Evidence for the Existence of Two-Phonon Collective Excitations in Deformed Nuclei

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For the first time, definite evidence for the existence of two-phonon collective states in deformed nuclei has been established through the measurement of the absolute transition rate for the decay of the double-γ $K^\pi=4^+$ vibration in ^{168}Er.

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For nearly three decades a significant issue in the nuclear structure of deformed nuclei has been whether or not two-phonon collective excitations, such as, e.g., double-γ or double-β vibrations, exist. This issue is central to our understanding of collectivity in nuclei and to the role of the Pauli principle in modulating the possible harmonic spectrum of multiphonon vibrational excitations. It also reflects directly on the practical intractability of large-basis shell-model calculations in heavy deformed nuclei and on the consequent needs to truncate the space used in the model calculations. As a consequence of this need, different truncation schemes, introducing different approximations, have reached different conclusions.

For example, for years the quasiparticle-phonon nuclear model[1] (QPNM), which restricts the basis to, at most, two-phonon states, has led to the conclusion that two-phonon collective vibrational excitations will not exist in deformed nuclei due to Pauli blocking of important quasiparticle components.

On the other hand, the multiphonon method[2] (MPM) embodies an entirely different truncation scheme. It uses only a few collective phonons and restricts the basis to all the corresponding multiphonon states up to eight phonons. This approach predicts that, for strongly collective vibrations, two-phonon $K^\pi=4^+$ excitations should appear at an energy of about 2.6 times the energy of the one-phonon $K^\pi=2^+$ state and keep some collective character in their decay to that one-phonon state.

Another model which does so is the extended interacting-boson model[3] (*sdg*-IBM) which gives extra SU(3) representations compared to the original *sd*-IBM model. Broken-SU(3) calculations in this approach[3] predict a $K^\pi=4^+$ band near 2 MeV in ^{168}Er with properties closely resembling a two-phonon γ vibration.

While these theoretical approaches differ mainly in their truncation schemes, they share an emphasis on the valence shells. By contrast, the dynamic-deformation model[4] (DDM) constructs the collective potential starting from a set of deformed single-particle basis states accommodating eight major shells. With no free parameters it also predicts a collective $K^\pi=4^+$ bandhead at almost exactly 2 MeV (but finds 1.075 MeV for the γ bandhead).

An alternative approach, the pseudosymplectic model (PSM), also brings into play a full multi-$\hbar\omega$ space. Here, an algebraic approach[5] utilizing the symplectic group structure Sp(3,*R*), based on the pseudo-SU(3) scheme, is exploited which allows the multishell complexity to be reduced by symmetry constraints. The Sp(3,*R*) approach, which incorporates several major shells, has the further interesting feature that the giant resonances and low-lying collectivity are treated on the same footing, without the need for effective charges. This approach also predicts high collectivity for the double-γ vibration.

The same problem has also been studied by Matsuo within the self-consistent collective-coordinate method (SCCM).[6] This theory describes large-amplitude collective motions like the strong nonlinear nuclear γ vibration in ^{168}Er and also predicts a $K=4$ $\gamma\gamma$ vibration.

In sum, the issue of the multiphonon vibrations in deformed nuclei elegantly exposes one of the unique features of the atomic nucleus, and of the many-body problem in finite quantal systems, namely, the interplay of single-particle quantum states and collective excitations incorporating ensembles of them.

The nucleus ^{168}Er offers a unique opportunity to test these different alternative theoretical approaches, and hopefully to finally resolve this issue. In many other deformed nuclei, the lowest collective vibration, generally the γ band, lies near or above 1 MeV, placing the expected two-phonon excitation considerably above 2 MeV, and therefore amidst the high density of levels that appear beyond the pairing gap. In ^{168}Er, however, the lowest state belonging to the γ vibration lies at 821 keV, opening up the possibility that the two-phonon γ vibration might occur in a reasonably clean part of the spectrum. An earlier detailed study of ^{168}Er (Ref. 7) with the (n,γ) reaction developed an essentially complete level scheme up to slightly more than 2 MeV of excitation. A result of this study was that the *lowest possible candidate* for a two-phonon $K^\pi=4^+$ γ vibration was the 4^+ bandhead at 2.055 MeV. This is the lowest-lying intrinsic $K^\pi=4^+$ excitation and it also has the expected energy and decay properties of a dominant $E2$ branch to the single-phonon γ vibration. However, as in other deformed nuclei where candidates for two-phonon states have been proposed,[8] $E2$ branching ratios are not a definitive test. Absolute $B(E2)$ values are needed to demonstrate collectivity and are not yet known.

It is the purpose of this Letter to report the measurement of the $B(E2{:}4^+ \rightarrow 2^+\gamma)$ value in ^{168}Er, as well as the companion one from the 5^+ rotational excitation of the $K=4$ band to the $3^+\gamma$ state. This will determine if these are of collective magnitude, and will allow a comparison of the experimental results with several theoretical approaches.

This study became possible only because of the development of a new method for lifetime measurements in nuclei near stability, the γ-ray-induced Doppler-broadening (GRID) technique[8,9] which exploits the remarkable energy resolution of the double-flat-crystal spectrometer GAMS4,[10] installed at the Institut Laue-Langevin (ILL) in Grenoble. This technique is based on the measurement of the extremely small Doppler shift characterizing a γ ray emitted from a nucleus which is recoiling in the bulk of the target due to the prior emission of another γ ray following thermal neutron capture. As the recoil directions are isotropically distributed, this leads to the measurement of a Doppler broadening for γ transitions emitted in flight. By comparing the time of γ-ray emission to the slowing down time in the target, the lifetime of excited nuclear levels can be measured. In heavy nuclei, such broadening typically amounts to only a few eV. An accurate determination of the level lifetimes via this Doppler technique therefore involves both highly precise energy measurements and careful calibrations.

The main problem encountered in GRID studies of such heavy deformed nuclei comes from the lack of knowledge of the recoil-velocity distribution at the moment the state under investigation is populated. This in turn is due to the presence of a multitude of paths feeding this level from the neutron-capture state. Generally, a level is fed not only by a primary transition (which would give a unique recoil velocity of $v_R = E_\gamma/Mc$) but also by multiple γ-ray cascades. The observed Doppler-broadened profile is then a function of three separate conditions: the original velocity distribution of the recoiling atoms, involving the energies and lifetimes of the intermediate states in the feeding cascades; the time differential behavior (slowing down) of the recoiling atoms; and the lifetime of the nuclear state, which deexcites by the emission of the γ ray being observed. The principle of the GRID technique is that, provided the first two are known, the lifetime can be extracted. Details concerning the experimental setup as well as the model used to describe the slowing down at these recoil velocities can be found in Ref. 9.

The original recoil distribution can—in principle—be calculated from a statistical-model description of nuclear states and transitions. Using (a) a constant-temperature Fermi-gas model[11,12] (CTF) and (b) the Bethe formula[11,12] we obtain, for the ^{168}Er levels in question, slightly different recoil distributions and hence slightly different lifetimes. Since this is the first use of such models for the description of feeding patterns in GRID measurements, the possible systematic errors produced by this approach are not yet well characterized. However, we can set stringent, model-independent, limits for the lifetimes in question by applying extreme feeding assumptions deduced from the previous extensive study of the level scheme.[7] From these data we can limit the primary feeding of the 4^+ (2.055 MeV) level to $5\% < 1\gamma < 20\%$ and of the 5^+ (2.169 MeV) level to $3\% < 1\gamma < 15\%$ of the total feeding strength for each level, respectively (see Fig. 1, inset). Combining these limits with extreme assumptions for the remaining feeding leads to the highest and lowest possible recoil-velocity distributions. The upper limit of the lifetime can be obtained by assuming the highest possible primary feeding fraction with the remainder from two-step feeding cascades via intermediate levels of "zero" lifetime. The lower limit is obtained from the other extreme, namely, the lowest possible direct primary feeding with the remainder via low-energy transitions with "infinite" lifetimes of the intermediate levels (e.g., only the immediately preceding transitions contribute to the recoil). For the purpose of this Letter

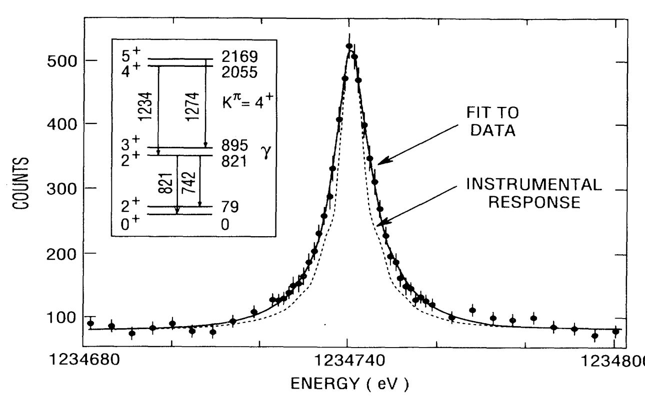

FIG. 1. Measured profile of the 1234-keV transition from a summation of ten individual scans. The solid-line fit to the data uses the Bethe formula for the extraction of the recoil velocities ($\tau=440$ fs). The dashed-line profile is the measured instrumental response function. Inset: Part of the ^{168}Er decay scheme.

TABLE I. Lifetimes obtained for the 2055-, 2169-, and 821-keV levels, respectively, using different approaches to describe the original recoil-velocity distributions. The quoted values come from a simultaneous fit to all individual scans using the computer code GRIDDLE (Ref. 13).

E_x (keV)	E_γ (keV)	τ (ps) (with Bethe)	τ (ps) (with CTF)	τ (ps) (lower limit)	τ (ps) (upper limit)
2055	1234	$0.44^{+0.09}_{-0.07}$	$0.55^{+0.11}_{-0.08}$	>0.24	<0.69
2169	1274	$0.26^{+0.13}_{-0.07}$	$0.34^{+0.15}_{-0.09}$	>0.10	<0.50
821	741	$3.5^{+2.1}_{-0.9}$	$4.3^{+2.7}_{-1.2}$		

the upper limit is the more important one.

The target, consisting of 3 g of natural Er_2O_3, was exposed to a thermal neutron flux of 5×10^{14} $n/\mathrm{cm}^2\mathrm{s}$, in the throughgoing beam tube H6-H7 of the ILL high-flux reactor.

The principal aim of this study is to obtain definite values for the lifetimes of the 4^+ and 5^+ states, at 2055 and 2169 keV, respectively, by measuring the Doppler broadening of the transitions of 1234 keV ($4^+\to2^+\gamma$) and 1277 keV ($5^+\to3^+\gamma$). In order to obtain high statistical precision these lines where scanned 14 and 8 times, respectively. Figure 1 shows a summation of ten individual scans for the 1234-keV transition (the remaining four were scanned in another reflection order). Also shown are the predicted line shapes for $\tau\gtrsim10$ ps and $\tau=40$ fs (using the statistical feeding obtained via the Bethe formula) from which it is evident that the profile is a sensitive function of the lifetime. The results for both levels are given in Table I, which gives the lifetimes as obtained with the two statistical-model approaches (Fermi gas and Bethe formula) as well as the limits obtained under the most extreme, model-independent, assumptions concerning the feeding. It is clear that the data are not overly sensitive to the details of the statistical-model feeding and that even the limits derived from the extreme feeding assumptions, detailed above, define a region of values which still allows definitive nuclear-structure interpretations. The error induced by the model-dependent slowing-down description is not included, but estimated to be of the order of 20%. As a consistency check, the lifetime measured for the 821-keV γ bandhead (see Table I) can be compared with previous measurements[14] reported as $\tau=3.93(13)$ ps. This also demonstrates that the GRID technique is sensitive to lifetimes as long as 4 ps in a nucleus such as ^{168}Er. From the limits for the lifetimes of the 4^+ and 5^+ levels, we obtain

$$0.014\,e^2\mathrm{b}^2 < B(E2{:}4^+\gamma\gamma\to2^+\gamma) < 0.041\,e^2\mathrm{b}^2,$$

$$0.017\,e^2\mathrm{b}^2 < B(E2{:}5^+\gamma\gamma\to3^+\gamma) < 0.090\,e^2\mathrm{b}^2.$$

These values are of the same order of magnitude as the known value of the $B(E2{:}2^+\gamma\to0^+)=0.0264(9)\ e^2\mathrm{b}^2$ and thus clearly demonstrate that these transitions are collective in nature.

This result supports the interpretation of the MPM, *sdg*-IBM, SCCM, DDM, and PSM approaches. A further test is provided by the description of the anharmonicities which are already present in the excitation energy of the $K=4^+$ bandhead. In a harmonic approach this excitation energy would be about twice that of the γ bandhead. Also such an approach gives a $B(E2{:}4^+\gamma\gamma\to2^+\gamma)$ that is 5.55 times the γ-to-ground $B(E2)$ value. The $B(E2)$ value obtained here confirms the anharmonic character of the γ degree of freedom which was already noted in the excitation energy [$E(K=4^+\gamma\gamma)\approx2.6E(K=2^+\gamma)$].

A quantitative comparison with specific models is more stringent and more revealing. To this end, we present such a comparison in Table II. The comparison includes the predictions of QPNM, MPM, SCCM, DDM, *sdg*-IBM, and two versions of the pseudo-SU(3) approach, one being the multi-$\hbar\omega$ Sp(3,*R*) symplectic model and the other a simpler, single-shell, pseudo-SU(3) approach. In Table II we compare the experimentally determined $B(E2)$ ratio

$$R(4^+)=B(E2{:}4^+\gamma\gamma\to2^+\gamma)/B(E2{:}2^+\gamma\to0^+)$$

with that predicted by the different models. This ratio is particularly sensitive to the phonon character of the 4^+ level.

Table II clearly shows that the quasiparticle-phonon model does *not* reproduce the data, while *all* the approaches in which the $K=4$ band is essentially of two-phonon structure are remarkably close to the experimental result. Indeed, it is interesting in itself that some of

TABLE II. Comparison of the experimental and several theoretical $B(E2)$ ratios: $R(4^+)=B(E2{:}4^+\gamma\gamma\to2^+\gamma)/B(E2{:}2^+\gamma\to0^+g)$.

	$R(4^+)$
Expt.	$0.52<R(4^+)<1.61$
QPNM	$<10^{-3}$ [a]
MPM	1.1
sdg-IBM	1.4
DDM	3.5
SCCM	3.7
Sp(3,*R*)	1.2
Pseudo-SU(3)	1.2

[a]Deduced from the wave functions given in Ref. 1.

these rather different approaches give such compatible results, all reflecting the essentially simple underlying two-phonon character of the $K=4$ band. It is apparent, however, that the SCCM (which predicts the correct anharmonicity for the energies) and DDM (which predicts a harmonic spectrum) predictions more closely resemble the harmonic approach and thus lie further from the experimental values for $R(4^+)$.

The measurement of lifetimes for both the 4^+ and 5^+ levels also allows a better analysis of the rotational character of the $K=4$ band and might give some clues as to its mixing with other rotational bands. Although the experimental errors are large, it appears that the measured $B(E2)$ values deviate somewhat from the Alaga rules.

To summarize, using the GRID technique for the first time in a deformed nucleus, we have measured the lifetimes of the 4^+ and the 5^+ levels of the $K^\pi=4^+$ intrinsic excitation at 2.055 MeV in ^{168}Er. The results are

$$0.014\,e^2\mathrm{b}^2 < B(E2{:}4^+(K=4)\rightarrow 2^+\gamma) < 0.041\,e^2\mathrm{b}^2\,,$$

$$0.017\,e^2\mathrm{b}^2 < B(E2{:}5^+(K=4)\rightarrow 3^+\gamma) < 0.090\,e^2\mathrm{b}^2\,.$$

Since the $B(E2{:}2^+\gamma\rightarrow 0^+g)=0.0264(9)\ e^2\mathrm{b}^2$, these results show, for the first time, definite evidence, from absolute transition rates, for the existence of essentially intact two-phonon vibrational states in deformed nuclei and show that they keep collective character in their decay. This settles the long-standing issue of whether such states can exist or whether they would be fragmented (by mixing with nearby "single-particle" states). The experimental results are well reproduced by several models, in all of which the $K^\pi=4^+$ excitation has essentially the character of a double-γ vibration.

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