# Pre-Equilibrium Effects in the Population of Giant Dipole Resonances

S. Flibotte,[1,2] Ph. Chomaz,[3] M. Colonna,[3] M. Cromaz,[4] J. DeGraaf,[4] T. E. Drake,[4] A. Galindo-Uribarri,[2]
V. P. Janzen,[2] J. Jonkman,[1] S. W. Marshall,[1] S. M. Mullins,[1] J. M. Nieminen,[1] D. C. Radford,[2]
J. L. Rodriguez,[1] J. C. Waddington,[1] D. Ward,[2] and J. N. Wilson[1]
[1]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*
[2]*AECL, Chalk River Laboratories, Chalk River, Ontario, Canada K0J 1J0*
[3]*GANIL, B.P. 5027, F-14021 Caen Cedex, France*
[4]*Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7*
(Received 1 June 1995)

High-energy $\gamma$ rays associated with the decay of the giant dipole resonance have been measured for two fusion reactions leading to the $^{140}$Sm compound nucleus at an excitation energy of 71 MeV. The observed yield increases with the asymmetry in the ratios of the number of neutrons to protons in the entrance channel. This is interpreted as resulting from giant dipole phonons excited at the moment of collision in an $N/Z$ asymmetric reaction. [S0031-9007(96)00937-4]

PACS numbers: 24.30.Cz, 25.70.Gh

The discovery [1] that giant dipole resonances (GDR) can be excited in hot rotating nuclei formed in fusion reactions has opened a rich field of investigation [2]. During the last decade, the GDR has been used as a probe to study the evolution and fluctuations of the nuclear shape as a function of temperature and angular momentum. Furthermore, it has been recently shown that the GDR decay can be affected by the reaction dynamics of heavy-ion collisions [3]. In a very simple model, giant dipole resonances can be considered as vibrations of a fluid composed of $Z$ protons against a fluid composed of $N$ neutrons [4,5]. This suggests that giant dipole phonons could be excited at the moment of the collision between heavy ions having different $N/Z$ ratios. Therefore, pre-equilibrium effects might be observed by studying GDR decays from the same compound nucleus populated via fusion reactions with different $N/Z$ asymmetries in the entrance channel. Microscopic calculations of reaction dynamics have recently predicted such pre-equilibrium effects [6].

In order to search for these pre-equilibrium effects, we have populated the $^{140}$Sm compound nucleus via the reactions $^{36}$S + $^{104}$Pd and $^{40}$Ca + $^{100}$Mo at bombarding energies of 160 and 170 MeV, respectively. These reactions were selected because they lead to the same composite system with quite different $N/Z$ asymmetries in the entrance channel, i.e., the S+Pd reaction is $N/Z$ symmetric ($N/Z = 1.25$ and 1.26) while the Ca+Mo reaction has a large $N/Z$ asymmetry ($N/Z = 100$ and 1.38). Furthermore, there is only a small difference in the mass asymmetry in the entrance channel between these reactions. Since both systems are located above the critical curve in the fissility–mass-asymmetry plane [7], the dynamical effects associated with mass asymmetry [3] in the entrance channel should be small. The shape of the GDR resonance is expected to be similar for the two reactions and an enhancement is predicted in the Ca+Mo case. Both reactions produced the compound system at an excitation energy of 71 MeV. Although the calculated maximum angular momentum $l_{\max}$ is $45\hbar$ and $60\hbar$ for the Ca- and S-induced reactions, respectively, it is possible to select similar angular momentum distributions in the off-line analysis. The self-supported $^{104}$Pd target consisted of a stack of two foils each of 0.6 mg/cm$^2$ thickness. The $^{100}$Mo target was a single foil of 1.4 mg/cm$^2$. The heavy-ion beams were provided by the MP Tandem from the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at the Chalk River Laboratories. Emitted $\gamma$ rays were detected with the $8\pi$ spectrometer [8,9] which comprises a spherical calorimeter of 71 bismuth germanate (BGO) scintillator surrounded by an array of 20 Compton-suppressed HPGe detectors. The high-energy $\gamma$ rays associated with the GDR decay were observed in the individual BGO elements and the germanium detectors were used to measure discrete $\gamma$ rays emitted by evaporation residues. The $\gamma$-ray detectors were energy calibrated with $^{88}$Y (0.898 and 1.836 MeV) and Pu-Be (4.439 MeV) $\gamma$ sources. The energy calibration of the BGO detectors was monitored in beam by measuring the 10.20 MeV $\gamma$ ray following the capture of thermalized neutrons by $^{73}$Ge [10]. The trigger to record an event on tape required that at least one Compton-suppressed HPGe detector and six BGO elements responded. In the $8\pi$ spectrometer, the BGO detectors are located at 11.0 cm from the target and their time resolution is not good enough ($\sim$8 ns) [11] to completely discriminate between the neutron-induced events and the $\gamma$ rays by a time-of-flight technique. However, the neutron contamination in the $\gamma$-ray spectra has been minimized in the off-line analysis by selecting a relatively narrow time window and by the selection of only the BGO elements in the backward hemisphere of the $8\pi$. An important aspect of the analysis was that angular momentum ranges in the compound system could be selected by imposing conditions on the number of BGO elements that fired, $K$. We have limited the data analysis to relatively low $K$ values to insure that the same angular momentum regions were selected in both reactions.

The measured $\gamma$-ray spectra associated with the conditions $7 \leq K \leq 17$ are presented in Fig. 1 for both reactions. This BGO-multiplicity window corresponds approximately to the spin range $13\hbar \leq I \leq 31\hbar$. These $\gamma$-ray spectra were generated by selecting BGO events gated by a 12 ns wide time window favoring prompt events and thus $\gamma$ rays over neutrons. Figure 1 clearly shows an increase of $\gamma$-ray intensity in the GDR energy region from the S- to the Ca-induced reaction. In order to enhance the GDR structure, these $\gamma$-ray spectra can be linearized by dividing them by a theoretical spectrum calculated with the computer program CASCADE [12] with a constant $E1$ strength function taking into account the response of the BGO detectors with the GEANT [13] subroutine package. Such linearized spectra are presented in Fig. 2. A definite enhancement is observed in the GDR energy region for the reaction having a strong $N/Z$ asymmetry in the entrance channel. More precisely, the $\gamma$-ray intensity integrated between 8 and 18 MeV in the linearized spectra increases by $\sim$16% from the S- to the Ca-induced reaction. The same enhancement was obtained when discrete $\gamma$ rays associated with evaporation residues were observed in the HPGe detectors in coincidence with the GDR photons. This proves that the enhancement is not due to target contaminations, or associated with a difference in the fission or deep inelastic cross sections between both reactions.

We have investigated the effects of the experimental uncertainties in the excitation energy and angular momentum of the compound nucleus. First, since the S-induced reaction can populate higher angular momenta in the compound system, it is expected that its angular momentum distribution associated with our $K$ window contains higher partial waves than that of the Ca-induced reaction. The difference in the spin distributions can be inferred from the measured relative intensity of discrete $\gamma$ rays observed by the HPGe detectors. The ratio of intensities measured for $\gamma$ rays associated with three- and four-particle channels suggests that our $K$ window contains higher angular momenta in the S-induced reaction. However, as shown in Fig. 3, the HPGe spectra are virtually identical for both reactions when a reduced window $7 \leq K \leq 14$ is used for the S-induced reaction. For example, the ratios of the intensity associated with the 285 and 337 keV $\gamma$ rays belonging to $p3n$ and $p2n$ evaporation channels are identical within an accuracy better that 0.5%. This strongly suggests that the window $7 \leq K \leq 14$ for the S-induced reaction is associated with an angular momentum distribution very similar to that associated with the window $7 \leq K \leq 17$ for the Ca-induced reaction. It should be noted that this reduced $K$ window was found by minimizing the $\chi^2$ between the HPGe spectra associated with the two reactions. The GDR spectra have been analyzed with these new $K$ conditions and the same result was found for the enhancement factor. Therefore, the enhancement of the GDR strength is not related to the experimental uncertainty in the selection of the angular momentum in the entrance channel.

The uncertainty in the excitation energy is dominated by the uncertainty in the energy loss by the projectiles in the targets. In order to investigate the effect of this

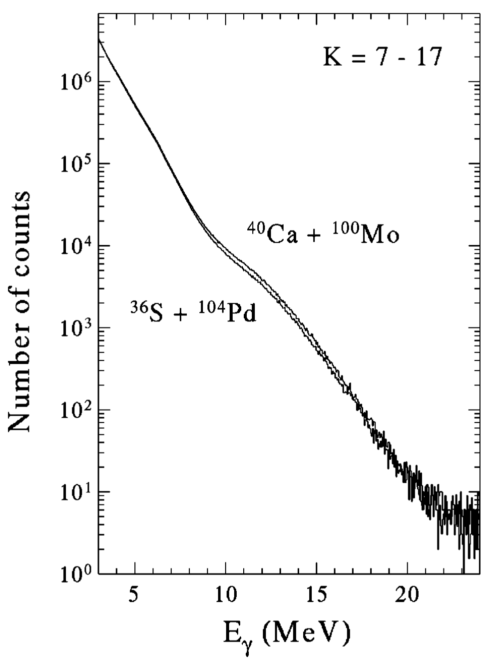


FIG. 1. Measured $\gamma$-ray spectra associated with the reactions $^{36}S + ^{104}Pd$ and $^{40}Ca + ^{100}Mo$ at bombarding energies of 160 and 170 MeV, respectively. The analysis was restricted to events having a BGO multiplicity $K$ between 7 and 17. These spectra were normalized in intensity between 3.0 and 3.5 MeV.

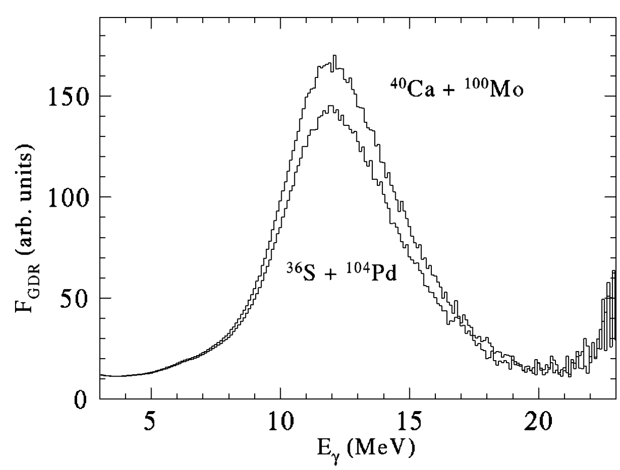


FIG. 2. Linearized plot of the experimental $\gamma$-ray spectra for the S- and Ca-induced reactions. The spectra were normalized in intensity between 3 and 4 MeV. The analysis was restricted to events having a BGO multiplicity $K$ between 7 and 17.

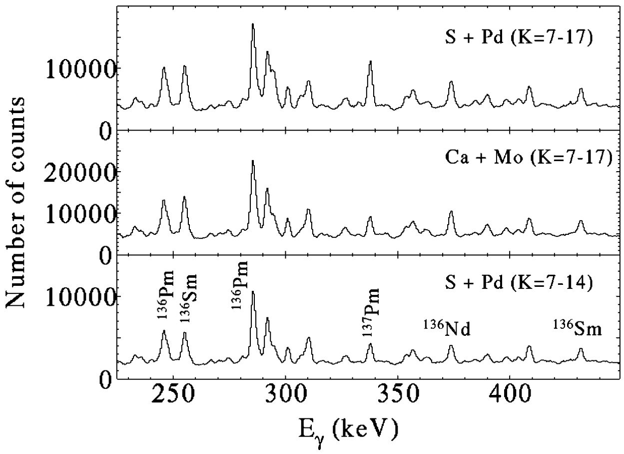


FIG. 3. Partial $\gamma$-ray spectra measured by the HPGe detectors for the S- and Ca-induced reactions. The selected BGO-multiplicity ($K$) windows are indicated and strong $\gamma$ rays emitted by the evaporation residues are labeled.

uncertainty, we reduced the energy of the Ca beam to 168 MeV without changing the target. With this new bombarding energy, both reactions produced the compound system at the same excitation energy for a fusion occurring at the entrance of the target, i.e., if the energy loss was neglected. The analysis of the GDR spectrum for this new bombarding energy gives nearly the same enhancement factor as before. More precisely, the intensity of the GDR peak in the linearized spectrum was reduced by 1% when comparing the Ca-induced reaction at bombarding energies of 170 and 168 MeV. This is in excellent agreement with the intensity reduction predicted by the statistical code CASCADE for fusion reactions occurring at the center of the target.

We have also investigated the effect of the neutron-induced background in the BGO detectors. The neutron-induced background associated with the thermalized neutrons is negligibly small for the selected time window. In fusion reactions, the relative cross section of the various evaporation residues is very sensitive to the initial excitation energy and angular momentum distribution. The $\gamma$-ray spectra presented in Fig. 3 show that it was possible to select the same excitation energy and angular momenta for both reactions. In other words, for the new set of $K$ windows the average number of fast neutrons was identical for both reactions. The analysis of $\gamma$-ray spectra measured with BGO detectors located at backward and forward angles showed that the small difference in the center-of-mass velocity produces only a negligible effect in the enhancement factor. Furthermore, a recent study showed [14] that the neutron contamination plays a minor role in our GDR spectra when comparing two reactions producing the same compound nucleus, even for systems presenting a large difference in their center-of-mass velocities.

The presence of a neutron-induced background at low energy in the BGO spectra could affect our normalization procedure. We have investigated various normalization procedures in order to eliminate this possible bias. For example, it is possible to normalize the BGO spectra on the total number of events in a given $K$ window. The application of this alternative normalization procedure revealed an enhancement factor of 15% between the GDR intensities measured for the Ca- and S-induced reactions, which is very close to the value of 16% following the previous analysis. In the $8\pi$ spectrometer, the HPGe detectors are located at four different angles with respect to the beam axis ($\pm 37°$, $\pm 79°$). The enhancement factor was found to be independent of the angle of the HPGe detectors used for the normalization. It should be noted that a normalization on discrete lines would give the same result, provided that the reduced $K$ window is used for the S-induced reaction. We therefore conclude that the enhancement of the GDR intensity is a pre-equilibrium entrance-channel effect.

Let us discuss the role of pre-equilibrium effects in the emission of GDR photons, from a theoretical point of view. We will follow the formalism of Refs. [15,16]: We consider a GDR phonon gas coupled to a phononless compound nucleus. The phonons are excited with a rate $\lambda$ and they decay with a rate $\mu$. The compound nuclei may also decay, with a rate $\gamma_{\mathrm{ev}}$, because of the evaporation of nucleons or other particles. It is easy to derive (see Refs. [6,15] for more details) that the probability that the system remains in the initial compound nucleus, and the total number of GDR phonons excited in the system, evolve according to the equations

$$\frac{dP(t)}{dt} = -\gamma_{\mathrm{ev}} P(t) \tag{1}$$

and

$$\frac{dn_{\mathrm{GDR}}}{dt} = -(\mu - \lambda) n_{\mathrm{GDR}} + \lambda , \tag{2}$$

respectively.

It should be noted that in this approach only the first step of the cascade is considered and so it can be affected by the pre-equilibrium effects. Therefore, we obtain

$$P(t) = P(0) e^{-\gamma_{\mathrm{ev}} t}, \tag{3}$$

$$n_{\mathrm{GDR}}(t) = \frac{\lambda}{\mu}\left[1 - \left(1 - n_{\mathrm{GDR}}(0)\frac{\mu}{\lambda}\right)e^{-\mu t}\right]. \tag{4}$$

The quantity $n_{\mathrm{GDR}}(0)$ is the number of phonons present in the initial conditions at the formation of the compound nucleus, and therefore is intimately related to the presence of pre-equilibrium effects. We note that $n_{\mathrm{GDR}}(t)$ tends to reach the statistical equilibrium, $n_{\mathrm{GDR}}(t_{\mathrm{eq}}) = \lambda/\mu \approx e^{-E_{\mathrm{GDR}}/T}$, $T$ being the temperature and $E_{\mathrm{GDR}}$ the energy associated with the GDR peak.

Since we are interested in the photon production, let us compute the $\gamma$-decay probability $P_\gamma = \int_0^\infty dt \gamma_\gamma \times P(t) n_{\mathrm{GDR}}(t)$, where $\gamma_\gamma$ is the partial width for photon emission. The integral gives

$$P_\gamma = \frac{\gamma_\gamma}{\gamma_{\mathrm{ev}}} \frac{\lambda}{\mu} + \left( n_{\mathrm{GDR}}(0) - \frac{\lambda}{\mu} \right) \frac{\gamma_\gamma}{\mu + \gamma_{\mathrm{ev}}} = P_{\gamma,\mathrm{eq}} + \Delta P_\gamma \,, \tag{5}$$

where the first term represents the equilibrium contribution, while the second term comes from pre-equilibrium effects. Starting from this equation, it is possible to write the ratio between the $\gamma$ production due to pre-equilibrium effects and the equilibrium value as follows:

$$\frac{\sum_\epsilon \Delta P_\gamma^\epsilon}{\sum_\epsilon P_{\gamma,\mathrm{eq}}^\epsilon} \approx \frac{1}{3} \frac{\sum_\epsilon n_{\mathrm{GDR}}^\epsilon(0)}{\mu} \gamma_{\mathrm{ev}} \frac{\mu}{\lambda} \,, \tag{6}$$

where the sum runs over the three polarizations $\epsilon = \pm 1, 0$. This ratio must be understood as the increase of the first chance $\gamma$ rays in comparison with the statistical model predictions. For the reactions studied in the present Letter, we have used the values $\mu = 4.8$ MeV, $T = 2.1$ MeV, and $\gamma_{\mathrm{ev}} \approx 0.03$ MeV.

The important difference between the two reactions considered is that in the asymmetric case (Ca+Mo), it is possible to obtain a value for the number of pre-equilibrium GDR phonons, $n_{\mathrm{GDR}}(0)$, which is different from zero. To investigate this effect, we have performed calculations of the Boltzmann-Uehling-Uhlenbeck type [17] for both reactions. In order to wash out the various fluctuations and focus only on entrance-channel effects, we have considered a set of ten events for each reaction and calculated the average of the dipole moments. No dipole excitation was found in the S+Pd reaction. However, in the case of the reaction Ca+Mo, if we consider the dipole moment along the beam axis $D_z = \bar{z}_Z - \bar{z}_N$ (where $\bar{z}_Z$ and $\bar{z}_N$ represent the coordinates of the center of mass of the protons and of the neutrons along the beam axis, respectively) it is possible to observe a dipole oscillation associated with a maximum elongation of $d \approx 0.14$ fm. This elongation is related to the number of excited phonons by the expression

$$n_{\mathrm{GDR}} = d^2 \frac{M E_{\mathrm{GDR}}}{2\hbar^2} \,, \tag{7}$$

where $M = ZN/(Z + N)m$ is the reduced mass of the neutron-proton system, $m$ being the nucleon mass. We therefore get a number of pre-equilibrium phonons $n_{\mathrm{GDR}} = 0.14$. If we now introduce this number in Eq. (6), we obtain finally $\Delta P_\gamma / P_{\gamma,\mathrm{eq}} \approx 0.78 = 78\%$. As previously discussed, this is the additional number of photons emitted by the initial compound nucleus, divided by its statistical decay rate. Calculations performed with the code CASCADE indicate that, in order to reproduce the experimental overall increase of about 16% over the full cascade, the number of statistical photons coming from the initial compound nucleus must be increased by about 100%. This is in good agreement with our theoretical prediction of ~78%.

In summary, $\gamma$ rays associated with the GDR decay have been measured for two fusion reactions leading to the same compound nucleus. Pre-equilibrium effects related to the $N/Z$ asymmetry in the entrance channel have been observed for the first time.

This work has been partially funded by the Natural Sciences and Engineering Research Council of Canada and Atomic Energy of Canada Limited. One of the authors (S.F.) wishes to thank Professor J. Barrette for a stimulating discussion.

[1] J. O. Newton *et al.*, Phys. Rev. Lett. **46**, 1383 (1981).
[2] J. J. Gaardhoje, Annu. Rev. Nucl. Part. Sci. **42**, 483 (1992), and references therein.
[3] M. Thoennessen *et al.*, Phys. Rev. Lett. **70**, 4055 (1993).
[4] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).
[5] Von Helmut Steinwedel and J. Hans D. Jensen, Z. Naturforsch. **5A**, 413 (1950).
[6] Ph. Chomaz *et al.*, Nucl. Phys. **A563**, 509 (1993).
[7] W. J. Swiatecki, Phys. Scr. **24**, 113 (1981).
[8] J. P. Martin *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **257**, 301 (1987).
[9] H. R. Andrews *et al.*, Report No. AECL-8329, 1984.
[10] W. Królas *et al.*, Z. Phys. A **344**, 145 (1992).
[11] J. P. Martin *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **270**, 101 (1988).
[12] F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977).
[13] R. Brun *et al.*, GEANT3 users guide, Report No. CERN DD/EE/84-1, 1985.
[14] S. Flibotte *et al.*, Phys. Rev. C **53**, R533 (1996).
[15] Ph. Chomaz, in *Proceedings of the 6th Franco-Japanese Colloquium, St. Malo, France, 1992*, edited by N. Alamanos, S. Fortier, and F. Dykstra (Commissariat a L'Energie Atomique, Saclay, France, 1993), p. 19.
[16] D. M. Brink, Nucl. Phys. **A519**, 3c (1990).
[17] M. Colonna *et al.*, Nucl. Phys. **A541**, 295 (1992).