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NUCLEAR STRUCTURE STUDIES WITH THE AGATA ARRAY AT LEGNARO*

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Results of three selected AGATA Demonstrator experiments performed at Legnaro National Laboratory of INFN (Italy), aiming at studying collective modes of excitations, such as rotation and vibration, under extreme conditions, are reported. Firstly, the K-hindrance to the γ decay is investigated in the warm rotating ^{174}W nucleus, focusing on the weakening of the selection rules of the K quantum number with excitation energy. A strong hindrance to the E1-decay between low-K and high-K rotational bands is found, giving evidence that K-mixing due to temperature effects is the leading phenomenon, contributing, for all discrete excited bands, to the progressive erosion of the K-quantum number with excitation energy. The second experiment concerns the study of the pygmy dipole resonance in the neutron rich ^{208}Pb nucleus, by inelastic scattering of ^{17}O at 20 MeV/u. The γ decay is measured with the AGATA Demonstrator coupled to an array of large volume $LaBr_3$:Ce scintillators. A preliminary comparison with (γ,γ') data indicate that states in the 5–8 MeV energy interval belong to two different groups, one with an isoscalar character and the other with an isovector nature. Finally, the breaking of isospin symmetry is studied in the hot compound $N = Z$ nucleus ^{80}Zr, by comparing the γ decay of the Giant Dipole Resonance from the fusion reactions ^{40}Ca+^{40}Ca at $E_{\mathrm{beam}} = 136$ MeV and ^{37}Cl+^{44}Ca at $E_{\mathrm{beam}} = 95$ MeV. Preliminary results show that the yield associated with the Giant Dipole Resonance is different in the two reactions because in self-conjugate nuclei the E1 selection rules forbid the decay between states with isospin $I = 0$. The experiment aims at providing information on the degree of isospin mixing at temperature around ≈ 2 MeV and to extrapolate the zero-temperature value, which is then compared with the latest predictions.

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1. Introduction

On April 9$^{\text{th}}$ 2010, the AGATA Demonstrator array [1], the first implementation of the European Advanced GAmma Tracking Array (AGATA) [2], was officially inaugurated at Laboratori Nazionali di Legnaro (LNL) of Istituto Nazionale di Fisica Nucleare (INFN), Italy. The setup consisted of five triple germanium detector clusters and had two major goals: first to validate the γ-tracking concept and second to perform an experimental physics program using the stable beams delivered by the Tandem-PIAVE-ALPI accelerator complex of LNL. In almost two years of activity, 20 experiments were performed, covering a large variety of physics topics, aiming at the investigation of both neutron and proton-rich nuclei. In this contribution, results, partly preliminary, on three selected experiments performed under the main responsibility of the Gamma Spectroscopy group of the Milano University and INFN are reported, focusing on the study of collective modes of excitations, such as rotation and vibration, under extreme conditions of angular momentum, excitation energy and isospin.

2. Weakening of *K*-quantum number with temperature in ^{174}W

The thermal environment is known to strongly influence low-lying modes of excitations. It is also considered, to a large extent, to be responsible for a gradual vanishing of selection rules, leading to a transition between order and chaos in the nuclear many body quantum system [3]. For deformed rare-earth nuclei, the order-to-chaos transition should take place at internal excitation energies U between 0.5 and 7 MeV. The upper limit is defined by the fully chaotic compound nucleus regime [4], the lower limit by studies of level spacing distributions of states belonging to rotational bands with well defined quantum numbers of quasiparticle excitations of a rotating field [5]. A way to investigate such a phenomenon relies on the study of the weakening of the selection rules of quantum numbers, such as K (the projection of the angular momentum on the symmetry axis of the deformed nucleus), as a function of internal energy [6–9].

In this contribution, we report on the analysis of the warm rotational motion of the ^{174}W nucleus by quasi-continuum γ spectroscopy, and on the dependence on excitation energy of the hindrance to the E1 decay between high-K and low-K structures. The results are directly compared, for the first time, with discrete spectroscopy studies focusing on the decay of high-K isomeric states [10, 11]. The ^{174}W nucleus is well suited for this purpose, being characterized by a stable deformation and by the existence of low-K ($\sim$ 3–4) and high-K ($\sim$ 8–12) rotational bands extending up to spin $39\hbar$, with two high-K bands ($K = 8$ and $K = 12$) built on isomeric states, with lifetimes larger than 120 ns [12, 13]. This feature will facilitate the selection of γ cascades based on high-K configurations.

The ^{174}W nucleus was populated by the fusion reaction of ^{50}Ti (at 217 MeV) on a ^{128}Te target [14]. The experimental setup consisted of four triple clusters of the AGATA Demonstrator array, coupled with 27 BaF_2 scintillator detectors (covering $\sim 25\%$ of the total solid angle). The weakening of selection rules of the K-quantum number is investigated by analysing γ–γ matrices selecting low-K and high-K structures and employing statistical fluctuation techniques, specifically developed for the analysis of quasi-continuum spectra [15], and successfully employed in different region of mass and deformation [16–22]. While the construction of low-K spectra of ^{174}W was based on standard energy gating techniques, spectra representative of the population of high-K bands were produced requiring delayed γ coincidences with respect to a time reference given by the HELENA array (see Fig. 1).

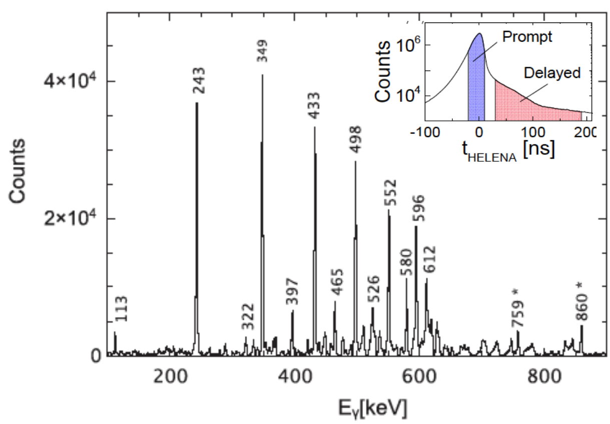

Fig. 1. γ spectrum of ^{174}W gated by the lowest spin transitions of the yrast band. Energies are given for the yrast and the intense negative-parity band, labelled 4 in Ref. [12]. Stars mark interconnecting transitions. The inset shows the HELENA time spectrum, highlighting the prompt ($-20 \leq t_{\mathrm{HELENA}} \leq 20$ ns) and delayed ($30 \leq t_{\mathrm{HELENA}} \leq 190$ ns) time windows, used in the data analysis.

The left column of Fig. 2 shows projections of the total (a), low-K (c) and high-K (e) matrices, at the average transition energy $\langle E_\gamma \rangle = 820$ keV, showing the rotational ridge structures, with a separation equal to $2 \times 4\hbar^2/\Im^{(2)}$, being $\Im^{(2)}$ the dynamic moment of inertia of the discrete bands. While the ridges are populated by discrete bands close to the yrast line, the valley originates from γ transitions of the warmer regime, where mixing among states takes place. In the right column, results of the fluctuation analysis performed on the ridges are given by symbols, providing a total number of ≈ 35 discrete excited bands in ^{174}W, roughly equally distributed between low-K and high-K structures [14]. These findings are at the basis of the experimental study of the hindrance to the E1 decay between the entire body of low-K and high-K rotational structures. Such an investigation can only be made through a microscopic simulation of the γ-decay flow of the warm rotating nucleus, here performed by the MONTESTELLA code [23].

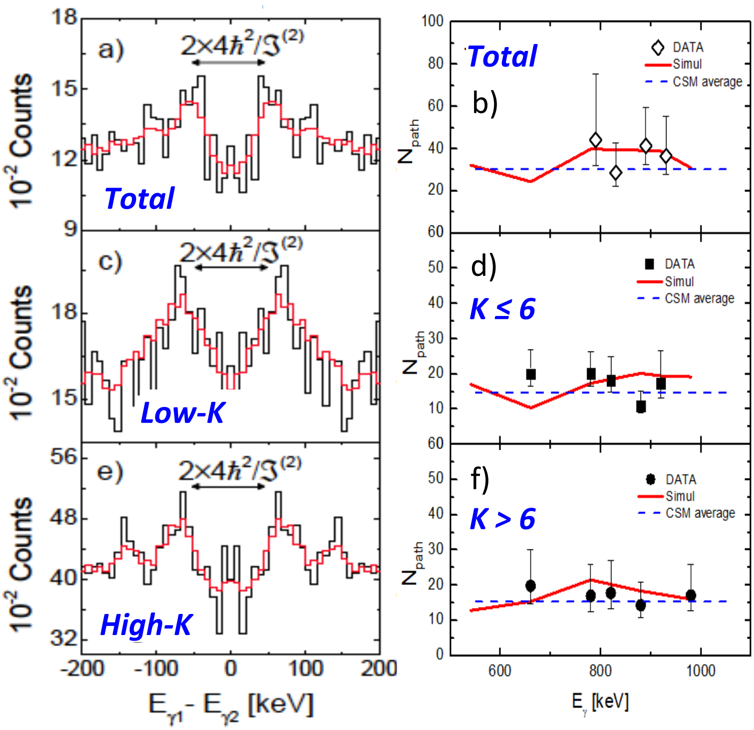

Fig. 2. (a), (c) and (e): Projections (60-keV wide) of the experimental γ–γ spectra of ^{174}W (at $\langle E_\gamma \rangle = 820$ keV) for the total, low-K and high-K distributions, respectively. Thin grey (red) lines are the first moment μ_1 spectra, used in the statistical fluctuation analysis to determine the number of discrete bands populating the ridge structures, by the relation $N_{\rm path} = \frac{N_{\rm eve}}{1-\mu_2/\mu_1} \times P$. $N_{\rm eve}$, μ_1 and μ_2 are the number of counts, the first and second moment of the event distribution in a typical $4\hbar^2/\Im^{(2)}$ energy region along the ridge. The factor P takes into account the finite detector resolution [15]. The results are shown in panels (b), (d) and (f) by symbols. Solid lines correspond to the fluctuation analysis performed on simulated γ–γ matrices, assuming $K \leq 6$ (> 6) for selecting low-K (high-K) spectra. Dashed lines give the average numbers of discrete bands predicted by the Cranked Shell Model [26].

The MONTESTELLA code simulates the γ-decay-flow through the competition between statistical E1 and collective E2 transitions, starting from a entry distribution in spin and internal energy, calculated by the Monte Carlo version of the code CASCADE [24]. The key feature of MONTESTELLA is the use of microscopically calculated levels obtained by the Cranked Shell Model of Ref. [25, 26]. This includes, in an approximate way, the effect of the K-quantum number on the energies of the rotational bands, by adding a $-J_z^2/2\Im$ term to the usual cranking Hamiltonian (being J_z the angular momentum operator of the constituent nucleons along the symmetry axis z, and $\Im$ the kinematic moment of inertia). The calculated rotational bands are mixed by a two-body residual interaction of surface delta type and the E2 decay branch to all possible final states at spin (I-2) is calculated [25, 26].

The E1 transition probability is defined in MONTESTELLA by the strength function of the Giant Dipole Resonance (GDR). Moreover, the microscopic structure of the quantum states connected by an E1 transition is taken into account by quenching the E1 transition probability by a factor $P_{\Delta K} = e^{-\frac{\Delta K}{\sigma}}$ which depends on the difference $\Delta K = |K_{\mathrm{i}} - K_{\mathrm{f}}|$ in the intrinsic K-distributions of the initial and final states, σ being a phenomenological parameter to be determined in comparison with the experimental results for the number of discrete excited bands.

Simulated spectra of ^{174}W representative of low-K (high-K) configurations have then been produced by selecting γ cascades with the two lowest spin transitions with $K \leq 6$ (> 6), consistently with the observation of a large number of rotational structures with $K \leq 6$ [12, 13]. The spectra have been analysed by statistical analysis techniques and the results are shown by lines in the right panels of Fig. 2. In all three cases (total, low-K and high-K), good agreement is found between experiment and model predictions (using $\sigma \approx 0.3$ in $P_{\Delta K}$), which implies a strong quenching in the E1 decay probability, of the order of 10^{-2} for $\Delta K \approx 6$. These results encourage the use of the MONTESTELLA code to further investigate the hindrance to the γ-decay associated to large differences of the K-quantum number between initial and final states, considering the entire body of discrete excited bands.

More precisely, one can calculate via the simulation the average reduced hindrance f_ν, starting from the definition $f_\nu = \left(\frac{T(\mathrm{E1})_{\mathrm{W}}}{T(\mathrm{E1})_\gamma}\right)^{1/\nu}$ [27], $T(\mathrm{E1})_{\mathrm{W}}$ being the E1 decay probability in Weisskopf units and $T(\mathrm{E1})_\gamma$ the effective E1 decay probability used in the simulation code [9], obtained by multiplying f_{GDR} by $P_{\Delta K}$, as discussed above. The results are shown by filled circles in Fig. 3 and clearly indicate that the reduced decay hindrances obtained from the present analysis of quasi-continuum spectra follow a trend with internal energy U very similar to the one obtained from high-K isomers studies, in the mass region $A \approx 160$–180 [28]. Altogether, the data are in agreement with predictions from a K-mixing model which assumes the level density as main responsible for the weakening of K-forbidden transition rates with U [29]. This suggests that K-mixing due to temperature effects is a general phenomenon which is relevant to the entire body of discrete excited states, playing a leading role in the progressive weakening of the K-quantum number already at rather low internal energy, *i.e.* in the onset region of the band mixing regime.

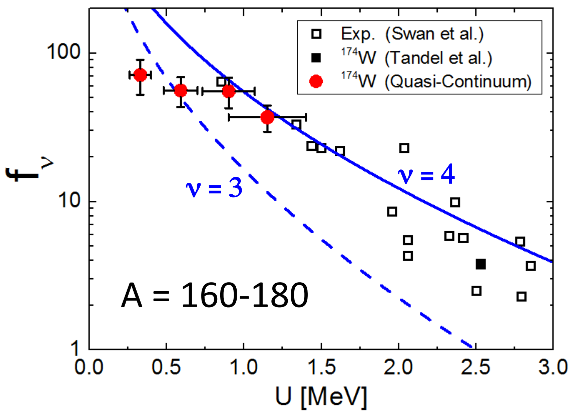

Fig. 3. Reduced hindrance f_ν, as a function of internal energy U, for nuclei in the mass region $A \sim 160$–180. Full (red) circles are obtained from the present quasi-continuum analysis of the quenching of the E1 decay between discrete excited bands of ^{174}W, using $\sigma = 0.3$ in the calculation of $P_{\Delta K}$ [14]. Square symbols are experimental data from Ref. [12, 28]. The solid (dotted) line represents the f_ν curve for $\nu = 4$ ($\nu = 3$), calculated with the analytical model of Ref. [29].

3. Pygmy resonance in ^{208}Pb by inelastic scattering of ^{17}O ions

A measurement of the high-lying states in ^{208}Pb has been made using ^{17}O beams at 20 MeV$/u$ [30]. The γ decay following inelastic excitation was measured with the detector system AGATA Demonstrator, coupled to an array of large volume LaBr$_3$:Ce scintillators and to an array of Si telescope detectors. Preliminary results in comparison with (γ, γ') data in stable neutron rich systems are presented here, for states in the 5–8 MeV energy interval. The focus is, in particular, on the E1 component of the spectra, which is commonly denoted as the Pygmy Dipole Resonance (PDR). This is an accumulation of electric dipole strength at energies around the particle threshold, larger than that due to the low energy tail of the Giant Dipole Resonance and possibly associated to the oscillation of the neutron skin against a symmetric proton–neutron core [31–35]. The study of the PDR is not only interesting as a phenomenon associated to the nuclear structure, but it is expected to provide information on the neutron skin and thus on the symmetry energy of the equation of state, and it has astrophysical implications [36–41]. From the experimental point of view, measurements performed with different probes are found to be complementary, altering the relative population of the different states. In particular, it becomes interesting to study PDR states using a probe interacting mainly at the surface of the nucleus, as the inelastic scattering by ^{17}O heavy ions, here discussed.

The left panel of Fig. 4 shows a picture of the experimental setup, employed at LNL. The detection of the scattered ^{17}O ions was performed with two segmented ΔE–E silicon telescopes (pixel type) from the TRACE project [30], installed around the target, into the scattering chamber. The γ-ray detection system consisted of the AGATA Demonstrator and by an array of 8 large volume $(3.5'' \times 8'')$ LaBr3:Ce scintillators from the HECTOR+ array [42]. Figure 4 shows an example of a two-dimensional spectrum of the Total Kinetic Energy (TKE) of ^{17}O ions, measured in one pad of the ΔE–E silicon telescopes, *versus* the energy deposit measured in the ΔE pad. A clear separation of the different oxygen isotopes is observed. In addition, the excitation energy transferred to the target nucleus is measured with medium resolution (1.2–1.5 MeV).

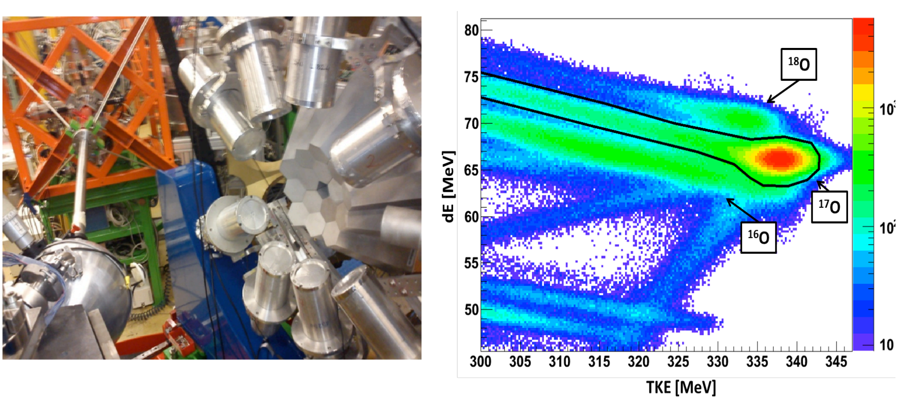

Fig. 4. Left: detection systems used to measure γ rays in the inelastic scattering experiment ^{17}O+^{208}Pb, comprising the AGATA Demonstrator and large volume LaBr3:Ce detectors. Right: two-dimensional histogram of the Total Kinetic Energy (TKE) measured in one pad of the TRACE telescopes *versus* the energy measured in the ΔE pad. The black line shows the separation of the ^{17}O isotope.

In panels (a) and (b) of Fig. 5, the γ spectrum obtained with the AGATA array is displayed in the 4.5–8 MeV region before and after unfolding by the AGATA Demonstrator response [43], respectively. This spectrum is obtained by selecting the inelastically scattered ^{17}O events, with the additional requirement that the energy of the γ rays is equal to the Total Kinetic Energy Loss values within a window ± 1.5 MeV wide. In addition, Doppler correction of the γ spectrum is also performed to account for the speed of the ^{208}Pb recoils (0.5% of the speed of light). Indeed, the γ-ray spectrum in the 5–8 MeV energy range is dominated by E1 transitions, although some E2 transitions are also present, therefore it becomes important to have the possibility to separate the two contributions through the different angular distribution of the emitted γ rays. In the case of the AGATA Demonstrator, it is possible to measure the emission direction of each γ ray with a remarkable precision ($\approx 1^0$), using Pulse Shape Analysis and tracking algorithms (a unique feature of this type of arrays) and considering for each event the angle $\theta_{\gamma,\mathrm{recoil}}$ between the γ emission direction and the ^{208}Pb recoil velocity vector (reconstructed using the information from the silicon telescope pad which detected the ^{17}O ion). Panels (c) and (d) display the angular distributions obtained for the two transitions at 5512 keV and 6194 keV, which are known to be pure E1 and E2 decay, respectively. Indeed, the expected trend for the E1/E2 transition is observed, allowing for an unambiguous de-

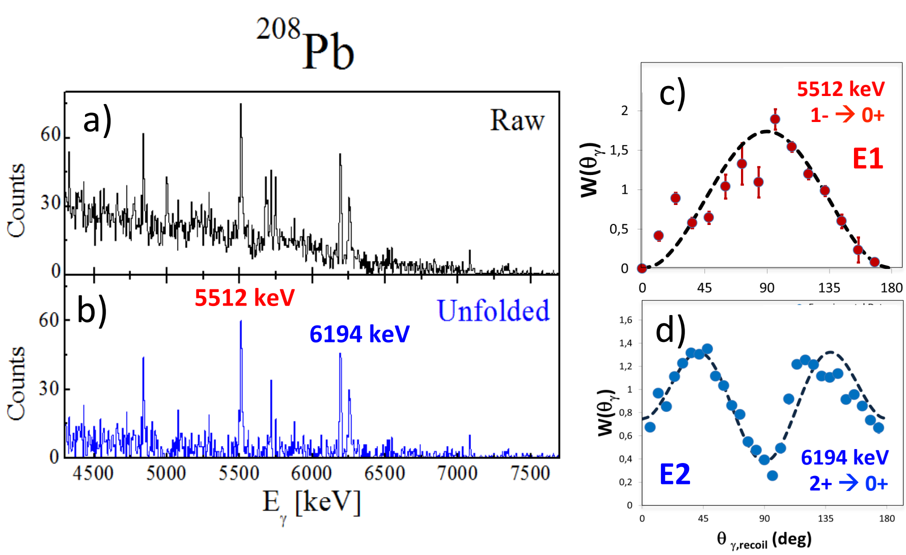

Fig. 5. Panels (a) and (b) show the gamma spectrum obtained with the AGATA array, displayed in the 4.5–8 MeV region, before and after unfolding by the detector response. Panels (c) and (d) give the angular distributions of the two transitions at 5512 keV (E1) and 6194 keV (E2), as measured by the AGATA array.

termination of the multipolarity. A preliminary analysis of the identified E1 strength in the 5–8 MeV region shows a selectivity in the population of these states as compared to photon scattering results, with an observed behaviour similar to what was found in other nuclei using (α, α'γ) reactions [40, 41]: a number of states is, in fact, better populated via the (^{17}O,^{17}O'γ) reaction, indicating the presence of a dominant isoscalar character.

4. Isospin mixing at finite temperature in ^{80}Zr

Isospin mixing induced by the Coulomb interaction has been studied in the compound $N = Z$ nucleus ^{80}Zr at temperature $T \approx 2$ MeV, making use of the first step of the Giant Dipole Resonance decay. This is the ideal excitation mode where the selection rule of E1 decay can be fully exploited. In fact, because of isospin symmetry, the E1 decays being isovector, in a $N = Z$ nucleus, if the isospin of the initial state is pure, $I = 0 \rightarrow I = 0$ transitions are forbidden and only the less numerous $I = 1$ states will be reached in the decay. Conversely, if the initial state is not pure in isospin but contains an admixture of $I = 1$ states, it can decay to the more numerous $I = 0$ final states. Hence, the first step of the GDR yield depends on the degree of admixture in the initial states. As a consequence, the isospin mixing probability can be extracted by comparing the γ-decay yield from the GDR with the prediction of a statistical model which includes the formalism of isospin [44]. This work addresses this problem at $T \approx 2$ MeV and it is an extension of a previous work at $T \approx 3$ MeV [45]. By comparison with the theoretical work of Ref. [46], it will be possible to study the temperature dependence of isospin mixing in ^{80}Zr and to extract the value at zero temperature, which is expected to be of the order of 4%, from theoretical calculation [46, 47].

In the experiment, two symmetric fusion-evaporation reactions, ^{40}Ca+^{40}Ca at $E_{\mathrm{beam}} = 136$ MeV and ^{37}Cl+^{44}Ca at $E_{\mathrm{beam}} = 95$ MeV, are used to form the compound nuclei ^{80}Zr (the isospin $I = 0$ channel) and ^{81}Rb (the $I \neq 0$ channel). The excitation energy is about 54 MeV in both cases, corresponding to the temperature $T \approx 2$ MeV. The study of the reaction leading to ^{81}Rb is necessary in order to fix the statistical-model and the GDR parameters. The experimental setup was composed by 4 triple clusters of the AGATA Demonstrator coupled to an array of 7 large volume $LaBr_3$:Ce scintillators from the HECTOR+ array [42].

The final γ spectra were obtained after an off-line time selection of the events and a background subtraction in the high energy region of the spectra, in order to eliminate the cosmic rays contribution. The high-energy γ spectrum of ^{80}Zr, populated in the ^{40}Ca+^{40}Ca fusion reaction, is given in the left part of figure 6, and clearly shows an excess yield in the 10–20 MeV

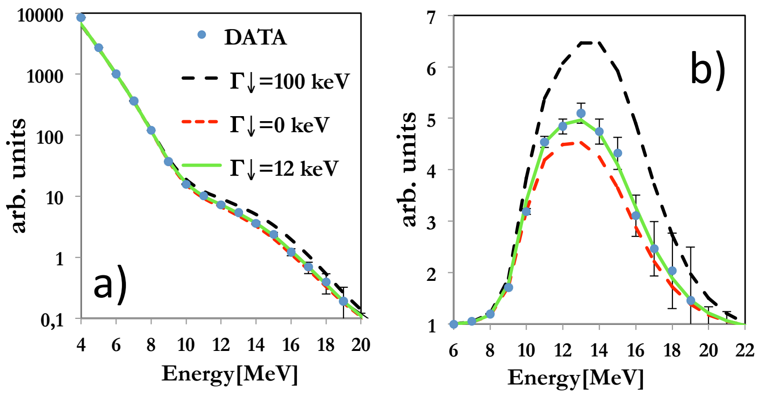

Fig. 6. Left: High-energy γ spectra of ^{80}Zr measured by the HECTOR+ array, following the fusion–evaporation reaction ^{40}Ca+^{40}Ca at $E_{\mathrm{beam}} = 136$ MeV. Lines show the statistical model calculations performed for three different values of the Coulomb spreading width $\Gamma^{\downarrow} = 0$ (no mixing), 12 keV and 100 keV (very large mixing). Right: The same spectrum and calculations shown on the left divided by an exponential curve, in order to underline the GDR peak shape.

interval, associated to the GDR γ decay. A statistical model analysis of the spectra was made with a version of the CASCADE code which includes isospin effects, already used in Ref. [45]. In the statistical model analysis, a first fit procedure is performed varying only the width of the GDR for the ^{81}Rb data, while the other GDR parameters (centroid and strength) are fixed to the value of Ref. [45], since they are not expected to change with the excitation energy of the compound nucleus. In a second step, the ^{80}Zr data are fitted in order to obtain the best value of the Coulomb spreading width $\Gamma^{\downarrow}$. This is shown by lines in the left part of Fig. 6, where statistical calculations are performed for the three different values $\Gamma^{\downarrow} = 0$ (no mixing), 12 keV and 100 keV (very large mixing). The right panel of Fig. 6 displays the spectrum and the calculations divided by an exponential curve in order to underline the GDR peak shape. This preliminary result indicates that the best value of the Coulomb spreading width is $\Gamma^{\downarrow} = 12$ keV $\pm$ 3 keV, which is consistent with the 10 keV $\pm$ 3 keV value obtained by Corsi *et al.* [45]. Indeed, $\Gamma^{\downarrow}$ is expected to be independent of temperature [48]. From this value, the isospin mixing probability α^2 in ^{80}Zr at $T = 2$ MeV will be extracted and, together with the already know result of $T = 3$, a more stringent comparison with theoretical models will be possible, in addition to the extrapolation at $T = 0$, using the predictions of Ref. [46] (see Fig. 7). The knowledge of isospin mixing plays a role in a wide range of phenomena, including the nuclear decay, particularly for the properties of the Isobaric Analog States and for the corrections to the Fermi β-decay of $N = Z$ nuclei around the proton drip-line.

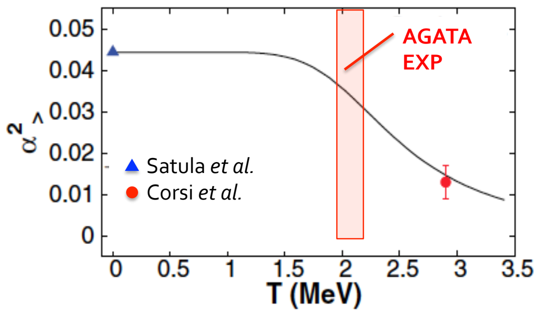

Fig. 7. Calculated temperature dependence of the isospin mixing parameter α^2 (solid line), in comparison with the prediction from Ref. [47] (triangle) and the experimental result of Ref. [45] (circle). The shaded area indicates the region probed by the AGATA experiment discussed in this work.

5. Conclusions

Three selected examples of experiments performed with the AGATA Demonstrator array, at Laboratori Nazionali di Legnaro of INFN, have been reported, focusing on the study of collective modes of excitations, such as rotation and vibration, under extreme conditions of angular momentum, excitation energy and isospin. They clearly show the feasibility of complex γ-spectroscopy studies with γ-tracking arrays, the advantages over more conventional systems (mostly related to an unprecedented spatial resolution) and contribute to shed further lights on physics issues related to collective excitations in the nuclear many body quantum system.

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