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Measurement of isospin mixing at a finite temperature in ^{80}Zr via giant dipole resonance decay

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Isospin mixing in the hot compound nucleus ^{80}Zr was studied by measuring and comparing the γ-ray emission from the fusion reactions $^{40}\mathrm{Ca} + {}^{40}\mathrm{Ca}$ at $E_{\mathrm{beam}} = 200$ MeV and $^{37}\mathrm{Cl} + {}^{44}\mathrm{Ca}$ at $E_{\mathrm{beam}} = 153$ MeV. The γ yield associated with the giant dipole resonance is found to be different in the two reactions because, in self-conjugate nuclei, the E1 selection rules forbid the decay between states with isospin $I = 0$. The degree of mixing is deduced from statistical-model analysis of the γ-ray spectrum emitted by the compound nucleus ^{80}Zr with the standard parameters deduced from the γ decay of the nucleus ^{81}Rb. The results are used to deduce the zero-temperature value, which is then compared with the latest predictions. The Coulomb spreading width is found to be independent of temperature.

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The issue of isospin impurity in nuclei has been a long-standing open problem in nuclear physics. In particular, its knowledge is interesting in connection with the properties of the isobaric analog states (IAS) and with the Fermi β decay of the $N \approx Z$ nuclei around the proton drip line. The evaluation of the isospin impurity provides an important correction to the Fermi-transition rates allowing the extraction, in a nucleus-independent way, of the up-down quark-mixing matrix element of the Cabibbo-Kobayashi-Maskawa matrix [1,2]. Concerning the IAS, they are known to have a narrow spreading width $\Gamma^{\downarrow}$ related to the isospin impurities [3,4] originating from the Coulomb interaction coupling them to states of different isospin.

In general, the breaking of isospin symmetry can be observed using, as a magnifying lens, the decays which would be forbidden by the selection rules if isospin mixing was not to occur. This is the case of the neutron decay from the IAS [5] and of the E1 decay from self-conjugate nuclei [6].

The giant dipole resonance (GDR), where the maximum strength of the E1 transitions is concentrated, is the ideal excitation mode where this selection rule of E1 decay can be fully exploited. This approach was employed to measure the E1 decay of the GDR in nuclei at a finite temperature produced with fusion-evaporation reactions [7–11]. Fusion-evaporation reactions allow the production of self-conjugate compound nuclei (CN) at high excitation energy which, in many cases, are far from the β-stability valley. The use of a self-conjugate projectile and target ensures 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 [12]. 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. Thus, the first-step γ yield depends on the degree of isospin mixing of the CN. In addition, at a 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 [13].

Up to now, the information on isospin mixing obtained from the GDR at a finite temperature in CN with mass up to $A \approx 60$ [7–11] 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 Ref. [8]. In the same reference it was also concluded that the isospin mixing width $\Gamma^{\downarrow}$ originating from the Coulomb interaction is essentially constant with temperature [14,15], in analogy with the intrinsic damping width of the GDR [16–18]. It should be noted that data for masses, relevant in connection with the study of the proton drip line up to $Z = N = 50$ ^{100}Sn, are not yet available.

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Calculations of the isospin mixing, particularly the ones recently published [1], show a rather rapid increase with Z, and the region $Z = 40$ to 50 is particularly interesting because of its sizable expected value. In addition, in this region predictions depend more strongly on the method and on the parametrization of the adopted nuclear interaction; thus, new experiments particularly focused on the region $Z > 30$ are important.

This paper presents the results of the first experiment aimed at studying the isospin mixing at a finite temperature in the CN ^{80}Zr with $Z = N = 40$. The goal is twofold: the first is to verify whether or not the Coulomb spreading width $\Gamma^{\downarrow}$ is temperature independent and the second is to obtain data to compare with recent predictions [1]. The model of Ref. [19] providing the temperature dependence of the isospin mixing will be used. The present experiment also provides more exclusive data than the existing ones for lighter nuclei and is thus expected to be more sensitive to small effects.

The reactions ^{40}Ca + ^{40}Ca and ^{37}Cl + ^{44}Ca at beam energies of 200 and 153 MeV were measured at the Laboratori Nazionali di Legnaro of the Isituto Nazionale di Fisica Nucleare (INFN, Italy). These reactions populate compound nuclei with very similar masses $A \sim 80$ 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. Therefore, it is essential to also measure a reaction with $I \neq 0$, such as ^{37}Cl + ^{44}Ca in this case, to fix the statistical-model and GDR parameters. This is a very important point because the hindrance of the first-step GDR decay from the $I = 0$ channel is indeed a very small effect.

The high-energy γ rays emitted by the CN were detected by the 8 large-volume BaF$_2$ scintillators of the HECTOR array [18,20]. The recoiling nuclei produced in fusion-evaporation reactions were identified and selected using an array of 32 PHOSWICH triple-stage scintillators [21] (covering angles between 5° and 13° with respect to the beam axis), while the light charged particles (α particles and protons) were also detected in the ΔE-E telescopes of the GARFIELD array [22]. In Fig. 1, the correlation between time of flight and energy loss (light output from the first stage of one PHOSWICH detector) is shown in the case of the ^{37}Cl + ^{44}Ca reaction. In the inset of the same figure are shown the ratio of proton and α energy spectra measured in coincidence with fusion-evaporation residues of the ^{40}Ca + ^{40}Ca and ^{37}Cl + ^{44}Ca reactions and normalized in the 16–26 MeV energy interval. These ratios are constant with energy as expected for statistical decay from compound nuclei formed at the same temperature.

The γ-ray spectra shown in Fig. 2 were obtained with a condition on the time of flight in the BaF$_2$ scintillators to reject neutrons and in coincidence with the fusion-evaporation residues.

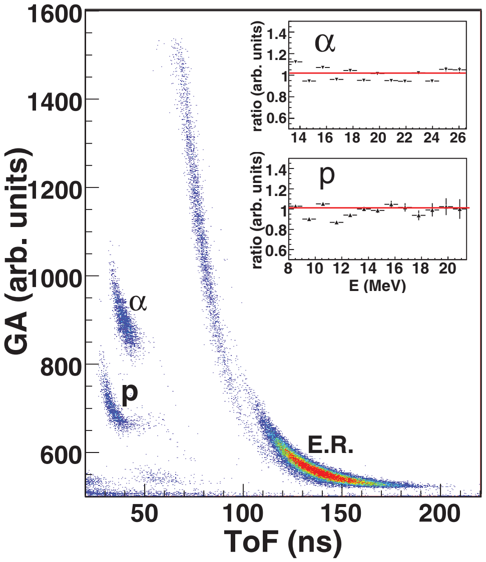

FIG. 1. (Color online) Light output vs time of flight for a PHOSWICH scintillator at forward angle. Evaporation residues (E.R.), protons (p) and α particles are labeled. In the insets, the normalized ratio between the energy spectra of α (top) and proton (bottom) spectra measured in the two reactions with GARFIELD telescopes are shown as a function of center-of-mass energy.

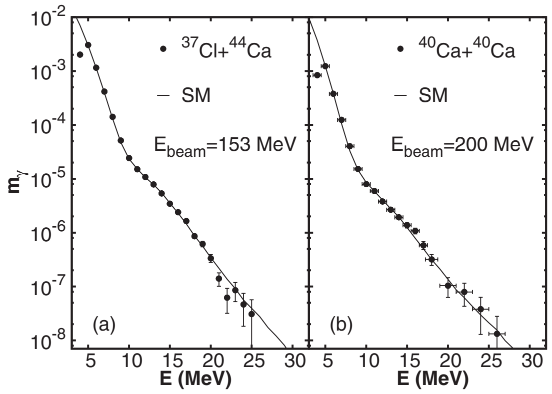

FIG. 2. The γ spectra measured for the ^{37}Cl + ^{44}Ca (left) and ^{40}Ca + ^{40}Ca (right) reactions are shown with filled circles and compared with the best-fitting statistical-model calculations (SM).

A statistical-model analysis was performed using the CASCADE code [23] including several modifications [7,8] as compared with the standard version. The geometry of evaporation-residues detector was taken into account since it induces a selection in the phase-space population of the CN. This effect was accounted for by evaluating with a Monte Carlo statistical-model simulation the correlation between the emission angle of residues and the angular momentum of the CN. The evaporation residues detected in this setup are characterized by angular momentum distributions with average values 34$\hbar$ and 38$\hbar$ for ^{37}Cl + ^{44}Ca and ^{40}Ca + ^{40}Ca, respectively. 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 $I = I_z + 1$), were treated separately. The isospin mixing was performed as in [15]; namely, the probability of mixing between < and > states is related to the Coulomb spreading width $\Gamma^{\downarrow}_{>}$ and $\Gamma^{\downarrow}_{<}$ while the decay probability of the CN is related to the decay width $\Gamma^{\uparrow}_{>}$ and $\Gamma^{\uparrow}_{<}$. $\Gamma^{\downarrow}_{>}$ is kept fixed along the decay cascade since it is expected to be substantially temperature independent. The Coulomb spreading width for the inverse mixing is calculated by applying 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 $\Gamma^{\uparrow}_{>}$ and $\Gamma^{\uparrow}_{<}$, the inverse of the lifetime of the CN, depend on the excitation energy, and its increase with temperature (corresponding to shorter CN lifetimes) drives toward a restoration of isospin symmetry in the highly excited CN.

The fraction $\alpha^2_{\gtrless}$ of states $\gtrless$ that mix with states $\lessgtr$ is defined as [8]

$$\alpha^2_{\gtrless} = \frac{\Gamma^{\downarrow}_{\gtrless}/\Gamma^{\uparrow}_{\gtrless}}{1 + \Gamma^{\downarrow}_{\gtrless}/\Gamma^{\uparrow}_{\gtrless} + \Gamma^{\downarrow}_{\lessgtr}/\Gamma^{\uparrow}_{\lessgtr}}. \tag{1}$$

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

$$\begin{aligned} \widetilde{\sigma}_{<} &= (1 - \alpha^2_{<})\sigma_{<} + \alpha^2_{>}\sigma_{>}, \\ \widetilde{\sigma}_{>} &= (1 - \alpha^2_{>})\sigma_{>} + \alpha^2_{<}\sigma_{<}. \end{aligned} \tag{2}$$

The statistical-model analysis of the γ spectra for both reactions was made following a recursive procedure. In the first step, the high-energy γ-ray spectrum, measured for the reaction $^{37}\mathrm{Cl} + {}^{44}\mathrm{Ca} \rightarrow {}^{81}\mathrm{Rb}$, was fit 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 $^{37}\mathrm{Cl} + {}^{44}\mathrm{Ca}$ reaction, the high-energy γ-ray spectrum measured for the ^{80}Zr compound was fit, 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 energy weighted sum rule (EWSR) strength was found to be $E_{\mathrm{GDR}} = 16.2 \pm 0.2$ MeV, $\Gamma_{\mathrm{GDR}} = 10.8 \pm 0.2$ MeV, and $S = 90 \pm 3.5\%$, respectively. The errors represent the statistical uncertainty of the χ^2-minimization procedure. The extracted Coulomb spreading width for ^{80}Zr was $\Gamma^{\downarrow}_{>} = 10 \pm 3$ keV. The measured ^{81}Rb γ spectrum is compared with the statistical-model calculations in the left panel of Fig. 2. For this spectrum the yield is found to be basically independent of $\Gamma^{\downarrow}_{>}$. The right panel of Fig. 2 shows the data and the statistical-model calculations for the ^{80}Zr case, with the Coulomb spreading width $\Gamma^{\downarrow}_{>} = 10$ keV. In order to visualize the details of the comparison between data and calculations these quantities are shown in a linear scale in Fig. 3 following a linearization procedure which is usually applied in the study of the GDR in hot nuclei. Namely, the measured and calculated spectra have been divided by equivalent spectra calculated using a constant B(E1). Statistical Model calculations without isospin mixing ($\Gamma^{\downarrow}_{>} = 0$ keV), with the value of $\Gamma^{\downarrow}_{>} = 10$ keV yielding the best fit and with a large mixing ($\Gamma^{\downarrow}_{>} = 100$ keV) are compared in the top panel of Fig. 3. We also checked whether or not the small change in yield could be due to a difference in the width of the GDR rather than to isospin mixing. For this reason, a statistical-model fit was performed with $\Gamma^{\downarrow}_{>} = 0$ and minimizing χ^2 as a function of Γ_{GDR}. The opening of more first-step γ-decay channels induced by the isospin mixing has the same effect of narrowing the GDR width by ∼1 MeV. In fact, the best fit corresponds to $\Gamma_{\mathrm{GDR}} = 9.7$ MeV. However, if this $\Gamma_{\mathrm{GDR}} = 9.7$ MeV value is used for ^{81}Rb, the measured γ spectrum is not satisfactorily reproduced (see bottom panels of Fig. 3).

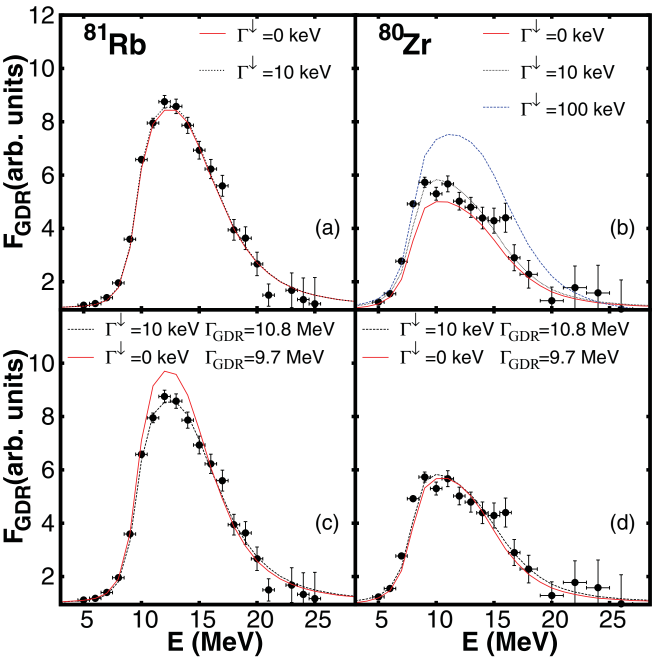

FIG. 3. (Color online) Spectra of Fig. 2 (left panels ^{81}Rb, right panels ^{80}Zr) divided by a statistical spectrum with constant B(E1). In the top panels are displayed spectra obtained with different values of the Coulomb spreading width $\Gamma^{\downarrow}_{>} = 0$ (red line in the online version), 10 (black line), 100 keV (blue line, plotted only for ^{80}Zr). The comparison with calculations with $\Gamma_{\mathrm{GDR}} = 9.7$ MeV (see text) for the cases $\Gamma^{\downarrow}_{>} = 10$ keV (black line) and $\Gamma^{\downarrow}_{>} = 0$ keV (red line in the online version) is shown in the bottom panels.

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 (see [15] and references therein) and in charge-exchange reactions populating the IAS [24–26]. Altogether, the data displayed in the inset of Fig. 4 show an increase of the Coulomb spreading width with increasing mass (and atomic number). Remarkably, the present result for the $A = 80$ CN at an average temperature $\langle T \rangle \approx 2$ MeV is in very good agreement with the value of the spreading widths of the ground state IAS of ^{80}Se [26]. This result is thus consistent with the fact that $\Gamma^{\downarrow}_{>}$ is a quantity independent of nuclear temperature. In addition it tells us that the Coulomb mixing can be considered as a basic intrinsic feature of the nucleus, similarly to the GDR intrinsic width, which is also found to be independent of temperature [16–18].

The value of the isospin mixing parameter in ^{80}Zr was then evaluated within the same statistical mixing approach [15] and the angular-momentum–dependent value of the degree of isospin mixing was averaged over the γ yield. In the present case, the degree of mixing averaged over the γ yield is $\langle \alpha^2_{<} \rangle = 5\% \pm 1\%$, which is higher than the one corresponding to zero

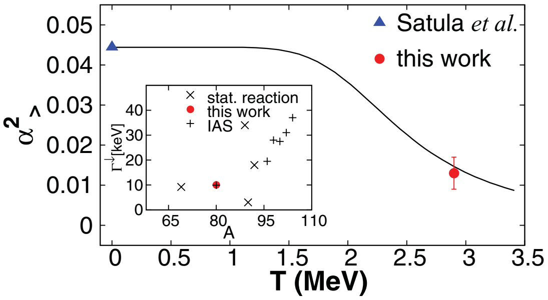

FIG. 4. (Color online) Calculated temperature dependence of the isospin mixing parameter $\alpha^2_>$ (full drawn line), the prediction from [1] (triangle), and the result of this work (full circle). In the inset, the value of the Coulomb spreading width obtained with this analysis is compared with data from statistical reactions (× from [15]) and from the IAS spreading width (+ from [24–26]).

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 $\langle \alpha^2_< \rangle = 5\% \pm 1\%$, which is higher than the ones found in [7–11], is however consistent with the previous measurements once the increasing strength of the Coulomb interactions 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 [19] has been adopted. Starting from the formalism already proposed in [27], which links the isospin mixing probability in the parent nucleus $\alpha^2_{I_0+1}$ with the spreading width of the isobaric analog state $\Gamma^\downarrow_{\mathrm{IAS}}$, the authors of [19,27] proposed an extension which includes the temperature dependence through the CN decay width $\Gamma^\uparrow_{\mathrm{CN}}(T)$. According to this formalism the expression for the temperature dependence (at zero spin) of the isospin mixing is given by

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

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 and the result is presented with the full drawn line in Fig. 4. In particular, this calculation imposes at $T = 0$ the value of $\alpha^2_> = 4.5\%$, as given by the most recent calculation in Ref. [1]. In general, the available calculations of isospin mixing at zero temperature [1,28–30] predict values between 2.5% and 4.5%, depending on the method and the type of interaction. The value of $\alpha^2 = 4.5\%$ obtained in [1] takes into account the mixing with all $I \leqslant I_0 + 5$ states and thus is an upper limit of the isospin mixing probability $\alpha^2_>$ of the statistical mixing model of [15]. 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 $\Gamma_{\mathrm{IVM}} = 225$ keV. The temperature-dependent CN decay width $\Gamma^\uparrow_{\mathrm{CN}}$ and the spreading width $\Gamma^\downarrow_{\mathrm{IAS}} = 10$ keV used in expression (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 $\alpha^2_> = 1.3 \pm 0.4\%$ was found (full circle in Fig. 4). It is surprising how well this simple estimate reproduces the result obtained with the present measurement.

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 us to obtain two interesting and relevant results. The first is the measurement of the isospin mixing at a finite temperature, which appears to be consistent with the temperature-dependence calculation fixed at $T = 0$ on the predicted value of 4.5% [1]. More measurements at a finite temperature should be made in the future to test in a more complete fashion the expected temperature dependance. The second is the measurement of the Coulomb spreading width at an average temperature of $\langle T \rangle = 2.1$ MeV, which is found to be consistent with $\Gamma^\downarrow_{\mathrm{IAS}}$ at $T = 0$. This confirms the fact that the Coulomb mixing is an intrinsic property of nuclear structure independent of temperature. With second-generation radioactive beams it will be indeed very interesting to measure isospin mixing as close as possible to $N = Z = 50$; for example, isospin mixing in ^{96}Cd could be studied by measuring the compound nucleus reaction ^{56}Ni + ^{40}Ca.

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