Search for experimental evidence supporting the multiphonon description of excited states in ^{152}Sm

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A study of available (t,p), (d,p), $B(E2)$, and $(\vec{p},p')$ results for ^{152}Sm reveals the lack of an adequate experimental foundation for the recent interpretation of levels as multiple phonon structures based on the 0_2^+ state at 685 keV. Each type of data agrees better with earlier descriptions, in which the calculated deformations are comparable to that of the ground state. Suggestions are made for experiments and calculations to help distinguish among the interpretations.

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I. INTRODUCTION

Several recent papers [1–6] propose a reinterpretation of the ^{152}Sm level structure, in which levels traditionally labeled as members of β and γ bands [7], and also other states, are instead multiphonon configurations based on the 0_2^+ level at 685 keV, which is assumed to have a relatively small deformation. The left portion of Fig. 1 shows known positive-parity levels, labeled with the traditional interpretation in Ref. [7]. The right side of Fig. 1 shows the proposed reinterpretation for nonyrast levels, labeled with the anharmonic vibrator notation (e.g., as in Ref. [4]).

Jolie *et al.* [8] have commented on some aspects of the new interpretation (mainly theoretical ones), while the present work examines the extent to which a foundation based on experimental evidence exists for it. This is important as the new description has been used as empirical evidence for phase coexistence in ^{152}Sm [2–6].

References [1–6] have demonstrated that the multiphonon description is consistent with some of the available experimental data. In order for any newly proposed interpretation to be considered successful it should satisfy additional criteria: (a) it should not have significant disagreement with any of the experimental data, and (b) it should reproduce the complete set of available data at least as well as the alternative descriptions. The general impression obtained from recent literature [1–6] is that no viable alternatives to the "new interpretation" exist. A significant part of the present work involves showing, as a counterexample, that the "traditional" 1974 pairing-plus-quadrupole (PPQ) model of Kumar [9] is at least as successful in explaining all the experimental data.

This study was initiated by the observation that several measurements differ markedly from expectations based on a multiphonon description.

(1) As pointed out in Ref. [8], the spacing between the 0_2^+ and 2_2^+ levels is only 126 keV, closer to the rotational separation of 122 keV for corresponding spin members of the ground band than to the energy of $\sim$334 keV for the 2^+ phonon in the spherical nuclide ^{150}Sm. The multiphonon prediction is far too large at $\sim$300 keV [4,6].

(2) The value of $B(E2{:}2_2^+ \rightarrow 0_2^+)$ is $\sim$111 W.u. [6], which is comparable to rotational values, and larger than usually observed for vibrational excitations in this region.

(3) The 0_3^+ state would have a two-phonon character in the new interpretation, but its very large (t,p) strength [10] is contrary to a two-phonon assignment [10,11].

(4) Multiphonon states should also be populated very weakly, if at all, in single-nucleon-transfer reactions, as the transitions would be forbidden [12,13]. The largest peak in the ^{151}Sm$(d,p)^{152}$Sm spectrum of Ref. [14] is for the 1293-keV 2^+ level, indicating that there is a significant two-quasiparticle component not explained by the three-phonon interpretation in the right half of Fig. 1. Also, the 2^+ and 3^+ levels at 1086 and 1234 keV have (d,p) cross sections among the largest in the spectra at smaller reaction angles [15], consistent with their traditional description as members of the single-phonon γ band, but not with two-phonon or three-phonon character.

Zamfir *et al.* [4] have shown that the first two of these results can be reproduced by a many-parameter two-band-mixing calculation in which the unperturbed bands are assumed to have different deformations. Their *sd* interacting boson approximation (IBA) calculation is also able to explain the value of $B(E2{:}2_2^+ \rightarrow 0_2^+)$ but not the 0_2^+ and 2_2^+ level spacing. Whereas the issues listed above were important in triggering this study, closer examination showed that

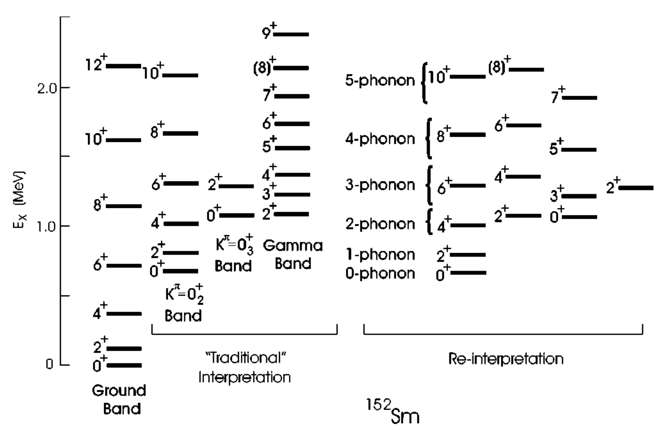

FIG. 1. Positive-parity levels of ^{152}Sm are shown on the left with the traditional interpretation [7], and nonyrast ones are shown on the right with the new interpretation of Ref. [4].

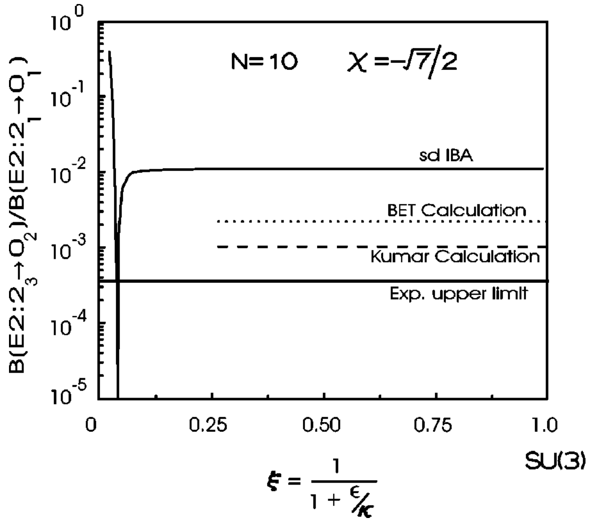

FIG. 2. $B(E2)$ ratios used to restrict sd IBA parameters to a narrow range [1,2,4]. Adapted from Fig. 5 of Ref. [2].

some of them [e.g., points (2) and (4) above] do not necessarily contradict the new interpretation. However, some additional weaknesses of it were revealed.

The main arguments used for the new interpretation involve level energies and $B(E2)$ values. Reference [4] states that the key considerations were the low value of $R_{4/2}^{(2)}$ (defined as the energy ratio $[E(4_2^+)-E(0_2^+)]/[E(2_2^+)-E(0_2^+)]$) and the small value of $B(E2{:}2_3^+\rightarrow 0_2^+)$. The experimental value of $R_{4/2}^{(2)}$ is 2.69, between the values of 2.0 expected for a pure vibrational structure and 3.33 for a rotational band, indicating that neither of these two limiting descriptions is ideal. Since the observed value of 2.69 is marginally *above* both the arithmetic and geometric means of 2.0 and 3.33 it is slightly closer to the rotational limit. Therefore, the observed ratio $R_{4/2}^{(2)}$ cannot be considered a strong argument for preferring the vibrational description. The corresponding ratio for the ground state band, considered rotational, is $R_{4/2}^{(1)}=E(4_1^+)/E(2_1^+)=3.01$.

It is argued that the small value of $B(E2{:}2_3^+\rightarrow 0_2^+)$ severely restricts the choice of the sd IBA model parameters to a narrow range, leading to the new interpretation [1,2,4]. This is shown in Fig. 2, adapted from Fig. 5 of Ref. [2]. The abcissa of this plot has the value $\xi=1$ for the SU(3) limit, while $\xi=0$ is closer to the U(5) limit. The plotted quantity is the ratio $B(E2{:}2_3^+\rightarrow 0_2^+)/B(E2{:}2_1^+\rightarrow 0_1^+)$, and the newer experimental result [4] of $\lesssim 0.000\,35$ is shown as a horizontal line. The sd IBA prediction for this ratio drops sharply to zero near $\xi=0.039$, due to destructive interference between terms in the transition amplitude [8]. As this is the only value of ξ for which the calculated ratio agrees with experiment, the sd IBA interpretation has been restricted to ξ near this value [1,2,4]. The validity of this restriction is discussed in Sec. II below.

New lifetime measurements were reported in Refs. [4,6], and the large set of ^{152}Sm $B(E2)$ values was considered to be additional evidence for the new description. Section II also contains a comparison of this set of $B(E2)$ values with predictions from Ref. [4] and two alternative descriptions. Section III discusses experimental evidence for admixtures of configurations outside the multiphonon description, which may affect the interpretation, and Sec. IV considers evidence pertaining to deformation values for excited states.

TABLE I. $E2$ strengths for transitions in ^{152}Sm.

Transition	$B(E2)$ (W.u.)			
	Expt.[a]	IBA[b]	PPQ[c,d]	BET[d,e]
$2_1^+\rightarrow 0_1^+$	144 (3)	144	134	145
$4_1^+\rightarrow 2_1^+$	209 (3)	216	206	220
$0_2^+\rightarrow 2_1^+$	32.7 (22)	55	43	49
$2_2^+\rightarrow 0_1^+$	0.92 (8)	0.1	0.7	1.9
$2_2^+\rightarrow 2_1^+$	5.5 (5)	10	6	8
$2_2^+\rightarrow 4_1^+$	19.0 (18)	20	29	26
$4_2^+\rightarrow 2_1^+$	0.7 (2)	0.1	0.04	1.6
$4_2^+\rightarrow 4_1^+$	5.4 (13)	8	5.6	7.5
$2_2^+\rightarrow 0_2^+$	111 (27)	89	154	89
$4_2^+\rightarrow 2_2^+$	204 (38)	140	230	162
$2_3^+\rightarrow 0_1^+$	3.62 (17)	3	4.5	5.6
$2_3^+\rightarrow 2_1^+$	9.3 (5)	3	11	5.8
$2_3^+\rightarrow 4_1^+$	0.78 (5)	4	0.54	1.1
$2_3^+\rightarrow 0_2^+$	$\leqslant$0.05	2	0.16	0.33
$2_3^+\rightarrow 2_2^+$	27 (4)	92	10	16
$4_3^+\rightarrow 4_2^+$	$\leqslant$35	25	6.6	6.6
$4_3^+\rightarrow 2_3^+$	50 (15)	63	76	67
χ_ν^2		408[f]	14[f]	47[f]

[a]Observed $B(E2)$ values, with the experimental uncertainties in the last digit given in parentheses. Data are the most recent of values from Ref. [7], Zamfir *et al.* [4], or Klug *et al.* [6].
[b]From sd IBA calculations of Zamfir *et al.* [4].
[c]From pairing-plus-quadrupole model of Kumar [9].
[d]1 W.u.$=B_W(E2)=[(1.2)^4/4\pi](\frac{3}{5})^2A^{4/3}=48.2\ e^2\,\mathrm{fm}^4$.
[e]From boson expansion technique of Kishimoto and Tamura [16].
[f]Transitions for which the experimental results are known only as upper limits are omitted from this calculation.

II. COMPARISON OF $B(E2)$ VALUES WITH PREDICTIONS OF DIFFERENT MODELS

This section first examines how well different interpretations can explain the large set of $B(E2)$ values presented as evidence for the multiphonon description [4,6]. The comparison is given in Table I, which includes all transitions from Fig. 5 of Ref. [4]. Column 3 shows the most recent experimental values and uncertainties from Refs. [4,6,7]. The predictions in column 4 are from sd IBA calculations [4], while those from the PPQ model of Kumar [9] and boson expansion technique (BET) calculations of Kishimoto and Tamura [16] are shown in the last two columns. At first glance all three calculations appear to give a reasonably good description of the experimental values. As quantitative figures of merit for the models, values of

$$\chi_\nu^2=\frac{1}{N-\nu-1}\sum\left[\frac{B(E2)_{calc}-B(E2)_{exp}}{\sigma_{exp}}\right]^2$$

are shown at the bottom of Table I. N is the number of data points in the calculation [in this case, 15, the number of $B(E2)$ values considered]. ν is the number of fitted model parameters and σ_{exp} are the experimental uncertainties.

The χ_ν^2 values were calculated using $\nu=2$, 2, and 3, for the sd IBA, PPQ, and BET models, respectively, as indicated by the authors [4,9,16]. Although there are additional parameters in each of the PPQ and BET models, Refs. [9,16] indicate that many of them were fixed from systematic properties of neighboring nuclei and were not fitted to these data. Also, as the calculations predated many of the $B(E2)$ measurements they could not have been fitted to these results. [Even if it were assumed that all the parameters in the PPQ and BET calculations had been fitted to these $B(E2)$ data, the values of χ_ν^2 for these models would increase by at most a factor of 2, so the PPQ would still have the lowest χ_ν^2 and the sd IBA would still have the highest.]

It is noted that the values of χ_ν^2 are $\geqslant 1$ for all cases, suggesting there are effects unaccounted for in each model. Nevertheless, the higher value of χ_ν^2 for the multiphonon description shows that the $B(E2)$ data do not indicate a preference for this model over earlier interpretations.

In Sec. I it was explained how the very small $B(E2)$ value for the $2_3^+ \to 0_2^+$ transition was used to limit the choice of sd IBA parameters to a region near $\xi=0.039$. However, other models also give reasonable explanations for this weak transition. In the traditional description [7], a very small $B(E2{:}2_3^+ \to 0_2^+)$ would be expected because the transition would be a two-step process involving the destruction of a γ phonon and the creation of a $K=0$ one. The PPQ and BET predictions for the $B(E2)$ ratio are shown in Fig. 2 by dashed and dotted horizontal lines, respectively, and are both very small. The PPQ prediction of 0.16 W.u. for $B(E2{:}2_3^+ \to 0_2^+)$ is nearer the experimental upper limit of $\leqslant 0.05$ W.u., close enough to provide a viable description for this very weak transition. The discrepancy of a factor of ~ 3 for such a weak transition is not serious enough to justify the rejection of this interpretation for ^{152}Sm. The suggested new interpretation also has discrepancies of factors $\geqslant 3$ for other transitions, including the strong $2_3^+ \to 2_2^+$ and $0_3^+ \to 2_2^+$ ones, as discussed by Zamfir *et al.* [4].

Closer examination shows that the argument for limiting ξ to a narrow range near 0.039 is a weak one, because it is based on a comparison of observed and predicted strengths for a very weak transition. When comparing model predictions with any measured spectrum it is commonly found that the largest intensities may be reproduced reasonably well by the model, but as one considers weaker and weaker transitions a stage is reached at which there are discrepancies (of random sign) comparable to the magnitudes of the values measured. It is not safe to make strong arguments based on calculated intensities near or below this level. For γ-ray spectra a probable cause for the discrepancies is the presence of admixtures, in the initial and/or final states, of configurations outside the scope of the model used. The $2_3^+ \to 0_2^+$ transition is three or four orders of magnitude weaker than the strongest ones in the spectrum. In such a case, a tiny admixture of any configuration resulting in a collective contribution to the weak transition could affect its strength significantly.

The analysis of $B(E2)$ values in Table I revealed that, in particular, the 2_3^+ level (formerly called the γ-vibrational bandhead) is not well described by the sd IBA description [4]. The three largest contributions to the χ_ν^2 value in Table I for this model are due to transitions from the 2_3^+ level, and these make up over 90% of its total χ_ν^2. These transitions, to the 2_1^+, 4_1^+, and 2_2^+ levels, have observed strengths of 9.3(5), 0.78(5), and 27(4) W.u. and sd IBA predictions of 3, 4, and 92 W.u., respectively. Such large discrepancies for these relatively strong transitions warn that there may be significant admixtures of other configurations present, and raise the question of how reliably this calculation could be expected to predict the very weak strength from the same level to the 0_2^+ state. Experimental evidence for admixtures in the 2_3^+ level, from outside the sd IBA model space, will be discussed in the following section, but first the possibility of an accidental cancellation of the $2_3^+ \to 0_2^+$ strength predicted by the sd IBA will be considered.

From Fig. 2 the sd IBA prediction for $B(E2{:}2_3^+ \to 0_2^+)/B(E2{:}2_1^+ \to 0_1^+)$ is ~ 0.012 over a wide range of values for the parameter ξ (e.g., $0.1 \leqslant \xi \leqslant 1$), so $B(E2{:}2_3^+ \to 0_2^+)$ would be 0.012×144 W.u.$=1.7$ W.u. One can consider the possibility that the actual situation is somewhere in this large parameter range, but that admixtures of configurations outside the sd IBA model space make a contribution (of unknown origin) to the $2_3^+ \to 0_2^+$ transition, with destructive interference, reducing the predicted 1.7 W.u. to $\leqslant 0.05$ W.u., without requiring the model parameter ξ to be near ~ 0.039. To estimate the probability for such an accidental cancellation the first step is to determine the range of B(E2) values which an unknown transition could have, to reduce the 1.7 W.u. prediction of the model to the experimental upper limit of $\leqslant 0.05$ W.u. If the IBA wave functions for the initial (2_3^+) and final (0_2^+) states are designated as $|\psi_i\rangle$ and $|\psi_f\rangle$, respectively, the original $E2$ transition strength is given by $|\langle \psi_f|E2|\psi_i\rangle|^2$, which corresponds to a $B(E2)$ of 1.7 W.u. If the initial state is now given a small admixture of some unknown configuration $|\psi_x\rangle$ its wave function becomes

$$|\psi\rangle = a|\psi_i\rangle + b|\psi_x\rangle.$$

The total transition amplitude is then

$$a\langle \psi_f|E2|\psi_i\rangle + b\langle \psi_f|E2|\psi_x\rangle.$$

The situation could be more complicated, as the final state could also have admixtures of other configurations, but this simpler case demonstrates the physics involved and for convenience is the only one considered here. If the admixture of $|\psi_x\rangle$ is a minor one, $a^2 \gg b^2$ and a is almost unity. Nevertheless, the two terms in the expression above may have comparable magnitudes, because $\langle \psi_f|E2|\psi_x\rangle$ may be much larger than $\langle \psi_f|E2|\psi_i\rangle$. [The $B(E2)$ of 1.7 W.u. produced by the latter is only about 1% of the strongest transitions in the decay, whereas the former could involve collective transitions which are much stronger.]

With the assumptions above, destructive interference could reduce the $B(E2)$ to $\leqslant 0.05$ W.u. if the magnitude of $b\langle\psi_f|E2|\psi_x\rangle$ were between $\sim$83% and $\sim$117% of $a\langle\psi_f|E2|\psi_i\rangle$, which would cause the combined amplitude to be $\leqslant$17% of $a\langle\psi_f|E2|\psi_i\rangle$. The strength for such an unknown transition, $|b\langle\psi_f|E2|\psi_x\rangle|^2$, corresponds to a $B(E2)$ between $\sim$1.17 W.u. and $\sim$2.33 W.u. This range of values may seem surprisingly large, but is just the result of the coherent summation of transition amplitudes.

The next step is to estimate the chance for the $2_3^+\rightarrow 0_2^+$ transition to have an admixture that might result in an unknown transition strength in the range 1.17 to 2.33 W.u. To gain some idea of the distribution of such unknown contributions, all the transitions in Table I were examined. For each one, the unknown contribution which would have to be added coherently to the *sd* IBA strength to make it equal to the observed result was deduced. It was found that $\geqslant$20% of the 15 values are in the range 1.17–2.33 W.u. Of particular interest in this case are transitions from the 2_3^+ level, because the weak transition being discussed originates from this level. Values for two of the four transitions from the 2_3^+ level are in the range 1.17–2.33 W.u. If one assumes that the relative phases are random, the probability of the interference being destructive would be $\sim$50%, these results suggest that the estimated probability of an accidental cancellation may be in the range of $\sim$10% to $\sim$25%. This is large enough for such an occurrence to be seriously considered as another possible explanation for the very small value of $B(E2{:}2_3^+\rightarrow 0_2^+)$, since it would invalidate the main argument claimed for the new interpretation.

III. EXPERIMENTAL EVIDENCE FOR OTHER CONFIGURATIONS IN THE STATES INVOLVED

A. Evidence for admixtures outside the *sd* IBA model space

As mentioned above, minor admixtures of unknown configurations in the initial and/or final states might seriously affect the value of $B(E2{:}2_3^+\rightarrow 0_2^+)$. In addition to evidence from the χ_ν^2 analysis above that the 2_3^+ level has components of configurations outside the *sd* IBA model space, there is direct experimental evidence for such admixtures in the 2_3^+ and other levels. One type of excitation outside the *sd* IBA model space arises from *g* bosons, and another type is pairing vibrations. This section will first describe the experimental evidence for *g* boson effects in this mass region, and specifically in the γ-vibrational band of ^{152}Sm. Then the significance of large (t,p) strengths to excited 0^+ states, and other data, will be considered as possible indications of pairing excitations.

1. g boson effects

The importance of these has been demonstrated [13] for ^{154}Gd, an isotone of ^{152}Sm with many structural similarities. The even gadolinium isotopes have low-lying $K^\pi=4^+$ bands with very large two-quasiparticle components and large $E4$ strength. All experimental information, including the significant $E2$ decay strengths to the γ band, is described better with the $K^\pi=4^+$ band assigned as a Γ (*g* boson, or hexadecapole) structure [13]. The *sd* IBA predicts that the lowest $K^\pi=4^+$ band would have predominantly a double-γ-phonon structure. However, the *sdg* IBA predicts that it would have Γ character. In analogy with a converging series expansion, if a significant change in the predicted result is caused by the removal of a term, that term must have been important. Thus, the *sdg* IBA calculations support the evidence from experimental data that *g* bosons are needed in the IBA for a proper description of these bands. Although no low-lying $K^\pi=4^+$ band has yet been established in ^{152}Sm [7], there may be significant components of some of the lower-K Γ bands in the known bands, which could affect properties such as $E2$ strengths. In fact, there is strong evidence that a $K^\pi=2^+$ hexadecapole (Y_{42}) component is required in the γ band (based on the 2_3^+ level) to explain $(\vec{p},p')$ data [20,21]. These very detailed measurements, using 65-MeV polarized protons, cover a wide range of closely spaced angles and show a great deal of structure in angular distributions of both the cross sections and analyzing powers. Coupled-channel analyses convincingly demonstrated the need for including a Y_{42} term as well as the usual Y_{22} one in the γ-vibrational bands. Measurements were made on a series of nuclides across the deformed rare earth region, including ^{152}Sm, and the size of the Y_{42} component varied smoothly across the region in a manner consistent with the Bertsch "polar-cap" model [22].

There is thus ample evidence that the 2_3^+ level contains configurations outside the *sd* IBA model space, making it unsafe to base strong arguments on the strength of a very weak transition from this level.

The coupled-channel calculations needed to explain the angular distributions of $(\vec{p},p')$ cross sections and analyzing powers depend strongly upon the $B(E2)$ values for transitions coupling members of the 2_3^+ band with the ground state band. As seen in Sec. II, the *sd* IBA calculation [4] did not reproduce these $E2$ strengths very well, so it is questionable whether it would explain the $(\vec{p},p')$ cross sections and analyzing powers properly. However, predictions by this model are not yet available for comparison with these data.

2. Pairing correlations

Devi and Kota [23] described properties of samarium isotopes with the *sdg* IBA, and reported that in order to reproduce large two-neutron transfer strengths to excited $K^\pi=0^+$ states it was necessary to use different model parameters for the initial and final nuclei, interpolating between dynamical symmetries to produce a phase change. Otherwise, for transitions that increase the boson number the predicted strength to excited states is small compared to that of the ground state. For transitions that decrease the boson number, the strength to excited states is predicted to be zero, even if *g* bosons are included [24]. In $N=108$ nuclei there are very strong (t,p) populations of excited 0^+ states [25] which are explained microscopically [26] and attributed to pairing effects caused by the subshell closure at $N=108$. The IBA prediction of zero strength to excited 0^+ states for these cases, for which the boson number is decreasing, does not explain the very strong (t,p) populations. Broglia *et al.* [27] have shown that pairing correlations are another type of excitation outside the usual IBA model space, and note that primed bosons are sometimes included to take them into account. Pairing correlations are important for two-neutron transfer strengths [9,11,27,28], and the (t,p) results for $N=108$ nuclei support the statement [27] that these are not properly included in the IBA. The very strong (t,p) populations for the 0_2^+ and 0_3^+ levels in ^{152}Sm suggest there may be significant pairing excitation components present.

The 0_3^+ level in ^{152}Sm has large (t,p) and weak (p,t) populations, while the 0_3^+ level in ^{150}Sm is strong in (p,t) and weak in (t,p) [10,29–31]. This pattern led to the suggestion that these 0_3^+ levels were shape-coexisting states with deformations different from those of the corresponding ground states. However, Kumar's calculation reproduced the large (t,p) strength to the 0_3^+ state in ^{152}Sm, even though its predicted deformation was comparable to the ground state value [9]. He concluded that the observed population was more likely due to pairing effects than to differences in deformation. In view of the results for $N=108$ nuclei, it seems questionable whether any part of the large (t,p) strength to excited states in ^{152}Sm that may result from pairing excitations would be properly explained by IBA calculations.

Devi and Kota [23] were able to reproduce a large value for the summed (t,p) strength to excited states of ^{152}Sm, but did not report predicted strengths for the individual 0^+ levels. The sd IBA calculations of Scholten *et al.* [18] showed a large (t,p) strength for the 0_2^+ state in ^{152}Sm, which is a single-phonon state in most descriptions and could therefore be populated by an allowed transition. However, they did not report a prediction for the 0_3^+ level, for which the (t,p) strength is more useful for distinguishing between interpretations. Specifically, the transition would be forbidden to the multiphonon 0_3^+ level of the new interpretation, but allowed for the single-phonon nature of this level in the PPQ description.

There is also additional experimental information, from single-nucleon-transfer data, suggesting the presence of significant pairing effects in the 0_2^+ level of ^{152}Sm. Excited $K^\pi=0^+$ bands are often not populated appreciably in single-nucleon transfer-reactions. However, those that do have significant strengths usually exhibit a pattern of relative cross sections within the band, similar to that of the ground state band. Some prominent examples of this behavior are found in ^{172}Yb [32] and ^{178}Hf [33]. These patterns indicate that the orbital of the transferred nucleon is the same as that forming the odd-mass target ground state. Thus, the $K^\pi=0^+$ band populated has all the nucleons paired in time-reversed orbitals. Such states have important pairing excitation components [11]. (In contrast, a traditional β vibration is expected to involve two-quasiparticle components with nucleons in different orbitals coupled to $K^\pi=0^+$ [11].) In ^{152}Sm, members of the $K^\pi=0_2^+$ band are populated in the (d,p) reaction with a cross section pattern very similar to that of the ground state band [14,15]. The spin 2 member has the largest cross section in this case, followed by that for the spin 4 level, with spin 0 and 6 members only weakly populated. The overall strength for the excited band is large, more than half that for the ground state band, suggesting the presence of significant pairing correlation effects. A less clear but somewhat similar behavior is observed for the single-proton transfer ^{153}Eu$(t,\alpha)^{152}$Sm reaction [34]. Although the orbital of the transferred nucleon is different, the 2^+ member of the ground band is coincidentally the one most strongly populated in this case, and the 2_2^+ level is again found to be populated more strongly than any other member of the $K^\pi=0_2^+$ band. These patterns could be readily explained by pairing correlations in this band. Such excitations could also be the explanation for at least part of the significant (p,t) and (t,p) strengths observed to the 0_2^+ level. In the new interpretation [4] the 0_2^+ and 2_2^+ levels are not multiphonon states, and therefore their population in single-nucleon-transfer reactions is not necessarily forbidden. However, no predictions with that model are yet available for comparison with these data.

There has been much discussion in the literature concerning the nature of the 0_2^+ level, and its character is still not clearly understood. However, the results discussed above seem to indicate that any model that does not include the possible presence of pairing correlations might not be able to produce a complete description of this structure.

B. Two-quasiparticle components

As mentioned in the Introduction, some levels assigned as multiphonon configurations in the new interpretation have large peaks in the (d,p) spectra [14,15], whereas transitions to such configurations should be forbidden. Although these data were instrumental in drawing attention to this study, closer examination of the results reveals that at present the lack of detailed knowledge for the ^{151}Sm target ground state wave function hinders quantitative analyses of the two-quasiparticle components populated in ^{152}Sm levels. For example, the two-quasineutron component populated in the 1293-keV 2_4^+ state could be as large as 100% or as small as $\sim$20%, depending on the configuration involved. The 2_3^+ and 3_1^+ levels, traditionally described as members of the γ-vibrational band, have (d,p) populations which are predominantly $l=1$, and the spectroscopic strengths are not large. This is consistent with expectations based on the quasiparticle phonon nuclear model (QPNM), in which most of the significant components predicted in the γ band are those that could not be populated by a (d,p) reaction on the $I^\pi=5/2^-$ ground state of the ^{151}Sm target, because they involve positive-parity nucleons [35]. If it is assumed that the target ground state has any of the reasonable possible configurations, and the neutron is transferred to a Nilsson orbital expected to have large $l=1$ cross sections, such as $1/2^-[521]$, the observed strengths would correspond to a two-quasiparticle admixture of only a few percent in the 2_3^+ band. This is the same order of magnitude as the QPNM predictions of 3.1% for the $3/2^-[521]+1/2^-[521]$ component and 1.2% for the $5/2^-[523]-1/2^-[521]$ component of the γ band [35].

The full value of the (d,p) data for determining ^{152}Sm level structures cannot be exploited until more reliable information on the ^{151}Sm ground state wave function is available.

Many of the levels probably do not have simple configurations of single-phonon, double-phonon, etc. character, but are complex mixtures. This is shown by the wave functions presented by Zamfir *et al.* [4]. For their most favorable cases (the 0_2^+, 2_2^+, 4_2^+, and 2_3^+ states), the probabilities for the multiphonon configurations in the right side of Fig. 1 are only about 50–60 %. Although the remaining components in these states may have some configurations that could be populated in single-nucleon-transfer reactions, calculations with this model are not available to test how well the available data are explained. For other levels, such as 0_3^+, 2_4^+, and 4_3^+, the multiphonon components shown in Fig. 1 are even smaller (than 50–60 %), so the dominant components for these could actually be other types of excitations. Further work is needed to determine which components are the dominant ones for these levels, so it is not yet clear which terminology is most appropriate for labeling them.

IV. EVIDENCE CONCERNING DEFORMATIONS FOR EXCITED STATES

It is important to note that both the Kumar and the BET calculations give predicted deformations for the excited states in question that are comparable to those of the ground state band, in contrast to the small deformations assumed for these levels in the new interpretation [5]. Kumar gives the predicted deformation parameter β and quadrupole moment for each state in Table II of Ref. [9]. The BET predicted quadrupole moments given in Table 6 of Ref. [16] are similar to those of Kumar. Klug *et al.* [6] have discussed the various Q invariants which can be determined from the $E2$ strengths in ^{152}Sm, and concluded that the sd IBA predictions for these are satisfactory. However, since the PPQ and BET calculations reproduce the $B(E2)$ values as well as the sd IBA does, these models should also reproduce the Q invariants, which are functions of the $B(E2)$'s. In fact, the Q invariant called q_2 calculated for the 0_2^+ state,

$$(q_2)_2=\sum_i B(E2;0_2^+\rightarrow 2_i^+),$$

is more than 80% of the corresponding value, $(q_2)_1$, for the ground state [see Eq. (8) of Ref. [17]]. If one considers these results in terms of a rotor description, where

$$q_2=e^2\left(\frac{3ZR^2}{4\pi}\right)^2\beta_{eff}^2$$

[6,17], the effective deformation, β_{eff}, for the 0_2^+ band would be about 90% of that for the ground state band. Thus, while these results can be explained by the new interpretation, they are also consistent with the 0_2^+ level having a rather large deformation as predicted in the PPQ and BET calculations, and therefore do not clearly distinguish which description is better.

Some evidence which appears to favor a larger deformation for the 0_2^+ level is found in the sequence of levels which have been assigned as a rotational band based on this level. As already mentioned, the energy difference $[E(2_2^+)-E(0_2^+)]$ is 126 keV, much closer to the corresponding value of 122 keV in the ground state band than to the multiphonon prediction of $\sim$300 keV (e.g., see Fig. 1 of Ref. [6]). The band-mixing calculation of Zamfir *et al.* [4] reproduces energies of the 0_2^+, 2_2^+, and 4_2^+ levels and $B(E2)$'s coupling these levels with the ground band, but involves a large number of fitted parameters. These authors point out that it would be difficult to describe the energies and $E2$ strengths for these levels and the ground state band by a two-band-mixing calculation that started with two deformed bands. Nevertheless, the PPQ calculation [9] reproduced the $B(E2)$ values and level energies very well for members of this band up to $I=6$, while predicting that the levels have large deformations. Rotational members up to $I=14$ have since been assigned as a band based on the 0_2^+ level [7], and a plot of excitation energy versus $I(I+1)$ for this band indicates a rather well-behaved rotational pattern [8]. For $I\geqslant\sim 4$ the slope of the line corresponds to a moment of inertia slightly larger than that of the ground band.

Another observation favoring larger deformations for excited levels is found in the $E2$ decay mode of the 2_3^+ level. In Sec. II it was pointed out that these $E2$ strengths were not in good agreement with the multiphonon predictions [4]. The branching ratio $B(E2{:}2_3^+\rightarrow 2_1^+)/B(E2{:}2_3^+\rightarrow 4_1^+)$ is 12 ± 1, a factor of $\sim$15 larger than the sd IBA prediction [4]. The observed value is more consistent with expectations for rotational nuclei than for vibrational ones. For example, predicted ratios for ^{148}Sm and ^{150}Sm are very small, typically $\leqslant 1$ (e.g., see Fig. 9 of Ref. [18]), similar to the sd IBA results in Table I. For more rotational nuclides (e.g., ^{154,156,158}Gd) the predicted ratios increase towards the Bohr-Mottelson rotational limit of 20 [19]. Thus, the observed ratio is more consistent with a description of ^{152}Sm levels nearer the SU(3) limit than with the multiphonon description.

V. CONCLUDING REMARKS

In summary, it appears that there is no experimental evidence that *requires* the excited levels in ^{152}Sm to be interpreted as multiphonons of small deformation. Each type of data can be explained as well, or better, by traditional interpretations such as the PPQ model, with bands based on single-phonon states and deformations comparable to that of the yrast band. In addition to having the best χ_ν^2 for the $B(E2)$ data in Table I, the PPQ also provides a good description of many other properties [9]. These include a quantitative explanation for the large (t,p) strength to the 0_3^+ state, which would be unexpected in the multiphonon description. Features such as the energy spacing $[E(2_2^+)-E(0_2^+)]$, the well-developed rotational band based on the 0_2^+ state, and the ratios $R_{4/2}^{(2)}$ and $B(E2{:}2_3^+\rightarrow 2_1^+)/B(E2{:}2_3^+\rightarrow 4_1^+)$ favor descriptions having larger deformations for the excited states involved. Levels populated strongly in single-nucleon-transfer reactions must have components outside the multiphonon description, but these are easy to reconcile with the single-phonon character of states in the traditional interpretation. Parameters used in the analysis of the $(\vec{p},p')$ data are also consistent with large deformations for the 2_3^+ state. The set of $B(E2)$ values, and the Q invariants q_2 based on them, appear to be consistent with the different interpretations considered, and therefore do not distinguish which is more successful.

The main arguments presented for the "new interpretation" have been shown to be weak ones. In particular, the small value of $B(E2{:}2_3^+ \rightarrow 0_2^+)$ is found to have alternative explanations. The PPQ predicted this strength to be very small with the 0_2^+ level having a large deformation. For the sd IBA it may not be necessary to restrict the parameter ξ to values near 0.039 as assumed [1,2]. A small admixture in the initial and/or final state, of a configuration outside the sd IBA model space, has a significant probability to cause an accidental cancellation of the small expected strength for $0.1 \leqslant \xi \leqslant 1$. Evidence has been presented in Sec. III A for admixtures outside the sd IBA model space in both the initial (2_3^+) and final (0_2^+) states.

The concept of phase coexistence in nuclear structure is an appealing one, and its realization would not be surprising, but as yet there is no adequate experimental foundation to claim that the ^{152}Sm levels are evidence for it. More efforts of both an experimental and theoretical nature are clearly needed to resolve present ambiguities, and it is hoped that this work will inspire some of these. A new Coulomb excitation experiment of the type reported for Os and Pt isotopes [36] could be useful. In that study, a large set of $E2$ matrix elements was determined in a model-independent manner, including intrinsic quadrupole moments of excited states and phase information for matrix elements. An experiment of this type for ^{152}Sm could be useful. A similar suggestion was made earlier [37], but is now of greater importance, since the new interpretation has been claimed as evidence of phase coexistence. Measurements of lifetimes for higher spin members of the $K^\pi = 0_2^+$ band could also be useful, to test whether the $B(E2)$'s were described better by a rotational pattern or a multiphonon one.

On the theoretical side, quantitative predictions for many of the available types of data are still needed. Obvious examples are (d,p), (t,α) and $(\vec{p},p')$ results for specific excited states. There is also a lack of predictions for (t,p) and (p,t) strengths to excited 0^+ states, presumably because a better treatment of pairing correlations is needed in all the models. Kumar concluded that pairing vibrations should be considered on an equal footing with shape vibrations, and that vibrations of higher order than quadrupole should be included. The discussion above suggests that these still seem to be among the most needed improvements. The structure of a transitional nucleus such as ^{152}Sm is very complex and the data already available indicate a rich variety of excitation modes. It may be unrealistic to hope that a model such as the sd IBA, with only two parameters, could explain all the features in detail, including the strengths of very weak transitions. g bosons would be needed to explain $(\vec{p},p')$ data for the γ band, and it would be useful to see the effect of adding these to the IBA description. For the nearby isotone ^{154}Gd, significant $E2$ strengths are associated with the g boson or hexadecapole excitations, and it would be interesting to learn how the addition of g bosons could affect the very weak $2_3^+ \rightarrow 0_2^+$ transition, which is central to this discussion.

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