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Abstract. The degree of isospin mixing in the hot compound nucleus ^{80}Zr has been extracted by statistical-model analysis of the γ-decay spectrum emitted in fusion reactions ^{40}Ca+^{40}Ca at E_{beam}= 200 MeV and ^{37}Cl+^{44}Ca at E_{beam}= 153 MeV. In the case of ^{40}Ca+^{40}Ca reaction an hindrance of first-step γ-decay is expected because in self-conjugate nuclei the E1 selection rules forbid the decay between states with isospin I=0. The results obtained at finite temperature (T $\sim$ 2 MeV) have been used to extrapolate the degree of mixing at zero temperature.

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1. Introduction

Isospin quantum number was introduced by Heisenberg to account for the basic symmetry of the nuclear force under the exchange of protons and neutrons. Nevertheless, a more accurate description of the nuclear wavefunction cannot leave aside the breaking of isospin symmetry due to the Coulomb interaction, expecially when dealing with proton-rich heavy nuclei.

The violation of isopin symmetry in nuclei can be probed by measuring the yield of the electric dipole (E1) γ decay in self-conjugate nuclei, which is forbidden by the selection rules. Since a large fraction of the E1 strength in the hot CN is carried by the Giant Dipole Resonance (GDR), its decay can be used to investigate the degree of isospin mixing of self-conjugate nuclei. Fusion-evaporation reactions allow to produce self-conjugate compound nuclei (CN) at high excitation energy and, for increasing mass, further and further from the β-stability valley. The use of self-conjugate projectile and target ensures the fact that the CN produced in fusion reactions has isospin I=0. Therefore, E1 emission associated with the decay of the GDR is hindered due to the fact that, if the isospin of the initial state is pure, only the less numerous I=1 final states can be reached in the decay [1]. 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. Therefore, the first-step γ yield depends on the degree of isospin mixing of the CN. In addition, at finite temperature one expects a partial restoration of the isospin symmetry because the degree of mixing in a CN is limited by its finite lifetime for particle decay. The competition between the timescale of the Coulomb-induced mixing and the CN lifetime (which decreases for increasing temperature) drives toward a restoration of isospin symmetry, as already predicted by Wilkinson in 1956 [2].

Up to now, the information on isospin mixing obtained from the GDR at finite temperature in CN with mass up to A≈60 [3, 4, 5, 6, 7] displays a temperature dependence of the isospin mixing. The relation between the degree of isospin mixing and the temperature of the CN has been discussed in reference [4]. In the same reference it was also concluded that the isospin mixing width $\Gamma^\downarrow$ originating from the Coulomb interaction does not substantially depend on temperature, as was already discussed in detail in [8, 9].

Calculations of the isospin mixing, particularly the ones recently published [10], show a rather rapid increase with Z and predict sizable values for proton-rich nuclei with Z=40-50. Consequently, a stronger dependence on the method and on the parametrization of the adopted nuclear interaction is found. Therefore new experiments particularly focused on the region Z> 30 are important.

We present here the results of the first measurement of isospin mixing in the nucleus ^{80}Zr with Z=N=40. After describing the experiment, the results will be discussed with special focus on the comparison with zero-temperature measurements and calculations.

2. Description of the experiment

The reactions ^{40}Ca+^{40}Ca and ^{37}Cl+^{44}Ca at beam energies of 200 and 153 MeV were measured at Laboratori Nazionali di Legnaro (Italy). These reactions populate compound nuclei with very similar masses A∼80 at the same excitation energy E*=83 MeV. Only the first one produces a CN in the isospin I=0 channel.

In order to deduce the isospin mixing a statistical model analysis of the γ emission is required. Since the hindrance of the first-step GDR decay from the I=0 channel is indeed a very small effect, it is essential to measure also a reaction with I ≠ 0, such as ^{37}Cl+^{44}Ca, in order to deduce from there the statistical-model and GDR parameters. In fact the intrinsic width and the centroid of the GDR depend essentially on the mass of the nucleus [12], while its increase at finite temperature and angular momentum is driven by the deformation and by thermal shape fluctuations [13, 14]. Nuclear structure effects, e.g. isospin effects, play a secondary role.

The high-energy γ rays emitted by the CN were detected by the 8 large-volume BaF_2 scintillators of the HECTOR array [14, 15]. The recoiling nuclei produced in fusion-evaporation reactions were identified and selected using an array of 32 PHOSWICH triple-stage scintillators [16](covering angles between $5°$ and $13°$ with respect to the beam axis) while the light charged particles (α's and protons) were detected in the ΔE-E telescopes of the GARFIELD array [18]. The γ spectra with the condition on the time of flight in the BaF_2 scintillators (to reject neutrons) and in coincidence with the fusion-evaporation residues are shown in figure 1. More details on the data analysis can be found in [19]

The analysis of the γ spectra was performed using a version of the CASCADE code [3, 4] which allows to treat separately two different classes of states with pure isospin, one labeled with $<$ (with the lowest possible isospin $I=I_z$) and the other with $>$ (with isospin $I=I_z+1$). In our version of the code the isospin mixing was performed according to the statistical mixing formalism of [9]. Within this formalism, the probability of mixing between $<$ and $>$ states is related to the Coulomb spreading width $\Gamma_{\gtrless}^{\downarrow}$ while the decay probability of the CN is related to the decay width $\Gamma_{\gtrless}^{\uparrow}$. The Coulomb spreading width $\Gamma_{>}^{\downarrow}$ is kept fixed along the decay cascade since it is expected to be substantially temperature-independent, as already discussed. The Coulomb spreading width for the inverse mixing is calculated applying the detailed balance and using the ratio of the level densities, which depends on the difference in binding-energy between the $I=0$ and $I=1$ configurations rather than on the excitation energy of the CN. Conversely $\Gamma_{\gtrless}^{\uparrow}$, the inverse of the lifetime of the CN, depends on the excitation energy and its increase with temperature (corresponding to the fact that the lifetimes of the CN becomes shorter) drives toward a restoration of isospin symmetry in the highly-excited CN.

The fraction $\alpha_{\gtrless}^2$ of states $\gtrless$ that mix to states $\lessgtr$ is defined as [4]:

$$\alpha_{\gtrless}^2 = \frac{\Gamma_{\gtrless}^{\downarrow}/\Gamma_{\gtrless}^{\uparrow}}{1 + \Gamma_{\gtrless}^{\downarrow}/\Gamma_{\gtrless}^{\uparrow} + \Gamma_{\lessgtr}^{\downarrow}/\Gamma_{\lessgtr}^{\uparrow}} \qquad (1)$$

The cross section for mixed isospin $\widetilde{\sigma}_{\lessgtr}$ can be defined as an overlap of the cross sections for pure isospin $\sigma_{\lessgtr}$ in terms of the mixing parameters defined above, namely:

$$\begin{aligned} \widetilde{\sigma}_{<} &= (1-\alpha_{<}^2)\sigma_{<} + \alpha_{>}^2\sigma_{>} \\ \widetilde{\sigma}_{>} &= (1-\alpha_{>}^2)\sigma_{>} + \alpha_{<}^2\sigma_{<} \end{aligned} \qquad (2)$$

The statistical model analysis of the γ spectra for both reactions was performed following a recursive procedure. In the first step, the high energy γ-ray spectrum measured for the reaction $^{37}Cl+^{44}Ca \rightarrow {}^{81}Rb$ was fitted with a $\Gamma_{>}^{\downarrow}=0$ condition to find the values of the GDR parameters. As a second step, with the GDR and statistical model parameters deduced from the best fit for the $^{37}Cl+^{44}Ca$ reaction, the high energy γ-ray spectrum measured for the ^{80}Zr compound was fitted leaving $\Gamma_{>}^{\downarrow}$ as a free parameter. With this new value of $\Gamma_{>}^{\downarrow}$ we restarted from step one until the routine converged. The χ^2 minimization was made in the γ-ray energy interval 8-14 MeV. The set of best fitting parameters for the centroid, width and fraction of the EWSR strength were found to be $E_{GDR}=$ 16.2±0.17 MeV, Γ_{GDR}=10.8±0.2 MeV, and S=90±3.5%, respectively. The errors represent the statistical uncertainty of the χ^2-minimization procedure. The extracted Coulomb spreading width for ^{80}Zr was $\Gamma_{>}^{\downarrow} = 10±3$ keV. The measured ^{81}Rb γ spectrum is compared with the statistical-model calculations with $\Gamma_{>}^{\downarrow}=0$ and 10 keV in the left panel of figure 1. For this spectrum the yield is found to be basically independent on the values of $\Gamma_{>}^{\downarrow}$. The right panel of figure 1 shows the data and the statistical model calculations for the ^{80}Zr case, with Coulomb spreading width $\Gamma_{>}^{\downarrow}=0$, 10 and 100 keV. In order to visualize the

details of the comparison between data and calculations these quantities are shown in a linear scale in the insets of figure 1 following a linearization procedure which is usually applied to the study of the GDR in hot nuclei.
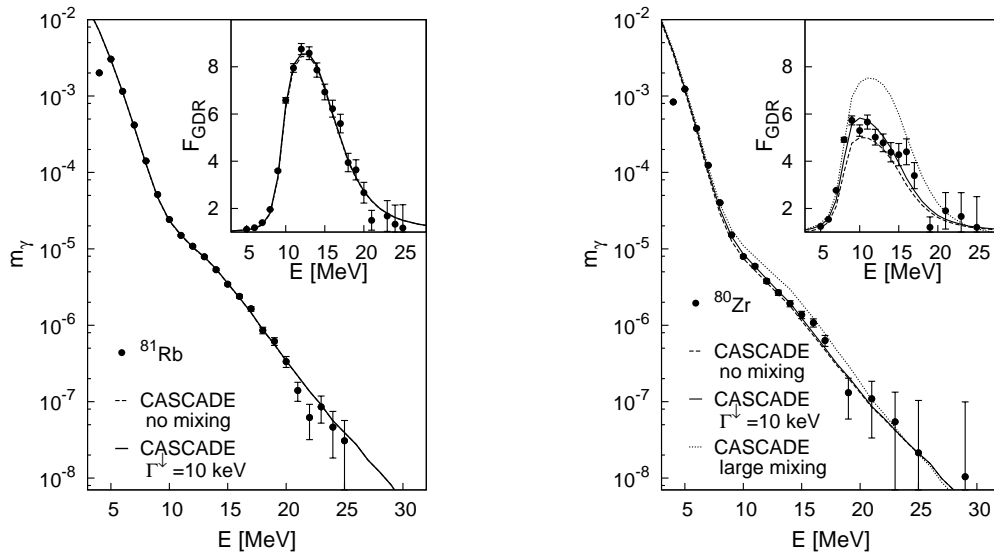

Figure 1. Measured γ multiplicity spectra for ^{81}Rb (left) and ^{80}Zr (right) CN compared with Statistical Model calculations with $\Gamma_>^\downarrow$=0 and 10 keV in the case of ^{81}Rb, $\Gamma_>^\downarrow$=0, 10 and 100 keV in the case of ^{80}Zr. The corresponding linearized spectra (data and calculations) are showed in the insets.

It is interesting to compare the present value of the Coulomb spreading width $\Gamma_>^\downarrow$= 10 keV with the values from systematics obtained in other measurements, namely in statistical reactions ([9] and references therein) and in charge−exchange reactions populating the IAS [20, 21, 22]. Altogether, the data displayed in figure 2 show an increase of the Coulomb spreading width with increasing mass (and atomic number). This can be intuitively understood since $\Gamma_>^\downarrow$ is proportional to the Coulomb matrix element. Remarkably, the present result for a CN at an average temperature $< T >\sim$ 2 MeV is in very good agreement with the value of the spreading widths of the ground state IAS of ^{80}Se measured by [22]. This result is thus consistent with the fact that $\Gamma_>^\downarrow$ is a quantity independent of nuclear temperature.
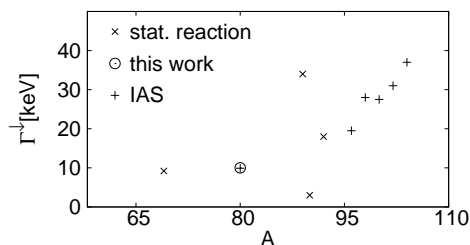

Figure 2. The value of the Coulomb Spreading width obtained with this analysis is compared with the physically analogous quantity measured in statistical reactions ($\times$ from [9]) and in measurements of the IAS spreading width (+ from [20, 21, 22]).

The value of the isospin mixing parameter in ^{80}Zr was then evaluated within the same statistical mixing approach [9] and the angular−momentum dependent value of the degree of isospin mixing was averaged on the γ yield. In the present case the degree of mixing averaged on the γ yield is $\langle\alpha^2_<\rangle$=5±1%, higher than the one corresponding to zero angular momentum. In fact, in the ^{40}Ca+^{40}Ca fusion reaction angular momenta up to 60 $\hbar$, corresponding to temperatures between 1.5 and 3 MeV, are populated and contribute to the weighted average. This value of $\langle\alpha^2_<\rangle$=5±1%, higher than the ones found by [3, 4, 5, 6, 7], is however consistent with the previous measurements once the increasing strenght of the Coulomb interaction in this heavier CN is taken into account.

In order to compare the present result with the calculations of isospin mixing at zero temperature the approach proposed by [11] has been adopted. Starting from the formalism already proposed in [23] which links the isospin mixing probability in the parent nucleus $\alpha^2_{I_0+1}$ with the spreading width of the isobaric analog state $\Gamma^\downarrow_{IAS}$, the authors of [11, 23] proposed an extension which includes the temperature dependence through the CN decay width $\Gamma^\uparrow_{CN}(T)$. According to this formalism the expression for the temperature dependence (at zero spin) of the isospin mixing is given by

$$\alpha^2_{I_0+1} \sim \frac{\Gamma^\downarrow_{IAS}}{\Gamma^\uparrow_{CN}(T) + \Gamma_{IVM}}, \tag{3}$$

where Γ_{IVM} is the value of the Isovector Monopole width at the energy of the IAS.

We have evaluated the above expression for the case of ^{80}Zr. This calculation has been performed by imposing at T=0 the value of $\alpha^2_>= 4.5\%$ as given by the most recent calculation in reference [10]. In general, the available calculations of isospin mixing at zero temperature [24, 25, 26, 10] predict values between 2.5 and 4.5% depending on the method and the kind of interaction used. The value of α^2=4.5% obtained in [10] takes into account the mixing with all I≤I$_0$+5 states and thus is an upper limit of the isospin mixing probability $\alpha^2_>$ of the statistical mixing model of [9]. Nevertheless, states with I>I$_0$+1 give a very small contribution to the mixing and the two parameters can be reasonably compared. With this value of α^2 the Isovector Monopole width at the energy of the IAS is found to be Γ_{IVM}= 225 keV. The temperature-dependent CN decay width $\Gamma^\uparrow_{CN}$ and the spreading width $\Gamma^\downarrow_{IAS}$=10 keV used in formula 3 are the ones obtained from the statistical model and from the fit to our data. The last step was then to deduce (again with the same statistical model) the $\alpha^2_>$ at zero angular momentum (corresponding to T = 2.9 MeV). The value $\alpha^2_>$=1.3±0.4% was found, in agreement with the result obtained with the present measurement.

More details on this procedure can be found in [19]. Indeed measurements at $\langle T\rangle < 2$ MeV are demanded in order to verify the temperature dependence obtained here.

In summary, the simultaneous study of the γ decay from the GDR in two compound-nucleus reactions leading to N=Z ^{80}Zr and to the ^{81}Rb nuclei has allowed to measure the isospin mixing at finite temperature and then to extract the value at T=0. More measurements at finite temperature are recommended in order to test this extrapolation procedure which yields a value consistent with a mixing of 4.5 % at T=0. The Statistical Model analysis yields a Coulomb spreading width of $\Gamma^\downarrow_{IAS}$=10 keV at an average temperature $\langle T\rangle = 2.1$ MeV. This is found to be consistent with $\Gamma^\downarrow_{IAS}$ in same mass region and confirms that the Coulomb mixing is an intrinsic property of nuclear structure independent on temperature.

use of the version of code CASCADE which included the isospin formalism. Discussions with
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