PHYSICAL REVIEW C, VOLUME 65, 031301(R)

Lifetime measurements of excited $K^\pi=0^+$ bands in ^{178}Hf

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(Received 1 September 2000; revised manuscript received 9 July 2001; published 6 February 2002)

Lifetimes of three excited $K^\pi=0^+$ bands have been measured in the same deformed nucleus (^{178}Hf). Evidence is presented for the first observation of two excited $K^\pi=0^+$ bands connected via collective $E2$ transitions. Five-band mixing calculations show that these collective transitions are not the result of mixing between the various bands. It is therefore suggested that the $K^\pi=0_5^+$ band at 1772.2 keV is a collective excitation built on the single phonon $K^\pi=0_2^+$ band at 1199.4 keV.

DOI: 10.1103/PhysRevC.65.031301 PACS number(s): 21.10.Tg, 21.10.Re, 21.60.Ev, 23.20.−g

One of the most important questions in nuclear structure today revolves around the nature of low-lying $K^\pi=0^+$ bands in nuclei. In the simplest geometric nuclear models, excited $K^\pi=2^+$ and $K^\pi=0^+$ bands are quadrupole oscillations of a nonspherical equilibrium shape. Extending this description to the spectra of deformed nuclei, the first excited $K^\pi=2^+$ and $K^\pi=0^+$ bands have traditionally been labeled as single-phonon "γ" and "β" vibrational excitations. The "γ" ($K^\pi=2^+$) excitations show typical $B(E2{:}2_\gamma^+\to 0_{\rm g.s.}^+)$ transition probabilities of 1–10 Weisskopf units (W.u.) that vary smoothly across a given isotopic chain and can be theoretically understood whereas the single $K^\pi=0^+$ "β" types of excitations have remained an enigma in nuclear structure physics. Figure 1 contains a compilation of all the known absolute $B(E2{:}2^+_{K^\pi=0_2^+}\to 0^+_{\rm g.s.})$ and $B(E2{:}2^+_{K^\pi=0_2^+}\to 4^+_{\rm g.s.})$ transition probabilities in W.u. depopulating the 2^+ state of the first excited $K^\pi=0^+$ bands. In contrast to the $K^\pi=2^+$ γ bands, there are enormous variations in collectivity for the $B(E2{:}2^+_{K^\pi=0_2^+}\to 0^+)$ values. For example in the $^{154-158}$Gd nuclei, this $B(E2)$ value varies from from 90 W.u. to 0.31 W.u. This large variation in $B(E2)$ values across the region is an indication of the complexity and varying nature of the first excited $K^\pi=0^+$ bands. It has been suggested that the low-lying excited $K^\pi=0^+$ bands in deformed nuclei are in fact pairing vibrations [1,2], or collective excitations [3–5] built on the γ vibration. The exchange of ideas, experiments, and publications on the subject has been quite vigorous [4–14] focusing on the nature of excited $K^\pi=0^+$ bands and specifically on the viability of a single-phonon β type of excitation mode for nuclei.

The main purpose of this Rapid Communication is to present the lifetimes for levels in several $K^\pi=0^+$ bands in ^{178}Hf. The results point towards the first observation of a collective excitation built on the first excited $K^\pi=0^+$ band in a deformed nucleus.

We have measured the lifetimes of three excited $K^\pi=0^+$ bands in the ^{178}Hf nucleus using the gamma ray induced Doppler broadening (GRID) technique [15]. GRID allows lifetime measurements of levels populated in thermal neutron capture reactions from the Doppler broadening of a transition affected by the recoil of a previously emitted γ ray. The recoil velocities are very small (typically 10^{-4} to 10^{-6} of c) with resulting Doppler shifts in the order of a few eV and very short slowing-down times in the target. The last point limits the optimum range of accessible lifetimes to a few picoseconds and lower. The essential ingredients that contribute to the line shape of a selected transition are the slowing-down process in the target material, the initial recoil velocity distribution feeding the level from which the transition is deexciting, temperature of the target, and the lifetime of the state of interest. If the first three are known (or determined), the lifetime can be extracted from the line-shape. The main uncertainty in heavy nuclei comes from the feeding of the chosen level. The line shape of a particular transition is measured using a double flat crystal spectrometer (GAMS4) [16,17] installed 15 m from the core of the high flux reactor of the Institut Laue Langevin (ILL) in Grenoble. The targets for the two experiments consisted of 9.592 g and 10.625 g of natural Hf oxide. The line shapes or specifically the wavelengths of chosen γ rays are measured by Bragg diffraction on ideal crystals where the energy resolution may be as good as $\Delta E/E\approx 2\times 10^{-6}$.

The ^{178}Hf nucleus is one of the most extensively studied nuclei besides ^{168}Er. It has been studied by a variety of re-

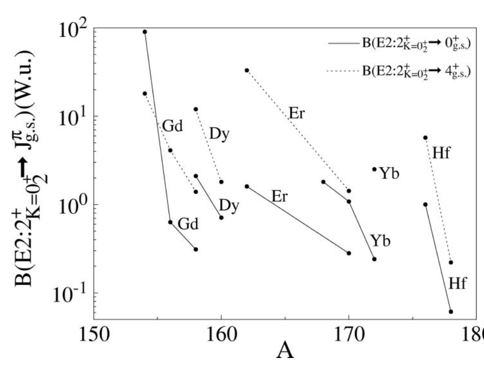

FIG. 1. A compilation of $B(E2{:}2^+_{K^\pi=0_2^+}\to J^\pi_{\rm g.s.})$ values in W.u. extracted from all the known lifetimes of first excited $K^\pi=0^+$ bands in deformed nuclei as a function of A.

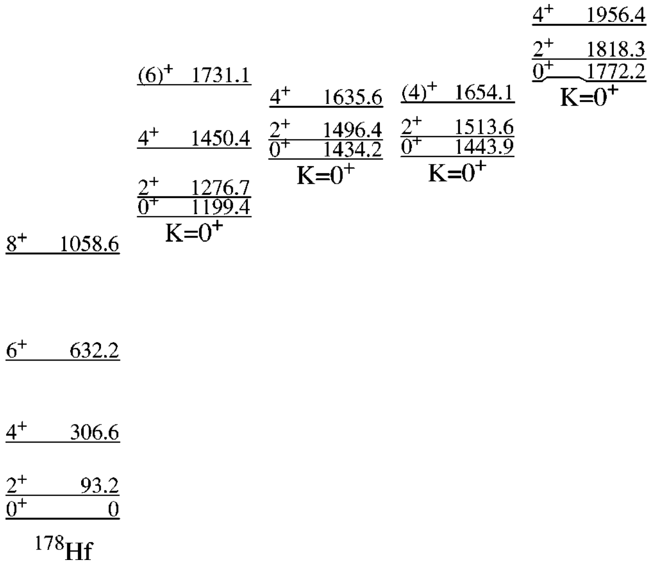

FIG. 2. All the known $K^{\pi}=0^{+}$ bands in the nucleus ^{178}Hf.

actions using high-precision methods for the measurements of γ rays and conversion electron studies [18]. The resulting level scheme has five known $K^{\pi}=0^{+}$ bands including the g.s. band below an excitation energy of 2 MeV. Figure 2 shows all the known $K^{\pi}=0^{+}$ bands. We have measured the lifetimes of the levels at 1276.7 keV, 1450.4 keV, 1496.5 keV, and 1818.3 keV. The broadened line shapes were fit with the GRIDDLE code [19].

Figure 3 shows an example of the fit to the observed broadening along with the instrumental response for the 1725 keV transition depopulating the level at 1818.3 keV.

The greatest uncertainties in these measurements arise from the unknown feeding of the level of interest. Therefore, in cases where the feeding of a particular nuclear level is not completely known, we have made rather extreme assumptions for the missing feeding in order to extract conservative *upper* and *lower* limits. The upper limit of the extracted lifetime is determined assuming that the level is totally fed by cascades of γ-ray transitions from the compound capture state. The lower limit is extracted by assuming that the missing feeding comes from the unplaced low energy transitions that were measured in this nucleus. The more realistic scenario would probably lie somewhere in the middle of the lifetimes resulting from these intentionally extreme feeding assumptions. The measured lifetimes and the extracted $B(E2)$ values are tabulated in Table I. The 1818.3 keV level is fed [18] to a large extent by primary γ-ray transitions from the neutron-capture state, therefore an unusually high percentage (47%) of the feeding of the level is known. For example, fits of the data for the upper and lower limits of the 1818.3 keV level are $0.718^{+0.321}_{-0.174}$ and $0.336^{+0.169}_{-0.093}$, respectively, yielding a range of $0.24\rightarrow1.04$ ps. The known feeding of the other levels at 1496.4 keV, 1450.4 keV, and 1276.7 keV are 5%,27%, and 20%, respectively [18].

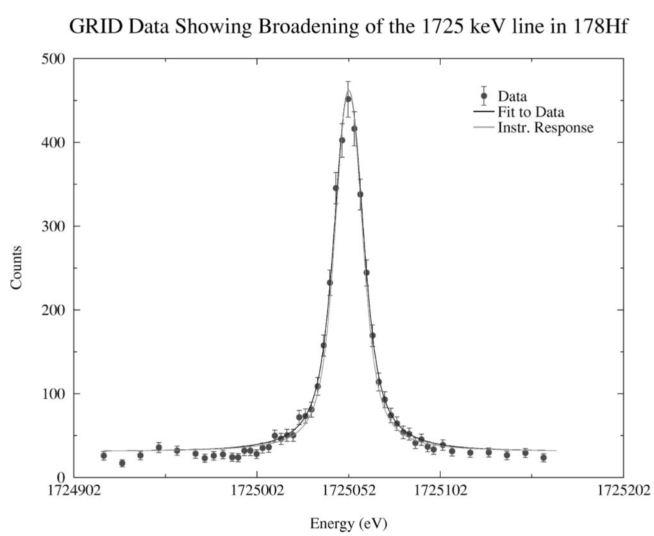

FIG. 3. The broadening of the 1725.1 keV transition depopulating the 1818.3 keV level of the $K^{\pi}=0^{+}_{5}$ band at 1772.2 keV. The inner solid line is the instrumental response.

The lifetime of the 1174.6 keV level (2^{+} of the γ band) was previously known and remeasured here as a test. The measurement yields a lifetime range of $0.27\rightarrow1.27$ ps resulting in a $B(E2{:}2^{+}\rightarrow0^{+})$ range of $2.7\rightarrow12.8$ W.u. in agreement with a previous Coulomb excitation measurement [21] a $B(E2{:}2^{+}_{\gamma}\rightarrow0^{+}_{\mathrm{g.s.}})$ value of 3.9 ± 0.1 W.u and therefore a lifetime of 0.90 ± 0.03 ps.

The first excited $K^{\pi}=0^{+}$ band is at 1199.4 keV. The lifetime of the 0^{+} bandhead level is not known. A lifetime of 8.8 ps had been shown in the literature but a recent reevaluation of the coulomb excitation data [22] shows the lifetime of the 2^{+} member of this band at 1276.7 keV to be $0.80^{+0.20}_{-0.15}$ ps. In this work, we have measured the lifetime of this level and extract a range of lifetimes from $0.35\rightarrow1.52$ ps. The corresponding $B(E2{:}2^{+}_{K^{\pi}=0^{+}_{2}}\rightarrow0^{+})$ values for a $14.4^{+2.1}_{-1.1}\%$ $E2$ component [23] yield a range of $0.3\rightarrow1.4$ W.u. Our value is in agreement with the reevaluated lifetime of this level.

The lifetime of the 4^{+} state of the same band at 1450.4 keV was measured for the first time. The $B(E2{:}2^{+}_{K^{\pi}=0^{+}_{2}}\rightarrow0^{+}_{\mathrm{g.s.}})$, the $B(E2{:}2^{+}_{K^{\pi}=0^{+}_{2}}\rightarrow4^{+}_{\mathrm{g.s.}})$, and the $B(E2{:}4^{+}_{K^{\pi}=0^{+}_{2}}\rightarrow6^{+}_{\mathrm{g.s.}})$ values are somewhat smaller but the same order of magnitude in collectivity to transitions between a single-phonon γ vibrational excitation and the g.s. band.

The next two $K^{\pi}=0^{+}$ bands in this nucleus are at excitation energies of 1434.2 and 1443.9 keV. The lifetime of the 1496.4 keV level (the 2^{+} of the $K^{\pi}=0^{+}_{3}$ band at 1434.2 keV) was measured while levels of the 1443.9 keV band were not due to the weak intensities of the depopulating transitions.

The most important result concerns the $K^{\pi}=0^{+}_{5}$ band in ^{178}Hf at an excitation energy of 1772.2 keV. The $0^{+},2^{+}$, and 4^{+} members of this band were known from very early work [25–27]. The $2^{+}\rightarrow0^{+}$ in-band transition (46.06 keV) has not been seen probably because of its low energy. The $2^{+}_{K^{\pi}=0^{+}_{5}}\rightarrow0^{+}_{\mathrm{g.s.}}$ transition was seen in the decay of ^{178}Ta [25] and ^{178}Lu [27] but not in (n,γ). All three states show large $E0$ transitions to the ground state supporting the $K^{\pi}=0^{+}$ assignment of the band. The decay of the 4^{+} member of this $K^{\pi}=0^{+}_{5}$ band is predominantly to the $4^{+}_{K^{\pi}=0^{+}_{2}},4^{+}_{K^{\pi}=0^{+}_{3}}$, and

TABLE I. Measured level lifetimes in the ^{178}Hf nucleus and the extracted $B(E2)$ values. Transition intensities and conversion coefficients α from Haque *et al.* [18] unless stated otherwise.

E_x(keV)	K_i^{π},J_i^{π}	τ(ps)	E_{γ}(keV)	K_f^{π},J_f^{π}	I_{γ}	α_{tot}	multipolarity	$B(E2)$ W.u.
1174.63	$2^{+},2^{+}$	$0.27<\tau<1.27$ [a]	1174.67	$0^{+}_{\mathrm{g.s.}},0^{+}$	11.167	0.00206	$E2$	2.73→12.78
			1081.45	$0^{+}_{\mathrm{g.s.}},2^{+}$	8.401	0.00317	$E2$	3.10→14.53
			867.99	$0^{+}_{\mathrm{g.s.}},4^{+}$	0.165	0.0037	$E2$	0.18→0.85
1276.69	$0^{+}_{2},2^{+}$	$0.35<\tau<1.52$ [b]	1276.68	$0^{+}_{\mathrm{g.s.}},0^{+}$	0.66	0.00216	$E2$	0.33→1.45
			1183.54	$0^{+}_{\mathrm{g.s.}},2^{+}$	3.59	0.01467	$E2$(14.4%) [c]	0.38→1.64
			970.11	$0^{+}_{\mathrm{g.s.}},4^{+}$	1.0	0.00409	$E2$	1.76→7.67
1450.36	$0^{+}_{2},4^{+}$	$0.14<\tau<2.60$	1357.12	$0^{+}_{\mathrm{g.s.}},2^{+}$	0.304	0.002	$E2$	0.06→1.12
			1143.76	$0^{+}_{\mathrm{g.s.}},4^{+}$	4.759	0.0095	$E0+(M1$ and/or $E2)$ [d]	2.30→41.38
			818.19	$0^{+}_{\mathrm{g.s.}},6^{+}$	0.376	0.0045	$E2$	0.97→17.45
			173.67	$0^{+}_{2},2^{+}$	0.045	0.50 [f]	$E2$	<270
1496.45	$0^{+}_{3},2^{+}$	$0.03<\tau<1.09$ [f]	1496.45	$0^{+}_{\mathrm{g.s.}},0^{+}$	1.447	0.0017	$E2$	0.58→20.86
			1403.26	$0^{+}_{\mathrm{g.s.}},2^{+}$	1.714	0.00929	$E2$(39%) [c]	0.37→13.28
1818.28	$0^{+}_{5},2^{+}$	$0.24<\tau<1.04$	1725.13	$0^{+}_{\mathrm{g.s.}},2^{+}$	1.440	0.00555	$E0+(M1$ and/or $E2)$ [d]	0.57→2.44
			1511.74	$0^{+}_{\mathrm{g.s.}},4^{+}$	0.593	0.00142	$E2$	0.46→1.95
			618.95	$0^{+}_{2},0^{+}$	0.020	0.0013 [e]	$E2$	1.33→5.68
			541.59	$0^{+}_{2},2^{+}$	0.097	0.023	$E2$ (50±11%)	6.32→26.95

[a]The result of a previous measurement by Coulomb excitation [21] was 0.90±0.03 ps.
[b]The result of a previous measurement by Coulomb excitation [20] was reported as 8.8 ps. A reevaluation has now led to the value of 0.80^{+20}_{-15} ps [22].
[c]Multipolarity of this transition measured by directional correlation measurements [23,24].
[d]No information is available on the $E2$ component of the transition; $B(E2)$ value has been calculated as an upper limit assuming 100% $E2$.
[e]Theoretical conversion coefficients were used in the absence of measured values [32].
[f]The result of a previous measurement by Coulomb excitation [20,21] was 1.3±0.3 ps.

the $2^{+}_{K^{\pi}=0^{+}_{4}}$ levels favoring the decay to the $K^{\pi}=0^{+}_{2,3}$ bands by a factor of 6 in relative $B(E2)$ values. The extracted $B(E2{:}2^{+}_{K^{\pi}=0^{+}_{5}}\rightarrow 4^{+}_{\mathrm{g.s.}})$ is $\leqslant 2$ W.u., while the transitions to the first excited $K^{\pi}=0^{+}_{2}$ band at 1199.4 keV are highly collective. The most important results emerge from the $B(E2)$ values of the 618.9 and 541.6 keV transitions to the 0^{+} and 2^{+} of the first excited $K^{\pi}=0^{+}_{2}$ band at 1199.4 and 1276.7 keV, respectively. The multipolarity of the 618.9 keV transition is $E2$ while the 541.6 keV transition is $M1+50\pm 11\% E2$ [18]. The deduced $B(E2{:}2^{+}_{K^{\pi}=0^{+}_{5}}\rightarrow 0^{+}_{K^{\pi}=0^{+}_{2}})$ has a range of 1.3→5.7 W.u. while the $B(E2{:}2^{+}_{K^{\pi}=0^{+}_{5}}\rightarrow 2^{+}_{K^{\pi}=0^{+}_{2}})$ range is 6.3→27 W.u for the $E2$ component of the transition. The observed high level of collectivity for the $E2$ component of the 541.59 keV transition is of particular importance since it is a $J\rightarrow J$ transition and therefore it is not affected by mixing [28] matrix elements between $K^{\pi}=0^{+}$ bands.

A five-band mixing calculation was carried out including four $K^{\pi}=0^{+}$ bands (g.s. band and the three excited $K^{\pi}=0^{+}$ bands for which lifetimes are measured) along with the $K^{\pi}=2^{+}$ band. The matrix elements to the g.s. band were extracted from the lifetime measurements and the bands were allowed to mix in order to see if it would be possible to produce collective transitions between the $K^{\pi}=0^{+}_{5}$ and the first excited $K^{\pi}=0^{+}_{2}$ band. The only possibility of creating collective transitions between these two bands was via mixing of the $K^{\pi}=0^{+}_{5}$ and the $K^{\pi}=2^{+}$ bands. Even then when the mixing matrix element was a factor of 10 larger than the other mixing matrix elements between all the other bands, it was impossible to reproduce both of the observed collective transitions. Therefore, we conclude that no mixing matrix element between the $K^{\pi}=2^{+}$ and the $K^{\pi}=0^{+}$ bands can result in the two observed collective transitions simultaneously. Another piece of evidence which further supports the relationship of these two $K^{\pi}=0^{+}$ bands at 1199.4 and 1772.2 keV is their identical dynamic moments of inertia. It had been shown that single and double gamma vibrational excitations exhibit identical dynamic moments of inertia [29,30]. The dynamic moment of inertia for a given rotational band is commonly deduced from the plots of the spins against the rotational frequency defined as half of the γ-ray energy. The slope of such a plot gives the dynamic moment of inertia. The slopes of the $K^{\pi}=0^{+}$ bands at 1199.4 and 1772.2 keV are identical (to less than 1%) while the other two $K^{\pi}=0^{+}$ bands at 1434.2 and 1443.9 keV show moments of inertia which are identical to within 9% but quite different from the g.s., the $K^{\pi}=0^{+}_{2}$, and the $K^{\pi}=0^{+}_{5}$ bands. Figures 4 shows a plot of the γ-ray energies as a function of spin for the $K^{\pi}=0^{+}$ bands.

In summary, lifetimes of several $K^{\pi}=0^{+}$ bands have been measured. This measurement reveals for the first time the existence of two excited $K^{\pi}=0^{+}$ bands connected by strongly collective transitions. The $B(E2)$ values from the second and third excited $K^{\pi}=0^{+}$ bands to the g.s. band would perhaps raise a question regarding the identification of

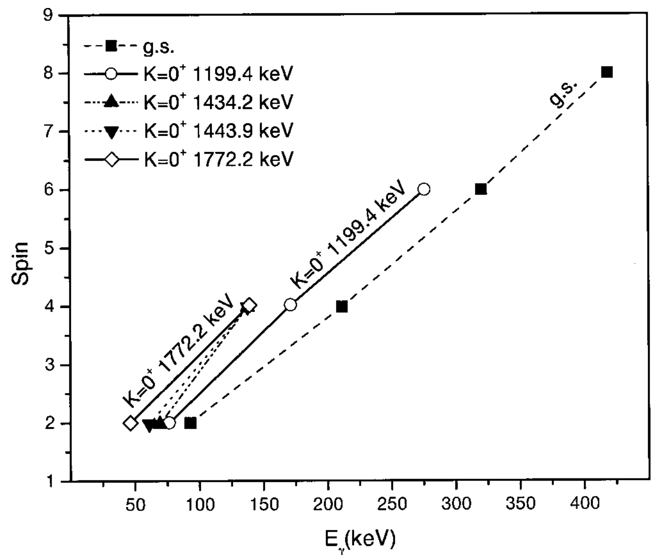

FIG. 4. Plot of γ-ray energies as a function of spin for all five $K^{\pi}=0^{+}$ bands. The slope of each line gives the dynamic moment of inertia for that band.

either band as the collective one-phonon β-vibrational excitation. However, the observed preference of decay from the 2^{+} and 4^{+} members of the $K^{\pi}=0_5^{+}$ band at 1772.2 keV band is to the band at 1199.4 keV. This is compatible with the expected behavior of a collective vibrational excitation built on the 1199.4 keV band. The outstanding question is the collectivity of the first excited $K^{\pi}=0^{+}$ band. Our new measurements are in excellent agreement with Coulomb excitation results for all three states. Our results indicate some significant degree of collectivity for the first excited $K^{\pi}=0^{+}$ band. The most important result is the indication for the first time of the existence of a collective $K^{\pi}=0^{+}$ excitation built on an excited $K^{\pi}=0^{+}$ band in any nucleus. If the collectivity of the first excited $K^{\pi}=0^{+}$ band can be more forcefully established, then this work would also point to the first observation of a two-phonon $\beta\beta$ vibration. Finally, five-band mixing calculations clearly show that it is impossible to reproduce the collective transitions between the two excited bands by $\Delta K=2$ or 0 mixing matrix elements. Two-phonon vibrational excitations are expected to occur at twice the excitation energy of the one phonon vibration. The harmonic value for the ratio of $B(E2:2_{\beta\beta}^{+}\rightarrow 0_{\beta}^{+})$ and $B(E2:2_{\beta}^{+}\rightarrow 0_{\text{g.s.}}^{+})$ is 2.0. In ^{178}Hf, the excitation energy ratio of the two bands is 1.5 and the range for the $B(E2)$ ratio is approximately $1\rightarrow 17$ consistent with the expected harmonic value. The two-phonon $\gamma\gamma$ vibrational excitation in ^{232}Th was similarly anharmonic in energy with an energy ratio of 1.8 and a $B(E2:4_{\gamma\gamma}^{+}\rightarrow 2_{\gamma}^{+})/B(E2:2_{\gamma}^{+}\rightarrow 0_{\text{g.s.}}^{+})$ ratio of 3.1 ± 0.4 [31] in agreement with the expected harmonic value of 2.78.

In conclusion, lifetimes of five levels in three excited $K^{\pi}=0^{+}$ bands have been measured in the ^{178}Hf nucleus using the GRID technique. The $K^{\pi}=0_2^{+}$ band is less collective but in the same order of magnitude as some of the single-phonon γ-vibrational bands in this region of deformed nuclei. An excited $K^{\pi}=0_5^{+}$ band at 1772.2 keV shows a preference of decay with transitions of collective strength to the $K^{\pi}=0_2^{+}$ band at 1199.4 keV. The collective transitions between the two bands cannot be reproduced by bandmixing. The consequence is the characterization of the $K^{\pi}=0_5^{+}$ band as a collective excitation built on the first excited $K^{\pi}=0_2^{+}$ band at 1199 keV.

Research supported by NSF and NATO under Contract Nos. PHY-9402761 and 91057, respectively. Discussions are gratefully acknowledged with P. Van Isacker, K. Heyde, R.F. Casten, and E.R. Marshalek.

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