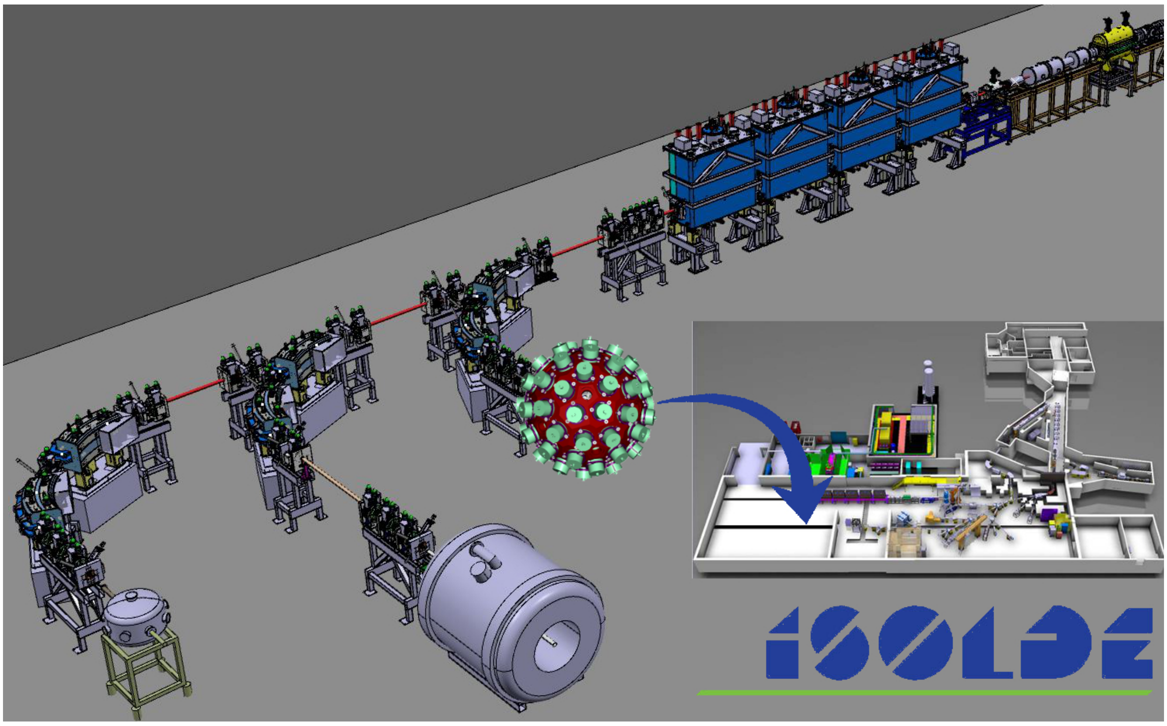

Figure 1: Possible location of AGATA on HIE-ISOLDE XT01 beam line.

At the beam energies of HIE-ISOLDE, AGATA provides the best energy resolution (with respect to intermediate or relativistic beam energies) thanks to the HPGe detectors and much reduced Doppler broadening due to pulse-shape analysis and γ-ray tracking technique. The high resolution and excellent Doppler-shift reconstruction is especially beneficial in Coulomb excitation, DSAM or plunger techniques, to measure transition strengths and identify bands. This is particularly important for studies of odd-mass nuclei, when many lines are expected in the γ-ray energy spectra, typically in a narrow range of energy. Also, when moving far from the stability, the nuclear half-lives become comparable with the time needed for beam separation and post-acceleration, and consequently the resulting beams of very exotic nuclei suffer from contamination due to in-flight decay. AGATA will provide higher resolving power, not only with increased efficiency, but also better peak-to-total value and higher granularity to allow for better

Doppler correction for peak identification. Moreover, higher granularity will enable determination of multipolarities of observed γ-ray transitions from measurements of angular correlations and polarisation of γ rays.

In transfer reactions, particle detection provides the cross sections, proportional to spectroscopic factors and related to initial and final shell occupancies. With radioactive ion beams and in inverse kinematics, there are strong limitations on the energy resolution of particle detection – rarely better than 300 keV. As shown in measurements performed at ISOLDE and elsewhere, the coupling to an efficient γ-ray array is in many cases essential. Efficiency is the key word here: the Miniball array, with around ~10% photopeak efficiency, forces the use of relatively thick targets that compromise particle-detection resolution further, and does not provide enough statistics to build angular distributions from γ-gated events. The 4π AGATA array would open a different scenario by providing good statistics for particle-γ coincidence events and, in turn, a much better background subtraction for pure particle-emission events populating, for example, the ground state or isomers with half-lives longer than a few tens of nanoseconds. The high statistics would also allow to collect particle-γ angular correlations, which can be used, together with the γ-γ coincidences from the decay of the populated states, to constrain the spins in the product nucleus. A highly-efficient γ-ray array is especially of interest for the full reconstruction of the strengths in the product nucleus, up to energies (even of a few MeV) above the shell gap, for which the density of states becomes important.

Some key physics cases, highlighting both the uniquely available beams at ISOLDE and the state-of-the-art capabilities of the AGATA array, are discussed below.

1. Studies of nuclei around magic numbers

Z=28 shell closure, from N=40 ^{68}Ni to doubly-magic ^{78}Ni

The shell evolution, as determined by the underlying nucleon-nucleon interaction, leads in this region to a number of remarkable effects, including the swift onset of collectivity observed below ^{68}Ni [Rot11], determined by the gaps in the neutron-orbital g-d-s sequence; the evolution of the proton $f_{7/2}$-$f_{5/2}$ splitting from N=40 to N=50 [Fla09,Mor15]; the lowering of the neutron $s_{1/2}$ orbital in the N=51 isotones from Z=40 to Z=28.

AGATA would be particularly beneficial in identifying weak components of the strength when it is fractioned to higher-lying states, for example in (d,p) transfer reactions on ^{68,70,72}Ni and possibly in Fe isotopes (to track the neutron-$d_{5/2}$ strength), and in (d,^{3}He) transfers on the even $^{72\text{-}78}$Zn isotopes (measuring the proton $f_{7/2}$-$f_{5/2}$ splitting). Further, it could provide a better characterisation of the low-lying ½$^+$ strength identified in ^{79}Zn [Yan16] and still looked for in ^{81}Zn.

Approaching the doubly-magic ^{100}Sn

In the light even-mass Sn isotopes a deviation has been found between predictions of large-scale shell model calculations, e.g. using microscopically derived interactions, and experimental reduced transition probabilities between the first excited 2$^+$ state and the ground state. Measurements using low- as well as high-energy Coulomb excitation (e.g [Ced07, Eks08, Ban05, Vam07]) display consistent results within measurement precision, but may indicate different trends towards the lighter masses. The reduced transition probabilities were also re-measured recently for the stable mid-shell nuclei, $^{112\text{-}124}$Sn. Surprisingly, those showed a decrease in the B(E2) values at mid-shell, contrary to earlier high-precision experiments and model predictions. This is particularly interesting since the even Sn chain has been a textbook example for simplified seniority models in the past.

This fluid situation with the new experimental results, have spurred new theoretical interest in the region. Calculations now predict different trends towards ^{100}Sn [Cor15,Tog18], but cannot be compared with precision data as these do not exist yet for the lightest isotopes. In particular, a clear assignment of non-yrast and 3^- states is important. The performance of AGATA combined with the advances in beam development will allow high-precision multiple Coulomb-excitation measurements as far as to ^{104}Sn.

Around the doubly-magic nuclei ^{132}Sn and ^{208}Pb

The two doubly-magic nuclei ^{132}Sn (50 protons, 82 neutrons) and ^{208}Pb (82 protons, 126 neutrons) have the features of a classic shell-model core.

The structure of neutron-rich isotopes beyond ^{132}Sn is related to the behaviour of the neutron $2f_{7/2}$ orbital as more neutrons are added, and to the possible ensuing shell closure at N=90 as predicted by calculations with empirical interactions. The latter issimilar to that of the Ca isotopes where the filling of the $1f_{7/2}$ orbital from N=20 onwards leads to the N=28 shell closure.

Future experiments with AGATA will aim to investige, in particular, the quadrants south-east of ^{132}Sn and ^{208}Pb, where excited states are scarcely known. For example, proton single-particle states and their interactions below Z=82, and indirectly the robustness of the N=126 closed shell, can be analysed by studying single proton-hole nuclei in the Tl and Hg nuclei with N≥126.

Another point of interest is the transition from a seniority behaviour to a collective character of excited states in nuclei when the number of valence particle increases. Such studies require a precise knowledge of the electromagnetic transition strengths for transitions de-exciting the yrast states and non-yrast 2^+ states. Good starting points for such measurements are ^{136}Te and ^{214}Po. The anomalous properties of 2^+_1 state of ^{136}Te are well known [Rad02], but neither lifetimes of the other yrast states are known nor the isovector 2^+ state has been identified. In the case of ^{212}Po, a peculiar low-collective behaviour is observed for both the yrast states and the isovector 2^+ state [Koc17], which cannot be explained in the framework of the shell model. Due to insufficient knowledge of lifetimes in ^{214}Po it is not clear whether this peculiarity persists with the increasing neutron number. The states of interest in both ^{214}Po and ^{136}Te can be populated in multistep Coulomb excitation or α-transfer reactions in inverse kinematics, and their lifetimes measured employing differential DSAM and plunger methods. The high efficiency of AGATA and its tracking capability, which enables precise Doppler correction of the gamma rays, are of utmost importance.

2. Reactions relevant for nuclear astrophysics

Reactions relevant to the rapid proton capture (rp) process - Light Curves and Waiting Points

Astrophysical X-ray bursts [Woo76, Sch01] are thought to be the result of thermonuclear explosions in the atmospheres of accreting neutron stars in close binary systems and are the most frequent stellar explosions to occur in our Galaxy.Detailed observations of these events have been obtained by a host of space-based X-ray observatories in recent years. Consequently, by obtaining a detailed understanding of the nuclear processes responsible for the shape of the resulting light curve, it will be possible to model the dynamical impact X-ray bursts have on the evolution of the Milky Way and will also gain significant insight into the properties of neutron stars, environments representing the extremes of nuclear matter. A number of reactions have been highlighted as having a particularly significant influence on the X-ray burst light curve which can be uniquely accessed with the suite of neutron-deficient beams available at HIE-ISOLDE. These include the waiting point nucleus ^{64}Ge, whose destruction can be investigated through the ^{64}Ge(d,p)^{65}Ge reaction and the ^{61}Ga(p,γ)^{62}Ge reaction, which is predicted to have a dramatic influence on the light curve – that can be studied indirectly with ^{61}Zn(d,p)^{62}Zn transfer.

Particle transfer as a surrogate for neutron capture in the s- and r-processes

New, indirect techniques must often be employed in order to estimate astrophysical neutron-capture rates since the cross sections cannot typically be directly measured. One such approach is to transfer a neutron using a (*d,p*) reaction to the same compound level (or levels) that would be populated in neutron capture and then to measure the subsequent γ-ray decay. This method relies on the assumption that the decay of the compound nucleus is independent of the entrance channel. The measurement of the γ-ray branching ratios in then needed to estimate the neutron-capture cross section. Such information can be obtained from studies of the (*d,pγ*) reaction on the exotic r-process nucleus of interest. This approach has already been tested: the cross sections for the (*d,pγ*) reaction on ^{171,173}Yb were compared with the known neutron-capture cross sections and the two were found to agree for neutron energies about 100 keV [Hat10]. Such studies pave the way for future measurements on more neutron-rich nuclei at HIE-ISOLDE.

3. Studies of quadrupole shapes and shape coexistence far from closed shells

At beam energies available at HIE-ISOLDE, the probability of multi-step Coulomb excitation is enhanced, promoting population of non-yrast states. Experiments where AGATA is combined with an electron spectrometer such as SPEDE will open the possibility to probe, in a single measurement the shapes, collectivity and location of band-head states of the excited nucleus. The search for coexisting configurations will strongly benefit from e^--γ coincidence measurements.

Shape coexistence in the neutron-deficient Pb-Po-Hg region

The neutron-deficient Pb region is well known for intruder configurations associated with different shapes [And00]. In the Po isotopes, intruder 0^+ states have been observed from ^{202}Po down to ^{196}Po. In-beam γ-ray data suggest the first excited state in ^{194}Po being the 0^+_2 state at ~230keV energy, making it one of the lowest such states in the nuclear chart. Similar cases with low-lying 0^+ states associated with intruder configurations were found e.g. in ^{186}Pb and ^{180}Hg.
The analysis of Coulomb-excitation measurements on light Hg, Po and Pb isotopes has proved to be difficult due to the lack of lifetime information. Such measurements can be realised by combining the standard Coulomb excitation setup with a plunger device, giving extra sensitivity from the independent determination of lifetimes and leading to a more precise extraction of quadrupole moments for yrast and non-yrast states. Complementary information can be obtained from studies of odd-mass nuclei. For example, studies of coupling of the odd-neutron to the even-mass core in the ^{185,187}Pb isotopes can provide direct evidence on the properties of the core itself, including shape, while one-neutron transfer to ^{189}Pb would probe the configuration of intruder states.

Neutron-deficient Kr-Se isotopes

Neutron-deficient Se and Kr nuclei are another classic region of shape coexistence [Bou03, Cle07]. Key nuclei to study are ^{68}Se and ^{70}Se. In the former, weak evidence for oblate shape has found, contrary to what was measured for the latter. The investigation of the excited 0^+ states in this region will help to solve this conundrum. In addition, the energies of the first 2^+ states show similar behaviour to those in the light Hg isotopes. In order to firmly establish the quadrupole moments of the coexisting structures, it is critical to determine the multipole mixing ratios and related E0 components of transitions between states of the same spin. This information can be obtained from angular correlation measured with AGATA combined with SPEDE.

4. Studies of octupole collectivity

Octupole collectivity in the actinide region

The region of the nuclear chart with the most experimental evidence for octupole deformation is the actinide region, north-east of ^{208}Pb and centred around ^{224}Ra [Gaf13]. It is this region that is of the greatest interest to EDM searches. Two of the candidates for these EDM experiments are ^{221,223}Rn, where no excited levels are yet known. Coulomb excitation of the odd-mass radon and radium isotopes proves to be a much greater challenge than for their even-even neighbours. The high density of low-energy transitions expected in the γ-ray spectrum comes from the parity-doublet structure of the rotational bands. AGATA provides excellent angular resolution, which will be crucial when trying to disentangle the complex level schemes of the odd-mass nuclei. The expected large conversion coefficients make those ideal experiments for the coupling of AGATA to the SPEDE electron spectrometer. With the ability to perform γ-e^- coincidences, transition multipolarites can be obtained and used to provide spin and parity assignments, determining the energy of the parity splitting for the first time.

Octupole collectivity in the rare-earth region

In the region of neutron-rich lanthanides, where strong octupole correlations are predicted and confirmed by the level structures, very few *E3* transition strengths are known. Coulomb-excitation measurements have recently been performed at HIE-ISOLDE on ^{142,144}Ba and ^{142}Xe, complementary to the studies of ^{144,146}Ba making use of the Argonne National Laboratory's CARIBU facility [Buc16, Buc17]; it is planned to extend the measurements at HIE-ISOLDE to other octupole-deformed nuclei in this region, for example ^{146,148}Ce.

The neutron-rich barium beams at both CARIBU and HIE-ISOLDE suffer from a large amount of isobaric contamination from stable and long-lived isotopes of neodymium, cerium and samarium. This gives rise to additional γ-ray transitions and background features in the energy spectrum. For example, the $1_1^- \rightarrow 2_1^+$ transition at 560 keV in ^{144}Ba, the intensity of which determines the population of the 1^- state, lies on the Compton background of the much more intense $2_1^+ \rightarrow 0_1^+$ transition at 696 keV in ^{144}Nd. Fitting the intensity of this weak transition amongst the large background is currently the limiting factor in the uncertainty of the $B(E3)$ (~60%). Combining AGATA's tracking capabilities with the better angular resolution over

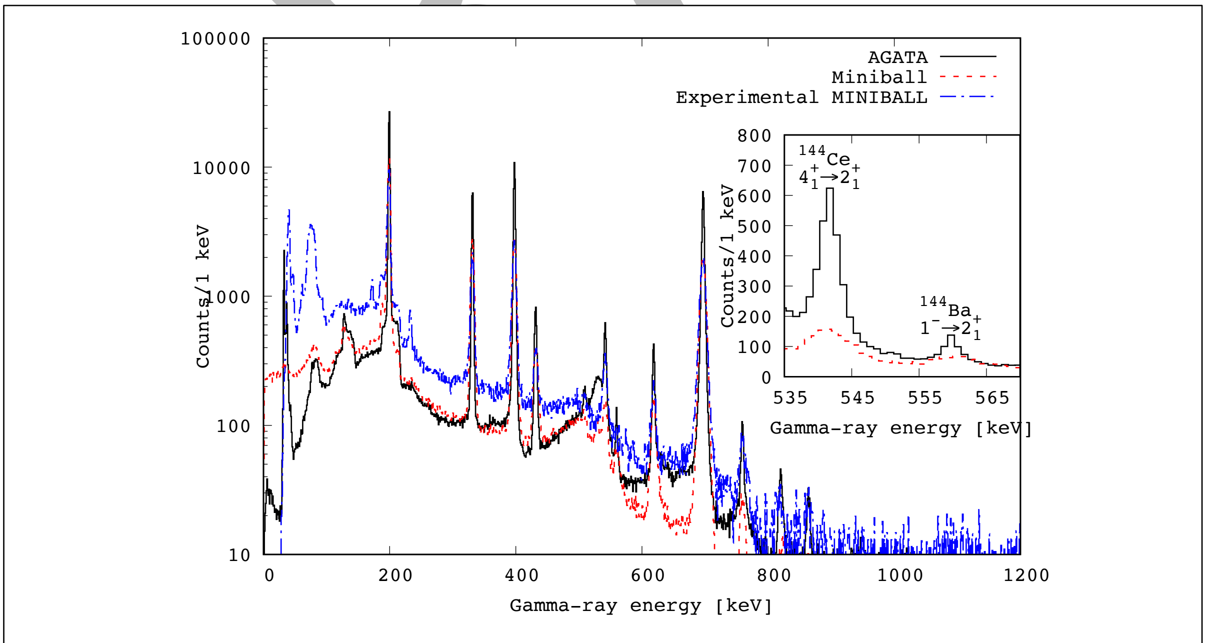

Figure 2: Comparison of an experimental Miniball spectrum with simulated spectra for AGATA and Miniball of a Coulomb excitation study of a radioactive ^{144}Ba beam on a ^{208}Pb target. ^{144}Ba is expected to show strong octupole correlations. The performance gain with AGATA is particularly visible for the weak transitions from the negative parity band (see insert).

Miniball will simultaneously reduce the Compton background and improve the Doppler correction, leading to a reduction in the peak-to-background ratio for weak transitions. Furthermore, the greater granularity and efficiency will allow γ –γ coincidences to be used for a clean and reliable extraction of the $3_1^- \rightarrow 2_1^+$ transition intensity in coincidence with the 199-keV $2_1^+ \rightarrow 0_1^+$ transition.

Octupole collectivity near magic numbers

Recently, the 3_1^- state in ^{132}Sn, which lies at an energy of 4352 keV, has been populated at HIE-ISOLDE. Another recent Miniball experiment studying Coulomb excitation of ^{206}Hg, a beam that is unique to the HIE-ISOLDE facility, shows also tantalising evidence for the 3_1^- state. The much-improved efficiency of the AGATA spectrometer at high energies and for γ–γ coincidences would be a huge advantage here. In this direction, an observation of the 3_1^- states in neutron-rich tin and tellurium isotopes north-east of ^{132}Sn will become feasible with the use of AGATA at HIE-ISOLDE.

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AGATA at the JYFL facility

The Accelerator Laboratory at the University of Jyvaskyla (JYFL) is one of the leading stable beam facilities in Europe. The K130 cyclotron can deliver a wide range of high-intensity stable beams. Over the last twenty years, the laboratory has supported a world-leading programme of γ-ray spectroscopy measurements on nuclei at the limits of stability, principally proton-rich nuclei. The efficiency of such studies and their ability to address the most exotic nuclei is strongly related to the power of the γ-ray detector array employed. Installing a near 4π AGATA array at JYFL therefore presents the opportunity to drive a paradigm shift in what is possible at JYFL. The full AGATA configuration would be needed for most studies since reactions will mostly be at Coulomb barrier energies where there is no significant forward-directed boost in the emission of γ rays.

Several major pieces of apparatus at JYFL can drive an innovative science programme. These include the RITU gas-filled and MARA vacuum-mode recoil separators. The flexibility in having two such systems allows high-efficiency studies of heavy nuclei and high-sensitivity studies of exotic lighter nuclei. A further important apparatus is the SAGE system for combined in-beam electron-γ-ray coincidence studies, which is unique worldwide.

1. **Superheavy nuclei**

Building on its long-standing track record in decay studies of superheavy nuclei with the RITU separator, over the last twenty years JYFL has established a dedicated, internationally-leading programme of in-beam studies of superheavy nuclei in the region around ^{254}No. Such studies provide key information on collectivity in this region. In addition, locating orbitals close to the Fermi surface provides a discriminating test of nuclear structure models in such superheavy nuclei and informs the search for a potential island of stability for superheavy nuclei. The limit so far reached at JYFL was in the study of ^{256}Rf [Gre12] with a production cross section of around 15 nb. This study employed the Jurogam germanium array, which has an efficiency of around 5% at 1.3 MeV. The employment of a near-4π AGATA would boost this efficiency to around 40%. With long running periods of a month and 2-3 fold increase in beam current, this would allow heavier nuclei such as ^{260}Sg, with a production cross-section of a few hundred pb, to be reached for the first time.

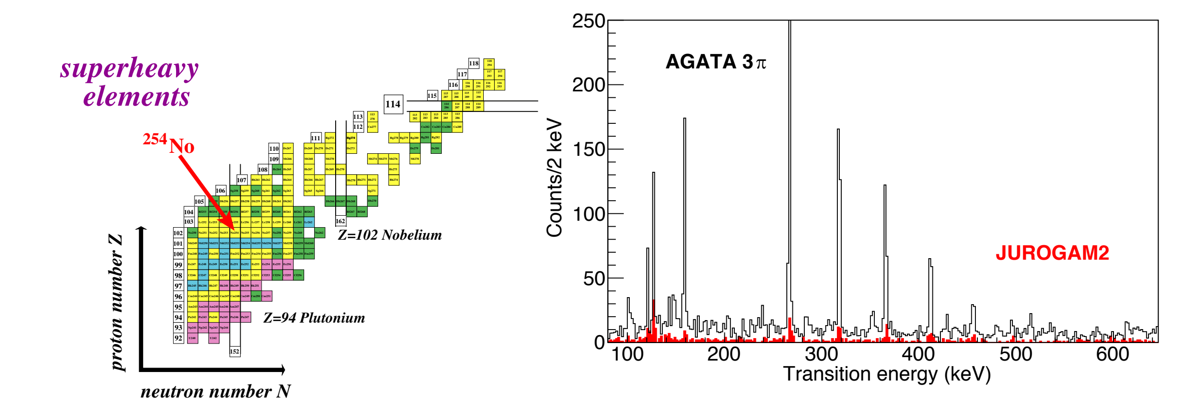

Figure 1 (left): Upper end of the nuclear chart showing the location of ^{254}No, the current limit for $\gamma\gamma$ spectroscopy. (right) Comparison of a $\gamma\gamma$ coincidence spectrum of ^{254}No (gated on the 214 keV transition) taken with JUROGAM2 (red) and simulated for a 3π AGATA array (black).

The increase in γ-γ detection efficiency by a factor of 50 with respect to the Jurogam array and the possibility to measure angular correlations and the linear polarisation of photons at all angles on gated spectra will allow detailed spectroscopy of the lighter super heavy Fm-Rf nuclei (see Figure 1).

In this way known structures can be extended to higher spins, new ones can be observed and the decay schemes can be established, in particular in odd-mass nuclei whose γ-ray spectra are notoriously difficult to disentangle. This would provide stringent tests of nuclear structure models in this region and information on the location and evolution of Nilsson orbitals.

2. Proton-rich nuclei

There is a strong programme of studies at JYFL on and along the proton dripline towards ^{100}Sn. In particular, there have been studies of N=Z-2 nuclei on and along the proton drip-line, which allow isospin-symmetry breaking forces to be studied across T=1 isospin triplets. These studies are truly at the limits of what is presently possible with production cross sections for e.g. ^{70}Kr and ^{74}Sr of around 10 nb. To extend to higher mass cases on and across the line of N=Z, a near-4π AGATA would provide an order of magnitude increased sensitivity. It would also be possible to carry out in-beam studies of nuclei around ^{100}Sn, probing the single-particle structure close to this doubly-closed shell nucleus, which is a key test of state-of-the-art nuclear structure models.

The ultimate limit of observable nuclei for odd-Z elements is expected to be determined by direct proton emission. Proton radioactivity is a quantum-tunnelling phenomenon where the barrier penetration probability, and consequently the measured half-life, depends sensitively on the size and shape of the barrier, the decay Q-value and the angular momentum of the emitting state. The approximate spherical symmetry of the heaviest known proton emitters allows a simplified tunnelling description to reproduce partial half-life measurements reasonably well [Bec69]. In recent years, more sophisticated theoretical approaches have been developed that provide precise predictions for the wave functions of proton-emitting states that account for configuration mixing and residual interactions e.g. [Kru00]. This is particularly important for the half-lives of proton-emitting states in highly deformed nuclei where rotational effects, such as Coriolis interactions, change the orbital admixtures that contribute to the nuclear wave function. Hence, a global understanding of proton-unbound nuclei requires a detailed knowledge of the effects of nuclear structure and dynamics. This needs not only proton decay data, but also information related to the structure of excited states, which can be obtained by measuring their γ-ray emissions. The high-efficiency of the AGATA spectrometer used in conjunction with the MARA recoil separator could enable measurements of nuclear lifetimes, reduced transition probabilities and quadrupole moments. Such detailed information on the nuclear deformation would provide unprecedented constraints on theoretical models of proton radioactivity.

Consideration of the extreme case of ^{131}Eu shows that lifetime measurements are also feasible for deformed proton-emitting nuclei. The working limit for coincidence recoil-distance Doppler-shift measurements using the angular positions of the JUROGAM detectors suitable for lifetime measurements is approximately 100 μb. The production cross section for ^{131}Eu from the ^{58}Ni(^{78}Kr,p4n) is estimated from previous experiments to be 70 nb. The γ-ray detection efficiency of the angles of the AGATA array usable for lifetime measurement is estimated to be 20% at 1.3 MeV, compared with 1.2% for the usable angles of JUROGAM. Furthermore, the number of distance settings required could be reduced using a triple foil plunger. Combining all these factors would allow the required sensitivity limit to study ^{131}Eu to be achieved using AGATA, MARA and a triple-foil plunger system in a four-week long experiment. There is no other facility in the world that would be able to perform such a measurement.

3. Studies employing incomplete fusion reactions

Incomplete fusion reactions, such as multinucleon transfer, deep-inelastic and direct reactions can provide access to regions in the chart of nuclei that have not so far been exploited at RITU or MARA.

In very asymmetric reactions, the light fragment is scattered backwards in the centre-of-mass frame, while the heavy partner can be transported to the focal plane of MARA or RITU separator for identification (recoil-decay tagging). While such studies can provide insight into reaction dynamics, those reactions can also be used to populate excited states in nuclei few nucleons away from the beam- or target-like nuclei. For example, a transfer of six nucleons from beam to target nuclei in the $^{65}Cu+^{209}Bi$ reaction has been shown at RITU [Jak07]. This provides access to in-beam spectroscopic studies of nuclei around ^{59}Cr and ^{215}Ra. In general, in-beam spectroscopy of neutron-rich nuclei is challenging due to methodological limitations and in particular, apart from manganese nuclei, the neutron-rich 23<Z<28 beams are not available as post-accelerated radioactive beams. The large variety of heavy-ion beams available at JYFL can be employed to access other regions of light neutron-rich nuclei, such as ^{44}Ar and the “island-of-inversion” around ^{32}Mg using Ca and S beams, respectively. The near-4π AGATA spectrometer will not only provide much improved γ-γ coincidence efficiency, but its superior position sensitivity will be needed for proper Doppler correction for γ-rays emitted in flight.

4. Study of fission barriers

Fission is a complex process that involves the competition between the disruptive Coulomb repulsion between the protons and the restoring strong interaction between all the nucleons in the nucleus. The way the quantum system evolves towards scission dictates fission time scales and fission-fragment masses and energies.

Fission has been known for many decades now, but to date no theory of fission, based solely on the interactions between protons and neutrons, exists. Yet fission is a fundamental decay process, which plays a crucial role in many domains. It is of course the driving force of the energy production in nuclear reactors. It also governs the stability of transuranium elements and thereby determines the

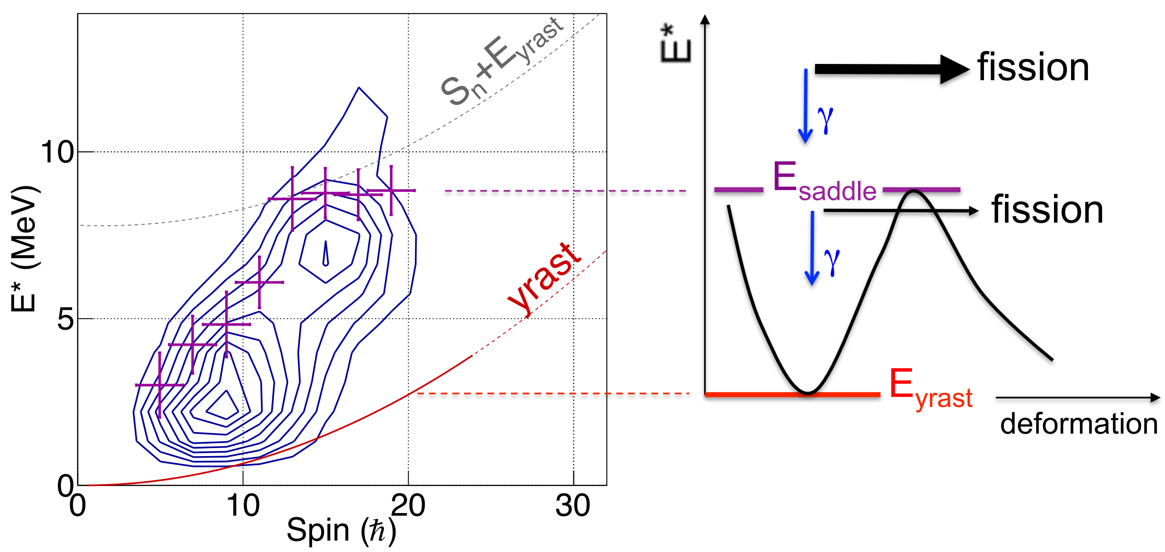

Figure 2: Entry distribution for the population of ^{254}No as function of excitation energy and spin, measured at 219 MeV bombarding energy (left). The solid and dashed lines correspond to the yrast line and neutron separation energy. The crosses, indicating the points where the distribution falls to half of its maximum value, show a saturation above spin 10 and can be directly related to the saddle point energies. The figure on the right shows the potential energy of the nucleus as a function of axial deformation and illustrates how gamma decay dominates below the saddle point energy while fission takes over at energies above the barrier.

limits of the Ségré chart and the periodic table of elements. Fission prevents the survival of nuclei produced in nuclear reactions and has therefore a strong impact on the experimental synthesis of new heavy isotopes and elements. Finally, fission of very neutron-rich very heavy nuclei is a key ingredient for modelling the r-process nucleosynthesis [Pet12,Gor15] since it shapes the final r-process abundance distribution. Whether or not Z>110 elements are produced in the r-process and can be found in cosmic rays or terrestrial matter [Ter15,Kor15] also depends on the fission properties of these nuclei.

Benchmarking the accuracy and reliability of theoretical models regarding the fission process is therefore required to improve predictions, especially for nuclei away from stability, for which large discrepancies appear between models [Gor15,Mam01]. Several observables have been suggested to validate theoretical calculations [Ber15]: fission-fragment mass distribution and kinetic energies, which are sensitive to the shape of the fissioning system, fission isomer excitation energies, fission half-lives and barrier heights.

Traditionally, barrier heights have been measured through the excitation function of fission induced either by virtual photons, transfer or neutron capture reactions, or following beta (EC) decay. In the region of transfermium nuclei, such techniques cannot be applied due to lack of long-lived targets, beams or unfavourable Q_β windows. A new method, pioneered at GAMMASPHERE [Rei00,Hen14] can nevertheless be used in the cases where the neutron threshold lies well above the fission barrier. It consists in using GAMMASPHERE as a calorimeter to measure the total energy and spin of the nucleus, which survives fission at various bombarding energies. The saturation of the entry distribution in excitation energy, observed in ^{254}No (see Figure 2), is due to the onset of fission near the top of the fission barrier and therefore provides a direct measurement of the height as well as the moment of inertia of the saddle point. In this particular case, the extracted barrier was found to be 2 MeV lower than the prediction of the Gogny functional [Egi00] and in agreement with microscopic-macroscopic type calculations using the finite range liquid drop model and the folded-Yukawa single-particle model [Mol09].

AGATA in a configuration close to 4π coupled to a high-acceptance recoil separator is the perfect tool to continue such systematic measurements in super heavy nuclei produced in fusion-evaporation reactions but also in deep-inelastic reactions. The enhanced energy resolution of AGATA over GAMMASPHERE in its calorimetric mode will reduce the uncertainty of the extracted barrier heights, which is necessary to constrain models.

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AGATA at the LNL/SPES facility

The **Laboratori Nazionali di Legnaro (**LNL) provides heavy ion beams from the 15 MV Tandem and from the ALPI superconductive LINAC, the latter used either coupled to the Tandem or to the heavy ion injector PIAVE. The stable beams range from protons to lead with energies up to 10-15 MeV/nucleon.

LNL is currently constructing the ISOL facility, SPES (Selective Production of Exotic Species), dedicated mainly to the production of neutron-rich beams. A proton beam of 40 MeV and 200 μA will impinge on an uranium carbide target, producing neutron-rich isotopes as fission fragments, with a rate of 10^{13} fission/s. The neutron-rich products will be extracted in a 1^{+} state, mass separated, transported to ALPI and accelerated up to 10 MeV/nucleon (see Figure 1).

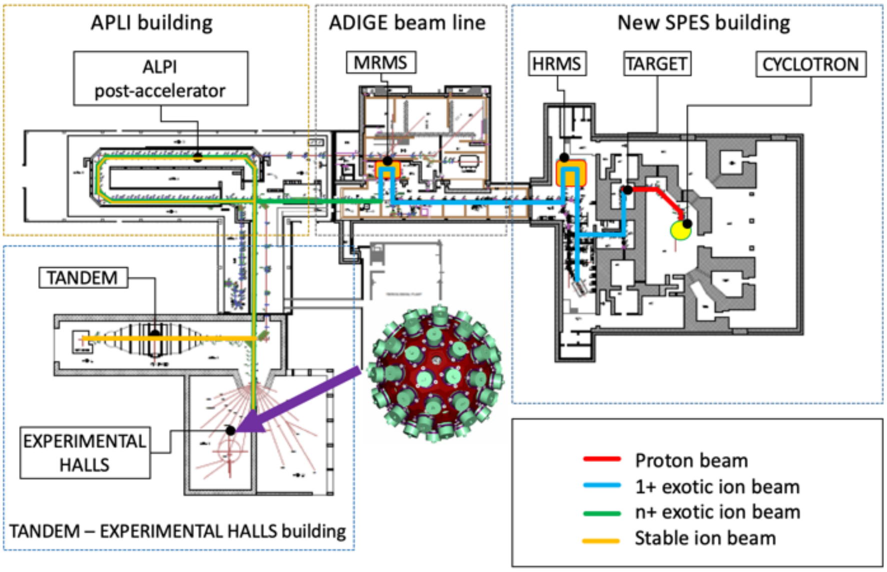

Figure 1: Possible location of AGATA at the Laboratori Nazionali di Legnaro and the SPES facility.

AGATA at LNL will be able to take advantage of both stable and ISOL beams. A mechanical configuration has been identified which allows using AGATA both at the grazing angle of the reaction, coupled with the magnetic spectrometer PRISMA, and at zero degrees, with ancillary detectors like NEDA. These two configurations warrant a rich physics program, which will be further strengthened by the availability of the most advanced detectors for light charged particles (e.g. GRIT, SPIDER, and conversion electron spectrometers), high-energy γ rays (e.g. PARIS and large volume scintillators), as well as a detection system for selection of evaporation residues (e.g. the Recoil Filter Detector (RFD)).

High-intensity stable beams will allow the exploitation of the extraordinary γ–ray detection capabilities of AGATA in orderto search for rare nuclear phenomena, boosting the discovery potential of traditional research themes carried out at LNL, and opening new physics programs. In the following a few examples are presented:

1. Collectivity and clusterisation in light nuclei

The existence of clusters of protons and neutrons [Ebr12] in light nuclei, from lithium and beryllium, to medium mass nuclei, is a well-known feature, with significant consequences on nucleosynthesis reactions, with the Hoyle state being an eminent case. Nuclear theorists have not yet uncovered the nature of this type of states from first principles [Epe11].

Investigations of γ decays from unbound near-threshold states, in light neutron-rich nuclei will provide first information on the onset of collectivization/clusterisation phenomena [Oko12]. This is an almost unexplored territory and AGATA will allow to access weak electromagnetic decays from such states in neutron-rich B, C, O and N nuclei, with decay branches of the order of 10^{-5}-10^{-4}. Fusion reactions induced by intense Li beams on Be, C, Li and B targets, followed by the evaporation of a single charged particle, detected in GRIT, will be exploited.

Light neutron-rich nuclei are also ideal to test the details of the nuclear force, in particular the three-body term of the nucleon-nucleon interaction. Here, the focus is on the decay properties of bound excited states in exotic systems like ^{20,22}O and ^{16,18}C, which can be reached in deep-inelastic reactions using intense ^{18}O beam on heavy targets. This kind of studies will benefit from the large angular coverage of AGATA coupled to the PRISMA magnetic spectrometer, significantly improving the sensitivity obtained in early AGATA experiments [Cie19].

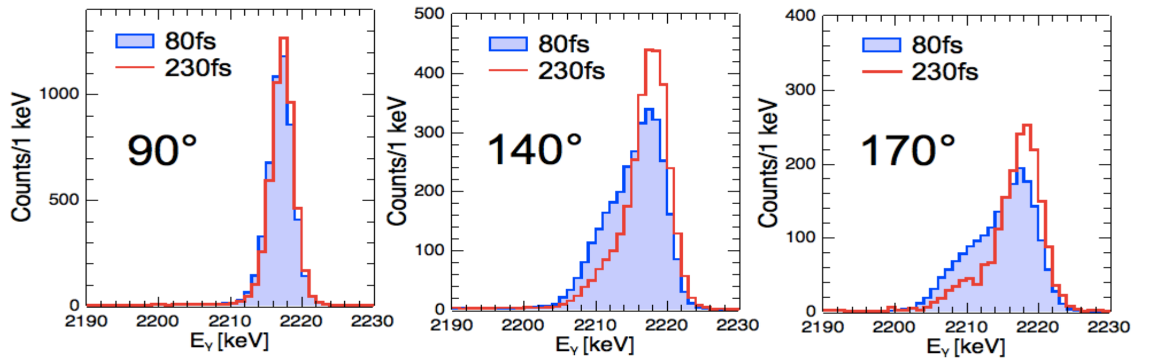

Figure 2 Simulated lineshapes of the 2217 keV transition deexciting the second 2^+ state of the hard-to-reach nucleus ^{16}C, produced in the deep-inelastic reaction ^{18}O+^{181}Ta (v/c~10%). Lifetime values of 80 fs and 230 fs are considered, as predicted by ab initio theory, including two-body or two-body+three-body interactions in the nuclear force. While the AGATA measurement at 90° (panel a)) would provide the most precise value of the γ transition (known, so far, within few keV, only), sensitivity to lifetimes will be reached at backward angles (e.g., 140° and 170°).

2. Isospin symmetry breaking in N=Z nuclei

Isospin symmetry breaking can be addressed via measurements of energies of excited states and electromagnetic decay properties in mirror nuclei. Lifetime measurements will allow i) to access isospin forbidden (ΔT=0) E1 transitions in heavy N=Z nuclei, following the study of ^{64}Ge [Far03], ii) to study proton-neutron isoscalar T=0, S=1 correlations in proton-rich N=Z nuclei populated up to high angular momenta, iii) to measure electromagnetic decay properties of yrast states in N=Z systems like ^{88}Ru, ^{90}Rh, ^{92}Pd and finally iv) the Giant Dipole Resonance (GDR) will be used to probe the dependence of the isospin mixing on temperature (e.g., in ^{52}Fe), following previous studies with AGATA at LNL on ^{80}Zr [Cer15]. Fusion-evaporation reactions will be employed, in strong synergy with the radioactive beam program (see Section 7).

Intense radioactive beams from the SPES facility will allow a rich γ-ray spectroscopy program with AGATA, *complimentary to the experimental investigations with stable beams*. In particular, the focus will be on: i) correlations in valence nucleons, as a fine test of realistic interactions, ii) the emergence of complex excitations, iii) shape coexistence and evolution, iv) pygmy resonances and v) isospin symmetry of the nuclear interaction.

3. Correlations in valence nucleons

Nuclei, whichare a few particles and/or holes away from the shell closures at N = 82 and Z = 50, are of particular interest to investigate shell-structure changes when approaching the neutron drip line. In this context, studies of the one-valence proton ^{134,135}Sb isotopes with two and three neutrons outside the doubly magic ^{132}Sn nucleus, may provide one of most sensitive tests of theoretical calculations, i.e., the direct comparison of transition matrix elements, measured with Coulomb excitation using intense SPES beams, with their predicted values depending on the matrix elements of the proton-neutron interaction between different major shells. Cluster transfer reactions with Sn beams on weakly-bound ^{7}Li targets [Bot 15] will further extend these studies to higher excitation energies (see Figure 2, general section).

4. Emergence of complex excitations

Systems built of one or two-valence particle(s) or hole(s) and a doubly magic core are ideal to study the coupling between single-particle excitations and collective responses of the nucleus (phonons in particular). Such couplings are considered the major source of partial occupancies of nucleonic orbitals and the doorway to damping phenomena in Giant Resonances [Bor98]. Systems like ^{130}Cd, $^{130\text{-}132}$In, $^{130,\text{-}134}$Sn and $^{132\text{-}134}$Sb, around the doubly magic ^{132}Sn core, are the most suited for the SPES facility, where pure and intense Sn-like beams will be available. A multifaceted scenario is expected to appear with increasing spin, pointing to a hybrid nature of these excitations [Boc16, Col17], in analogy to similar phenomena known in other branches of physics, including condensed matter [Bro04]. The coupling of the AGATA array with the PRISMA spectrometer and, possibly, with light charged particle detection devices (e.g., GRIT), will allow very selective studies using transfer and cluster-transfer reactions.

Fission reactions induced by a stable heavy beam, such as ^{208}Pb, impinging on a light target could offer, in addition, the possibility to populate nuclei in the ^{78}Ni region (N=50), reaching states with energy and angular momentum high enough to observe N=50 core-breaking states and/or single particle states in the large-j shells above N=50, like $\nu g_{7/2}$.

5. Shape coexistence and evolution

Exotic nuclei produced at SPES will offer the extraordinary opportunity to investigate in great detail the phenomenon of shape coexistence and its extreme manifestation as shape isomerism [Leo17]. Retarded γ-decay branches between different configurations are fingerprints of this phenomenon, which provide a powerful insight into the microscopic origin of nuclear deformation, when experimental data are compared with sophisticated shell model calculations [Tsu14, Cau05].

The most promising cases, predicted by various theoretical approaches [Mol09,Ner17,Qua17] are the Cd and Pd nuclei with A=112-118, which can be studied at SPES by one-proton transfer reactions, using intense Ag beams with A=113-119 on light or heavier targets (e.g., ^{10,11}B or ^{93}Nb), with GRIT and/or PRISMA to select the reaction products.

The evolution of the nuclear shape will also be studied in neutron-rich nuclei near N = 60 and with Z = 36-40. Here, the most dramatic shape change in the nuclear chart has been observed, (see general section), with the typical characteristics of a quantum-phase transition [Tog16], and strong impact on the r-process nucleosynthesis path as well. Cluster-transfer reactions with intense $^{94\text{-}96}$Sr and $^{94\text{-}96}$Rb beams on a ^{7}Li target will be the ideal tool to access hard-to-reach excited structures built on isomeric states associated with different intrinsic configurations, in particular in the case of the most complex odd-odd systems. Nuclei like ^{96,97}Y and ^{96,97}Sr could be studied at SPES by detecting in GRIT the α particle emitted in the reaction process, and in PRISMA the final reaction products, thus reaching an unprecedented level of sensitivity. Similar phenomena have been also observed in heavier regions, which could be reached at SPES by multinucleon-transfer reactions [Joh14] (see Figure 3).

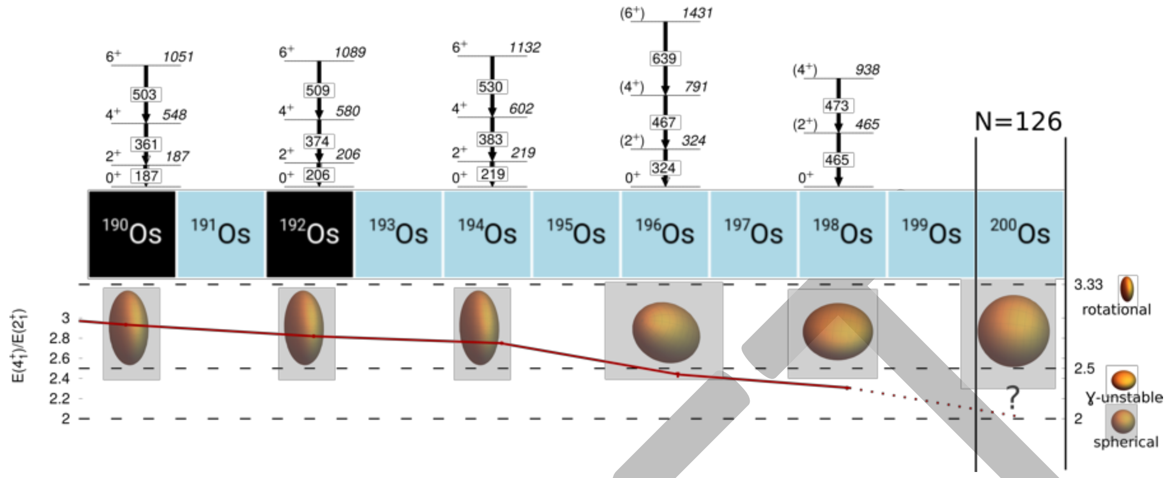

Figure 3: Yrast band excitation energies for $^{190-198}$Os isotopes. The experimental ratio of the energies of the 4$^+$ and 2$^+$ states indicates a shape evolution from a prolate (^{190}Os) to an oblate shape (^{198}Os), passing by an almost perfect gamma-unstable/triaxial rotor (^{196}Os). The red solid line indicates the theoretical E(4$^+$)/E(2) limit for an axial rotor, a vibrational and a γ-unstable/triaxial rotor.

The shape-coexistence program, at SPES, will have a strong Coulomb excitation component, using AGATA coupled to the high-efficiency segmented Si detector SPIDER. Neutron-rich Kr and Rb nuclei, produced at SPES with very high intensities, will enable extremely detailed and precise studies of quadrupole moments, searching for signatures of configuration inversion and shape coexistence near N=60. Experimental information on configuration mixing and triaxiality in $^{90-98}$Kr and $^{78-82}$Ge nuclei will provide important benchmarks for beyond-mean-field and large-scale shell-model (LSSM) calculations. The unprecedented Doppler-correction capabilities of AGATA and SPIDER will be particularly beneficial for Coulomb-excitation studies of odd-A nuclei, when many γ-ray transitions are expected in a narrow energy range.

The appearance of very elongated, super-deformed (SD) shapes, in rapidly rotating, highly excited nuclei is one of the most striking examples of shape changes within the same nucleus. The existence of extremely elongated shapes, named hyper-deformed (HD), still needs to be experimentally confirmed. Other extreme phenomena occurring at high excitation energies are Jacobi- and Poincare-shape transitions; they can be tackled by investigating the Giant Dipole Resonance (GDR) strength function [Maj04]. Up to now, the limiting factors were the strong fission competition and limited detection efficiency. In experiments at SPES the fission competition will be largely reduced by employing reactions high intensity neutron-rich Sn-like beams and a ^{48}Ca target. Compound nuclei will be populated well above spin 80$\hbar$, leading to residua with spins around 70$\hbar$, where HD and SD states are expected to be populated. Reaching such ultra-high spins will also enable searches for a shape transitions towards fission, via a series of elongated tri-axial shapes, as reported in the ^{160}Er region [Paul07, Wan11, Afa12]. AGATA coupled to scintillator arrays, such as PARIS, will provide the required detection efficiency and sensitivity.

6. Pygmy Resonances

Pygmy dipole resonances are associated with oscillations of a neutron skin against the core. They will be studied at LNL in an exotic region of the nuclear chart, following their evolution along isotopic chains. Pygmy states in stable systems have been investigated at LNL using inelastic scattering with ^{17}O heavy ions (at 20 MeV/nucleon) [Bra15] and the very first implementation of AGATA, coupled with segmented silicon detectors of the TRACE project [Men14]. A new mode of nuclear excitation, associated with a concentration of low-energy electric quadrupole strength, was also observed – the Pygmy Quadrupole Resonance (PQR) [Pel15]. Similar experiments could be performed with SPES exotic beams in inverse kinematics at the highest available incident energies (about 10 MeV/nucleon), where appreciable cross sections are still expected. Here, γ-ray tracking capabilities will be fundamental to provide an optimal Doppler correction. Interesting cases will be neutron-rich $^{90,92,94}Sr$ isotopes, produced at SPES with high intensities, which could be probed by inelastic scattering reactions (e.g. $(\alpha,\alpha'\gamma)$ and $(p,p'\gamma)$), on solid or liquid targets, using AGATA coupled to highly granular particle detectors, such as GRIT. Stable systems, such as ^{88}Sr, would be an important point of reference, to be investigated in detail by stable beam and target combinations (see Figure 7 in the general section). By performing (d,p) reactions with intense ^{132}Sn-like beams, one might also access PDR states by transfer reactions, obtaining information on the related single-particle strength.

Finally, SPES beams could provide the opportunity to observe the predicted separation of the pygmy dipole peak in deformed nuclei into two bumps [Pen09,Lan16], as it occurs for the Giant Dipole Resonance (GDR) peak.

7. Isospin symmetry

The isospin symmetry of the nuclear interaction and its breaking by the Coulomb force can be studied at LNL exploiting very intense, light, radioactive beams of SPES, e.g., ^{7}Be, giving access to N=Z nuclei produced via 2n and 3n fusion-evaporation reactions with cross-sections down to about 10 μb. The most exciting case is the T = 3/2 isospin quadruplet $^{45}_{24}Cr_{21}$ - $^{45}_{23}V_{22}$ - $^{45}_{22}Ti_{23}$ - $^{45}_{21}Sc_{24}$ and in particular its most exotic member, the T_Z = -3/2 nucleus ^{45}Cr, with the largest Z difference between the mirror nuclei. Studies of its excited states would give information on Coulomb energy differences and isospin non-conserving phenomena, which can be compared with large-scale Shell Model calculations. AGATA coupled to the neutron detector array NEDA and a 4π charged-particle array will push these studies beyond their current limits.

8. Proton-rich nuclei

Intense LIGHT radioactive beams from SPES, apart from ^{10}Be, lie on the proton-rich side, offering the chance to study new phenomena that may arise from a large proton excess. The keywords are proton-proton correlations, halo effects, pairing, two-proton emission, at or close to the proton drip line. Very interesting cases are ^{9}C and ^{28}S, populated by reactions like $^{7}Be(^{3}He,n)^{9}C$ and $^{26}Si(^{3}He,n)^{28}S$, which would require the use of a powerful neutron detector. While ^{9}C is a candidate for being a halo nucleus (having one proton more than the suspected one-proton halo nucleus ^{8}B) [Xu13], strong correlations have been found between the two protons emitted from high-lying states in ^{28}S [War02]. Detailed spectroscopic studies of the configuration of these states will shed light on the role of pairing close to the proton dripline.

9. Nuclear astrophysics

In the region around doubly magic ^{132}Sn, astrophysically relevant neutron-capture cross sections for the r-process could be measured at SPES by using indirect techniques, like the surrogate method

[Esc12]. A early experiment at SPESwith a limited proton beam intensity of 5 μA, could be ^{133,134}Sn(d,p) and (d,t).

On the proton-rich side, astrophysically important proton-rich nuclei involved in the rp-process nucleosynthesis could be also explored with the available ^{25,26}Al beams, using indirect approaches such as (^{3}He,d) or (d,n) reactions. Knowledge of resonant states in ^{26}Si and their γ-decay branches are key to constraint the reaction rates of the ^{25}Al(p,γ)^{26}Si reaction that are required to understand the synthesis of ^{26}Al in explosive hydrogen burning. Indirect (d,p) reactions can also be used to obtain information on single-particle resonances in their mirror partners. The use of AGATA combined with a thick cryogenic target will constitute a breakthrough in this type of studies.

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