Two-phonon γ-vibrational state in ^{168}Er

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In order to identify double-γ vibrational states in well-deformed regions, we have made a Coulomb excitation experiment for ^{168}Er. We could observe 1235-keV and 962-keV γ transitions decaying from the 2056-keV 4^+ state. The measured $E2$ transition probabilities support the assignment of the 4^+ state as a two-phonon γ-vibrational state.

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Multiphonon vibrational excitations are known to be well established in near-spherical regions. In deformed or transitional regions, however, the experimental knowledge of even the two-phonon state is scarce. Its existence and collectivity is one of the central problems for elucidating the collective excitation of nuclei [1–7]. A candidate for the double-γ 4^+ state in ^{168}Er was assigned at 2056 keV by Davidson *et al.* [8]. A relatively large $B(E2)$ value of 5.2 Weisskopf units was reported for the transition from this state to the one-phonon γ-vibrational state at 821 keV by a new Doppler-shift technique utilizing the recoil in neutron capture reaction [9]. So far this state has not been reported in Coulomb excitation in spite of the expectation that the large $B(E2)$ value of the transition between the two-phonon and one-phonon states enhances two-step Coulomb excitation. Here we applied Coulomb excitation for this study, because it can become a universal tool for identifying such collective states, and for determining the absolute $B(E2)$ value between the two-phonon and one-phonon states. Such a $B(E2)$ value is important for discussing the nuclear collectivity and anharmonicity of collective vibration.

In this paper, it is shown that Coulomb excitation can be used to identify a two-phonon γ-vibrational state and to determine accurately the related $B(E2)$ values. This could be done by optimizing the bombarding conditions for observation of the known transitions from the candidates for the two-phonon to the one-phonon state.

The ^{168}Er nucleus was multiply Coulomb excited with a beam of 295-MeV ^{74}Ge, which was obtained from the tandem accelerator at Japan Atomic Energy Research Institute. The ^{168}Er target was a self-supporting metallic foil of 1.8 mg/cm^2 and 95% isotopically enriched. Scattered projectiles were detected with two PPAC's (parallel plate avalanche counters), which were placed symmetrically with respect to the beam so that they covered backward angles. The size of the PPAC was 10×10 cm^2, and the distance between the center of the PPAC window and the target was 7 cm. The PPAC's provided the two-dimensional position signals of detected particles. The position resolution is 5 mm FWHM Deexcitation γ rays were measured with 12 Ge

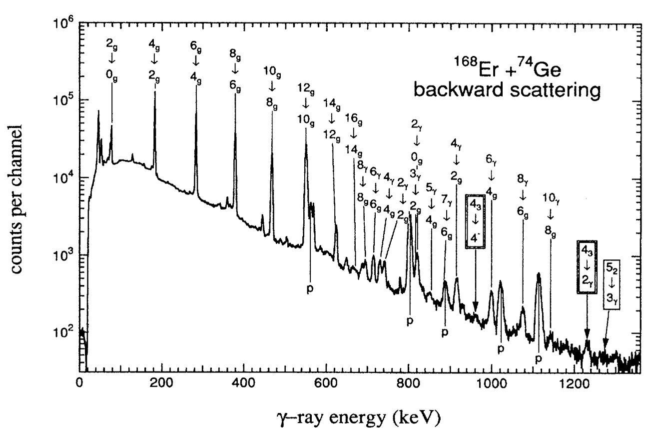

FIG. 1. A γ-ray spectrum in coincidence with backward scattered particles in multiple Coulomb excitation of ^{168}Er with ^{74}Ge. Doppler-shift correction has been made by utilizing position signals of position-sensitive detectors.

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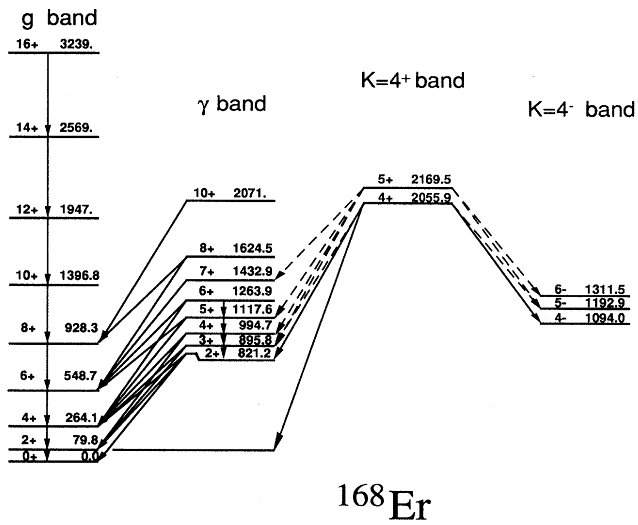

FIG. 2. A partial level scheme of ^{168}Er. Transitions observed in the present experiment are shown with solid lines. Dashed lines denote transitions reported elsewhere, but not observed in the present experiment.

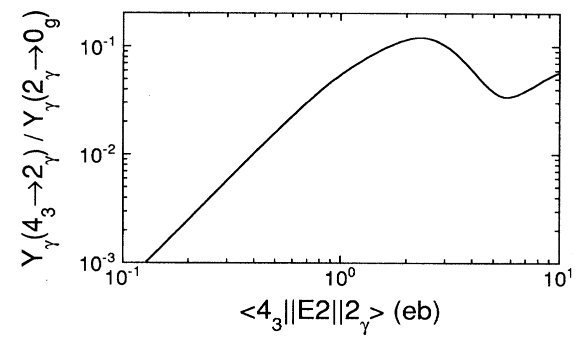

FIG. 3. Relative γ-ray yield of the $4_3\to 2_\gamma$ transition to that of the $2_\gamma\to 0_g$ transition as a function of the $E2$ matrix element between 4_3 and 2_γ states. The yield is integrated over particle angles covered by PPAC gas counters.

detectors in coincidence with scattered projectiles. The observed γ-ray spectra were corrected for Doppler shifts kinematically by using the position signals of the scattered particles.

In order to achieve low background in the γ-ray spectrum, we have attempted several heavy-ion beams such as ^{32}S, ^{58}Ni, and ^{74}Ge. Figure 1 shows the γ-ray spectrum obtained with a ^{74}Ge beam. Generally the germanium beam is not used for Coulomb excitation. The reason is obvious in Fig. 1: there are many peaks due to projectile excitation denoted by p in Fig. 1, which often disturb observation of γ rays of interest emitted by the target nucleus. Except those peaks, the background level is low in the energy region of 1.0–1.4 MeV, and it is advantageous in searching for the two-phonon γ-vibrational state. The peaks of projectile excitation change their positions relative to those of the target excitation in the spectra for different combinations of particle- and Ge-detector angles. In this way it was possible to distinguish between these peaks.

The Coulomb excitation cross section of a state is calculated unambiguously from the $E\lambda$ matrix elements concerned. In order to derive $E\lambda$ matrix elements we have made an analysis based on the Coulomb excitation code GOSIA [10], which takes into account the energies and $E\lambda$ matrix elements of all the states and transitions observed, and calculates γ yields following multiple Coulomb excitation.

Figure 2 shows a partial level scheme of ^{168}Er derived from the present experiment. We observed members of the g band up to 16^+ and of the γ band up to 10^+; the 14_g^+, 16_g^+, and 10_γ^+ states are newly assigned. Most importantly, the 1235-keV transition from the candidate for two-phonon γ-vibrational state to the one-phonon γ-vibrational state has been observed for the first time in Coulomb excitation.

The yield of the observed $4_3\to 2_\gamma\gamma$ ray can be used to extract the $E2$ matrix element between the 2056-keV 4_3^+ state and the one-phonon 2_γ^+ state. There are a lot of excitation paths to the 4_3^+ state as seen in Fig. 2. The GOSIA analysis has been done by taking into account all the levels and transitions in Fig. 2. The strongest path to the 4_3^+ state is the two-step process via the one-phonon 2_γ state ($0_g^+\to 2_\gamma^+\to 4_3^+$). Figure 3 shows the relative γ-ray yield of the $4_3\to 2_\gamma$ transition to that of the $2_\gamma\to 0_g$ transition, in coincidence with backscattered particles, as a function of the $E2$ matrix element between the 4_3 and 2_γ states. (In this calculation other $E2$ matrix elements which contribute to the excitation of the 4_3 state are fixed; the known matrix elements [8,11] in and between the g and γ bands were used in the calculation; unknown matrix elements for the g and γ bands were estimated by using the rigid-rotor model.) The left-hand side of the graph indicates that the yield is proportional to the square of the $E2$ matrix element or $B(E2)$, which is expected in one-step Coulomb excitation above the one-phonon states. The behavior at the right-hand side reflects the fact that the dominance of the particle angular distribution shifts to a forward angle as the matrix element increases.

We derived the $B(E2)$ value for the $4_3^+\to 2_\gamma^+$ transition as 0.039 ± 0.009 e^2 b^2. The propagation of errors was included

TABLE I. Results for $K=4_3$ state in ^{168}Er. The values of $E(2^+)$ and $B(E2;0_g\to 2_\gamma)$ are 821 keV and 0.132 ± 0.005 e^2 b^2, respectively.

Reference	$R=E(4^+)/E(2^+)$	$B(E2;2_\gamma\to 4_3)/B(E2;0_g\to 2_\gamma)$	$B(E2;4_3\to 3_\gamma)/B(E2;4_3\to 2_\gamma)$
Present exp.	2.503	0.53(12)	0.64(18) [a]
Previous exp. [9]	2.503	0.38(20)	
QPNM [1]		0.16	
MPM [2]	2.5	0.40	0.56
sdg-IBM [4]	2.5	0.50	0.56
DDM [3]	2.5	1.44	0.56
SCCM [5]	2.54	0.68	0.56
Harmonic limit	2.00	1.00	0.56

[a]From γ-ray branching ratio derived by Davidson *et al.* [8].

TABLE II. Properties of two-phonon γ-vibrational states.

Nucleus	J	$B(E2;2_\gamma\rightarrow 4_3)$ (s.p.u.)	$B(E2;4_3\rightarrow 2_g)/B(E2;4_3\rightarrow 2_\gamma)$	Reference
Harmonic limit	4		0.0	
^{168}Er	4	7.0(16)	<0.005	Present
^{232}Th	4	10(3)	0.006(3) [a]	Korten *et al.* [12]

[a]Present experiment.

in this result. The value agrees with the previously reported one, 0.028 ± 0.014 e^2 b^2, of Ref. [9] within the experimental accuracy. The observed $B(E2;4_3\rightarrow 2_\gamma)$ value corresponds to 7.0 Weisskopf units. Such large collectivity supports the interpretation of the 4_3 state as a γ-vibrational two-phonon state.

Table I shows the comparison with several calculations based on the quasiparticle-phonon nuclear model (QPNM) [1], the multiphonon method (MPM) [2], the dynamic deformation model (DDM) [3], the extended interacting boson model with s, d, and g bosons (sdg-IBM) [4], and the self-consistent collective coordinate method (SCCM) [5]. We used the ratios $R=E(4^+)/E(2^+)$ and $B(E2;2_\gamma\rightarrow 4_3)/B(E2;0_g\rightarrow 2_\gamma)$, which become 2.0 and 1.0, respectively, at the limit of harmonic vibration and show a straightforward measure of the anharmonicity. The present value of $B(E2;2_\gamma\rightarrow 4_3)/B(E2;0_g\rightarrow 2_\gamma)$,$0.53\pm0.12$, shows definite evidence of collectivity, suggesting a dominant two-phonon configuration of this state. This has not been obvious based on the previous value of Börner *et al.* [9], 0.38 ± 0.20, because the lower limit is only 0.18. The MPM, sdg-IBM, and SCCM calculations seem to be consistent with the present result as well as with the previously reported value [9]. The experimental $B(E2;4_3\rightarrow 3_\gamma)/B(E2;4_3\rightarrow 2_\gamma)$ ratio is 0.64 ± 0.18, which is consistent with the rigid-rotor value, 0.58, with definite K quantum number.

Table II shows the derived $B(E2;2_\gamma\rightarrow 4_3)$ value and the $B(E2;4_3\rightarrow 2_g)/B(E2;4_3\rightarrow 2_\gamma)$ ratio for ^{168}Er and ^{232}Th nuclei, based on which two-phonon states have been proposed. Since the ratio becomes zero in the harmonic limit, it gives a measure of the goodness of the two-phonon picture. The experimental $B(E2)$ ratios for ^{168}Er and ^{232}Th are sufficiently small and consistent with their interpretation as two-phonon states. It should, however, be noted that this fact does not necessarily demonstrate the two-phonon picture of this state as was suggested in Ref. [13]. The degree of K hindrance, $|K_i-K_f|-\lambda$, is equal to 2 for the $4_3\rightarrow 2_g$ $E2$ transition. The derived hindrance factor, 0.035, of this transition is consistent with the compilation by Loebner [14], which indicates that the hindrance is in the order of 10^{-2}.

The 0^+ double-γ state in ^{168}Er has not been identified so far, although all the levels below 2.1 MeV have been known in the previous (n,γ) experiment [8]. The absence of the state below 2.1 MeV is consistent with the predictions made by the above models [1–5].

We reported elsewhere [15] the observation of a Coulomb excited level, at 2205 keV and 2102 keV, decaying to the γ-vibrational band in neighboring nuclei ^{166}Er and ^{164}Dy, respectively. In both cases, the measured $B(E2;2_\gamma\rightarrow 4_3)$ values are large, suggesting the two-phonon nature of these levels. Interestingly, the anharmonicities in the $B(E2)$ ratio 0.47 ±0.35 and 0.9 ± 0.5 and the energy ratio 2.673 and 2.894 in ^{166}Er and ^{164}Dy, respectively, are similar to those for the two-phonon state in ^{168}Er. The $K^\pi=4^+$ two-phonon states in ^{166}Er and ^{164}Dy are predicted by the SCCM calculation [5] with similar anharmonicity to ^{168}Er in accordance with the Coulomb excitation measurements.

Recently, Wu *et al.* [16] claimed that $K^\pi=4^+$ bands in many rare-earth nuclei are two-phonon states on the basis of the branching ratio. It should be noted, however, that most of the $K^\pi=4^+$ states they discussed, except in ^{166,168}Er and ^{164}Dy, have a small energy ratio $R<2.0$ which is very different from the value $R=2.50$ in ^{168}Er. On the other hand, Burke [13] claimed that some of the $K^\pi=4^+$ levels discussed in Ref. [16] are not of the two-phonon nature on the basis of nucleon-transfer and β-decay data. This argument, however, applies neither to the 2056-keV level in ^{168}Er nor to the 2102-keV level in ^{166}Er. It seems probable that the $K^\pi=4^+$ levels in rare-earth nuclei other than ^{166,168}Er and ^{164}Dy might have different character from the two-phonon states in ^{168}Er as well as the candidate states in ^{166}Er and ^{164}Dy. In this respect, it is interesting to note that theoretical analysis based on the SCCM suggests strong N and Z dependence of the two-phonon γ vibration [5]. In fact, the SCCM predicts two-phonon states with similar anharmonicity in ^{162,164}Dy, and ^{164,166,168}Er while in other rare-earth nuclei it predicts strong coupling between the two-phonon states and $K^\pi=4^+$ hexadecapole one-phonon modes or $K^\pi=4^+$ two-quasiparticle modes. This may suggest a possible qualitative difference in the two-phonon structure of rare-earth nuclei. Accurate experimental data especially of $B(E2)$ and $B(E4)$ will be necessary to clarify such vibrational structure in this region.

The two-phonon γ-vibrational mode in ^{168}Er has been studied through multiple Coulomb excitation. The $B(E2)$ value for the transition from the 2056-keV 4_3 state to the one-phonon state in ^{168}Er demonstrates that the $K^\pi=4^+$ state has a dominant γ-vibrational two-phonon component. The anharmonicity of this state is rather large and is consistent with several nuclear models.

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