Two-Phonon Background for the Double Giant Resonance

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The direct excitation of a "sea" of two-phonon configurations above 15 MeV from the ground state is considered. It is concluded that these configurations form a flat physical background in photoexcitation cross sections and Coulomb excitation in heavy ion reactions at relativistic energies. The contribution of the background to the total cross section in Coulomb excitation of ^{208}Pb in the double giant dipole resonance (DGDR) energy region is about 15%. It should be considered while drawing conclusions on anharmonicity effects for the DGDR. [S0031-9007(97)04579-1]

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One of the most exciting features of the recently discovered double giant dipole resonance (DGDR) is the absolute value of its excitation cross section in relativistic heavy ion collisions. These values were extracted from total cross sections by separating a contribution arising from the excitation of the single giant dipole resonance (GDR) and of the giant quadrupole resonance (GQR) and were found to be enhanced by factors of the order of 2–3 for ^{136}Xe [1] and ^{197}Au [2] as compared to any theoretical calculations available. Although for ^{208}Pb [3] the experiment-theory correspondence is much better, an enhancement of 1.33(16) is still observed relative to the harmonic approximation.

At the present time we have an experimental proof [3] that Coulomb excitation of the DGDR in relativistic heavy ion collisions occurs in a two-step process. The DGDR states are embedded in a sea of other two-phonon states. In this paper we consider the sea contribution to the total cross sections. It will be concluded that numerous two-phonon states, other than $[\mathrm{GDR} \otimes \mathrm{GDR}]$ ones, excited in one-step processes form a physical background in the DGDR energy region which has to be taken into account in the analysis of experimental data.

The first investigation of the direct excitation of two-phonon states at high energies from the ground state was done in Refs. [4,5]. The main purpose of these papers was to look for resonance structures in photoexcitation cross sections related to the excitation of rather selected two-phonon configurations. Although in Ref. [5] it was pointed out that $[\mathrm{GDR} \otimes \mathrm{GQR}]_{1^-}$ and $[\mathrm{GDR} \otimes 2_1^+]_{1^-}$ configurations were not the only ones (among many different two-phonon $[1^- \otimes 2^+]_{1^-}$ states) to determine the total cross section, two-phonon 1^- configurations made of phonons of other multipolarities were omitted in the calculation.

While dealing with electromagnetic, or with Coulomb excitations from a 0^+ ground state, prime attention has to be paid to the final states with the total angular momentum and parity $J^\pi = 1^-$. Making use of the formalism presented in Ref. [5] we have calculated first the cross section for the photoexcitation of two-phonon states $[\lambda_1^{\pi_1} \otimes \lambda_2^{\pi_2}]_{1^-}$, where $\lambda_1^{\pi_1}$ and $\lambda_2^{\pi_2}$ are both natural λ^{π^n} $[\pi^n = (-1)^\lambda]$ and unnatural λ^{π^u} $[\pi^u = (-1)^{\lambda+1}]$ parity phonons with multipolarity λ from 0 to 9. A phonon basis is obtained by solving quasiparticle-random-phase approximation (RPA) equations for each multipolarity λ^π within the quasiparticle-phonon model (QPM) [6]. These equations provide a set of one-phonon states $\lambda^\pi(i)$ with the same spin and parity, but with different excitation energies $E(i)$ and internal fermion structure of phonons; the index i is introduced to distinguish between them.

The results of the calculation for ^{136}Xe and ^{208}Pb integrated over the energy interval from 20 to 35 MeV are presented in Table I. Each configuration $[\lambda_1^{\pi_1} \otimes \lambda_2^{\pi_2}]$ in the table means a sum over plenty of two-phonon states made of phonons with a given spin and parity $\lambda_1^{\pi_1}$, $\lambda_2^{\pi_2}$, but different RPA root numbers i_1, i_2 of its constituents

$$\sigma([\lambda_1^{\pi_1} \otimes \lambda_2^{\pi_2}]) = \sum_{i_1,i_2} \sigma([\lambda_1^{\pi_1}(i_1) \otimes \lambda_2^{\pi_2}(i_2)]) \, .$$

The total number of two-phonon 1^- states included in this calculation for each nucleus is about 10^5, and they exhaust 25% and 15% of the energy-weighted sum rule (EWSR) in ^{136}Xe and ^{208}Pb, respectively. The absolute value of the photoexcitation of any two-phonon state under consideration is negligibly small but altogether they produce a sizable cross section. Table I demonstrates that different two-phonon configurations give comparable contributions to the total cross section which decreases only for very high spins because of the lower densities of such states. As a rule, unnatural parity phonons play a less important role than natural parity ones. For these reasons we presented in the table only the sums for [natural ⊗ unnatural] and [unnatural ⊗ unnatural] two-phonon configurations.

The cross section for the photoexcitation of all two-phonon 1^- states in the energy region 20–35 MeV from the ground state equals in our calculation 511 and 423 mb for ^{136}Xe and ^{208}Pb, respectively. It is not surprising that we got a larger value for ^{136}Xe than for ^{208}Pb. This is because the phonon states in Xe are composed of a

TABLE I. Cross sections for the direct photoexcitation of different two-phonon configurations from the ground state integrated over the energy interval from 20 to 35 MeV in ^{136}Xe and ^{208}Pb. The GDR cross section integrated over the energy of its location is presented in the last line for a comparison.

Configuration	σ_γ, mb ^{136}Xe	^{208}Pb
$[0^+ \otimes 1^-]_{1^-}$	4.4	3.9
$[1^- \otimes 2^+]_{1^-}$	36.6	44.8
$[2^+ \otimes 3^-]_{1^-}$	82.8	33.1
$[3^- \otimes 4^+]_{1^-}$	101.0	56.7
$[4^+ \otimes 5^-]_{1^-}$	68.9	37.3
$[5^- \otimes 6^+]_{1^-}$	49.2	46.2
$[6^+ \otimes 7^-]_{1^-}$	31.9	49.8
$[7^- \otimes 8^+]_{1^-}$	13.6	12.5
$[8^+ \otimes 9^-]_{1^-}$	4.9	9.0
$\sum_{\lambda_1,\lambda_2=1}^{9}[\lambda_1^{\pi_1^n} \otimes \lambda_2^{\pi_2^u}]_{1^-}$	71.4	58.5
$\sum_{\lambda_1,\lambda_2=1}^{9}[\lambda_1^{\pi_1^u} \otimes \lambda_2^{\pi_2^u}]_{1^-}$	46.7	71.1
$\sum_{\lambda_1,\lambda_2=0}^{9}[\lambda_1^{\pi_1^{n,u}} \otimes \lambda_2^{\pi_2^{n,u}}]_{1^-}$	511.4	422.9
$[\mathrm{GDR} \otimes \mathrm{GDR}]_{2+}$	0.33	0.22
$\sum_{\lambda_1,\lambda_2=1}^{9}[\lambda_1^{\pi_1^n} \otimes \lambda_2^{\pi_2^n}]_{2^+}$	38.1	21.7
GDR	2006	2790

larger number of two-quasiparticle configurations due to the pairing. The same values for two-phonon states with angular momentum and parity $J^\pi = 2^+$ are an order of magnitude smaller. We point out that the direct excitation of $[1^- \otimes 1^-]_{2^+}$ or $[\mathrm{GDR} \otimes \mathrm{GDR}]_{2+}$ configurations is negligibly weak. The calculated values should be compared to the cross section for the photoexcitation of the single-phonon GDR which in our calculation equals 2006 and 2790 mb, respectively. A contribution of two-phonon 1^- states to the total cross section at GDR energies is weaker than at higher energies because of the lower density of two-phonon states and the lower excitation energy and can be neglected considering the GDR itself.

For ^{208}Pb photoexcitation cross sections are known from experimental studies in (γ, n) reactions up to the excitation energy about 25 MeV [7,8]. It was shown that QPM provides a very good description of the experimental data in the GDR region [7], while theoretical calculations at higher excitation energies which account for contributions from the single-phonon GDR and GQR$_{iv}$ essentially underestimated the experimental cross section [8]. The experimental cross sections above 17 MeV are shown in Fig. 1 together with theoretical predictions. The results of the calculations are presented as strength functions obtained with averaging parameter equal to 1 MeV. The contribution to the total cross section of the GQR$_{iv}$ (short-dashed curve), the high energy tail of GDR (long-dashed curve), and their sum (squared curve) is taken from Ref. [8]. The curve with triangles represents the contribution of the direct excitation of the two-phonon

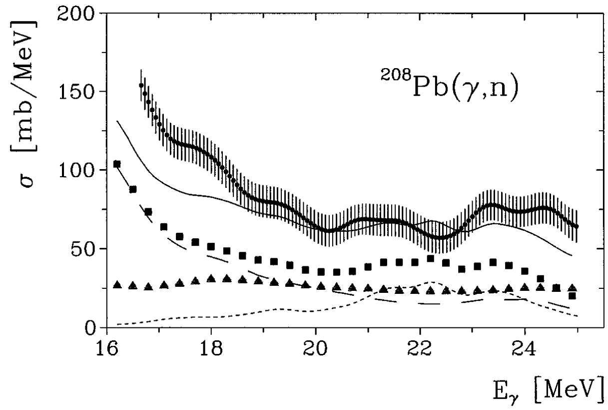

FIG. 1. Photoneutron cross section for ^{208}Pb. Experimental data (dots with experimental errors) are from Ref. [8]. The long-dashed curve is the high energy tail of the GDR, the short-dashed curve is the GQR$_{iv}$, and the curve with squares is their sum. The contribution of two-phonon states is plotted by a curve with triangles. The solid curve is the total calculated cross section.

states from our present studies. The two-phonon states form practically a flat background in the whole energy region under consideration. Summing together the photoexcitation cross sections of all one- and two-phonon states we get a solid curve which is in very good agreement with the experimental data.

From our investigation of photoexcitation cross sections we conclude that in this reaction very many different two-phonon states above the GDR contribute on a comparable level, forming altogether a flat physical background which should be taken into account in the description of experimental data. On the other hand, Coulomb excitation in relativistic heavy ion collisions provides a unique opportunity to excite a very selected number of two-phonon states by the absorption of two virtual γ's in a single process of projectile-target interaction [9]. Theoretically this process is described using the second order perturbation theory of the semiclassical approach of Winther and Alder [9,10]. Since excitation cross sections to second order are much weaker than to first order of the theory, two-phonon states connected to the ground states by two $E1$ transitions are predominately excited. These two-phonon states have the structure $[1^-(i) \otimes 1^-(i')]_{0^+,2^+}$ and form the DGDR.

To describe the properties of the DGDR in ^{208}Pb we applied the technique developed in Refs. [11,12]. Within this technique we couple two-phonon $[1^-(i) \otimes 1^-(i')]_{0^+,2^+}$ states with many three-phonon ones. Two-phonon states are built from the same six $1^-(i)$ RPA phonons as in Ref. [13] which have the largest $B(E1)$ values and exhaust 90.6% of the EWSR. Only 0^+ and 2^+ components of the DGDR were considered (see Ref. [13] for the quenching of the 1^+ component). We included in the calculation about 7000 three-phonon states which have the largest matrix elements for the interaction with the selected 21 two-phonon states. Diagonalization of the QPM Hamiltonian on the basis of these two- and three-phonon states yields a set of 0^+ (and 2^+) states; the wave function of each state includes all two- and three-phonon terms with different weights for different states. To distinguish between these states we introduce the index ν. To obtain the Coulomb excitation cross section in second order perturbation theory we also need to have the structure of the GDR as an intermediate state. For that we calculated the GDR fine structure by coupling the same six strongest one-phonon $1^-(i)$ states to about 1200 two-phonon 1^- states in the GDR region.

The cross section of the DGDR($\nu_{0^+,2^+}$) states excitation via the GDR(ν_{1^-}) states in this reaction equals

$$\sigma_{\nu_{0^+,2^+}} = \left| \sum_{\nu_{1^-}} A(E_{\nu_{1^-}}, E_{\nu_{0^+,2^+}}) \langle 1^-(\nu_{1^-}) \| E1 \| 0^+_{\mathrm{g.s.}} \rangle \times \langle [1^- \otimes 1^-](\nu_{0^+,2^+}) \| E1 \| 1^-(\nu_{1^-}) \rangle \right|^2,$$

where $A(E_1, E_2)$ is the energy dependent reaction amplitude. A straightforward calculation of the two-step process for the excitation of 7000 DGDR states via 1200 intermediate GDR states is very time consuming. Making use of a very smooth dependence of the function $A(E_1, E_2)$ on both arguments, we tabulated this function and used it in the final calculation of the DGDR Coulomb excitation cross section in relativistic heavy ion collisions. We considered the excitation of the DGDR in the projectile for a ^{208}Pb (640A MeV) $+^{208}$Pb collision, according to the experiment in Ref. [3], and used the minimum value of the impact parameter, $b = 15.54$ fm, corresponding to the parametrization of Ref. [14].

The cross section for Coulomb excitation of the DGDR is presented in Fig. 2 by the short-dashed curve as a strength function calculated with an averaging parameter equal to 1 MeV. The width of the DGDR for ^{208}Pb is very close to $\sqrt{2}$ times the width of the single GDR, which comes out naturally as a result of a folding of two independent phonons [15]. The contribution of the background of the two-phonon 1^- states to the total cross section is shown by a long-dashed curve in the same figure. It was calculated in first order perturbation theory. The role of the background in this reaction is much less important than in photoexcitation studies. First, it is because in heavy ion collisions we have a special mechanism to excite selected two-phonon states in the two-step process. Second, the Coulomb excitation amplitude is exponentially decreasing with the excitation energy, while the $E1$ photoexcitation amplitude is linearly increasing. Nonetheless, Fig. 2 shows that the direct excitation of two-phonon 1^- states cannot be completely excluded from consideration of this reaction. Integrated over the energy interval from 20 to 35 MeV these states give a cross section of 50.3 mb which should be compared to the experimental cross section in the DGDR region for the ^{208}Pb (640A MeV) $+^{208}$Pb reaction which is equal to 380 mb [3]. Appreciable values of one-step processes in DGDR excitation is not in contradiction with experimental findings. It is known that Coulomb excitation of a projectile in an n-step process has the following dependence on the target charge: $Z_T^{n(2-\delta)}$. The reported value $n = 1.8(3)$ in the DGDR region for ^{208}Pb [3] allows for some contribution of one-step transitions.

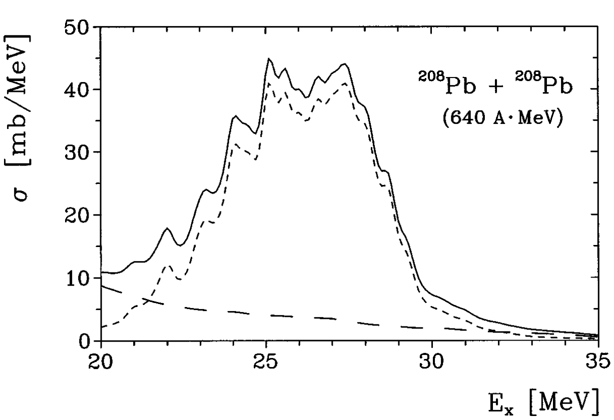

FIG. 2. The contribution for the excitation of two-phonon 1^- states (long-dashed curve) in first order perturbation theory, and for two-phonon 0^+ and 2^+ DGDR states in second order (short-dashed curve). The total cross section [for ^{208}Pb (640A MeV) $+^{208}$Pb] is shown by the solid curve.

The solid line in Fig. 2 is the sum of DGDR and two-phonon background excitations in relativistic heavy ion collisions. Experimentally it is not possible to separate these two parts. The first and second moments of excitation functions, displayed by the short-dashed and solid curves in Fig. 2, indicate that the centroid of the total strength is 200 keV lower and the width is 16% larger than the same quantities for the pure DGDR. The same tendency with respect to the harmonic picture of the DGDR excitation, although with large experimental uncertainties, was reported in Ref. [3]. We point out that this 200 keV shift is even somewhat larger than the one due to the anharmonicities studied in ^{208}Pb [16].

Direct excitation of the two-phonon 1^- states in ^{208}Pb (640A MeV) $+^{208}$Pb reaction was investigated before in Ref. [16]. The reported effect (a difference between 5.07 and 3.55 mb for $22 < E_x < 28$ MeV) is much weaker than in our calculation because of a rather limited two-phonon space. Another source of the DGDR enhancement in [16] is due to anharmonicity effects. We also checked the last by coupling one-phonon GDR states to (the most important) 1200 two-phonon 1^- states in the DGDR region. Because of the constructive interference between one- and two-phonon states at DGDR energies we got an additional enhancement of 24 mb, which is again larger than the difference between 6.42 and 3.55 mb obtained in Ref. [16] for the same reason. Taking into account that the DGDR itself has an excitation cross section of 245 mb in our calculation, these two effects together practically remove the discrepancy between experiment and theory.

In conclusion, we investigated the contribution of the direct excitation of a sea of two-phonon states above the GDR to photoneutron cross sections and to cross sections in relativistic heavy ion Coulomb excitation. These states form a flat structureless background which is very important for the correct description of the photoneutron data. Because of the peculiarities of Coulomb excitation in heavy ion collisions, its role is less important in this case, but its consideration appreciably removes the disagreement between experiment and theory.

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