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$K^{\pi}=4^{+}$ double-γ vibration in ^{164}Dy

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A search for the double-γ vibration is performed using thermal neutron capture on ^{163}Dy. A level at 2173 keV in ^{164}Dy is found to exhibit a collective enhancement in its decay to the single-γ vibration, suggesting a contribution from the $K^{\pi}=4^{+}$ double-γ excitation. Both its energy and the measured $B(E2)$ value to the single-γ vibration are in reasonable agreement with the different theoretical predictions. [S0556-2813(97)50209-3]

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Recent experimental improvements in nuclear spectroscopy following Coulomb excitation [1], inelastic neutron scattering [2], and thermal neutron capture [3] make possible the measurement of lifetimes of highly excited, low-spin states that have been previously inaccessible. Knowledge of the level lifetimes allow, for instance, reduced transition rates [most importantly $B(E2)$ values] to be determined, which are one measure of the collectivity in the wave function for a state. The transition rates often present detailed tests of our understanding of the nuclear many-body problem, because they can confront well-established descriptions of low-energy states, and excitations built on them at higher energies.

In the present work, one of the cornerstones in the collective model description of well-deformed rotational nuclei, the γ vibration [4], will be studied by the search for its double excitation. Although the single-γ vibration is a firmly established feature of deformed nuclei [4], the double excitation was only recently observed for the first time in ^{168}Er [5]. Once identified, the properties of double-γ excitations can address two fundamental questions about the γ vibration: the amount of collectivity and the degree of anharmonicity.

The first question concerns the study of the microscopic interpretation of this vibration in terms of its fermionic constituents. The long-debated question whether the Pauli principle, in conjunction with the restricted number of twofold degenerate Nilsson orbits close to the Fermi surface, forbids the creation of a double-γ vibration was answered in [5]. Since this observation, some of the nuclear models have been refined [6].

The second question deals with the geometrical interpretation of the γ vibration. The observation of a single-γ vibration does not answer the question whether the atomic nucleus vibrates with respect to an axially symmetric or a γ-deformed equilibrium shape. However, in the former case the double-phonon excitation gives rise to $K^{\pi}=0^{+}$ and 4^{+} bands at approximately twice the energy of the single $K^{\pi}=2^{+}$ vibration. In the latter case, the double excitations are much higher in energy [7,8]. The question of the anharmonicity is still controversial. Most theoretical models predict anharmonicities which lead to double-phonon $K^{\pi}=4^{+}$ ($4^{+}_{\gamma\gamma}$) states at about 2.8 times the energy of the single-γ vibration. As an example, for ^{164}Dy the multiphonon method (MPM) predicts 2.87 [9], the quasiparticle-phonon nuclear model (QPNM) 2.82–3.02 [10], and the self-consistent collective-coordinate method (SCCM) 2.63 [11].

While agreement exists between the theoretical descriptions, the experimental situation is not at all clear. A systematic search for candidates for double-γ vibrations in well-deformed rare-earth nuclei, based essentially on branching ratios, by Aprahamian and co-workers [12,13] found candidates with energies ranging from 1.29 to 2.89 times that of the γ vibration. However, it has been argued [14] that single-nucleon transfer data rule out the possibility that the dominant component in the wave functions of these candidate levels was two-phonon in nature. The very low-energy ratios for some states found in Ref. [12,13] together with the criticisms by Burke [14], cast serious doubt on whether branching ratios alone are sufficient to identify double-γ vibrations. It is clear that more absolute $B(E2)$ values, as well as the consideration of all data, are needed to settle the question.

The present work will focus on ^{164}Dy because it is one of the three candidates identified by QPNM calculations [10] and not ruled out by Burke [14]. The other two candidates are ^{166}Er and ^{168}Er for which the double-γ vibration has been found [5,15,16]. An earlier attempt to identify the $4^{+}_{\gamma\gamma}$ state in ^{164}Dy was undertaken by Winchell *et al.* [17] using Coulomb excitation. This work excluded the existence of a double-γ vibration below 2.05 MeV, which corresponds to an energy ratio of 2.7. Therefore, the theoretical predictions can still be correct if the $4^{+}_{\gamma\gamma}$ state occurs in an energy window from 2.05 MeV to 2.3 MeV. The earlier claim [12,13,18] for the $4^{+}_{\gamma\gamma}$ level at 2205 keV falls within the energy window. However, this claim is based on a questionable level scheme [19] as will be shown below.

In order to identify possible candidates for a $4^{+}_{\gamma\gamma}$ state which are populated after thermal neutron capture, unpublished [20] (n,γ) data measured at the high-flux reactor of the Institut Laue-Langevin (ILL) have been reanalyzed. These data consist of γ-ray energies measured with the bent-crystal spectrometer GAMS2/3 and the pair spectrometer PN4, electron spectra measured with the BILL spectrometer, and γ-γ coincidences. The coincidences are used to identify possible candidates in the following way. Two series of gates connected with the decays from γ band were placed. The upper part of Fig. 1 shows transitions coincident with the 754.8 keV ($3^{+}_{\gamma}\rightarrow 2^{+}_{\mathrm{gsb}}$) transition, whereas lower part shows coincidences with the 761.8 keV ($2^{+}_{\gamma}\rightarrow 0^{+}_{\mathrm{gsb}}$) and 688.4 keV ($2^{+}_{\gamma}\rightarrow 2^{+}_{\mathrm{gsb}}$) transitions. If a candidate for a $K^{\pi}=4^{+}$ level exists, it should show decay lines in both spectra (the Alaga rules predict that the decay to the 2^{+}_{γ} level should dominate) with a relative energy shift equal to the $3^{+}_{\gamma}-2^{+}_{\gamma}$ energy difference of 66.3 keV. Only two states can be constructed in the 2.05 to 2.3 MeV energy window from the data in Fig. 1. They correspond to excited states at 2173 keV and 2206 keV. The latter one is the state suggested in Refs. [12,13,18]. Its decay branch to the 2^{+}_{γ} is, however, doubtful as can been seen from Fig. 1, and this transition is not observed in the high-resolution γ-ray data. Therefore, from the present data the 2173 keV level is the only reasonable candidate for the $4^{+}_{\gamma\gamma}$ state.

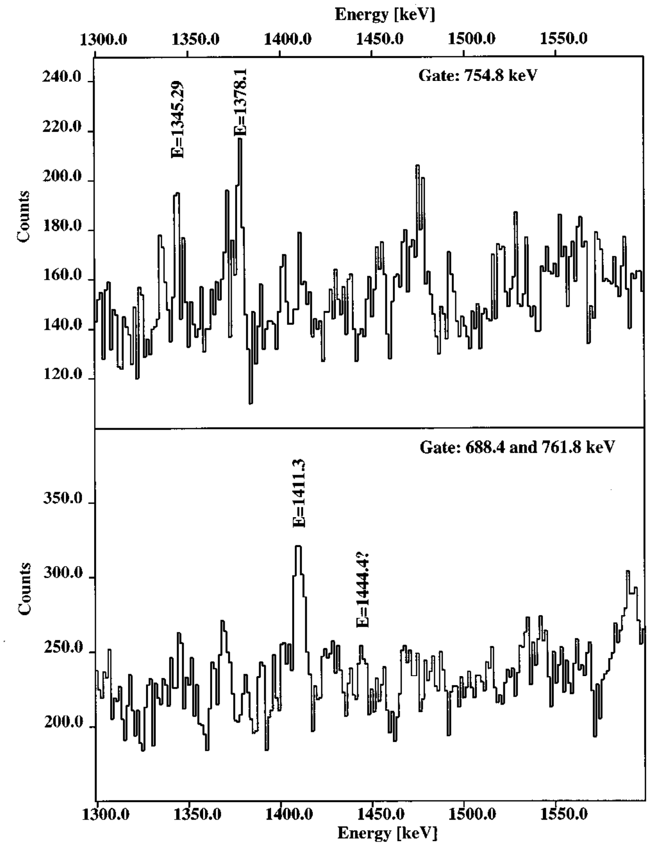

FIG. 1. Selected coincidence spectra from the ^{163}Dy(n_{th},γ)^{164}Dy reaction. The upper part shows coincidences with the 754.8 keV ($3^{+}_{\gamma}\rightarrow 2^{+}_{\mathrm{gsb}}$) transition, while the lower part displays the sum of coincidences with the 761.8 ($2^{+}_{\gamma}\rightarrow 0^{+}_{\mathrm{gsb}}$) and 688.4 keV ($2^{+}_{\gamma}\rightarrow 2^{+}_{\mathrm{gsb}}$) transitions.

The 2173 keV level was observed previously in the β^{-} decay of ^{164}Tb. Based on coincidence relations, the 1345.3 keV γ-ray is assigned as the $2173\rightarrow 3^{+}_{\gamma}$ transition. The conversion coefficient $\alpha_K=0.0011(4)$ is determined for this transition from the electron conversion data, and thus it is $E2$ in nature. (The theoretical conversion coefficients [21] for an $E2$ and $M1$ multipolarity are $\alpha_K=0.0014$ and 0.0028, respectively.) Table I lists the transitions decaying from the 2173 keV level and the measured intensities per 10000 neutron captures. It should be noted that the nonobservation of the transitions previously listed as decaying from this level is not due to insufficient sensitivity, since much weaker transitions than those expected from the 2173 keV level are observed. Similar problems appear with the decay of the 2206 keV level for which many transitions given in Ref. [19] are

TABLE I. Transitions from the 2173.1 keV level.

E_{γ} (keV)	I_{γ}	E_f (keV)	J^{π}_f	λL
1411.301(112)	82.2(20.6)	761.793(1)	2^{+}_{γ}	$E2$
1345.288(178)	23.8(5.1)	828.181(1)	3^{+}_{γ}	$E2$
1930.876(114)	26.3(2.0)	242.223(1)	2^{+}_{gsb}	$E2$

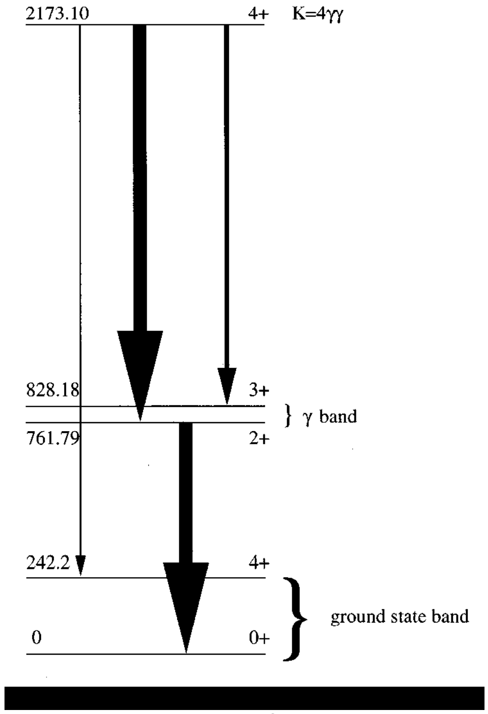

FIG. 2. Partial level scheme of ^{164}Dy. The widths of the arrows are proportional to the $B(E2)$ values determined from the known lifetime of the 2^{+}_{γ} state, and the lifetime obtained from the statistical model description of the feeding for the 2173 keV level.

absent from the high resolution γ-ray spectra. The revised decay scheme for the 2173 keV level is shown in Fig. 2. The combination of the level scheme and the fact that the 2173 keV level is fed in the decay of ^{164}Tb suggests that the previously adopted $I^{\pi}=4^{+}$ value is correct. [The decay scheme limits the spin to be $(2-4)^{+}$, whereas the feeding of a level with $I<4$ by the β^{-} decay of the 5^{+} ^{164}Tb ground state is highly unlikely.] With the $I^{\pi}=4^{+}$ assignment, the Alaga rules can be used to determine the K value. The experimental value of the ratio $B(E2;2173\rightarrow 3^{+}_{\gamma})/B(E2;2173\rightarrow 2^{+}_{\gamma})=0.37(9)$ can be compared to the theoretical values of 14.1 ($K=0$), 6.9 ($K=1$), 2.2 ($K=2$), 0.14 ($K=3$), and 0.56 ($K=4$). The only values with similar $B(E2)$ ratios to the experiment are those for $K=3$ and $K=4$. However, $K=3$ can be eliminated since in this case the most intense transition should be to the 4^{+}_{γ} level, rather than the 2^{+}_{γ} state. Therefore, the $I,K^{\pi}=4,4^{+}$ assignment is adopted for the 2173 keV level.

The γ-ray induced doppler broadening (GRID) technique [3], using the two-axis flat crystal spectrometer GAMS4 [22], was used to measure the lifetime of the 2173 keV level. The GAMS4 spectrometer, installed at the high-flux reactor of the Institut Laue-Langevin (ILL), is able to measure γ-ray energies with an energy resolution up to $\delta E/E=10^{-6}$. After the capture of a thermal neutron, the newly formed nucleus is in an highly excited state from which it will quickly decay by the emission of an energetic primary γ ray. Each emission of a γ ray induces a small recoil to the atom. Due to the extreme resolving power of GAMS4, the observation of Doppler broadening on the line profile of subsequently emitted γ rays caused by these recoils becomes possible. The exact form of the line shape depends essentially on three effects:

TABLE II. Lifetime for the 2173.16 keV level derived under different feeding assumptions.

Feeding	Lower limit	Upper limit	Stat. model
τ (fs)	190^{+212}_{-89}	477^{+293}_{-134}	409^{+278}_{-129}

(1) the slowing-down process in matter, (2) the initial recoil distribution, and (3) the nuclear lifetime of the excited state which decays by the measured γ-ray transition. Provided that the two first processes are understood, the observation of the Doppler broadening allows the determination of lifetimes in the fs to ps range [3]. However, in the few ps range one often reaches the limit of the energy resolution of the instrument and, depending on the recoil distribution, only lower limits for the lifetimes can be deduced.

The target used consisted of 1.2 g of Dy_2O_3 enriched to 95% in ^{163}Dy and contained in three carbon containers. The sample was placed at the in-pile target position of the high-flux reactor within a neutron flux of $5\times 10^{14}\,\mathrm{n/cm^2s}$. This high neutron flux is necessary due to the low efficiency of a double flat-crystal spectrometer. The lifetime of the 2173 keV level was measured by scanning in second order of reflection the 1411.3 keV transition. The standard procedure described in [3] was used to analyze the data. The instrumental broadening taken into account by the so called ''excess width'' was determined to be 0.211(13) fringes which equals 8.4(5) marcsec. The thermal velocity was deduced from scans of the 277 keV and 688 keV lines, decaying transitions from relatively long-lived states, and equaled 516(22) m/s. In order to accumulate enough statistics, the 1411.3 keV line was scanned extensively. The broadened line profile has been fitted with the code GRIDDLE [23]. The slowing down of the recoiling nucleus was treated in the framework of the mean free path approximation (MFPA) [3]. Figure 3 shows the comparison between the fit of the data and the experimental line shape, obtained from summing all data. Note that the lifetimes were fitted to all individual scans in order to avoid effects due to possible long term drifts of the spectrometer.

The main difficulty in applying GRID to heavier nuclei is the uncertainty concerning the feeding paths. The lifetime limits are obtained with extreme feeding assumptions: to determine the upper limit direct feeding of the level under investigation was assumed, whereas for the lower limit all known lines feeding the level have been taken into account and the rest of the intensity has been assigned to come from four hypothetical states situated 0.5, 1.0, 1.5, and 2 MeV above the 2173 keV level. All transitions were assumed to arise from states with an infinite lifetime. Results derived with the different feeding assumptions are listed in Table II. From these limits, the lifetime is determined to be (taking account of lower and upper uncertainty estimates, respectively) in the interval from 110 to 770 fs. Also shown is the result obtained from a statistical model [24] describing the γ cascades feeding the level, which leads to the most likely value for the lifetime of 410^{+280}_{-130} fs.

Having obtained the multipolarities, conversion coefficients, branching ratios, and lifetime, the upper and lower limit for the $B(E2;2173\rightarrow 2^{+}_{\gamma})$ values are found to be 16.8 W.u. and 2.2 W.u., respectively. The most likely value, obtained from the statistical description of the feeding, is

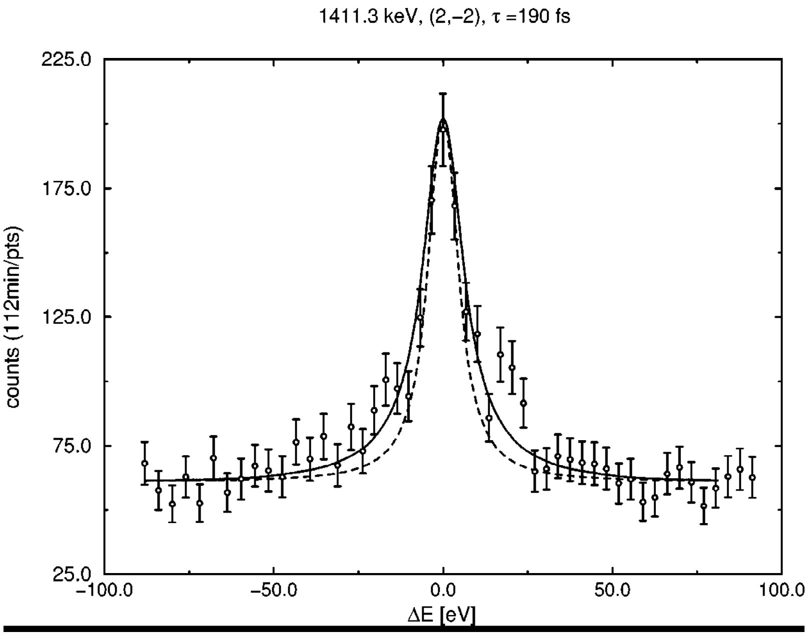

FIG. 3. Comparison between the fitted and experimental line shape for the 1411.3 keV transition. The dashed line shows the instrumental response. The full line shows the fitted line shape.

$4.1^{+3.0}_{-1.7}$ W.u. Adopting the lifetime of 6.6(4) ps [19] for the 2^+_γ state, the experimental ratio $B(E2;2173\rightarrow 2^+_\gamma)/B(E2;2^+_\gamma\rightarrow 0^+_{\mathrm{gsb}})$ in the interval 0.5–3.9 is determined. If the most likely value of the lifetime of the 2173 keV level is adopted, a $B(E2)$ ratio of $1.0^{+0.8}_{-0.4}$ is determined, which is similar to the values of 1.3 and 1.5 found for the assigned $4^+_{\gamma\gamma}$ states in ^{166}Er and ^{168}Er. The $B(E2)$ ratio is smaller than, but still in reasonable agreement with, the theoretical predictions of the QPNM, MPM, and SCCM models, which predict a ratio of approximately 1.8, as listed in Table III. Also given in this table are the energy ratios $E_x(4^+_{\gamma\gamma})/E_x(2^+_\gamma)$, and good agreement is found between experiment and theory.

The rather large interval for $B(E2;2173\rightarrow 2^+_\gamma)$ covers the values expected for a weakly collective state, to a highly collective one. While there appears to be some degree of collective enhancement, the uncertainty on the $B(E2)$ value does not allow one to determine definitely if the 2173 keV level is predominately two-phonon in character, or if it merely has a minor two-phonon component in its wave function. If the K values for the states were good quantum numbers, transitions which violated the $\Delta K \leqslant \lambda$ rule, λ being the multipolarity of the γ ray, would not be observed. Therefore, the placement of the 1930.8 keV γ ray implies a certain degree of K mixing in the wave functions. Since the low-spin members of the ground-state band are energetically very isolated from other levels of the same spin, and hence are expected to remain rather pure with $K=0$, it is likely that the K mixing occurs in the wave function for the 2173 keV level. Thus, it can be argued that the 2173 keV level cannot be a pure $K^\pi=4^+$ two phonon state, and the (probable) $B(E2)$ ratio of unity may be a reflection of K mixing. It is noteworthy that K mixing was also invoked to explain deviations from the Alaga rules observed for the double phonon states in ^{166}Er and ^{168}Er. An alternative explanation could be mixing of the $K^\pi=4^+$ state with the known two quasiparticle state at 2194 keV [26]. This might explain the population of the level in the β decay of ^{164}Tb and the decay branch to the ground state band.

TABLE III. Comparison of the experimental energy and $B(E2)$ ratios with model predictions [25,11,9] for the proposed double-γ state.

	Exp.	QPNM	SCCM	MPM
$\frac{E_x(4^+_{\gamma\gamma})}{E_x(2^+_\gamma)}$	2.85	2.83–2.93	2.63	2.82–3.02
$\frac{B(E2;4^+_{\gamma\gamma}\rightarrow 2^+_\gamma)}{B(E2;2^+_\gamma\rightarrow 0^+_{\mathrm{gsb}})}$	0.5–3.9	1.94	1.83	1.75

In this work, candidates for the $K^\pi=4^+$ double-γ vibration in ^{164}Dy were sought. To this aim thermal neutron capture was used. The measurements involved the use of crystal spectroscopy, coincidence measurements, electron spectroscopy, and the γ-ray induced doppler broadening method. An $I,K^\pi=4,4^+$ state exhibiting some degree of collective enhancement in its decay was found at 2173 keV. This collective enhancement suggests a two-phonon γ-vibration component in its wave function, although the present data does not determine if it is the dominant component in the wave function. If the most probable lifetime for the 2173 keV level is adopted, the $B(E2;4^+\rightarrow 2^+_\gamma)$ value is similar to those of $4^+_{\gamma\gamma}$ states in ^{166}Er and ^{168}Er, and reasonable agreement would be found with all theoretical models which predict two-phonon γ-vibrational states in ^{164}Dy. As such, in all nuclei for which all the theoretical models predict a collective double-γ vibration, i.e., ^{166}Er, ^{168}Er, and ^{164}Dy, a collective state occurs at the right energies. Whether the double-γ vibration also exists in other nuclei and at relatively low-excitation energies remains an open question. For that reason, it would be very useful to measure lifetimes for more controversial candidates.

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