PROMPT HIGH ENERGY DIPOLE γ EMISSION*

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(Received January 28, 2011)

Version corrected according to Erratum, *Acta Phys. Pol. B* **44**, 675 (2013)

The study of the collective properties of a nuclear system is a powerful tool to understand the structure which lies inside the nucleus. A successful technique which has been used in this field is the measurement of the γ-decay of the highly collective Giant Dipole Resonance (GDR). In fact, GDR can be used as a probe for the internal structure of hot nuclei and, in addition, constitutes a clock for the thermalization process. Using the fusion–evaporation reaction, it has been recently possible to study *(i)* the yield of the high-energy γ-ray emission of the Dynamical Dipole which takes place during the fusion process and *(ii)* the degree of isospin mixing at high temperature in the decay of ^{80}Zr. In the first case it is important to stress the fact that the predictions of the theoretical models might differ depending on the type of nuclear equation of state (EOS) and on the N–N in-medium cross-section used in the calculations while, in the second physics case, the data are relative to the heaviest $N=Z$ nucleus which has been possible to populate in the $I=0$ channel using fusion–evaporation reaction. Both experiments were performed at the Laboratori

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", August 30–September 5, 2010, Zakopane, Poland.

Nazionali di Legnaro using the HECTOR-GARFIELD array. The high-energy γ-rays were measured in coincidence with light charged particles and fusion–evaporation residues.

DOI:10.5506/APhysPolB.42.619
PACS numbers: 24.30.Cz, 25.70.–z, 23.20.–g

1. Introduction

Heavy-ion reactions are a powerful tool to study the structure of the nucleus and the dynamics of the nuclear reactions. During heavy-ion collisions, in the complete fusion channel, a variety of single and collective modes of the nucleons takes place leading to the formation of a compound nucleus (CN). The CN is a long-lived system, at thermal equilibrium, whose features and decay mode do not depend on the reaction entrance channel except for parity, energy and angular momentum conservation [1].

At the very early stage of the fusion process, when two heavy ions interact, the density of neutron excess changes very rapidly in time until it reaches an equilibrium value. This process, known as charge or N/Z equilibration, is relevant when projectile and target have a large difference in the N/Z ratio. In such a scenario, it has been predicted that the charge equilibration should take place with a collective motion known as Dynamical Dipole (DD) since it appears as a dipole oscillation that is a source of γ-rays emission [2–4]. The description of the Dynamical Dipole requires as important input parameters the N–N collision cross-section and the nuclear equation of state with its symmetry term. In fact, being the DD emission related to an isospin oscillation in the neck region between projectile and target, it is affected by the value of symmetry energy at densities lower than the saturation one.

During the thermalization process, the last degrees of freedom to attain equilibration in the CN are the collective ones, *i.e.* the Giant Resonances. The $E1$ γ-rays emission associated with the statistical decay of the Giant Dipole Resonances is a probe of the bulk properties of the nuclei. It depends on the structure of initial and final states and on the selection rules associated with the specific transition. In particular, the transitions from a $I_{\mathrm{initial}} = 0$ to a $I_{\mathrm{final}} = 0$ state (with I isospin quantum number) are forbidden in self-conjugate nuclei. Such a selection rule can be used to study the role of the nuclear interaction in compound nucleus formation using the GDR decay from an $I = 0$ CN [5–7]. In fact, the hindrance of GDR γ-decay from $I = 0$ CN is due to a partial restoration of isospin symmetry at high nuclear temperature (T), since the excited compound nucleus lifetime is too short for the relatively weak Coulomb interaction to mix states with different isospin.

In both the physics cases previously mentioned, the measurement of prompt γ radiation in heavy-ions fusion–evaporation reactions and the identification of the reaction channel, are necessary. This has been possible using the GARFIELD-HECTOR array [8–12] at the Laboratori Nazionali di Legnaro described in Section 2. In Section 3 the experimental results on the measurement of the Dynamical Dipole γ-ray yield in the reaction ^{16}O+^{116}Sn at 12 MeV/u are discussed. These data integrate those taken at 8.1 and 15.6 MeV/u already published [19]. In Section 4 the data relative to the measurement of isospin mixing for ^{80}Zr at high temperature are discussed. It is important to stress that this nucleus is the heaviest $N = Z$ isotope in which isosopin mixing was measured with this technique. The used reaction is ^{40}Ca+^{40}Ca $\rightarrow$ ^{80}Zr ($E^* = 83$ MeV) which produces ^{80}Zr in the $I = 0$ channel while the reference fusion–evaporation reaction was ^{37}Cl+^{44}Ca $\rightarrow$ ^{81}Rb at E^* =83 MeV which produces ^{81}Rb in the $I = 7/2$ channel.

2. The experimental apparatus

The experiments presented in this work were performed at Laboratori Nazionali di Legnaro. The high energy γ-rays were measured (using the HECTOR array [8, 9]) in coincidence with the evaporation residues (using an array of phoswich detectors [10]), the light charged particles (using the GARFIELD array [11, 12]) and the pre-equilibrium neutrons (using a part of the HELENA array [13]). The time reference of the experiments was given by the accelerator radiofrequency or by an array of fast scintillators placed near the target (from the HELENA array [13]).

The HECTOR array is composed of 8 BaF_2 scintillators, each of $\simeq$ 3000 cm^3 of volume, placed in the backward direction relative to the beam. The absolute full energy peak efficiency of the array was $\simeq$ 1% at 15 MeV. The BaF_2 intrinsic time resolution was 600 ps and the energy resolution was $\simeq$ 12% at 1.3 MeV. In this experimental campaign HECTOR scintillators operated under the high vacuum (10^{-5} mbar) of the GARFIELD scattering chamber (a cylinder of $\simeq$ 3 m of diameter and $\simeq$ 5 m of length). To avoid overheating of the electronics, the voltage dividers were placed outside the chamber and the signals from the photomultipliers were sent via dedicated cables. The detectors were calibrated with standard sources for low energy γ-rays and using the 15.1 MeV γ rays emitted in the reaction ^{11}B (19.1 MeV) $+d =^{12}$C$+n + \gamma$ [14–18].

GARFIELD is a high-granularity 4π array dedicated to charged-particle identification. Charge identification can be achieved with ΔE–E, isotope identification with the pulse shape analysis of the signal coming from the stop scintillator detector (E). In the experiments only the forward chamber, covering angles $0° < \phi < 360°$ and $30° < \theta < 85°$, was used.

PHOSWICH scintillators were arranged in 4 boxes surrounding the beam line at a distance of $\simeq 160$ cm from the target and covering a polar angle between 5° and 13°. Inside one of the PHOSWICH boxes a fast plastic scintillator of small dimensions was also placed to detect the elastically scattered beam. These PHOSWICH detectors consist of three coupled stages of scintillators followed by one photomultiplier. The scintillation light of the different stages has different decay constants and can be consequently identified and separated in the digitized pulses.

Additional BaF_2 scintillators from HELENA array were also employed. In the experimental setup 5 detectors were placed close to the target to provide an alternative time reference with respect to radio-frequency. In forward direction, 7 detectors at $\simeq 80$ cm from the target were used to measure neutrons via time of flight.

3. Dynamical dipole emission

As previously mentioned, during heavy-ion fusion-evaporation reactions the density of neutron excess changes very rapidly in time until it reaches an equilibrium value. This process is particularly relevant if the colliding nuclei have a different N/Z ratio; in this case, it has been predicted that the equilibration should take place with a collective oscillation [2–4].

As both high energy γ-rays emitted in the hot GDR statistical decay and in the pre-equilibrium DD emission have a dipole nature and their energy spectra are centred in the interval 10–15 MeV, it is extremely difficult, if not impossible, to directly measure the DD emission yield from only one fusion–evaporation reaction. The typical experimental procedure relies on the fact that DD emission is not expected in N/Z symmetric fusion–evaporation reactions. Consequently, the measurement of the DD yield requires a second reference fusion–evaporation reaction producing the same compound nucleus at the same excitation energy and angular momentum but in an N/Z symmetric channel. The comparison between the γ-ray spectra measured in the N/Z symmetric and N/Z asymmetric channel will evidence the DD contribution.

Since 1993, a series of experiments [19, 23–28] has measured an extra yield in γ emission that has been associated with the Dynamical Dipole (DD) emission. The available data are concentrated mainly in the $A \simeq 132$ mass region and seem not to follow [19, 27] the theoretical predictions concerning the DD intensity dependence on the beam energy. In particular, a very pronounced rise and fall behaviour, not fully accounted for by theory, has been measured in the systems $^{32}S+^{100}Mo$ [25] and $^{36}Ar+^{96}Zr$ [26] (see the left panel of Fig. 1). Qualitatively, an increase of the DD yield with beam energy is expected as the dynamics in the neck region between projectile and target, where the DD oscillation develops, becomes faster. A decreasing yield for higher beam energies is similarly expected due to the damping related to fast processes like pre-equilibrium neutron emission and p–n direct collisions that reduces the N/Z asymmetry and damps the isovector oscillation. The DD yield dependence with beam energy is the result of the interplay between these two phenomena.

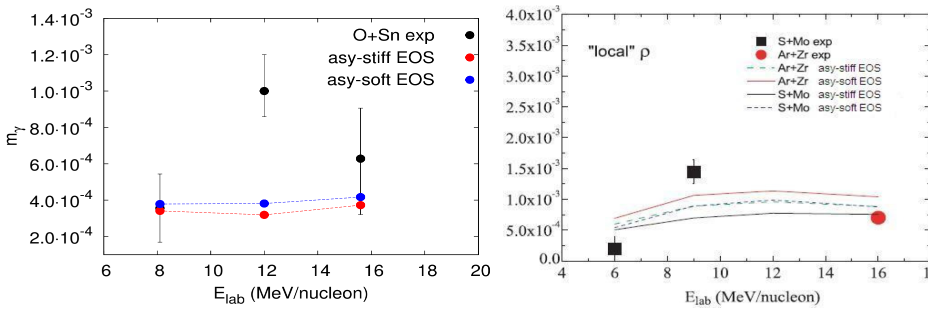

Fig. 1. The Dynamical Dipole γ emission yield measured in mass region $A \simeq 132$ for beam energies ranging from 6 to 15 MeV/u. Right panel: data reported for the reactions $^{32}S+^{100}Mo$ [25] and $^{36}Ar+^{96}Zr$ [26, 27]. Left panel: data reported in Ref. [19] for the reaction $^{16}O+^{116}Sn$ at 8.1, 12 and 15.6 MeV/u. The diamond in the plot, at 12 MeV/u is still a preliminary result [20, 22]. In both plots theoretical calculations are connected with dotted or dashed lines.

The measured DD total yield measured in the reaction $^{16}O+^{116}Sn$ is shown in the left panel of Fig. 1. The data points at 8.1, 15.6 MeV/u were already discussed in Ref. [19]. The one at 12 MeV/u is preliminary and provides a measurement of the Dynamical Dipole emission in the region between the data points previously taken [20, 22]. The beam energy was chosen to have information exactly where data from [25] disagree from calculations. In the present data analysis the fusion–evaporation reaction used to tune the statistical model calculations was $^{64}Ni+^{68}Zn$ (E_{lab} = 4.7, 6.2 and 7.8 MeV/nucleon) [8].

The integrated DD yield measured in the $^{16}O+^{116}Sn$ reaction and plotted in the left panel of Fig. 1 shows the same rise and fall behaviour as reported in Ref. [27] and in the right panel. Even though the analysis of the measured data and of the theoretical calculations are still in a preliminary phase, as far as the reaction at 12 MeV/u is concerned, the "rise and fall" trend of the DD multiplicity as a function of beam energy is clearly seen in the measured data but not in the results of theoretical calculations. The different EOS parametrizations used in the calculations [4, 29] do not seem to produce either a better agreement with measured data or the large differences in the total yield as in the case of Ref. [4]. This is probably due to the much larger N/Z asymmetry in the reaction channel of Ref. [4].

This difference between the expected and measured DD total γ-ray yield calls for further investigation, *e.g.* performing new theoretical calculations with different parametrization of N–N cross-section and a more detailed description of the pre-equilibrium particle emission. The angular distribution of γ-rays measured in the backward hemisphere (covered by HECTOR detectors) will be extracted from data at 12 MeV/u and the comparison with the one obtained within theoretical model will provide a much deeper detailed check of the model.

4. Isospin mixing

In the isospin formalism, neutrons and protons are assumed to be two different states of the nucleon with values 1/2 and −1/2 of the projection I_z of the isospin operator I. According to this definition, the projection of isospin for a nucleus can be written as: $I_z = (N - Z)/2$. The ground state of most even–even and odd–odd mass nuclei has isospin $I = I_z$. The consequence which is relevant for this work is that $N = Z$ nuclei are in a $I = 0$ state. This makes possible the formation of a CN in an $I = 0$ state through the use of $N = Z$ isotopes as projectile and target.

In the nuclear ground state isospin symmetry is largely preserved and the degree of mixing is given by the mixing parameter α^2 [6, 7] defined as

$$\alpha^2 = \sum_{I=I_0+1} \frac{|\langle I = I_0 + 1|H_{\mathrm{C}\Delta I=1}|I = I_0\rangle|^2}{\left(E_{I=I_0+1} - E_{I=I_0}\right)^2},$$

where H is the isovector part of the Coulomb potential.

Isospin symmetry breaks as energy is given to the nuclear system. In fact, nuclear levels come closer and develop a finite width making more effective the mixing between levels of different I induced by Coulomb force. In compound nuclei, if the excitation energy is high enough, the mixing process can be interrupted by statistical decay with the consequent restoration of isospin symmetry [5–7, 30]. In such a situation, where the mixing is expected to be small, α^2 parameter can be approximated as the ratio between the Coulomb spreading width $\Gamma^{\downarrow}$ (which represents the time-scale over which the symmetry violation occurs) and the compound decay width Γ_{CN} [6]. Practically, in the hot CN the degree of isospin mixing is given by the interplay between $\Gamma^{\downarrow}$ and Γ_{CN}. The higher is the excitation energy, the stronger is expected to be the restoration of isospin symmetry.

As discussed in Introduction, due to the $E1$ nature of the γ decay, the GDR is a good probe for the measurement of isospin mixing. The experimental procedure requires two fusion evaporation reactions producing the same compound at the same excitation energy and angular momentum (as in the case of Section 3). One reaction is used to tune the statistical model calculations, the other one to measure the isospin mixing. The analysis method that has been used in this work is based on the assumption that the statistical decays of ^{81}Rb (at $E^* = 83$ MeV) (produced via the reaction ^{37}Cl+^{44}Ca) and that of ^{80}Zr (at $E^* = 83$ MeV) (produced via the reaction ^{40}Ca+^{40}Ca) have the same features. This condition was verified as the measured energy spectra of light charged particles (alpha and protons) have the same slope for both ^{81}Rb and ^{80}Zr compound nuclei [21, 22].

The spectra displayed in Fig. 2 show the high energy γ-rays measured in both reactions. The results of statistical model calculations are indicated with a continuous line. The spectra in Fig. 2 were measured in coincidence with fusion–evaporation residues and were analysed with a version of CASCADE Statistical Model code which includes isospin physics [6, 22, 31, 32]. Phase-space population modified by the kinematic selection induced by PHOSWICH geometrical efficiency has been adopted instead of the standard one.

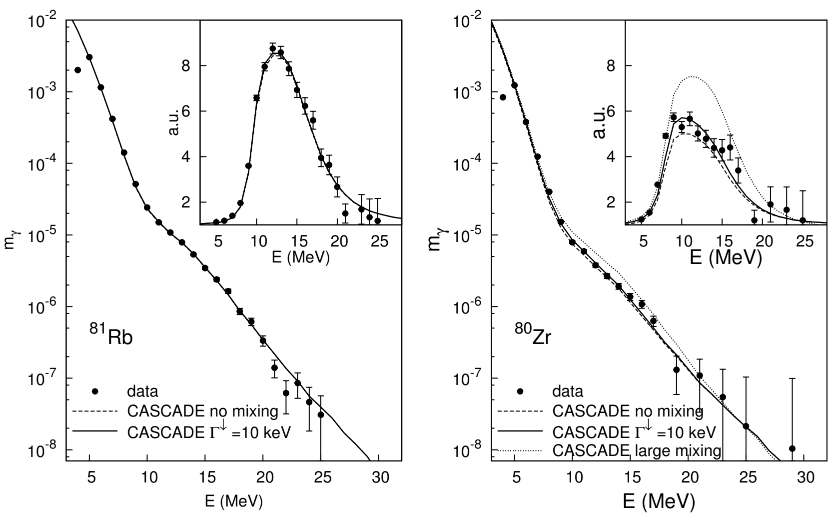

Fig. 2. The high energy γ-ray spectra measured in the reaction ^{37}Cl+^{44}Ca $\rightarrow$ ^{81}Rb at $E^* = 83$ MeV (left panel) and in the ^{40}Ca+^{40}Ca $\rightarrow$ ^{80}Zr ($E^* = 83$ MeV) reaction (right panel). In the insets, the linearised spectra are shown. The statistical model calculations (see text) are displayed with continuous line [21, 22].

The analysis of the data was done using a recursive fitting procedure based on a χ^2 minimization technique. The analysis of the reference ^{81}Rb system allowed to fix GDR and statistical model parameters which were then used for the system ^{80}Zr. In this second step, the Coulomb spreading width $\Gamma^{\downarrow}$, that is a free parameter, has been tuned to have the best fitting curve in the decay of ^{80}Zr (see Table I). Finally, it was verified that the set of best fitting parameters listed in Table I and a Coulomb spreading width $\Gamma^{\downarrow}$ of 10 keV still reproduce the γ-decay spectrum of ^{81}Rb. The index "<" used in Table I, in accordance with the notation of Ref. [6, 31, 32], refers to the $I = 0 \rightarrow I = 1$ mixing which is directly probed in our measurement.

TABLE I

Best fitting parameters obtained from the statistical model analysis [21, 22] together with their statistical error. In the first three columns the GDR centroid $\mathrm{E_{GDR}}$ (MeV), width Γ_{GDR} and EWSR strength are reported. These parameters were obtained from ^{81}Rb γ-ray spectra analysis. In the last two columns the Coulomb spreading width ($\Gamma^{\downarrow}_{>}$) and the isospin mixing parameter ($\alpha^2_{<}$), obtained from ^{80}Zr analysis, are listed [21, 22].

$\mathrm{E_{GDR}}$ (MeV)	Γ_{GDR} (MeV)	EWSR	$\Gamma^{\downarrow}_{>}$ (keV)	$\alpha^2_{<}$ %
16.2 ± 0.15	10.8 ± 0.3	0.90 ± 0.03	10 ± 3	5 ± 1

This analysis has shown that the hindrance of GDR decay in the self-conjugate nucleus ^{80}Zr makes possible the evaluation of the degree of isospin mixing present in a highly excited compound nucleus. The value of the Coulomb spreading width extracted from the statistical model analysis $\Gamma^{\downarrow}_{>}$ [6, 31, 32] is comparable to the width of the isobaric analogue state $\Gamma^{\downarrow}_{\mathrm{IAR}} = 9.9$ keV measured in ^{80}Se [33], a nucleus with a similar mass and deformation as ^{80}Zr. As stated in Ref. [7], the value of $\Gamma^{\downarrow}_{\mathrm{IAR}}$ is equivalent to zero temperature $\Gamma^{\downarrow}$, this means that the mixing mechanism, as Wilkinson proposed [30], is the same independently of the excitation energy. The measured value of the isospin mixing coefficient at $T \simeq 2$ MeV $\alpha^2_{<}$, extrapolated to $T = 0$ using the technique described in [5, 6, 32, 33], has given a value of $5 \pm 1\%$ which is consistent with the one calculated in Ref. [34] of 4.5% for ^{80}Zr at zero temperature.

5. Conclusions

In this work high energy γ-ray emission from hot nuclei has been used for the measurement of the total yield of the Dynamical Dipole in the reaction ^{16}O+^{116}Sn at 8.1, 12 and 15.6 MeV/u and of the isospin mixing in ^{80}Zr at $E^* = 83$ MeV. In both the experiments it has been necessary to measure, as a reference, the high energy spectra emitted in a fusion–evaporation reaction which produces a similar compound nucleus (^{132}Ce in DD physics case and ^{81}Rb in the isospin mixing case) at the same excitation energy and angular momentum but where DD was not present and $E1$ decay not hindered. The preliminary results of the data analysis have shown that: *(i)* there is the same "rise and fall" trend of the total DD γ-ray yield as was observed in Ref. [27] and that preliminary theoretical calculations do not manage to reproduce the experimental trend; *(ii)* A Coulomb spreading width in ^{80}Zr at $T \simeq 2$ MeV of 10 ± 3 keV was extracted from data. Following the analysis procedure discussed in Ref. [31, 32] a mixing coefficient $\alpha^2_< = 5 \pm 1$ % was extracted. Both results are consistent with previous data (the $\Gamma^{\downarrow}_{\mathrm{IAR}}$ in ^{80}Se was measured to be 9.9 keV [33]) and very recent theoretical calculations [34]. Even though data analysis is not concluded yet these preliminary results call for new measurements and theoretical calculations. In fact, it is not yet present a simple technique to compare the $\alpha^2_<$ values measured at high excitation energies with theoretical values calculated at zero temperature.

The work has been supported by the Italian National Institute of Nuclear Physics (INFN), by the Polish Ministry of Science and Higher Education Grants No. N N202 486339 and No. N N202 309135.

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