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Nuclear Structure aspects of gamma decay from giant resonances

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Abstract. The gamma decay of the giant dipole resonance (including its tail region) is an important tool to probe the properties of these states, and thus to test the predictions of mean field theories. This paper focuses on two main aspects concerning the electric dipole excitation in nuclei. These are the study of the isospin character of the low energy tail of the Giant Dipole Resonance (GDR), the so-called Pygmy resonance, and the isospin mixing of nuclear systems at finite temperature. In the first case, the Pygmy resonance has been populated in the inelastic scattering reaction ^{17}O+^{124}Sn at 20 MeV/u. Its gamma decay has been measured using the AGATA Demonstrator and an array of 8 large volume $LaBr_3$:Ce scintillators. In the second case, the gamma decay of the GDR in thermalized nuclear systems, formed in fusion evaporation reactions, has been used to investigate the isospin mixing in ^{80}Zr. For this work the reactions ^{40}Ca+^{40}Ca at 3.4 MeV/u and ^{37}Cl +^{44}Ca at 2.6 MeV/u were used.

1 Introduction

The gamma decay of the high-lying electric dipole states up to the region of the giant dipole resonance is an important tool to address relevant physics questions of nuclear structure related to nuclear collectivity and isospin effects.

This paper reports on preliminary results of two experiments performed at the LNL/INFN laboratory using the AGATA demonstrator array. These experiments address two different specific problems. The first is the isospin character of the low-lying part of the dipole response, commonly denoted as the Pygmy resonance, due to the much smaller size of its strength in comparison with the Giant Dipole Resonance (GDR). In recent years, experimental and theoretical investigations, on both stable and radioactive nuclei, revealed that the presence of the pygmy resonance is a common phenomenon in a large number of atomic nuclei [1]. The hydrodynamical model describes this pygmy strength as associated to the vibration of the neutron skin. The second topic concerns the investigation of isospin mixing at finite temperature by measuring the gamma decay of the GDR excitation. The E1 decay from excited states of $N = Z$ nuclei is forbidden by the pure isospin selection rules. Because of the small size of the isospin mixing responsible of E1 decay, the best case to study isospin effects is the de-excitation of the GDR where most of the strength is concentrated. Here the isospin mixing is studied at finite temperature using fusion evaporation reactions. These experiments and some of their results are described in the following sections.

2 Pygmy states with the ^{124}Sn(^{17}O,^{17}O$^{*}\gamma$)^{124}Sn reaction

The use of medium heavy ions inelastic scattering at approximately 20 MeV/u to study highly excited states (up to the region of the Giant Quadrupole Resonance) is a good tool to understand the nature of nuclear collective excitations. This is possible only when the measurement of the subsequent gamma decay is also performed with high resolution. The understanding of the electric-dipole response in the low energy tail of the GDR is presently attracting interest since the dipole strength distribution in that region affects considerably the reaction rates in astrophysical scenarios, where photodisintegration reactions are important. In addition, the E1 strength is also interesting because it is expected to provide information on the neutron skin and thus on the symmetry energy of the equation of state (see e.g. Refs. [2–4]). In recent years, several experimental and theoretical investigations, on both stable and radioactive nuclei, were made to learn on the microscopic properties of the pygmy states. An interesting feature of the pygmy states has been observed [5–8] in a number of different stable nuclei, by comparing results of photon-scattering and α scattering experiments. In particular, it has been found that one group of states is excited in both types of reactions, while another group of states at higher energies is only excited in the (γ, γ') case [9]. These experimental findings are in qualitative agreement with different phonon models, which predict a low-lying isoscalar component dominated by neutron-skin oscillations and a higher-lying group of states with a stronger isovector character associated to the tail of the giant dipole resonance.

The use of an additional probe as the inelastic scattering of ^{17}O at 20 MeV/u having, similarly to alpha particles, a rather strong isoscalar character is expected to add valuable information on the quest of the nature of these low-lying E1 states.

The experiment described here concerns the nucleus ^{124}Sn for which alpha and gamma scattering experiments have been already performed [6, 7, 9]. The comparison of excitation using different probes is important as one expects that pygmy states have mixed isoscalar and isovector components that could be differently populated by the ^{17}O and alpha hadronic probes, being different the components of their isoscalar and Coulomb interactions. In this experiment, a ^{17}O beam at the energy of 20 MeV/u in the laboratory frame, provided by PIAVE-ALPI accelerator system of the Legnaro National Laboratories of INFN was used together with a ^{124}Sn target. The choice of ^{17}O beam is motivated by the fact that this nucleus has a rather small neutron separation energy (i.e. 4.1 MeV). Consequently, this property implies the absence of the background in the gamma spectra coming from the projectile excitation at energies above 4 MeV. The detection of the scattered ^{17}O ions was performed with two segmented $\Delta E - E$ silicon telescopes. These are pixel detectors with the geometrical features of the future TRACE project [10], expecting to cover a large solid angle. The ΔE detectors were 200 μm thick, corresponding to an energy loss of about 70 MeV for a ^{17}O ion of 340 MeV (20 MeV/u). The E detectors were 1 mm thick. This last thickness is enough to stop the ^{17}O ions completely. Each detector is segmented in 60 pads of 4×4 mm^2, with an active area of 20×48 mm^2. The large active area provides good solid angle coverage. The main feature of these detectors is the identification in charge and mass of the scattered ions. In addition the excitation energy transferred to the target nucleus is measured with medium resolution (1.2-1.5 MeV). The gamma detectors are part of two separated arrays: i) the AGATA (Advanced GAmma-ray Tracking Array) Demonstrator [10, 11], namely the first step of the new generation segmented HPGe gamma-ray spectrometer AGATA, and ii) an array of 8 large volume (3.5" $\times$ 8") $LaBr_3$:Ce scintillators [12] from the HECTORplus array [13]. The gamma spectrum measured with the $LaBr_3$:Ce detector array in the region of the pygmy resonance is shown in Fig. 1. This spectrum is obtained after selecting the inelastic scattered ^{17}O events and rejecting accidental background and feeding from higher-lying states. Doppler correction due to the speed of the recoils (of the order of 0.5% of the speed of light) was applied. In this figure several E1 transitions known from (γ, γ') measurements [9] were identified. The angular distribution of these transitions was measured and found

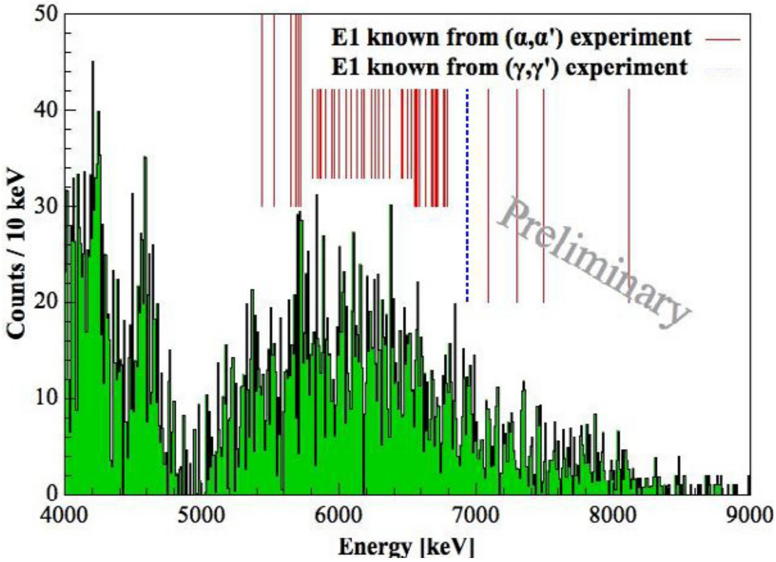

Figure 1. Gamma-ray spectrum for ^{124}Sn measured with $LaBr_3$:Ce detectors obtained with the condition that the energy of the scattered ^{17}O is equal (within ±1 MeV) to the gamma-ray energy of the de-exciting nucleus. The red and blue lines indicate the known E1 transitions [7, 9].

to be compatible with an E1 character in the region 5-8 MeV. Since the E1 strength in the pygmy region is highly fragmented, it becomes difficult to obtain a precise evaluation of the background under the peaks. Therefore both the estimated yields in the peaks and the total counts in 100 keV bins are given in Fig. 2. The latter represents the upper limit and it is a particularly useful information when comparing with (γ, γ') in the region above 7 MeV. Fig. 2 shows the comparison of the present data with the results obtained for the same nucleus with (α, α') and (γ, γ') reactions. It is worth noting that in the case of (^{17}O,^{17}O') and (α, α') a similar picture is obtained for the excitation cross section, namely the region between 7-8.5 MeV is very weakly excited as compared with the region 5-7 MeV. This is in contrast with the finding from the (γ, γ') reaction.

3 Isospin mixing at finite temperature in in the proton rich ^{80}Zr

The question of isospin impurity in nuclei has been a long-standing open problem in nuclear physics. In particular the knowledge of the isospin impurity is interesting in connection with the properties of the Isobaric Analog States (IAS) and for the Fermi β-decay of the $N \approx Z$ nuclei near the proton drip line. The effect of the isospin impurity on the beta decay has implications in the Fermi transition rates and thus on the Cabibbo – Kobayashi – Maskawa matrix [14]. In the case of the IAS states it is known that they have a narrow width $\Gamma^{\downarrow}$ originating from Coulomb interaction coupling these states to the continuum [15]. In general the breaking of isospin symmetry can be observed by decays, which would be forbidden by the selection rules if isospin mixing were not to occur. This is the case of the E1 decay from self-conjugate nuclei [16]. To fully exploit this property of the E1 decay one should go

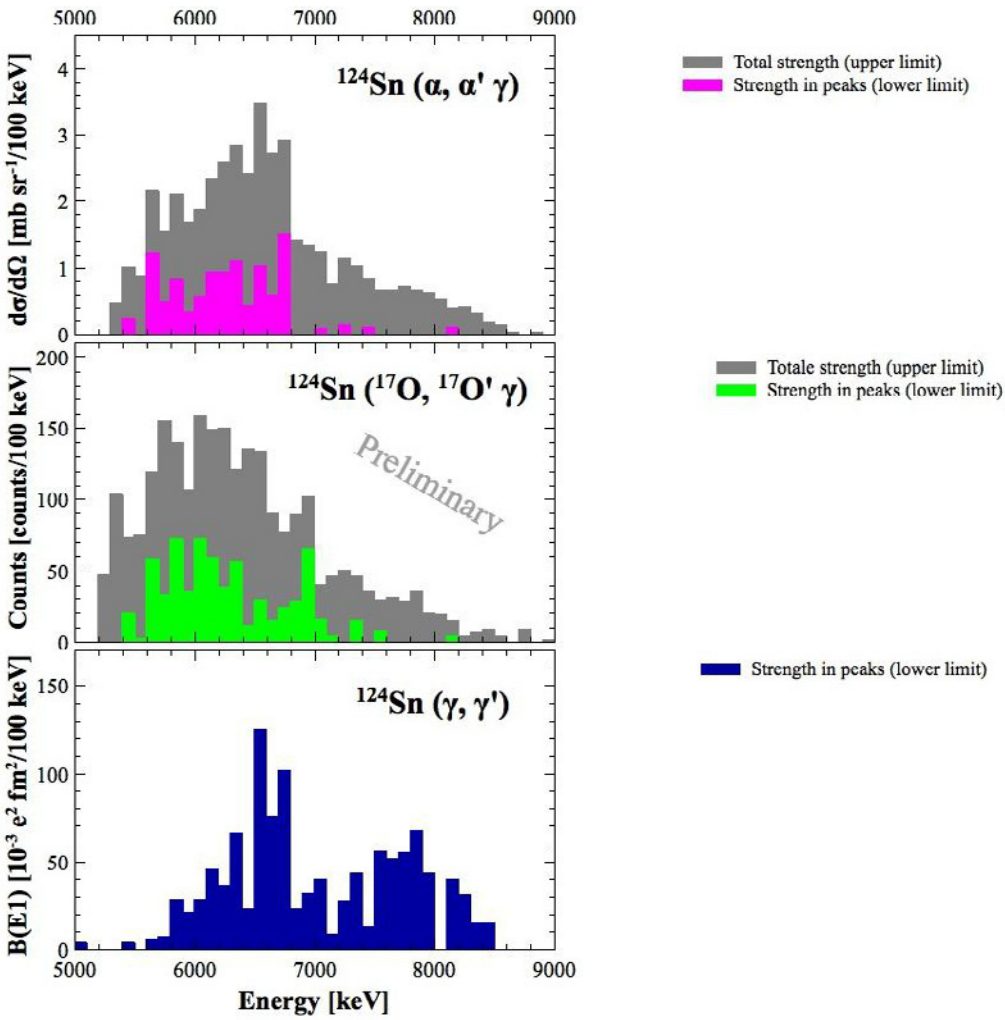

Figure 2. Gamma-ray strength for ^{124}Sn measured with $LaBr_3$:Ce detectors (central panel) compared to the one measured in α-scattering [7] (upper panel), and the photon-scattering experiment of [9] (bottom panel). The data are integrated in bins of 100 keV. The gray areas represent the complete ground state decay while the colored ones show the strength in peaks.

in the region of the Giant Dipole Resonance (GDR) where the maximum strength of the E1 transitions is concentrated [17, 18]. Indeed this approach was employed for the E1 decay of the GDR in nuclei at finite temperature T, formed in fusion evaporation reactions. Fusion-evaporation reactions allow to produce self-conjugated Compound Nuclei (CN) at high excitation energy. The use of self-conjugate projectile and target ensures population of CN with $I = 0$ and thus with hindered E1 decay from the GDR. At variance, if the initial state is not pure in isospin but contains an admixture of $I = 0, 1$ states, it can decay to the more numerous $I = 0$ final states. In addition, at finite temperature one expects a partial restoration of isospin symmetry because the degree of mixing in a compound nucleus is limited by its finite lifetime for particle decay [19, 20].

Efforts are made to study isospin mixing in the mass region $A = 80 - 100$ for which different model predictions give the largest discrepancies among them. In a previous work, the isospin mixing in the hot compound nucleus 80Zr was deduced from gamma-ray measurements in the fusion reactions ^{40}Ca+^{40}Ca at $E_{beam} = 136$ MeV and ^{37}Cl+^{44}Ca at $E_{beam} = 95$ MeV. The gamma-decay yield from the Giant Dipole Resonance (GDR) was found to differ between the two reactions. With the result obtained for the isospin mixing at finite temperature, the value at zero temperature was derived using existing model predictions [20]. In spite of the interesting result obtained, it is clear that this model dependence has to be checked with more experimental points. For this reason a new measurement at lower temperature was made with the AGATA Demonstrator at the LNL laboratory.

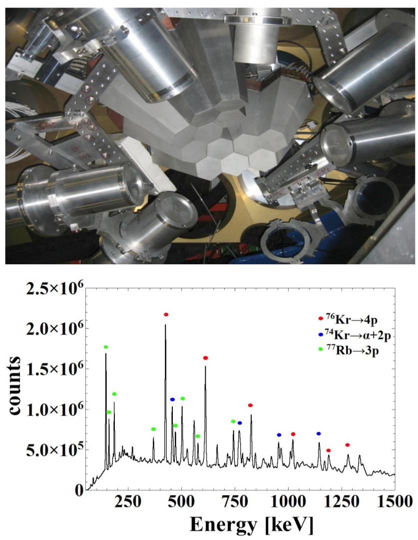

Figure 3. In the top panel the experimental set up is shown. In the bottom panel the low energy gamma-ray spectrum for the ^{40}Ca+^{40}Ca reaction is shown. The colored dots indicate the identified transitions of the residual nuclei.

In Fig. 3 the picture of the experimental set up, including 6 large volume $LaBr_3$:Ce detectors coupled to the AGATA array, is shown. In the bottom panel of the same figure the low-energy gamma-ray spectrum obtained with HPGe detectors of AGATA is shown. The transitions identifying the final residual nuclei in the ^{40}Ca+^{40}Ca reaction are indicated with colored dots in the figure.

Since the isospin mixing is deduced from the statistical model analysis of the high-energy gamma-ray spectra, a useful test to verify the input parameters of the model is to compare the experimental distribution of the population of the residual nuclei with that predicted by the model. In Fig. 4, the predicted and measured distributions of residual nuclei are shown with different conditions on the coincidence fold M_γ. It is clearly seen that the calculations made with the statistical model are in excellent agreement with the experimental results. The same statistical model parameters have been used for the calculation of the high-energy spectra, and the energy and width of the GDR were deduced by fitting the data. The set of best-fitting parameters for the centroid, width and strength was found to be $E_{GDR} = 16.4 \pm 0.2$ MeV, $\Gamma_{GDR} = 7.2 \pm 0.4$ MeV and $S_{GDR} = 88 \pm 2\%$, in agreement with

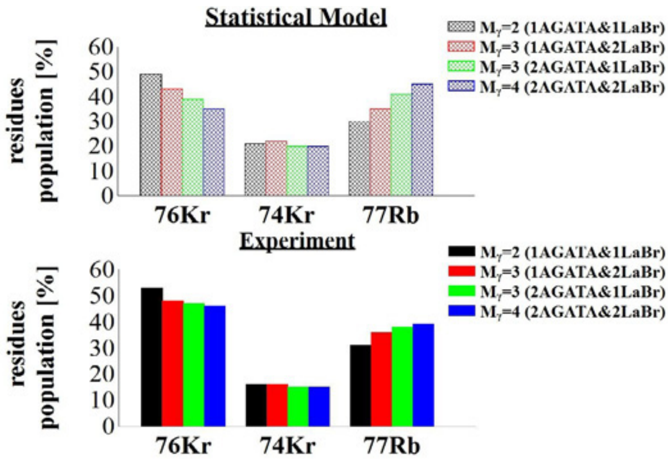

Figure 4. Residues population for different values of the coincidence fold M_γ in the reaction $^{40}Ca+^{40}Ca$. The predictions obtained with the Statistical Model are in the top panel and the experimental data are in the bottom panel.

the systematics. The preliminary value of the Coulomb spreading width for ^{80}Zr was found to be $\Gamma^{\downarrow} = 12 \pm 3$ keV. The best fitting curves are shown together with the experimental results in Fig. 5.

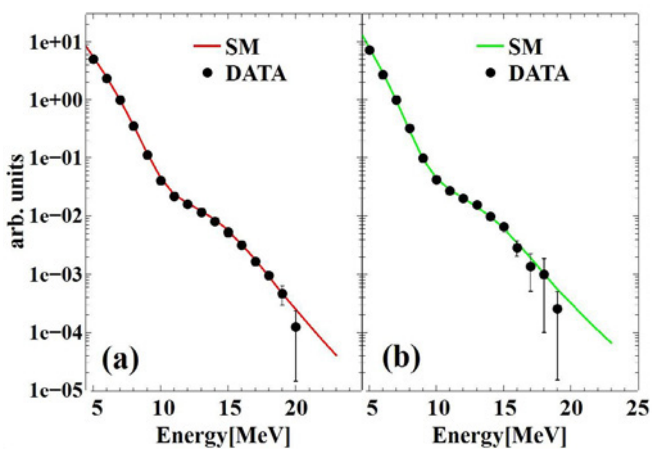

Figure 5. The gamma-ray spectra measured with $LaBr_3$:Ce detectors for the $^{37}Cl+^{44}Ca$ (a) and $^{40}Ca+^{40}Ca$ (b) reactions are shown with filled circles and compared with the best-fitting statistical-model calculations (SM) shown with full drawn lines.

The present status for the study of isospin mixing in the ^{80}Zr nucleus is illustrated in Fig. 6, which was adapted from reference [21]. One can note that this new measurement will provide a datum at finite temperature in the $T = 2$MeV region, of interest to predict the value at $T = 0$. The future work in this direction is expected therefore to be indeed enlightening.

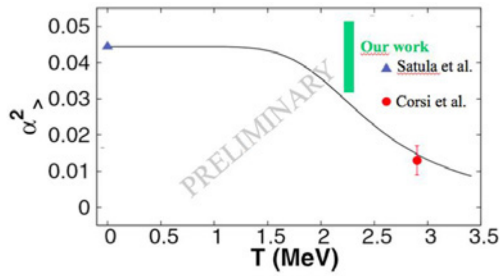

Figure 6. Dependence of the isopin mixing probability with the nuclear temperature in ^{80}Zr. The full line shows the prediction obtained using the theoretical model of Ref. [20]. The blue triangle is the theoretical value from Ref. [22], the red dot is the experimental datum reported in Ref. [21], and the green rectangle shows the preliminary result for the present experiment.

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