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Note on a search for the two-octupole phonon 2^+ state in ^{208}Pb with resonant photon scattering [☆]

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Abstract

Results of a ^{208}Pb(γ, γ') experiment are presented aiming at an identification of the 2^+ member of the long-sought two-octupole phonon multiplet. Four E2 excitations have been observed below 6.5 MeV excitation energy, two of them for the first time. However, in contrast to new results of calculations within the quasiparticle–phonon nuclear model (QPM), no obvious candidate for the two-octupole phonon vibration could be found in the present study. We discuss the $J^\pi = 2^+$ states detected in this as well as previous experiments with respect to their possible two-octupole phonon structure. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Low-lying states of natural parity in atomic nuclei represent a well established feature of collective motion throughout the nuclear landscape [1]. These excitations are commonly referred to as phonons and usually exhibit excitation strengths from the ground state (g.s.) which are large compared to single-particle estimates. Within a simple collective description, these bosonic excitations can be coupled and form multiplets of states. Thus, the identification of the excitation energies and transition strengths of multi-phonon states leads to valuable information concerning the purity of the phonon states, their intrinsic fermionic structure, and admixtures to their wave functions.

In contrast to the decays of stretched two-octupole $\otimes$ particle configurations in nuclei around ^{146}Gd [2], the attempts of finding double-octupole excitations were less successful for the case of the doubly magic nucleus ^{208}Pb although it represents the unparalleled case of a stable nucleus where the first excited state is a collective 3^- state. We refer to the literature cited in [3] for an overview over the topic. Only recently, a candidate for the 0^+ member of the expected $0^+, 2^+, 4^+, 6^+$ quadruplet could be identified in inelastic neutron scattering experiments [4] by an E3 decay to the one-phonon state. The interpretation of this level at $E_\mathrm{x} = 5241$ keV is supported by results from deuteron scattering in combination with coupled channel calculations [5]. Attempts to identify the remaining states in $(n, n'\gamma)$ turned out to be more difficult [6] due to the fact that a clear signature is lacking, as would be a collective E3 decay to the one-phonon state. Electric octupole strength can only be found for the decay of the 0^+ state of the two-phonon multiplet, for the 2^+ and 4^+ members, however, E1 decay dominates by several orders of magnitude, and the E3 contribution cannot be extracted with sufficient accuracy. Furthermore, the main decay branch of the 6^+ two-phonon state will probably not lead to the one-octupole excitation but rather to other states with $J \approx 5-6$. It is therefore of importance to find out whether enhanced electric dipole strength in the decay of the 2^+ and 4^+ states represents a suitable signature for the identification of two-octupole structures. At present the situation with respect to the existence or not of a two-octupole phonon multiplet is very unclear.

Based on quasiparticle–phonon model (QPM) calculations, it was suggested [3] to search for the 2^+ member of the quadruplet in resonant photon scattering experiments [7,8]. We report here briefly on this search. Although this method is mainly selective on dipole excitations, new detector technologies (as large-volume high-purity Ge crystals or composite detectors like the Euroball-Cluster detector [9]) permit a considerable increase of the sensitivity of (γ, γ') experiments [10].

2. Experiment

The photon scattering experiment was performed at the superconducting Darmstadt electron linear accelerator S-DALINAC [11] operated in 3 GHz continuous-wave mode and delivering electron beams of about 30 μA with an energy of 6.75 MeV for bremsstrahlung production in a Ta radiator. A description of the setup as well as of the method of data processing and analysis can be found in [12,13]. The continuous photon spectrum was scattered off a 3 g enriched ($> 99\%$) ^{208}Pb sample which was combined with a few 100 mg of natural boron for photon flux calibration purposes. The scattered γ rays were detected by two Euroball-Cluster detectors placed at 94° and 132°, respectively, relative to the incident photon beam.

3. Results and discussion

The total spectrum (singles and coincident events) taken with the Cluster module placed at 94° with respect to the incident photon beam is shown in the upper part of Fig. 1 for photon energies of 4–7 MeV. Besides well-known E1 excitations [14] strongly excited in the (γ, γ') reaction, one recognizes also the population of the lowest 2^+ state at 4086 keV as well as a previously known state at 6193 keV. For the 2^+ state at 5716 keV the tentative assignment of angular momentum and parity could be confirmed from the measurement of

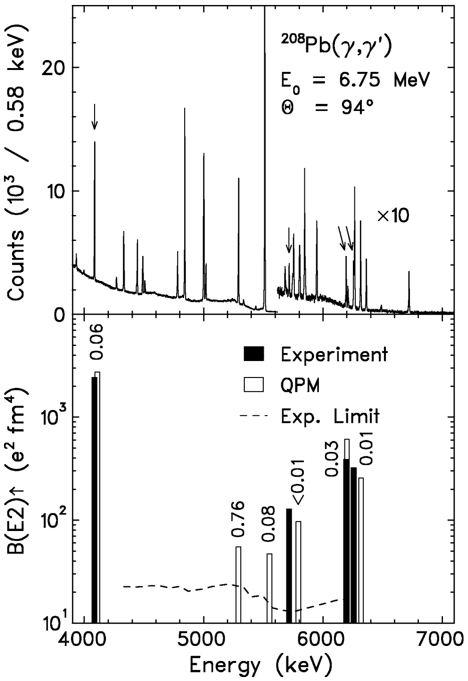

Fig. 1. Upper part: Gamma-ray spectrum of the ^{208}Pb(γ, γ') reaction taken with one Euroball-Cluster detector placed at 94° with respect to the incident photon beam for the energy interval between 4 and 7 MeV. Ground state transitions depopulating $J^\pi = 2^+$ states are marked with arrows. Other lines are due to dipole transitions, escape peaks, or stem from the calibration material ^{11}B. Lower part: Measured E2 strength distribution in ^{208}Pb (full bars) in comparison to predictions of the quasiparticle–phonon nuclear model (QPM, open bars). The dashed line indicates the gross shape of the observation threshold using the g.s. branching ratio predicted by the QPM. The numbers indicate the contributions of the $3_1^- \otimes 3_1^-$ two-octupole phonon 2^+ configuration to the calculated 2^+ QPM wave functions. Note the logarithmic scale.

Table 1
Electric quadrupole excitations in ^{208}Pb observed in the present experiment. Given are the excitation energies, the excitation strengths, and the transition widths from the present experiment and from the literature [15]. The branching ratio Γ_0/Γ was assumed to be 1. A self-absorption correction was applied

E_x (keV)	$B(\mathrm{E2})\uparrow$ (e^2 fm^4)	Γ (eV)	Γ (eV) [15]
4085.5 (2)	2434 (168)	0.45 (3)	0.62 (5)
5715.5 (4)[a]	127 (17)	0.13 (2)	–
6193.1 (4)	388 (48)	0.57 (7)	0.68 (5)
6255.6 (4)[b]	323 (47)	0.50 (0)	–

[a] Strength determined for the first time.

[b] State observed for the first time.

the angular distribution, and the $B(\mathrm{E2})$ value was determined for the first time. The E2 excitation at 6256 keV was observed in the present experiment for the first time. The numerical results for the 2^+ states are given in Table 1. A self-absorption correction [8,14] has been applied both for the lines stemming from ^{208}Pb and from the calibration material ^{11}B. For estimating the observation thresholds, self-absorption effects have been neglected. The lower part of Fig. 1 displays the E2 strength distribution for the energy interval under consideration (solid bars).

The widths deduced from the present experiment (see Table 1) agree roughly with the widths given in the literature [15] for the two previously known 2^+ states. The transition width of the 4086 keV state given in [15] was deduced using the $B(\mathrm{E2})$ value determined in an electron scattering experiment [16]. From backward-angle (e, e') experiments [17], the strength of the 6193 keV level was determined. However, the resolution of the experimental apparatus was limited to about 50 keV (FWHM).

Next we try to understand the observations in terms of up to date QPM predictions and to identify candidates for the two-phonon 2^+ state searched for.

3.1. *QPM predictions*

Besides the detailed description of the 2^+ member discussed in [3], the entire two-octupole-phonon quadruplet and especially the fragmentation of the two-phonon strength has been studied recently within the QPM [18]. The results of the calculations for the g.s. transitions are shown in the lower part of Fig. 1 (open bars). The model predictions exhibit an excellent agreement with the experimental data from the present experiment (full bars), except for two 2^+ states at 5.3 and 5.5 MeV which were not observed. Based on these QPM calculations, it was concluded that an enhanced E1 decay from the $2^+, 4^+$ states of the two-octupole phonon quadruplet to the single-phonon 3^- state cannot be used as unique signature of a two-octupole state. This is important for the interpretation of experimental data from neutron-induced reactions both in ^{208}Pb as in the Gd mass region [6,19]. Furthermore, the QPM results [18] indicate that the 2^+ state of the quadruplet exhibits indeed a certain fragmentation in contrast to the 4^+ and 0^+ members. But the predicted fragmentation of the two-phonon state with $J^\pi = 2^+$ is much smaller than that of the $J^\pi = 6^+$ state. For the latter case the fragmentation of two-octupole contributions has been studied within a recent Coulomb excitation experiment [20] by determining the $B(\mathrm{E3}; 3_1^- \to 6^+)$ values. It was found that the expected E3 strength from the excitation of two-octupole states is distributed over a large energy interval between 4.4 and 6 MeV in good agreement with the calculation of Ref. [18].

The contributions of the $(3_1^- \otimes 3_1^-; 2^+)$ configuration to the wave functions of the predicted 2^+ states are included in Fig. 1. Even the lowest 2^+ state in ^{208}Pb at 4086 MeV is expected to carry a small fraction of two-phonon amplitudes in its wave function. One 2^+ state at 5.29 MeV is predicted to carry a strong (76%) two-phonon component in the wave function. This state should occur — as the entire multiplet — close to the harmonic expectation value of the two-phonon energy. Another 2^+ level is expected from the QPM around 5.5 MeV. The model predicts that the wave function of this state is dominated by $1p1h$ contributions besides an admixture of about 8% from the two-octupole configuration. From these considerations based on the QPM results it becomes clear that one cannot speak of *the* two-phonon state anymore, but only of a 2^+ state with a sizable two-phonon amplitude in its wave function. This makes the experimental search for it very tedious.

For the state with dominant two-phonon component both the E1 decay branch to the 3_1^- one-phonon state and the E2 g.s. transition have been reexamined within a detailed QPM calculation. In order to test the robustness of the model results, the strength of the residual interaction was varied by ±30% according to the procedure presented in Ref. [3]. From this we obtain for the excitation strength $B(\mathrm{E2}; 0_1^+ \to 2^+) = 55(^{+25}_{-19})\, e^2\,\mathrm{fm}^4$ and for the decay branch to the single-phonon state $B(\mathrm{E1}; 2^+ \to 3_1^-) = 0.70(^{+0.36}_{-0.32}) \cdot 10^{-3}\, e^2\,\mathrm{fm}^2$. Thereby it should be kept in mind that a variation of the strength of the residual interaction of this amount dramatically reduces the agreement with the observed excitations both in excitation energy as in transition strength and shifts the energy of the two-phonon state by several 100 keV. It turned out that even such a large variation of the strength of the residual interaction leads only to minor changes in the predicted branching ratio for the case of the two-octupole-phonon 2^+ state so that a reliable extraction of detection thresholds from the photon scattering spectrum is possible.

3.2. Observation limits

Table 2 summarizes the detection limits from the present experiment for energies close to the harmonic limit (based on the branching ratio deduced from the QPM) in comparison with the latest QPM results. As can be seen from Fig. 1, the g.s. decay of the proposed two-phonon state should be clearly visible on the background (3σ, dashed line, note the logarithmic scale). The observation limit was estimated from the nonresonant background in the spectrum using the branching ratio predicted by the QPM. In the vicinity of strong signals in the pulseheight spectrum shown in the upper part of Fig. 1, however, the sensitivity is reduced compared to this estimate. In contrast to the expectations from the model, no signal from a g.s. decay of a possible 2^+ member of the two-phonon quadruplet

Table 2
Experimental observation limits for an E2 excitation in ^{208}Pb close to the excitation energy expected for a two-octupole–phonon state in the harmonic limit in comparison with the prediction of the QPM calculation. For the extraction of the experimental limit (3σ), the branching ratio between g.s. decay and the transition to the 3_1^- state was taken from the QPM. The middle row displays the result and the detection threshold for the only 2^+ state between 5 and 6 MeV found in the present experiment. The lower two rows show candidates for the two-phonon 2^+ state discussed recently in [6]

	$B(\mathrm{E2}; 0^+ \to 2^+)$ ($e^2\,\mathrm{fm}^4$)	$B(\mathrm{E1}; 2^+ \to 3^-)$ ($10^{-3}\,e^2\,\mathrm{fm}^2$)
Exp. limit at $E \approx 5280$ keV	$\leqslant 23.6$	$\leqslant 1.59$
QPM	55.0	0.70
$E_\mathrm{x} = 5716$ keV (this work)	127 (17)	$\leqslant 0.8$
$E_\mathrm{x} = 5286$ keV [6]	$\leqslant 0.5$	0.47
$E_\mathrm{x} = 5561$ keV [6]	$\leqslant 6.2$	0.34

was observed in the vicinity of the harmonic limit. No decay branch to the octupole phonon state could be identified, either.

3.3. Candidates for the two-phonon 2^+ state

In the present experiment the strength for a 2^+ state at 5716 keV could be determined for the first time. Its excitation energy deviates by about 10% from the harmonic limit and thus also contradicts the QPM expectation of 5.29 MeV. The g.s. transition strength observed is more than two times larger than the model prediction, and the observation limit for a possible branch to the 3_1^- state amounts to $B(\mathrm{E1}; 2^+ \to 3^-) \leqslant 0.8 \times 10^{-3}\,e^2\,\mathrm{fm}^2$ which is in the order of the expected transition strength for the decay of the double-octupole state but also of other 2^+ states in this energy region. The excitation energy and strength of this mode agrees nicely with a level predicted by the QPM with a nearly pure $1p1h$ structure.

The state at $E_\mathrm{x} = 5286$ keV discussed in [6] might be a candidate for the two-phonon state because its g.s. transition could easily be hidden in the tail of the strong 5292 keV E1 excitation. The excitation energy of this state is in good accord with the QPM prediction for the two-phonon vibration. However, the measured $B(\mathrm{E1};2^+ \to 3^-)$ and lifetime from DSAM [6] result in an upper limit for the g.s. transition strength of $0.5\,e^2\,\mathrm{fm}^4$ (see Table 2) in severe conflict with the QPM. An inspection of the $E_\mathrm{x} = 5561$ keV state with $J^\pi = 2^+, 4^+$ discussed in [6] reveals comparable findings. For another 2^+ state listed in [21] at 5548 keV, the deduced intensity ratio for the transitions to the 3_1^- state and the g.s. also rules out an interpretation as two-phonon state on the basis of the QPM results.

In the compilation by Schramm et al. [22] reporting on γ spectroscopy in nucleon transfer and pickup reactions, none of the aforementioned states showed up. However, it should be noted that it is a priori not evident that a two-phonon state can be detected in this kind of experiment. A detailed comparison of this set of data with results from proton, deuteron and alpha scattering taken at the Munich tandem laboratory [5] is in preparation [23].

4. Concluding remarks

In summary, we have performed a nuclear resonance fluorescence experiment on ^{208}Pb from which sensitive limits for the g.s. excitation strength of the 2^+ member of the expected two-octupole phonon quadruplet have been deduced. In comparison to the results of Ref. [14], the experimental sensitivity could be increased by about a factor of 30 with the present setup. In contrast to expectations from well-established microscopic calculations, no 2^+ state close to the harmonic limit was detected. However, for two 2^+ states around 6 MeV the g.s. transition strength was determined for the first time.

Summarizing the present experimental and theoretical information on the two-octupole 2^+ state in ^{208}Pb, we see no clear evidence for such a state up to now in comparison to the QPM approach. The lack of a suitable candidate in the present (γ, γ') experiment implies that either the QPM calculations fail to predict the correct branching ratio or the degree of fragmentation. With respect to the fragmentation, the two-phonon contributions might be smeared out over additional 2^+ states from the two-proton and two-neutron pairing vibration which are beyond the scope of the model. On the other hand, the comparison between QPM and the fragmentation of two-phonon 6^+ states [20] is remarkable. Furthermore, it is possible that the main fragment of the 2^+ two-phonon state is hidden under a strong peak from one of the strong E1 transitions in ^{208}Pb. In this case, other probes should be capable of resolving the two-phonon excitation. The candidates suggested so far are, however, in severe conflict with the QPM predictions. Therefore, on the basis of the present experimental as well as theoretical knowledge, the puzzle of the two-octupole phonon vibrations in ^{208}Pb remains unsolved.

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