SEARCH FOR EXTRA YIELD IN HOT Ni ISOTOPES BELOW THE GIANT DIPOLE RESONANCE*

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The high-energy γ rays from the Giant Dipole Resonance (GDR) decay of $^{56,60,62}\mathrm{Ni}^*$ nuclei at finite temperature between approximately 1.5 and 2 MeV, produced in the $^{32,34,36}\mathrm{S}+^{24,26}\mathrm{Mg}$ reactions at bombarding energies between 78 and 90 MeV, were measured. The experiment was then analyzed with a statistical model using a Monte Carlo approach. Some evidence is found within the analysis on the presence of an extra yield on the tail of the Giant Dipole Resonance which may be attributed to a Pygmy Dipole Resonance in an excited nucleus.

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1. Introduction

For more than half a century, the γ decay from the Giant Dipole Resonances has been studied intensively at zero and finite temperatures [1–3]. The discovery of the presence in the E1 strength function of an additional strength at energies around the neutron binding energy, denoted as Pygmy Dipole Resonance (PDR), was identified in several nuclei (see [4] and references therein) and was related to the neutrons excess to the $N = Z$ core. Indeed, the strength of the PDR was found to rise with the increasing neutron excess. A good example of this trend was seen in the Ni isotopes, which were also studied with radioactive beams [5, 6].

The interest in this mode is related to the possibility of testing nuclear structure models, the connection to the neutron skin [7], and due to its possible impact on stellar and astrophysical processes [8]. Nevertheless, no experiments have searched the PDR mode at finite temperature (called HOT-PDR), and in the literature, only a few predictions for it are available [9, 10].

Here, the first preliminary results of such an experiment are presented. Since it is not obvious that the PDR can survive in highly excited (above some tens of MeV), finite temperature and initially not thermalized and rotating nuclei, the experimental findings are important to answer the question about the existence of the HOT-PDR.

2. Setup and experiment

To create a series of nuclei at finite temperature at around 1.5 MeV that differ only in neutron number, we created three different Compound Nuclei (CN) in the Ni isotopic chain with an excitation energy of 49 MeV (see Table 1) using the IFIN 9 MV Tandem facility that delivered a beam of sulfur isotopes impinging on solid magnesium targets. The solid magnesium targets were gold-plated to avoid deterioration.

Table 1. Table of the reaction parameters and the populated CN.

Beam	Beam energy [MeV]	Target [1 mg/cm^2]	CN	E^* [MeV]	$L_{\rm max}$	Fusion cross section [mb]
^{32}S	90	^{24}Mg	^{56}Ni	49.1	19.1	530
^{34}S	79	^{26}Mg	^{60}Ni	49.3	14.6	338
^{36}S	78	^{26}Mg	^{62}Ni	49.3	12.1	247

Three different Ni isotope compound nuclei were created in the reactions to observe a possible trend in the strength of the HOT-PDR with a neutron number. The first measured Ni isotope, ^{56}Ni is an $N = Z$ nucleus where no extra neutrons are distributed around the core and thus, we do not expect a measurable HOT-PDR. The other two compound nuclei were ^{60}Ni and ^{62}Ni with 4 and 6 extra neutrons away from the $N = Z$ core.

The beam had an intensity of around 1–2 pnA and was pulsed by an electrostatic capacitor with a time resolution of around 1–2 ns. This time resolution is sufficient to separate neutrons from γ rays emitted in coincidence during the decay of the compound nuclei by using their different time of flight between the target and the large volume scintillator detectors (TOF-discrimination).

The γ rays were detected by the BGO Compton-suppressed large-volume $LaBr_3$:Ce and $CeBr_3$ detectors (see Fig. 1). In addition, 4 Compton-suppressed HPGe detectors were mounted at 90 degrees to observe γ-decay radiation from residues. A more detailed description of the set-up can be found in [11].

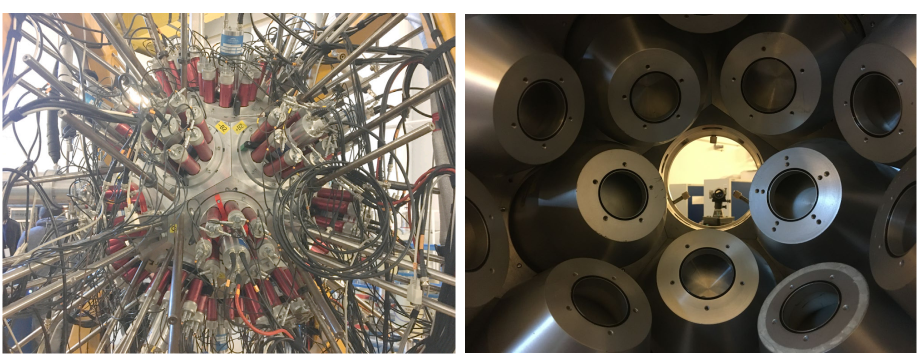

Fig. 1. Global photograph of the $LaBr_3$: Ce and $CeBr_3$ ELIGANT detector array (left panel) [11] mounted in the experimental configuration together with the BGO anti-Compton shield. On the right panel, a front view approximately from the target position of the detectors is shown.

3. Analysis

The γ-ray yield of all three reactions were measured and compared with the Monte Carlo statistical model simulations. As shown in Fig. 2, a very good agreement for the GDR part was found. The decay of the compound nucleus follows a chain of light-charged particles (LCP), neutron and γ-ray emissions, and populates different residues, most of them known as γ-ray emitting excited nuclei. They can therefore be identified in the γ-ray spectra taken with the 4 HPGe detectors. With the help of the residues population, a normalization of the measured γ-decay yield was possible.

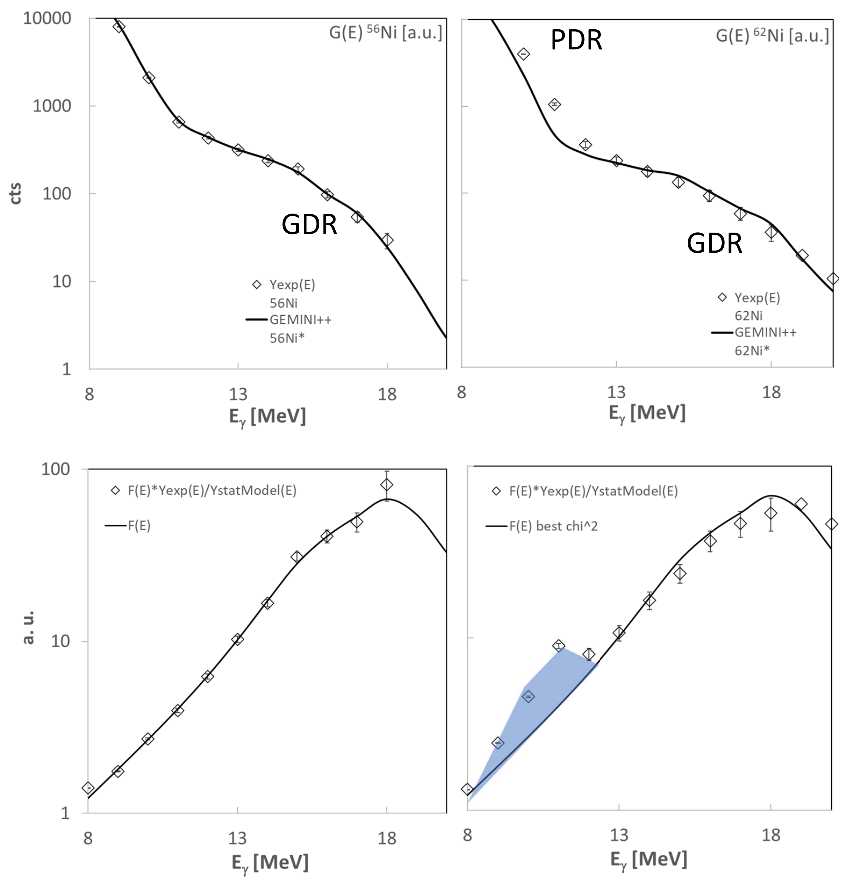

Fig. 2. Plot of the γ-ray yields for the decay of two different CN in the upper panels. In the lower panels, normalized, linearized spectra (see the text) are compared with the Lorentzian function used in the statistical model calculations to describe the GDR decay [3]. The extra yield energetically below the GDR is shaded in the lower normalized plots. One can note the increase with the neutron number of the extra yield at energy lower than the GDR centroid.

Additionally, in a second experiment, light charged particles were measured and included in the analysis to control the statistical model parameters and crosscheck the nuclear temperature. For the evaluation of the statistical model, the Monte Carlo code GEMINI++ [12] was used intensively.

In order to verify the correctness of the statistical model simulations, the measured amount of the residues populated in the reactions was compared to the simulations. A good agreement of the ratio between the most populated residue and the weakest ones was found even with absolute normalisation on the integrated measured beam current.

The average temperature on which the HOT-PDR is built during the CN decay was evaluated to be $\langle T_{\mathrm{PDR}} \rangle = 1.6$ MeV, calculated with a Monte Carlo statistical model [12]. The statistical model parameters, such as the initial conditions that dominate the subsequent steps of the decay [2] such as widths, positions, and strengths of the E1 resonances states of the equilibrated CN were chi-square fitted to the first CN reaction which builds an $N = Z$ nucleus ^{56}Ni for which no extra yield coming from the HOT-PDR is expected.

The used statistical model [12] takes into account isospin mixing suppression effects [13, 14] of the GDR even if it is a small effect when compared to the expected extra yield. This fusion–evaporation reaction gives rise to an excited CN that decays after thermal equilibration and building with a certain probability of GDR, GQR or similar modes. The GDR mode is the strongest one and dominates all other collective modes in this scenario. This is used to fit the position and width of a GDR formed by two overlapping Lorentzial curves (due to a small deformation) in this Ni isotope and to tune the statistical model parameters like level density.

These values of the strength, position, and width of the GDR have then been kept fixed to analyze the γ-ray yield from the two heavier isotopes, selecting the chi-square minimisation only by the energy part above 15 MeV for the CN systems, where the neutron number is not equal to the proton number. For the latter, the kinematics, mass, and beam energy were changed accordingly. The deformation (in other words, the splitting of the GDR into two peaks) of the CN, position and widths of the two GDR peaks were treated as free parameters to fit the high-energy part of the GDR for the ^{60,62}Ni compounds and it was assumed that only the GDR is present. The chi-square minimisation resulted in a prolate deformation with a beta value around 0.2 and a splitting of the GDR that is in line, and excellent agreement with the predictions of the Lublin–Strasbourg Drop (LSD) model [15] as can be seen in Fig. 3.

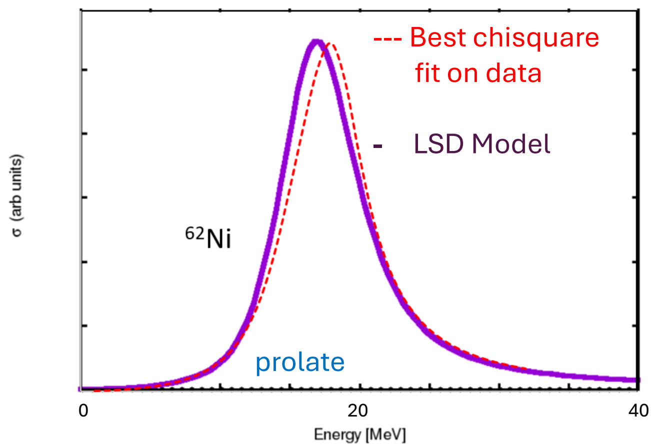

Fig. 3. Plot of the found line shape of the GDR with chi-square minimisation (full drawn line) with the predictions of the Lublin–Strasbourg Drop (LSD) model (dashed line) [15].

4. Results

The resulting fits reproduce very well the GDR at high-energy but not so well on the low-energy part (in the region of 8–12 MeV) of the detected γ-ray emission spectra.

No sets of physical parameters could reproduce the lower-energy tail of the GDR together with the dominant part of the GDR at above 12, 15 or 20 MeV, even assuming an unphysical huge deformation and an extremely large GDR width and strength as starting conditions of the statistical decay steps and chains, the data could not be reproduced, see Fig. 2. The more natural assumption is to look at the extra yield at the tail of the GDR as not originating from the GDR E1 strength.

This extra strength or additional resonance may be attributed to the HOT-PDR state since it appears only in the neutron-rich Ni isotopes at finite temperatures as it was predicted in [9, 10]. A good agreement with the data can be found, as seen in Fig. 4, by introducing an additional resonance at lower energy around 10.3 MeV for the Ni isotopes with $N \gtrsim Z$.

Additionally, in Fig. 4, one can note that with the increasing number of neutrons in the nucleus going from ^{60}Ni to ^{62}Ni, the strength of the extra yield (denominated in the plot as HOT-PDR) is growing. For the pygmy resonance, a strength of around 4% of the Thomas–Reich–Kuhn (TRK) energy weighted sum rule [1] of the GDR is used in the case of ^{62}Ni to reproduce the data.

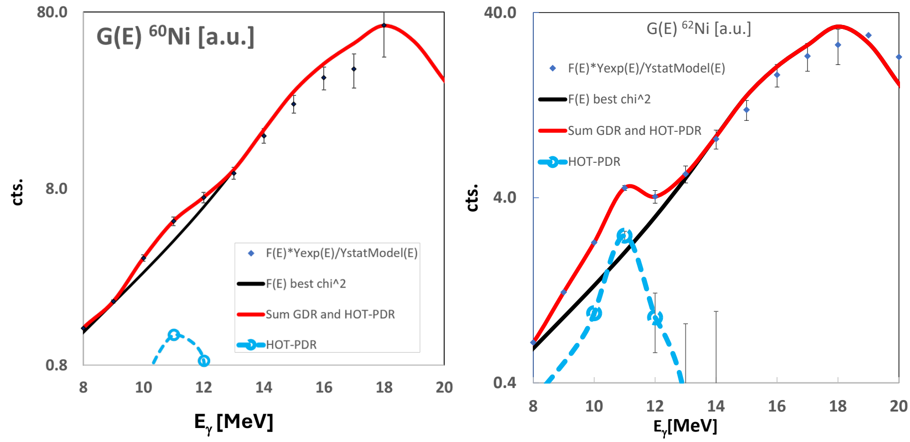

Fig. 4. Plot of the linearized measured γ-ray yield of the decay of ^{60}Ni (left panel) and ^{62}Ni (right panel) together with the best chi-square fit of the statistical model using the γ-ray emission from GDR and adding strength in the lower-energy tail in the statistical model calculation to reproduce the measured data.

5. Resume

This described experiments in which three different compound nuclei were built and populated at the same excitation energy, similar angular momentum, and temperature. Their subsequent γ-ray emission was measured with the ELIGANT scintillator array.

At finite and zero temperatures, no or very small PDR is expected in the $N = Z$ nucleus ^{56}Ni. This CN was used to benchmark the statistical model and from this starting point, the GDR γ-ray decay yield of the heavier and more neutron-rich Ni isotopes with 4 and 6 additional neutrons were fitted, allowing for only different kinematics and the fit of the high-energy part of the strength function.

6. Conclusions

The measured yield cannot be reproduced by the GDR decay unless one adds lower-lying resonance as the starting condition of the statistical subsequent decay steps, called here HOT-PDR. This resonance has been found to be at between 9 to 11 MeV and with a much smaller strength than the GDR.

The appearance of such HOT-PDR may be related to the difference between the hot rotating neutron fluid and the proton fluid, especially for the nucleons located near the surface. The hot rotating neutron fluid radius grows probably faster than the proton fluid and forms a skin-like enhancement in excited nuclei [16]. This new feature may strongly influence astrophysical stellar processes. These aspects should be addressed by theoretical evaluations.

In an additional, complementary measurement with stable Ni nuclei as a target, their features at zero temperature were and will be studied in contemporary experimental campaign at CCB IFJ-PAN in Kraków (PL).

The authors continue this exploratory research and plan in the near future new experiments with measurements in different isotopic chains and in more neutron-rich Ni isotopes at different temperatures. It is planned to detect also light-charge particles at wider angles and with fully coincidence detection of residues to select specific reaction channels and to pin down uncertainties.

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