# Gamma-Decay from Isovector Giant Dipole Resonances: a Pilot Experiment

RCNP-E498 Collaboration

Isovector giant dipole resonance (IVGDR) is a collective vibrational excitation that commonly exists in all the atomic nuclei [1]. The IVGDR is described as a collective dipole oscillation between the neutrons and protons. Gross properties like excitation energy and strength are well reproduced by microscopic models. The width of the IVGDR is, however, not yet fully explained owing to the complex damping mechanism. The decay of giant resonances in nuclei is a prime example of how a well-ordered collective excitation dissolves into disordered motion [2]. Giant resonances are in a first approximation described by coherent superposition of particle ($p$) - hole ($h$) configurations. The most probable damping mechanism is caused by their coupling to progressively more complicated states of $2p$-$2h$ character up to the eventual compound nucleus state, *i.e.* the disordered motion. The associated contribution to the total width, the so-called spreading width, is the dominant one. In addition to the fragmentation into several bumps in light nuclei, *e.g.* in the *sd*-shell region [3], a pronounced fine structure is observed in heavy nuclei in recent high-resolution experiments [4, 5]. The present research focuses on the damping mechanism of the IVGDR as well as its fine structure with the scope for an extension to other types of collective modes.

The key of the present study is the measurement of the gamma-decay branching ratio of the IVGDR. The electric dipole ($E1$) reduced transition probability in the excitation process, $B(E1)\uparrow$, can be determined from the Coulomb-excitation cross section by proton scattering at zero degrees [6, 7]. The $E1$ reduced transition probability of the ground state (g.s.) gamma decay, $B(E1)\downarrow$, is related to $B(E1)\uparrow$ by the principle of detailed balance with a statistical weight of the initial and final spins [1]. $B(E1)\downarrow$ is translated into the partial width of the g.s. gamma-decay $\Gamma_{\gamma_0}$. Thus the partial width is known from the Coulomb excitation process. While from the gamma-coincidence measurement the g.s. gamma-decay branching ratio, $\frac{\Gamma_{\gamma_0}}{\Gamma}$, is determined. Here, the total width ($\Gamma$) includes all the contribution of many decay channels including the spreading width. Thus $\Gamma$ can be studied independently from the line shape of the resonance. Moreover, $\Gamma$ is determined as a function of the excitation energy across the IVGDR within the experimental resolution. The $\Gamma$ would contain the information on the characteristic width that is relevant to the fine structure of the giant resonance.

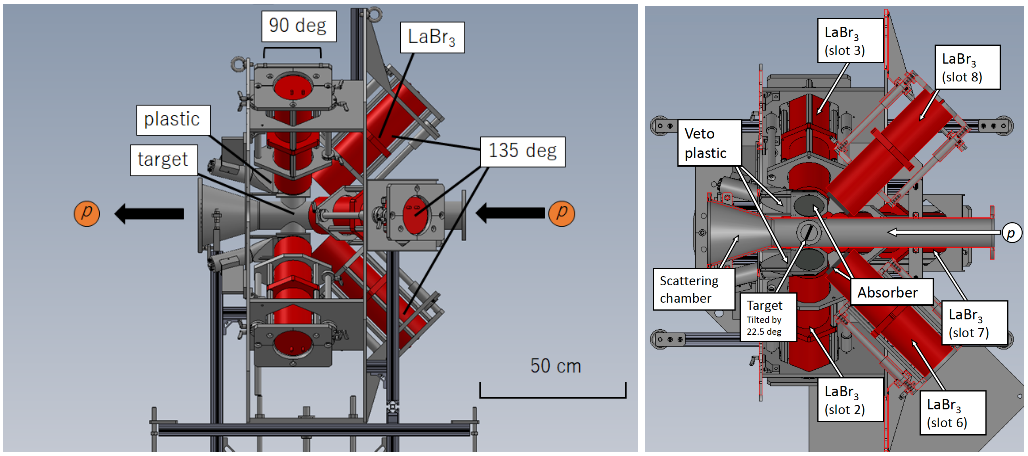

Figure 1: Side view (left panel) and top view (right) of the gamma detector array SC$\gamma$LLA constructed for E498 [12].

The primary motivation of the experiment, RCNP-E498 [10], was to study the experimental feasibility of measuring the g.s. gamma-decay from the IVGDR in $^{90}$Zr as a pilot experiment of future campaign. The Grand Raiden [8] spectrometer was placed in the zero-degree beam transmission mode [6, 9]. The proton beam energy was $E_p$=392 MeV that was suitable for Coulomb excitation covering fully the IVGDR in the energy acceptance. Eight large-volume LaBr$_3$ detectors [13, 14] (3.5"$\phi\times$8"L) were mounted in the SC$\gamma$LLA (Supporting Construction for $\gamma$ ray detecting Large volume LaBr$_3$ detector Array) setup. Four detectors were placed at 90° and the other four at 135° from the beam direction with a distance 137 and 135 mm, respectively, from the target center to the front face of the detectors. Lead (2 mm thick) and cupper (4 mm) absorber plates where placed in between the target and the detectors for reducing low energy X rays and gamma-rays as well as for stopping low-energy charged particles. A plastic scintillator with a thickness of 2 mm was placed in between the absorber and the LaBr$_3$ detector for each of the 90° detectors for excluding charged particles in the data analysis. The target vacuum chamber was made of 3 mm thick aluminum pipes (for details see [11]). It was originally facilitated for the CAGRA+GR campaign experiments and the top part was modified for E498 for optimizing the position of the target controller. The target was tilted by 22.5° from the angle perpendicular to the beam in order not to obstruct the gamma-ray detection by the target supporting materials. The main target was $^{90}$Zr with a thickness of 20 mg/cm$^2$. A $^{12}$C target (natural isotopic abundance) with a thickness of 29 mg/cm$^2$ was used for calibrating the gamma-ray energy and the detector efficiency. The typical rate of the LaBr$_3$ detectors at 90° was 70-200 kHz corresponding to the beam intensity of 1-3 nA for both targets while it was 50-100 kHz for the case of a blank-frame target and 20 kHz when the beam was off. The signal from the PMT of each LaBr$_3$ detector was shaped, divided, and discriminated by a LaBr$_3$-pro module, developed by the Milano group. The analogue signals were digitized by Mesitec MADC32 ADCs, and the timing signals by CAEN V1190A TDCs. The details of the experiment are reported in [12].

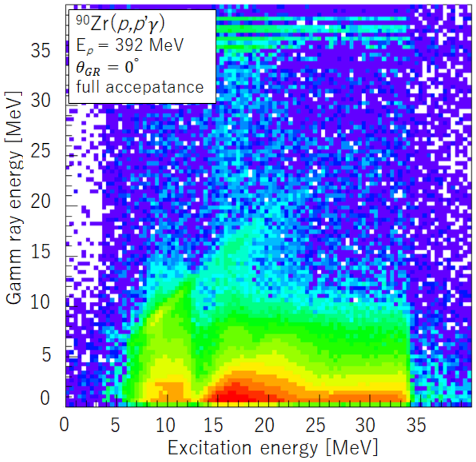

Figure 2: Coincidence matrix between the excitation energy determined by the Grand Raiden spectrometer and the energy deposit in the LaBr$_3$ detectors [12]. The data above 32 MeV in the vertical axis saturated due to the upper limit of the electronics.

The data analysis is still in a preliminary stage. A coincidence matrix between the excitation energy determined by the Grand Raiden spectrometer and the energy deposit in the LaBr$_3$ detectors is plotted in Fig. 2. Random coincidence events were subtracted by using the timing difference between GR and SC$\gamma$LLA. The g.s. gamma decays were successfully observed including the GDR region of 10-22 MeV as a diagonal line where the excitation energy and the detected gamma-ray energy coincide to each other within the experimental resolution.

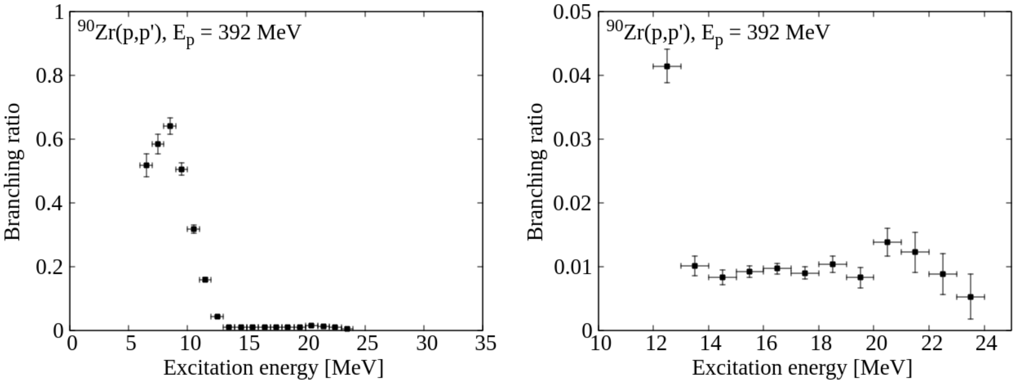

Figure 3: The g.s. gamma-decay branching ratio as a function of the excitation energy with two different vertical scales (preliminary) [12].

The ground-state gamma-decay branching ratio is plotted as a function of the excitation energy in Fig. 3 [12]. The branching ratio decreases above 8 MeV as the excitation energy increases up to the neutron separation energy of $S_n$=11.97 MeV due to the relative increase of the cascade gamma-decay components as well as the opening of the proton decay channel at $S_p$=8.35 MeV. Above ($S_n$), the branching ratio quickly decreases to 1%

due to the dominance of the neutron decay. It has been found that the branching ratio in the GDR region is almost flat. A slight enhancement observed at $E_x$=20-22 MeV is interpreted as the contribution of the isospin-upper ($T = 6$) GDR, the neutron decay of which to the low-lying $^{89}$Zr states is forbidden by the isospin-selection rule. Further discussion on the decay width and the fine structure of the IVGDR is in progress.

In summary the pilot experiment E498 has successfully shown the feasibility of the gamma-decay coincidence measurement in the energy range of 10-20 MeV with a branching ratio of the order of 1% or smaller. A proposal for a campaign experiment with the GR+SC$\gamma$LLA setup is under preparation.

## References

[1] M.N. Harakeh and A. von der Wood, *Giant Resonaces: Fundamental High-Frequency Modes of Nuclear Excitation* (Oxford University Press, New York, 2001).

[2] P.F. Bortignon, A. Bracco and R.A. Broglia, *Giant Resonances, Nuclear Structure at Finite Temperature* (Harwood Academic Publishers, Amsterdam, 1998).

[3] R. W. Fearick *et al.*, Phy. Rev. C **97**, 044325 (2018).

[4] A. Tamii *et al.*, Phys. Rev. Lett. **107**, 062502 (2011).

[5] C. Iwamoto *et al.*, Rev. Lett. **108**, 262501 (2012).

[6] P. von Neumann-Cosel and A. Tamii, a review paper submitted to Euro. Phys. J. A. (2019); arXiv:1903.11159 [nucl-ex].

[7] A. Bracco, E. Lanza and A. Tamii, Prog. in Part. and Nucl. Phys. **106**, 360 (2019).

[8] M. Fujiwara *et al.*, Nucl. Instrum. and Meth. in Phys. Res. A **422**, 484 (1999).

[9] A. Tamii *et al.*, Nucl. Instrum. and Meth. in Phys. Res. A **605**, 326 (2009).

[10] *Gamma decay from giant resonances: a pilot experiment*, experimental proposal E498 at RCNP by A. Bracco, P. von Neumann-Cosel and A. Tamii *et al.*

[11] Internal report on the CAGRA+GR campaign experiments at RCNP (2018).

[12] S. Nakamura, master thesis, Osaka University (2019), unpublished.

[13] A. Giaz *et al.*, Nucl. Instrum. and Meth. in Phys. Res. A **729**, 910 (2013).

[14] G. Gosta *et al.*, Nucl. Instrum. and Meth. in Phys. Res. A **879**, 92 (2018).