The AGATA Campaign at GANIL

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Abstract. The Advanced Gamma Tracking Array, AGATA, is presently in its construction phase in which the European \(^\gamma\)-spectroscopy research community is involved since several years. This powerful HPGe array offers unique possibilities for the study of rare phenomena in nuclei by detailed gamma-ray spectroscopy. The physics campaign in GANIL foresees different setups, with AGATA coupled to different spectrometers, to study nuclear structure properties of nuclei all across the nuclear chart, from light nuclei to very heavy species, using stable and radioactive beams. After a brief description of the AGATA concept, some recent results are presented together with the very interesting opportunities for nuclear structure research in the forthcoming years with AGATA at GANIL.

1. Introduction

The Advanced Gamma Tracking Array, AGATA \([1]\), is a new-generation high-resolution \(^\gamma\)-ray spectrometer, based on the novel technique of \(^\gamma\)-ray tracking. Since several years, the European \(^\gamma\)-spectroscopy research community is involved in the construction of this high-efficiency HPGe-detector array which has started its physics campaign in 2010 in LNL (Italy), and continued in GSI (Germany) in 2012, in configurations that included a small fraction of the 180 detectors planned for the complete array. In 2014 AGATA was installed in GANIL (France), for a new physics campaign with an increased number of detectors.

The GANIL facility delivers high-intensity beams of stable nuclei up to Uranium as well as radioactive-ion beams from SPIRAL1. This combination allows to study a large variety of nuclear properties all along the nuclear chart with \(^\gamma\)-ray spectroscopy techniques, coupling AGATA to different complementary instrumentation.

The physics campaign in GANIL started in 2015 and has been organized in a bottom-up approach, following calls of letters of intent that have been discussed yearly in dedicated AGATA@GANIL workshops. Among the proposed physics cases to be studied in the GANIL campaign we can mention: the evolution of the shell structure in neutron- and proton-rich nuclei and the effect of three-body forces, exotic nuclear shapes and shape-coexistence phenomena, proton-neutron pairing and isospin symmetry along the \(N = Z\) line, clusterization phenomena, the effect of the coupling to the continuum in weakly-bound systems, the structure of super-heavy nuclei, properties of nuclear astrophysics interest, etc.

The AGATA array installed at GANIL \([2]\) consists of triple (TC) and double (DC) clusters, organized in a compact geometry that will reach up to 45 detectors. Four different setups have been identified since the first collaboration workshop held in GANIL for the AGATA campaign in 2013 to study different nuclear properties. By coupling AGATA to the large-acceptance...
magnetic spectrometer VAMOS++ [3], heavy-ion beams of high intensity can be used in inverse kinematics in multi-nucleon, deep inelastic and induced-fission reactions. Proton-rich nuclei can be selected in fusion-evaporation reactions by coupling AGATA to the new neutron array NEDA [4] plus the Neutron Wall [5]. To study very heavy nuclei the use of VAMOS in gas-filled mode [6, 7] is foreseen. Light and medium-mass exotic nuclei can be studied in transfer or Coulomb-excitation reactions induced by radioactive beams from SPIRAL1 and detected in the new charge-particle array MUGAST.

2. The first sub-campaign with AGATA coupled to VAMOS++

The setup with AGATA coupled to the large-acceptance magnetic spectrometer VAMOS++ [3] took data from 2015 to 2017 (Fig. 1). The clusters were grouped at the most backward angles, symmetrically around the optical axis of the VAMOS++ spectrometer [2]. This arrangement maximizes the peak-to-total ratio, the Doppler effect correction and the efficiency for lifetime measurements. Indeed, thanks to the performances of both the pulse-shape analysis and the the $\gamma$-ray tracking, consisting in a major improvement with respect to the EXOGAM array, the whole solid angle covered by the AGATA clusters can be used for lifetime measurements based on the analysis of Doppler shifts. Some experiments aimed at measuring lifetimes by means of the Recoil Doppler Distance Shift method for which plunger devices were placed at the target position [8, 9]. Arrays of scintillator detectors such as FATIMA [10] and PARIS [11] were also used to measure lifetimes and high $\gamma$ rays, respectively. From 2015 to 2017, the beamtime devoted to AGATA experiments has been of about 150 days.

A wide physics program has been covered by the performed experiments that aimed at investigating nuclear structure properties such as the evolution of the shell structure far from stability and the development of deformation near magic numbers, exotic shapes and shape-
coexistence phenomena and lifetimes measurements of astrophysics interest.

One of the current problems in nuclear structure physics is the characterization of the islands of inversion, formed near the magic numbers. These are new regions of deformation where the rotational bands are constructed on well deformed intrinsic states whose main configuration involves intruder orbitals from the above main shell. While a signature of deformation is given by the energy of the first excited states, the measurement of their lifetimes allows a better understanding of their properties. By using the OUPS plunger device [8], M. Klintefjord and collaborators [12] have measured the lifetimes of several nuclei in the Island of Inversion around \( N = 40 \) via the multi-nucleon transfer \(^{238}\text{U} + ^{64}\text{Ni} \) reaction in inverse kinematics. Lifetimes of the \( 4^+ \) states in \(^{62,64}\text{Fe} \) and the \( 11/2^- \) states in \(^{61,63}\text{Co} \) and \(^{59}\text{Mn} \) were measured. The extracted experimental \( B(E2) \) values have been compared with large-scale shell model calculations using the LNPS interaction [13] and with beyond mean-field calculations using the Gogny D1S interaction [14]. An increase of quadrupole collectivity approaching \( N = 50 \) is observed in all isotopes. In the same framework, lifetimes in neutron-rich Ti isotopes, that are predicted to lie at the border of this Island of Inversion, have also been measured recently in an experiment by Ch. Fransen and collaborators with the Cologne plunger [9]. Above \( Z = 28 \), lifetimes in \(^{75,75}\text{Ga} \) have been measured with the plunger technique for the first time with the \(^{208}\text{Pb} + ^{76}\text{Ge} \) reaction by I. Celikovic and coworkers. The analysis of these two experiments is in progress.

Proton-rich nuclei towards \(^{100}\text{Sn} \) have been populated for the first time by multi-nucleon transfer reactions in two experiments with AGATA and VAMOS++. The first aimed at measuring the lifetimes of the first excited states in \(^{106,108}\text{Sn} \) with the plunger technique. These nuclei were populated using a \(^{106}\text{Cd} \) beam on a \(^{58}\text{Ni} \) target. Previous measurements of the \( B(E2; 2^+ \rightarrow 0^+) \) in these isotopes present large error bars and depart from the parabolic behaviour expected from shell model calculations in the truncated \( gds \) space. This unconventional reaction mechanism for studying proton rich nuclei directly populates low spin states with large probability avoiding the isomeric \( 6^+_1 \) state, thus allowing the measurement of the lifetime of the \( 2^+ \) states with the differential plunger method. Preliminary results suggest a reduction of the \( Z = 50 \) shell gap [15].

The second experiment using the same method measured the lifetimes of the even-even \( N = 50 \) isotopes \(^{92}\text{Mo} \) and \(^{94}\text{Ru} \). These nuclei present similarities with Ni isotopes, in the sense that neutrons in Ni isotopes are filling the same orbitals as protons in \( N = 50 \) isotones. Indeed, the energy of the lowest \( 2^+ \) and \( 4^+ \) states in \(^{70-76}\text{Ni} \) isotopes are quite similar to those in \(^{92}\text{Mo} \), \(^{94}\text{Ru} \), \(^{96}\text{Pd} \) and \(^{98}\text{Cd} \). For the transition probabilities \( B(E2; 2^+ \rightarrow 0^+) \) shell model calculations by Lisetskiy et al. [16] in the \( fpq \) space predict a similar trend for the \( N = 50 \) isotones and \( Z = 28 \) isotopes, while a relative inversion of the trend is predicted for the \( B(E2; 4^+ \rightarrow 2^+) \) values, probably owing to the strong pairing predicted for the \( N = 50 \) isotones near \(^{100}\text{Sn} \). Very scarce information was available in this mass region before this experiment was performed. Preliminary results seem to confirm the theoretical predictions and will be published soon [17].

On looking at the evolution of the shell structure far from stability, a very interesting problem is that related to the size and stability of the gap at the magic number \( N = 50 \) in very neutron-rich systems, together with the energy of the single-particle levels around it. To investigate this mass region the ideal reaction mechanism that exploits the optimum characteristics of the AGATA plus VAMOS++ setup is the fusion-fission reaction in inverse kinematics. Exotic species can be selected by properly choosing the angle of VAMOS++ with respect to the beam line.

Two experiments have been performed with this technique. The first one aimed at the measurement of excited states involving cross-shell configurations in \( N = 50 \) isotones above \(^{78}\text{Ni} \). These states are predicted to follow the same trend as that of the gap as a function of the proton number [18, 19]. A local minimum in the effective \( N = 50 \) gap, defined as \( \Delta = S_{2n}(N = 52) - S_{2n}(N = 50) \), has been found at \( Z = 32 \) and an increase is predicted going from \( Z = 32 \) to \( Z = 30 \). This would allow to probe the robustness of the \( Z = 28 \) gap
Figure 2. The setup shows AGATA coupled to the FATIMA array for the 2017 run.

near $^{78}$Ni. The analysis of these data is in progress and a publication of new results in $^{81}$Ga is in preparation [20]. Interestingly, other nuclei near $N = 60$ have been populated in the same reaction allowing to identify new excited states in $^{96}$Kr that show a sudden transition from strongly deformed to almost spherical shapes in the $N = 60$ isotones [21]. To better characterize the interplay between single-particle and collective degrees of freedom at $N = 50$, a similar reaction, using the plunger device, has been performed to measure the lifetimes in these nuclei. The analysis is in progress and preliminary results in $^{84}$Ge suggest an increase of collectivity with respect to the neighboring isotones and isotopes [22].

Close to $^{132}$Sn, $\gamma$-ray spectroscopy after fusion-fission was performed in 2016 by N. Alahari and coworkers to explore this mass region and look at the evolution of structure both in angular momentum and isospin. Some of these nuclei are characterized by the presence of isomeric states and therefore, to be able to perform prompt-delayed $\gamma$-ray coincidences, EXOGAM detectors were placed at the focal plane of VAMOS++ [23].

The structure of nuclei in the region around $^{208}$Pb has also been studied by measuring lifetimes with the plunger techniques by G. Georgiev, D. Ralet and coworkers. There are preliminary results for $^{207}$Pb and the analysis of other nuclei is in progress.

Taking profit of the position sensitivity of AGATA, lifetimes in the order of magnitude of few femtoseconds were measured with the Doppler shift attenuation method by C. Michelagnoli and collaborators. The state of interest is a resonant state in $^{23}$Mg at 7786 keV excitation energy, just 205 keV above threshold, that decays also by proton emission. This measurement is of astrophysical interest as the lifetime and proton branching ratio, measured in the same experiment, will provide a precise determination of the rate of the $^{22}$Na($p, \gamma$)$^{23}$Mg reaction.

The run of 2017 included in the setup the coupling of AGATA and VAMOS++ to large arrays of LaBr$_3$ scintillator detectors (Fig. 2) for lifetime and high energy $\gamma$-ray measurements from the PARIS [11] and FATIMA [10] collaborations for the study of subjects related to the effect
of three-body forces in light nuclei, shape transitions in rear-earth nuclei, shape coexistence in fission fragments and alpha clusterization in heavy nuclei.

3. Future Campaigns
The next foreseen experimental configuration will see AGATA coupled to the NEDA/Neutron-Wall array [4, 5] and the charged-particle detector DIAMANT [24] for a very ambitious scientific program to study neutron-deficient nuclei and the structure of $N \sim Z$ nuclei.

The approved experimental program at GANIL aims at studying proton-neutron pairing effects, isospin symmetry breaking in mirror nuclei, shape-coexistence phenomena at $N = Z$ near $A = 70$ via lifetime measurements, shell structure near $^{100}$Sn together with octupole correlations and clusterization phenomena in light nuclei. The final mechanical design of NEDA + Neutron-WALL foresees the use of 54 self-produced NEDA detectors at forward angles and 14 Neutron-WALL detectors at around 90 degrees.

Two letters of intent have been submitted to the GANIL PAC proposing two different detectors to be coupled to AGATA: MUGAST, that will use radioactive beams from SPIRAL1, and VAMOS in gas-filled mode [6, 7]. Both setups are in construction and will be ready to take data from 2019. Several proposals have been presented and discussed at the AGATA Workshop organized in GANIL in 2016. For VAMOS in gas-filled mode the main interest is focused in studying the spectroscopy of very heavy nuclei populated mainly in fusion-evaporation reactions induced by stable beams, while SPIRAL1 beams will be used in transfer and Coulomb excitation reactions to study single-particle and collectivity, neutron-proton pairing, shell evolution and subjects of nuclear astrophysics interest with the charged-particle array MUGAST.

4. Conclusions and Perspectives
The AGATA physics campaign in GANIL, started in 2015 has attracted the interest of a large community for the study of nuclear structure and reactions dynamics of nuclei far from the valley of stability by means of gamma spectroscopy. The high intensity stable beams delivered by the GANIL cyclotrons up to U, together with the radioactive beams of SPIRAL1 allow to use different reaction mechanisms to populate the nuclei of interest. The sensitivity of AGATA largely increases by the coupling to particle detectors. In particular, the first campaign of experiments has seen AGATA coupled to the magnetic spectrometer VAMOS++ and, in some cases the plunger device and scintillator detectors from the FATIMA and PARIS collaborations. The following campaigns will use AGATA coupled to NEDA/Neutron WALL and the light charged-particle detector array DIAMANT, VAMOS in gas-filled mode and the charged-particle array MUGAST which will be used with radioactive ion beams.

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