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Excitation and Decay of Two-Phonon Giant Dipole Resonances *

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In heavy ion collisions at near relativistic energies, electromagnetic excitation of the double giant dipole resonance occurs with large cross sections. We summarize the presently available experimental data and discuss related theoretical efforts. Emphasis is paid to the question of anharmonicities and to the damping of the two-phonon states.

1. Introduction

After discovery about one decade ago, the investigation of multiphonon giant resonances is of continued interest. Like their building blocks, the single-phonon giant resonances, multiphonon giant resonances are understood in terms of quantized collective vibrations of the nuclear system. The main question behind a study of their properties is: how large are the phonon-phonon interaction and the anharmonicity, that is, the deviation from the picture of harmonic boson-type excitations of a finite fermion system, such as the atomic nucleus. Anharmonicities may manifest themselves in the spectral distribution of multiphonon giant resonances, in their excitation probabilities in specific reactions, or in their decay properties. This contribution focuses on the double giant dipole resonance, excited in heavy ion collisions at near relativistic bombarding energies. Related aspects are discussed in a number of other contributions to this conference, we also refer to a very recent review of the subject [1]. Here, we first present a brief summary of experimental results. Then, we discuss in more detail two specific aspects, addressing the enhancement observed for electromagnetic cross sections together with theoretical attempts of an interpretation in terms of anharmonicities, and addressing the damping of the double-phonon states.

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2. Experimental Results

A number of measurements exploring the double-phonon giant dipole resonance (DGDR) has been performed at the heavy ion synchrotron SIS at GSI, Darmstadt. Experiments are of inclusive or exclusive type. Both rely on the electromagnetic excitation of the DGDR in peripheral heavy ion collisions at bombarding energies around 500 - 1000 MeV/u. In such reactions, cross sections of the order of barns for the single giant dipole resonance (GDR) and of several hundreds of millibarns for the DGDR are observed, owing to the interaction with the Lorentz contracted (transversal) electromagnetic field imposed by the high nuclear charge of the reaction partner. In heavy nuclei, both GDR and DGDR, decay predominantly by neutron emission, the number of neutrons being determined by the excitation energy. Thus, the cross section for observation of certain neutron-removal product nuclei bears information on the (D)GDR excitation cross sections, being utilized in the inclusive experiments. Inclusive experiments have been performed by Aumann and collaborators for $^{197}$Au [2] and $^{238}$U [3]. In the latter case, the competing fission decay channel has to be taken into account in the analysis (see [3] for details). This process of Coulomb fission was as well subject to dedicated studies carried out by Armbruster et al. [4] and Rubenh et al. [5]. Inclusive measurements, however, cannot deliver details of the strength distributions of the DGDR.

Figure 1. Differential cross sections $d\sigma/dE^*$ for electromagnetic excitation of $^{208}$Pb at 640 MeV/u on a Pb target. Top: Calculation using known parameters for single giant dipole resonance (dashed curve) and isoscalar plus isovector quadrupole excitations (dotted curve). The cross section for the double GDR indicated by the dot-dashed curve results from a fit to the data (see text). Middle: Experimental cross section $d\sigma/dE^*$ for the Pb target compared to the calculation (solid line) shown above after applying the experimental filter. Bottom: same as in the middle panel but for the Sn target. Adapted from [7].

Spectral distributions can be obtained from exclusive studies as performed by our LAND collaboration for $^{136}$Xe [6] and, more recently, for the doubly magic $^{208}$Pb [7]. The excitation energy distribution is obtained from an invariant-mass analysis, which involves the measurement of fragment and neutron momenta as well as of $\gamma$-rays emitted from fragments. The experimental setup comprises a large-gap dipole magnet and heavy ion counters for fragment identification, a large-area neutron detector (LAND), and a $\gamma$-
Figure 2. Comparison of experimental quantities $X$ for the two-phonon giant dipole resonance in $^{208}$Pb with those ($X^{\text{harm.}}$) obtained in the independent phonon model. Results for the resonance peak energy $E_0$, width $\Gamma$, and the electromagnetic cross section $\sigma$ are from [7,8]. The value for the spreading width $\Gamma^\dagger$ is derived in Section 4. The values $X^{\text{harm.}}$ are obtained from the experimentally known properties of the single giant dipole resonance.

detector of high granularity such as the Darmstadt-Heidelberg NaI Crystal Ball. Each of the systems is of high detection efficiency and subtends almost completely the relevant solid angle (for details see [7]). Examples of excitation energy spectra for $^{208}$Pb are shown in Fig. 1. The spectra are compared with cross sections calculated in semi-classical approximation for one-phonon dipole and quadrupole giant resonances, which match the spectra (after applying the experimental response) perfectly for excitation energies below about 22 MeV. The excess cross section found at higher energies is attributed to the DGDR in $^{208}$Pb. This assignment could be verified on the basis of the characteristic $Z$ dependence, $Z$ denoting the nuclear charge of the target, which was measured with targets in a range $50 \leq Z \leq 92$. The observed $Z$ dependence was found to be in accord with that for the expected electromagnetic two-step excitation mechanism, and to be significantly different from that of one-step excitations of the single-phonon states. The parameters deduced from such spectra for the DGDR in $^{208}$Pb are shown in Fig. 2 in comparison with those obtained in the independent-(harmonic-)phonon model. It is noticed that the DGDR peak energy coincides within errors with the harmonic value, while both, the cross section and the width deviate. A similar experiment of the LAND collaboration for the deformed nucleus $^{238}$U as well as a re-examination of $^{136}$Xe is presently being analyzed.

A summary of experimental data, including such from pion double charge exchange reactions [9] and for the double giant quadrupole resonance [10], is presented in Fig. 3, taken from a recent review of multi-phonon giant resonances by Aumann, Bortignon and Emling [1], to which we refer for further details. As in the specific case of $^{208}$Pb (Fig. 2), it is noticed that the width and the electromagnetic cross sections tend to deviate from the pure harmonic picture. The DGDR width, on the average, is smaller than expected. The cross sections are larger than calculated in the harmonic limit, the deviation becoming more pronounced with decreasing mass. These two effects and their implications will be discussed in the subsequent chapters.

3. Cross Section Enhancement and Anharmonicity

In the case of the electromagnetic DGDR excitation, deviations from the harmonic limit are observed most strikingly in the measured cross sections. Anharmonicities influence
multiphonon cross sections in two ways: For example, the multiphonon excitation energies may shift downward in comparison to the harmonic values, in which case cross sections increase because the electromagnetic excitation favors low excitation energies. At the same time, as a consequence of the energy-weighted sum rule, the corresponding E1 transition matrix element increases in proportion to the decreasing excitation energy, again yielding larger cross sections. Both effects act in the same direction.

The nonlinear response of a three-dimensional quantum anharmonic oscillator was treated phenomenologically by adding a quartic term [11] or cubic and quartic terms [12] to the internal harmonic oscillator Hamiltonian. Fig. 4 shows results of Bortignon & Dasso's calculations [11] describing the anharmonic potential by a quartic term only. The figure shows excitation energies of the DGDR relative to that of the GDR, as well as electromagnetic excitation probabilities for the double-phonon states relative to the harmonic values, for a varying degree of anharmonicity. The excitation probabilities are calculated in second-order perturbation theory. Results are provided for the collision systems $^{208}$Pb (640 MeV/u) + Pb and $^{136}$Xe (700 MeV/u) + Pb, which have been investigated experimentally [7,6]. The excitation probability is evaluated for an impact parameter $b = 30$ fm, but qualitatively similar results are obtained at other impact parameters in the relevant range [11]. The shaded area on the left-hand side of Fig. 4 indicates the range of the anharmonic term that is compatible with the experimental cross section enhancement from our measurement [7] (see Fig. 2). The corresponding ratio of excitation energies is also compatible with the experimental findings. The shaded area in the case of $^{136}$Xe is obtained from that shown for $^{208}$Pb by exploiting a mass-scaling of the anharmonic term according to an $A^{-2/3}$ dependence, i.e. in proportion to the number of nucleons in the active shells. Again, the resulting values appear to be compatible with the experimental values [6] (shown in Fig. 3), both for the cross section enhancement and the DGDR peak.
energy. It should be noticed, however, that the anharmonic term also affects the energy of the single-phonon state and thus its excitation probability, since, in the spirit of the model, the eigenfrequency of the unperturbed mode is kept fixed. In a quantitative comparison with experimental cross sections, the eigenfrequency of the unperturbed mode would have to be rescaled in order to reproduce the experimental value. The calculations of Volpe et al. [12] lead to conclusions similar to those of Bortignon & Dasso [11]. In summary, calculations using a macroscopic model support the interpretation of experimental results of enhanced cross sections in terms of anharmonicities. The origin of the anharmonicities, however, must be studied in a microscopic approach.

The experimental data on double-phonon giant resonances, particularly the DGDR cross section enhancement, inspired a number of large-scale microscopic calculations. Methods such as particle-vibration coupling [13], boson mapping techniques [14], or fully microscopic calculations in a fermion space were applied [15]. Each method has its own limitations, because of either diagrammatic selections or truncations in the model space.

Figure 4. Calculations in an anharmonic oscillator model for the reaction $^{208}$Pb + $^{208}$Pb at a bombarding energy of 640 MeV/u (left), and for $^{136}$Xe + $^{208}$Pb at 700 MeV/u (right). Top: Probability for the electromagnetic excitation of the DGDR in $^{208}$Pb and $^{136}$Xe, respectively, as a function of the anharmonicity parameter B. The values are normalized to the harmonic case (B=0). Bottom: Ratio between the energy of the "two-phonon" state and twice the energy of the "one-phonon" state as a function of the anharmonicity parameter B. The full and dashed curves correspond, respectively, to the components with angular momentum $I^\pi = 2^+$ and $0^+$. See text for an explanation of the shaded areas. Adapted from Bortignon & Dasso [11].
Lanza et al. [14] (see also Lanza et al., contribution to this conference) took a boson mapping approach for the nuclei $^{40}$Ca and $^{208}$Pb. They constructed the one-phonon basis in RPA with the SGII Skyrme interactions and retained a relatively small number of the most collective phonons. Within this basis, the residual interaction was diagonalized, resulting in couplings between one- and two-phonon states and also among the two-phonon states. The former couplings are of the order of a few hundred keV, the latter ones about one order of magnitude smaller. Due to their coupling, the various double-phonon states have two paths to be excited in one step, via either their one- or their two-phonon components, in addition to the two-step processes. Electromagnetic cross sections were computed taking into account interferences along the various paths. The authors derived that the phonon-phonon couplings increase by 10% the electromagnetic DGDR cross section in the system $^{208}$Pb (640 MeV/u) + Pb. If, in addition, the cross sections of all states in the vicinity of the DGDR (above 22 MeV excitation energy) are summed up, a cross section of 310 mb was obtained, close to our experimental result of 380 ± 40 mb.

Ponomarev et al. [13] considered coupled one- and two-phonon states for $^{136}$Xe, but in a much larger basis than the one discussed above for $^{208}$Pb. The authors calculated electromagnetic cross sections for the collisional system $^{136}$Xe (700 MeV/u) + Pb, but they could not reproduce the experimental DGDR cross section [6], which exceeds that in the harmonic limit by a factor of about 2.5 ± 0.6 (see Fig. 3). The calculation took only two-step transitions into account, neglecting one-step transitions of the type discussed above for $^{208}$Pb and also neglecting transitions between configurations of two-phonon character. For a further discussion, see Ponomarev, contribution to this conference.

4. Width and Damping of the DGDR

Microscopic calculations, such as addressed above, in general predict small anharmonicities. Typically, shifts of the DGDR peak energies with respect to the harmonic value and, likewise, the splitting of the $I^* = 0^+, 2^+$ components are found of the order of a few hundred keV at most. At present, experimental data are not precise enough to determine such small shifts. Larger effects, however, are observed experimentally for the apparent width $\Gamma$ of the two-phonon states. In a simple minded picture of two coexisting, non-interacting phonons, the width of the DGDR, no matter whether it arises from decay or from collisional damping, should be twice that of the one-phonon state. As seen in Figs. 2 and 3, the experimental data, on the average, are below this value. Ponomarev et al. [16] made an important step concerning the intrinsic two-phonon structure by diagonalizing the particle-vibration coupling Hamiltonian by including three-phonon states. For $^{136}$Xe, the three-phonon states, more than 5000 in number, were built from phonons of angular momenta up to $I^* = 4^+$, neglecting phonons carrying small fractions of strength. The two-phonon coupling to the 3p-3h doorway states is considered to be most efficient in breaking the coherent state and should account for most of the spreading width $\Gamma^1$. Thus, at present, this calculation is the most realistic one in describing the width of two-phonon states in comparison to the one-phonon states. In fact, from the calculated strength distributions, single and double GDR widths of 4.7 MeV and 6.8 MeV were obtained, in excellent agreement with the experimental values for $^{136}$Xe of 4.8 MeV and 6.3 ± 1.6 MeV [6], respectively.
Experimentally, aside from the apparent width of the strength distribution, the spreading width itself can be determined independently as outlined in [1]. This requires experimental information of the direct $\gamma$-decay sequence: two-phonon state → one-phonon state → ground state. Combining the $\gamma$-decay data of Ritman et al. [8] for $^{208}$Pb with our neutron decay data, we deduced the direct $2\gamma$- to neutron-decay branching ratio for the DGDR in $^{208}$Pb, amounting to $BR_{2\gamma/n}^{2\text{ph}} = (4.5 \pm 1.5) \cdot 10^{-4}$ (see [7]). This has to be contrasted with the direct gamma- to neutron-decay branching ratio of the single dipole resonance, found to be $BR_{\gamma/n}^{1\text{ph}} = (1.9 \pm 0.2) \cdot 10^{-2}$. The independent-phonon model predicts a $2\gamma$-decay branching ratio as follows:

$$BR_{2\gamma/n}^{2\text{ph}} = \frac{\Gamma_{2\text{ph}}^\gamma}{(\Gamma_1)^{2\text{ph}}} \frac{\Gamma_{1\text{ph}}^\gamma}{(\Gamma_1)^{1\text{ph}}} = 2 \cdot \frac{(\Gamma_1)^{1\text{ph}}}{(\Gamma_1)^{2\text{ph}}} \left[ \frac{\Gamma_{1\text{ph}}^\gamma}{(\Gamma_1)^{1\text{ph}}} \right]^2,$$

using $\Gamma_{2\text{ph}}^\gamma = 2 \cdot \Gamma_{1\text{ph}}^\gamma$ for the $\gamma$-decay width, which takes into account the Bose factor for identical phonons; $(\Gamma_1)^{2\text{ph}} = 2 \cdot (\Gamma_1)^{1\text{ph}}$ would be expected as well for non-interacting phonons.

Equation 1 is derived with the following reasoning: Neglecting pre-equilibrium particle emission, two competing mechanisms are at work, which destroy the coherent giant resonance states: the direct gamma decay and the damping into complex configurations. Only after damping does neutron decay occur. Neutron decay of the thermalized state proceeds at a much slower rate than both gamma decay and damping, as can be verified by a statistical model calculation. Thus, the branching ratios $BR_{\gamma/n}^{1\text{ph}(2\text{ph})}$ should be identical to the ratios $\frac{\Gamma_{1\text{ph}}^\gamma}{(\Gamma_1)^{1\text{ph}}}$ and $\frac{\Gamma_{2\text{ph}}^\gamma}{(\Gamma_1)^{2\text{ph}}}$ for one- and two-phonon states, respectively.

We may thus use Equation 1 to obtain an independent estimate of the relative spreading width $(\Gamma_1)^{2\text{ph}}/(\Gamma_1)^{1\text{ph}}$, using the experimental values of the gamma-decay branches of the single and double giant resonances. Two effects, however, must be taken into consideration: First, a cross section enhanced by a factor $1.33 \pm 0.16$ was observed experimentally for the double-phonon state, and consequently, $\Gamma_{2\text{ph}}^\gamma$ has to be increased by this amount. Second, statistical decay may also contribute to gamma transitions into the ground state; the statistical component contributes about 20–30% to the gamma decay in the case of the $^{208}$Pb dipole resonance [17]. These two effects practically cancel each other. For the DGDR, we find that statistical contributions to the direct $\gamma$ decay can be neglected because of the increased level densities at the higher excitation energies. By taking these correction factors into account, we obtain from Equation 1 an independent result for the relative spreading width $(\Gamma_1)^{2\text{ph}}/(\Gamma_1)^{1\text{ph}} = 1.6 \pm 0.5$. This value is included in Fig. 2. It agrees well with the value obtained from the apparent width of the strength distributions. Both together indicate a somewhat reduced spreading width in the two-phonon state in comparison to the independent-phonon model, which requires $^2(\Gamma_1)^{2\text{ph}}/(\Gamma_1)^{1\text{ph}} = 2$.

\footnote{An estimate of the relative spreading width $(\Gamma_1)^{2\text{ph}}/(\Gamma_1)^{1\text{ph}} \approx \sqrt{2}$ was recently derived [18] for a harmonic oscillator with dissipative coupling. See also [19].}
5. CONCLUDING REMARKS

From these latter findings for the DGDR (spreading) width, in particular, it appears that, although located at much higher excitation energies than single-phonon states, and thus being embedded in a continuum of uncorrelated nuclear states of much increased level density, the double-phonon giant resonances retain a remarkable stability against decay into incoherent particle motion.

A description of double-phonon excitations in various reactions in terms of a sequential two-step process, treating the excitation of each of the phonons on the same footing, also turned out to account qualitatively for the observed cross sections. Discrepancies, however, between measured and calculated cross sections cannot be ignored; they are found in pion double charge exchange and heavy-ion reactions. Macroscopic models, based on an anharmonic ansatz for the nuclear response, indicate that the deviations may be explained by invoking small anharmonicities. In fact, large-scale microscopic calculations reproduce nonlinear effects due to phonon-phonon interactions, which are of about the right magnitude to reproduce cross section enhancements observed for the doubly magic \(^{208}\)Pb. The degree of complexity in calculations involving many-phonon configurations in case of open-shell nuclei increases dramatically and can hardly be handled at present.

Observation of higher-order multiphonon strength is one of the main experimental goals as nonlinearities will produce more pronounced effects since, with increasing phonon number, one steps away from the small amplitude limit.

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