PHYSICAL REVIEW C

NUCLEAR PHYSICS

THIRD SERIES, VOLUME 57, NUMBER 4 APRIL 1998

RAPID COMMUNICATIONS

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The first excited 0^+ state in ^{152}Sm

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(Received 3 September 1997)

The properties of $K=0^+$ excitations in deformed and transitional nuclei have recently been of intense interest. We present results of a study of the deexcitations of the lowest excited 0^+ state in ^{152}Sm from the ϵ-decay of ^{152}Eu, yielding one of the few precisely known values of the branching ratio $R_{0g}^{\gamma}=B(E2;2_{\gamma}^+\to 0_2^+)/B(E2;2_{\gamma}^+\to 0_1^+)$ $=0.048(4)$, which is extraordinarily small. From $T_{1/2}(2_{\gamma}^+)$ we also obtain $B(E2;2_{\gamma}^+\to 0_2^+)=0.17$ W.u. Values of R_{0g}^{γ} calculated in the interacting boson model (IBA) go to zero extremely rapidly, changing by orders of magnitude for a narrow range of parameter values. ^{152}Sm is a rare case of a transitional nucleus that lands almost at the minimum. ^{152}Sm and ^{154}Gd are the only nuclei from $90\leqslant N\leqslant 114$ where the $B(E2)$ values for all four transitions $2_{\gamma}^+\to 0_2^+$, $2_{\gamma}^+\to 0_1^+$, $0_2^+\to 2_1^+$, and $2_1^+\to 0_1^+$ are now known. In ^{152}Sm these $B(E2)$ values span three orders of magnitude, from 144 to 0.17 W.u. and are reproduced to within a factor of 2–3 by the IBA. The rather strong $B(E2;0_2^+\to 2_1^+)$ value of 33 W.u. suggest that the 0_2^+ level is an example of a good low energy β-vibration. [S0556-2813(98)50104-5]

PACS number(s): 21.10.Re, 21.60.Fw, 23.20.Js, 27.70.+q

The study of phonon and multiphonon states is crucial to our understanding of collectivity in nuclei. Although the γ-vibrational mode has been well determined, the nature of $K=0^+$ excitations in deformed and transitional nuclei has remained enigmatic, despite much study, both experimental and theoretical. Interpretations as β-vibrations, 2-phonon γ-vibrations, and 2-quasiparticle excitations, or a mixture thereof, compete. Key observables providing clues to their structure are $B(E2)$ values connecting 0^+ states to the γ-band and appropriate branching ratios involving these 0^+ states. If the 0^+ states are β vibrations, the reduced matrix elements $\langle K=0\|E2\|\gamma\rangle$ should be weak (forbidden in the harmonic deformed collective model). They are unlikely to be strong in the 2-quasiparticle case either. However, a $K=0$ $\gamma\gamma$-2-phonon state should have a collective $E2$ matrix element to the 1-phonon γ-band, comparable to the $\gamma\to g$ matrix element.

The two branching ratios:

$$R_{\gamma g}^{0}=\frac{B(E2;0_2^+\to 2_{\gamma}^+)}{B(E2;0_2^+\to 2_1^+)}, \qquad (1)$$

$$R_{0g}^{\gamma}=\frac{B(E2;2_{\gamma}^+\to 0_2^+)}{B(E2;2_{\gamma}^+\to 0_1^+)} \qquad (2)$$

where the superscript labels the initial state, are, along with absolute $B(E2)$ values, the essential information needed to address these issues in deformed nuclei. The first ratio is most useful if the 0_2^+ state is above the γ-bandhead, and the second if the order is reversed. Unfortunately, only a handful of $R_{\gamma g}^{0}$ values are known (most of these have $R_{\gamma g}^{0}>1$). R_{0g}^{γ} values are even rarer since the γ-band is usually below the lowest $K=0^+$ band. The nucleus ^{152}Sm, however, provides a good case study since the 0_2^+ excitation lies sufficiently below the 2_{γ}^+ level that one might expect to be able to ob-

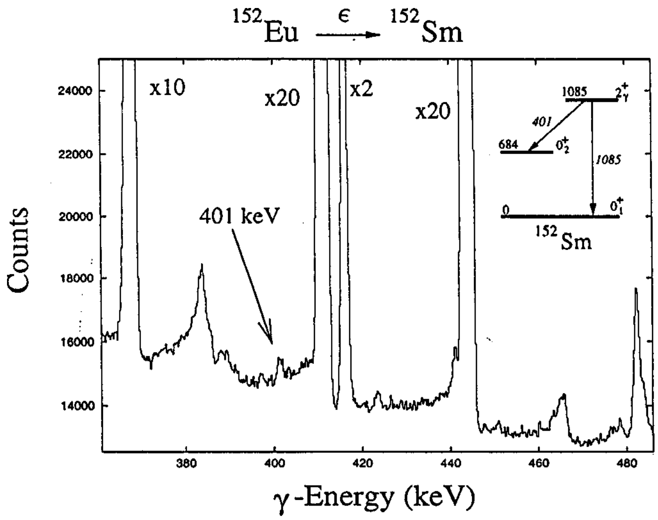

FIG. 1. Portion of the γ-ray spectrum of ^{152}Sm observed in the decay of ^{152}Eu. The 401 keV $2_\gamma^+ \to 0_2^+$ transition is marked.

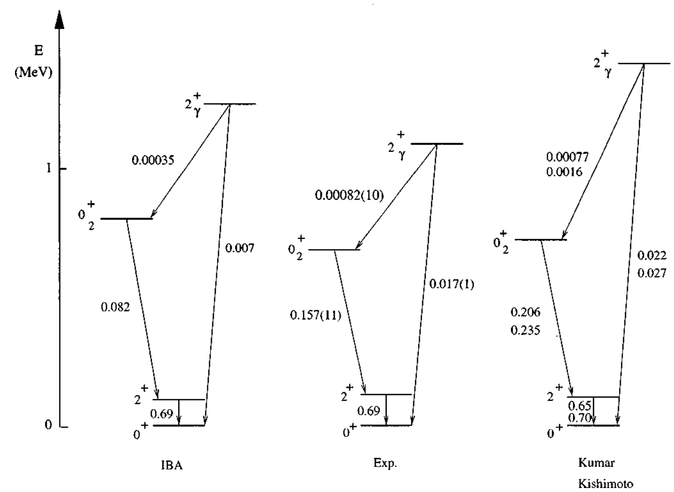

FIG. 2. Experimental results from this study along with calculations with the IBA (left) and by Kumar [7] and Kishimoto and Tamura [8] (right). The $B(E2)$ values are given in units of e^2b^2. For the IBA, the parameters are $N_B=10$, $\epsilon=470$ keV, $\kappa=20$ keV, $\chi = -\sqrt{7}\ /2$. The effective charge has the typical value of $e_B = 0.13$ eb. For the calculations on the right, the upper $B(E2)$ values are from Kumar [7], and the lower from Kishimoto and Tamura [8]. The excitation energies in the two calculations are very similar. For definiteness, those of Kumar are shown.

serve their connecting γ-ray and yet the ratio R_{0g}^{γ} is not known. Actually, a value for the relative intensity for the $2_\gamma^+ \to 0_2^+$ transition has been reported [1], but with 100% uncertainty, and subsequent evaluators [2,3] have decided to drop it from the list of adopted γ-radiations. In fact, although the 1969 result had been discarded, it is actually not far from the much more accurate value we present here.

It is the purpose of this Rapid Communication to present new results on the ϵ decay of ^{152}Eu ($T_{1/2} = 13.5$ y) to ^{152}Sm, yielding one of the first results for a precise branching ratio from the γ-band to excited and ground $K=0^+$ bands and for an absolute $2_\gamma^+ \to 0_2^+$ matrix element. We will show that the ^{152}Sm result represents an isolated phenomenon. In the interacting boson model (IBA) it corresponds to a very narrow pocket of parameter values that seems applicable only within the class of transitional nuclei where the first excited 0^+ state is below the quasi-γ-band. The IBA reproduces the four $B(E2)$ values, $B(E2;2_\gamma^+ \to 0_2^+)$, $B(E2;2_\gamma^+ \to 0_1^+)$, $B(E2;0_2^+ \to 2_1^+)$, $B(E2;2_g^+ \to 0_1^+)$, which span three orders of magnitude, to within a factor of 2–3. Moreover, the R_{0g}^{γ} goes to zero in the IBA for a narrow range of parameters and ^{152}Sm appears to be a rare example of a nucleus that occurs nearly at the minimum.

The experiment utilized anti-Compton suppressed Ge detectors from the OSIRIS Cube array [4] at the Institut für Kernphysik in Köln. The detectors have typical photopeak efficiency of $\epsilon_{ph}=25\%$ of NaI. The resolution ranged from $\Delta E \sim 1.3$ keV at $E_\gamma=300$ keV to $\Delta E \sim 2$ keV at $E_\gamma=1$ MeV. A standard ^{152}Eu source of strength 7.2 μCi was placed at the target position of the OSIRIS cube. Figure 1 shows the interesting portion of the γ-ray spectrum along with a partial level scheme (inset). The level scheme of ^{152}Sm is extremely well known below the ^{152}Eu decay energy of 1769.10 keV. The *only* location where the 401.4(2) keV transition, clearly observed in Fig. 1, can fit, is from the 2_γ^+ level to the 0_2^+ level. The placement is therefore reliable. We can thus deduce an experimental value of R_{0g}^{γ},

$$R_{0g}^{\gamma} = 0.048 \pm 0.004.$$

[Note the interesting fact that if, for some reason, the 401 keV transition is not correctly assigned in ^{152}Sm, then the branching ratio R_{0g}^{γ} must be even *smaller* and all the discussion and calculations below become even more interesting.] The lifetime of the 2_γ^+ state is known [3,5,6] and hence the data yield the absolute value for the $B(E2;2_\gamma^+ \to 0_2^+)$ of 0.17 W.u. as well. These results and the calculations discussed below are shown in Fig. 2. Clearly, we can conclude that the 0_2^+ excitation in ^{152}Sm is not a $\gamma\gamma$-double-phonon mode. Since the $B(E2;0_2^+ \to 2_1^+)$ value is nearly twice as large as the $B(E2;0_1^+ \to 2_\gamma^+)$ value, the 0_2^+ state seems to have a collective $E2$ relationship to the ground state. Thus it is a good candidate for a true β-vibration—a mode which is in fact rarely established [9] in deformed nuclei despite the commonly used terminology and common perception. It is interesting therefore that an example appears at low energy in the transitional nucleus ^{152}Sm.

The present results constitute one of a handful of known examples of an $E2$ transition connecting the γ-band and the lowest excited $K=0^+$ band. Usually, these bands lie close in energy so that the E_γ^5 energy dependence of $E2$ transitions weakens the transition strength between them *even if* the intrinsic matrix element is large. For nuclei where the 0_2^+ band lies *below* the γ-band there are only two other known examples: In the near-sibling nucleus ^{154}Gd (also transitional with $N=90$), $R_{0g}^{\gamma}=0.21(5)$ [10] and in ^{172}Yb, where the γ-band lies very high [$E(2_\gamma^+)=1466$ keV], $R_{0g}^{\gamma}=1.82$ (23) [11].

It is a challenge to interpret the present results theoretically. In the IBA [12], an appropriate approach is that of the extended consistent Q-formalism (ECQF) [13] where

$$H = \kappa\left(\frac{\epsilon}{\kappa} n_d - Q \cdot Q\right) \tag{3}$$

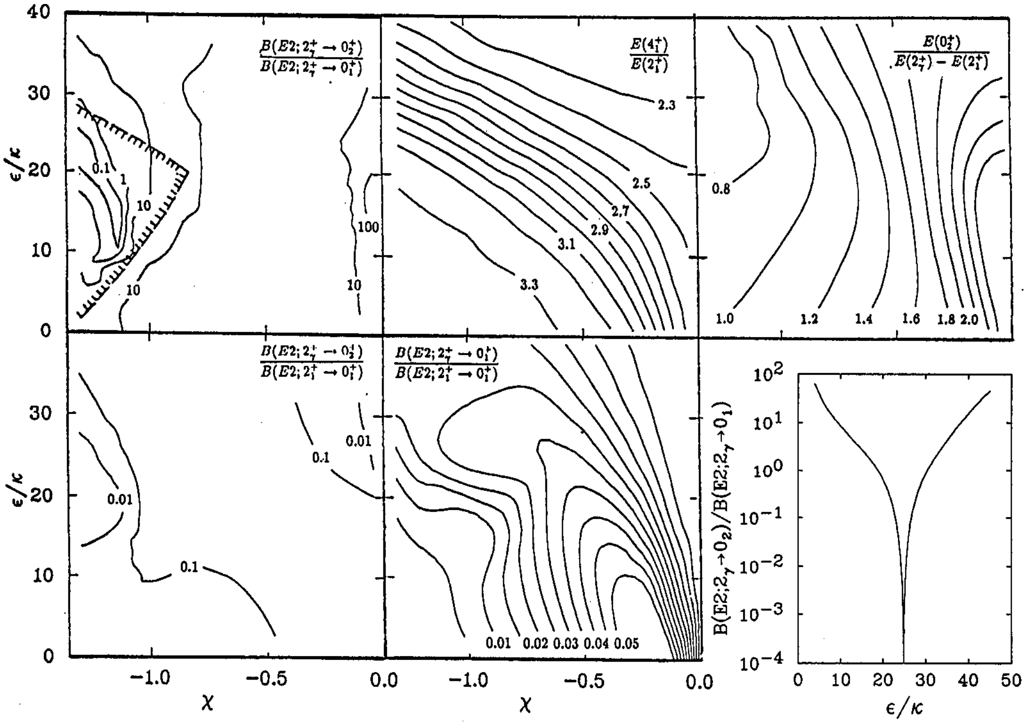

FIG. 3. Contour plots, calculated in the ECQF for boson number $N_B=10$, relevant to the discussion of the structure of the 0_2^+ state. The lower right-most panel shows the behavior of R_{0g}^{γ} against ϵ/κ for $\chi=-\sqrt{7}/2$, exhibiting an extremely sharp minimum ($R_{0g}^{\gamma}\rightarrow 0$ at $\epsilon/\kappa\rightarrow 24.85$). See text for discussion.

with

$$Q=(s^{\dagger}\tilde{d}+d^{\dagger}s)+\chi(d^{\dagger}\tilde{d})^{(2)} \quad (4)$$

and the $E2$ operator is $T(E2)=e_BQ$, where e_B is an effective charge. The same χ value is used in the Hamiltonian and the $E2$ operator $T(E2)$. In the ECQF, the symmetries are obtained with the following parameters: U(5): $\kappa=0$, $\chi=0$; O(6): $\epsilon=0$, $\chi=0$; SU(3): $\epsilon=0$, $\chi=-\sqrt{7}/2\simeq-1.32$. Since there are only two parameters, ϵ/κ and χ, that determine the structure [wave functions and $B(E2)$ values], one can construct contour plots of any observable against ϵ/κ and χ. We have calculated a number of such observables in the IBA with the code PHINT [14]. They are shown in Fig. 3.

The most striking and relevant result for this study is that there is only a single small pocket of parameter combinations of χ and ϵ/κ that gives $R_{0g}^{\gamma}<1$, as shown in the top left panel of Fig. 3. This pocket slopes diagonally downward to the right from $\chi=-1.32$ and $\epsilon/\kappa\sim$ 30 to $\chi\sim-1.1$ and $\epsilon/\kappa\sim10$. These are the *only* parameter combinations for the IBA Hamiltonian of Eq. (3) that give preferential decay of the γ-band to the ground band rather than to the $K=0^+$ band for a boson number $N_B=10$. It is interesting to inspect the individual $B(E2)$ values in more detail to understand the behavior of R_{0g}^{γ}. The lower panels of Fig. 3 show the $B(E2;2_{\gamma}^+\rightarrow0_2^+)$ and $B(E2;2_{\gamma}^+\rightarrow0_1^+)$ values on a consistent scale relative to the $B(E2;2_1^+\rightarrow0_1^+)$ value. The most interesting point is that the $B(E2;2_{\gamma}^+\rightarrow0_1^+)$ value behaves smoothly throughout the contour plot, while the $B(E2;2_{\gamma}^+\rightarrow0_2^+)$ value actually drops to zero, changing by *orders of magnitude* in the very restricted range of parameter values, $\epsilon/\kappa\sim20-30$, $\chi\sim-1.32\rightarrow-1.2$. It is therefore especially the drop in this $B(E2;2_{\gamma}^+\rightarrow0_2^+)$ value [and not the $B(E2;2_{\gamma}^+\rightarrow0_1^+)$ value] that leads to R_{0g}^{γ} values $<$ 1.

The vanishing of the $B(E2;2_{\gamma}^+\rightarrow0_2^+)$ value does not relate to a level crossing or to mixing of the 2_{γ}^+ and $2_{K=0_2^+}^+$ states. Rather, it results from a specific cancellation in the two contributions to the matrix element, from the $(s^{\dagger}d+d^{\dagger}s)$ and $(d^{\dagger}d)^2$ terms in the $E2$ operator of Eq. 4. [The $(d^{\dagger}d)^2$ term decreases rapidly and changes sign at $\epsilon/\kappa=24.85$ while the $(s^{\dagger}d+d^{\dagger}s)$ term is more or less stable.] Interestingly, though these calculations with a large ϵ, are far from SU(3), this is the same *type* of cancellation mechanism that characterizes the vanishing of $K=0\rightarrow g$ and $\gamma\rightarrow g$ $B(E2)$ values in that limit. It would be interesting to study whether this cancellation is accidental or the result of a selection rule from some undiscovered symmetry property.

It is also interesting to relate this pocket of parameters to values for $R_{4/2}\equiv E(4_1^+)/E(2_1^+)$ and $R_{02}\equiv E(0_2^+)/[E(2_{\gamma}^+)-E(2_1^+)]$. The experimental values in ^{152}Sm are $R_{4/2}=3.01$ and $R_{02}=0.71$. Contour plots for these observables, similar to those in Ref. [15], are shown on the top in Fig. 3. The loci of $R_{4/2}>3.0$, denoting deformed nuclei, and $R_{02}<1.0$, denoting nuclei where the 0_2^+ state is below the 2_{γ}^+ level, are indicated in the top left panel as the area to the left of the angled-hatched border. We note the confluence of these results: the $R_{4/2}$ and R_{02} observables constrain the parameter space almost identically as R_{0g}^{γ}. Indeed, this panel makes clear that preferential decay of the γ-band to the $K=0^+$

band is, by far, the norm in the IBA and that small R_{0g}^{γ} values should occur only for a particular small subset of nuclei where the $K=0^+$ band is near or below the γ-band and where $R_{4/2}\geqslant 3.0$.

The particular parameter range where $R_{0g}^{\gamma}<1$ is of interest in another context. Traditionally, nondeformed nuclei have been associated with small values of $|\chi|$ in the ECQF, whereas we have associated large $|\chi|$ with ^{152}Sm. However, the results of a recent global summary [15] of 145 nuclei from $Z=50-82$, $N=82-126$, show that the best parameters for near vibrational and transitional nuclei do indeed involve large $|\chi|$ values. Interestingly, this result was actually suggested by Lipas, Toivonen, and Warner [13] over a decade ago.

To reproduce the observed value of R_{0g}^{γ} as well as the $B(E2)$ values in ^{152}Sm, the allowable parameters collapse to essentially a single point given by $\epsilon=470$ keV, $\kappa=20$ keV, and $\chi=-1.32$. It is worth stressing how extremely sensitive R_{0g}^{γ} is to ϵ (or ϵ/κ). Near the minimum value ($R_{0g}^{\gamma}=0$), a 0.02%($\sim$0.1 keV) change in ϵ changes R_{0g}^{γ} by over 100%. This is illustrated in the lower right-most panel of Fig. 3 which gives the R_{0g}^{γ} values for a cut in the upper left panel of this figure corresponding to $\chi=-1.32$. The dependence on ϵ/κ has a near singularity at $\epsilon/\kappa=24.85$.

The observable R_{0g}^{γ} seems to be a heretofore unrecognized, yet highly sensitive, signature of the class of shape transition exhibited in the $A=150$ mass region. R_{0g}^{γ} has the kind of behavior that has long been sought as a marker of the structural transition from spherical to well deformed but whose existence was in doubt. Indeed, the behavior of R_{0g}^{γ} highlights the remarkable nature of ^{152}Sm. Since ϵ/κ is a continuous variable whereas nuclear structure varies as a function of discrete variables (proton and neutron numbers), one would hardly have expected an actual nucleus to exhibit the extreme behavior seen in the lower right panel of Fig. 3. One would anticipate at best a highly modulated dip in R_{0g}^{γ} for some (N,Z) value. It is therefore striking that a particular nucleus, ^{152}Sm, seems to land almost exactly at the minimum. While other cases of such nuclei are not known, it is possible that they may exist far off stability and may be found in future radioactive beam experiments.

With the above set of parameters for ^{152}Sm we can compare IBA calculations for a number of interesting $E2$ observables with the data since the 0_2^+ and 2_γ^+ lifetimes are known [3]. The comparison is shown in Fig. 2. This figure also includes a comparison with the $B(E2)$ values from two other existing calculations–those of the pairing plus quadrupole model of Kumar [7] and those of Kishimoto and Tamura [8]. In both cases the predictions were made long before the present data were obtained and are also remarkably good. Both the IBA and these microscopic calculations reproduce the energies and the key $E2$ observables relating to the collective character of the equilibrium ground state configuration and the lowest intrinsic modes, even though these $B(E2)$ values range *over three orders of magnitude*.

From these results we can also extract the independent $B(E2)$ ratio of Eq. (1), namely $R_{\gamma g}^{0}$. The results are $R_{\gamma g}^{0}$(exp) $=0.026(4)$ and $R_{\gamma g}^{0}$(IBA)$=0.021$. It is interesting and instructive that the IBA results (and the data) for ^{152}Sm deviate from the ''robust'' predictions of Ref. [16] and the theorem of Ref. [17] by more than an order of magnitude. The reason is that the ''rules'' of Refs. [16,17] apply only to deformed nuclei and the use of only the $Q\cdot Q$ term in the IBA Hamiltonian. Clearly, they do not apply to transitional nuclei with a large ϵn_d term, such as ^{152}Sm.

In summary, we have measured the ratio $R_{0g}^{\gamma}=B(E2;2_\gamma^+\rightarrow 0_2^+)/B(E2;2_\gamma^+\rightarrow 0_1^+)$ in ^{152}Sm and found a value of 0.048(4). This is one of only three such values that are known in nuclei with $R_{4/2}>3.00$. The value for R_{0g}^{γ} is extremely small and can be reproduced in the IBA for $N_B=10$ by $\epsilon/\kappa\sim 23$ and $\chi\sim-\sqrt{7}/2$. These IBA calculations also reproduce approximately the observed excitation energies of the $K=0^+$ and γ- excitations, as well as the essential $B(E2)$ values defining the equilibrium structure of the ground state and the collective vibrational structure of the lowest $K=2^+$ and 0^+ modes to within a factor of 2–3. This is remarkable if one considers the fact that the empirical $B(E2)$ values range over three orders of magnitude. The IBA parameters for ^{152}Sm do not remotely correspond to any of the dynamical symmetries of the model and appear to be unique to a certain class of transitional nuclei, exemplified by ^{152}Sm. In the IBA, R_{0g}^{γ} exhibits an extremely sharp minimum ($R_{0g}^{\gamma}\rightarrow 0$ for $\epsilon/\kappa\rightarrow$ 24.85). ^{152}Sm seems to be an exceedingly rare example of a transitional nucleus which exhibits an R_{0g}^{γ} value very near the minimum. The vanishing of R_{0g}^{γ} results from the same type of cancellation mechanism as occurs (for other $E2$ transitions) in SU(3), suggesting the possibility of an undetected symmetry or selection rule.

We are grateful to F. Iachello for very useful discussions. Research was performed under contracts DE-FG02-91ER40609, DE-AC02-76CH00016, DE-FG02-88ER40417 with the U.S. DOE, and by the DFG under contract Br 799/8-1.

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