Directional Correlation of the Gamma Rays in W^{182}†

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Directional correlation measurements were performed on seven cascades involving the gamma rays in W^{182}. The angular momenta of the excited states and the character of the gamma transitions which were determined by the correlation measurements are in good agreement with the values as determined by previous investigators. There is evidence for the existence of three rotational bands with the possibility of a fourth band in W^{182}. The nature of these rotational bands is explained in terms of the Bohr-Mottelson model for spheroidal nuclei. The levels are characterized by the quantum numbers (K, I, π). After correction for x-ray interference the 1.222 Mev−0.068-Mev correlation results in a spin of 3 to the 1.290-Mev level. The 0.068-Mev gamma ray is essentially pure dipole radiation. The results of the 1.231 Mev−0.100-Mev correlation are in good agreement with spin 3 to the 1.331-Mev level with a quadrupole content of 2±0.5% for the 1.231-Mev radiation. The 0.152 Mev-1.222-Mev correlation is only in agreement with an assignment of spin 3 to the 1.374-Mev level with a quadrupole content of less than 0.5% for the 0.152-Mev transition. The 0.152 Mev-1.122-Mev correlation yields a quadrupole content of (3–11% or 94–99%) for the 1.122-Mev transition. The 0.222 Mev-1.231 Mev, 0.264 Mev-1.222-Mev correlations are in good agreement with the assignment of spin 4 to the 1.554-Mev level. However, spins of 3 or 5 for the 1.554-Mev level are also in agreement with the correlation data.

INTRODUCTION

THE decay of Ta^{182} to W^{182}, as is found in a great many of the heavy isotopes, is described by numerous beta- and gamma-ray transitions. These transitions have been the subject of a number of investigations with the result that various schemes have been proposed to represent the decay.[1–9] The most extensive treatment of this decay has been carried out by Murray, Boehm, Marmier, and DuMond,[6] Fig. 1. The multipolarities of the gamma transitions which are based on measurements of the internal conversion coefficients are shown in the same figure. Using these data, Alaga et al.[10] were able to classify the gamma transitions and the excited states of W^{182} by the theory for deformed nuclei. The energy levels were fitted into three rotational bands, with the possibility of the start of a fourth band. The quantum numbers (K, I, π) listed in Fig. 1 are those proposed by Alaga et al. In general the spins values (I) are in agreement with those values given by Murray et al.

The present investigation is concerned with the angular correlation of the various gamma radiations which are involved in this complicated decay. For many years gamma-gamma angular correlation techniques have proved to be very valuable in nuclear spectroscopy in helping to establish the spins of the excited states and the multipole order of the gamma radiations. Where the transitions do not appear to be described by a single multipole order, the mixture content of multipoles can be determined. From the gamma-gamma angular correlation measurements, along with the work of the previous investigators, it was hoped that more positive

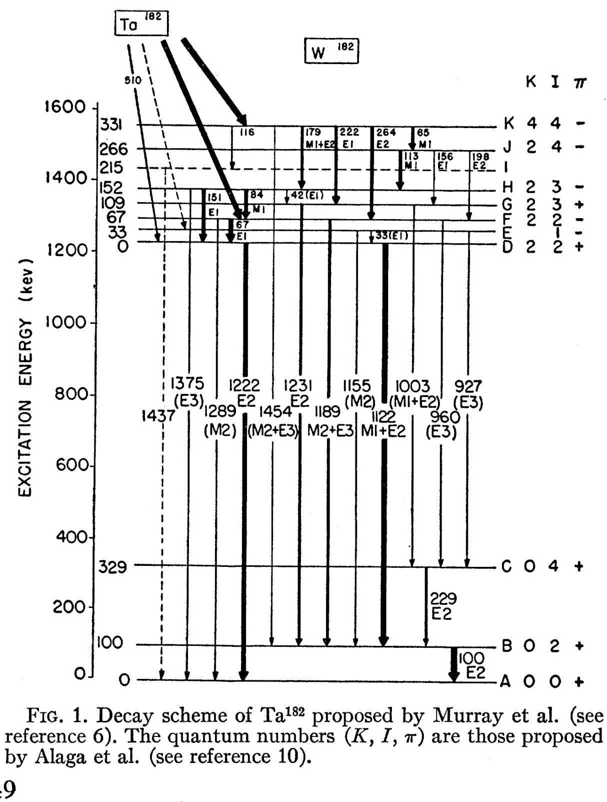

FIG. 1. Decay scheme of Ta^{182} proposed by Murray et al. (see reference 6). The quantum numbers (K, I, π) are those proposed by Alaga et al. (see reference 10).

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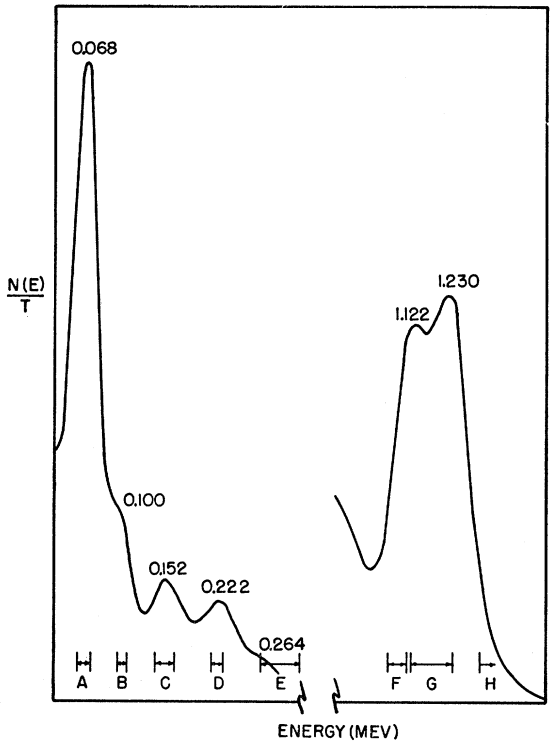

FIG. 2. Scintillation spectrum of the gamma rays in W^{182}. The letters indicate the various discriminator settings used in the correlation experiments.

assignments of spins could be made for some of the excited states and the mixture content of a few of the gamma rays determined.

PROCEDURE

The angular correlation measurements were carried out with a conventional "fast-slow" coincidence circuit with an effective resolving time of 3.5×10^{-8} seconds. The scintillation counters consisted of 2 in.×2 in. NaI(Tl) crystals coupled to Dumont type 6292 photomultipliers. The counters were shielded frontally by $\frac{3}{16}$-inch aluminum. Although differential discrimination was used to provide energy selection, lateral lead shielding was also employed in the measurements to eliminate coincidences due to scattering. The sources were in the form of Tantalate in KOH solution. In all cases a least squares fit of the correlation data was made to the function

$$W(\theta)=A_0+A_2P_2(\cos\theta)+A_4P_4(\cos\theta).$$

The errors which were calculated for the coefficients A_2 and A_4 represent the root mean square statistical errors. The effect of finite angular resolution was computed from the results of a collimated beam experiment by Arns.[11]

RESULTS

The gamma-ray spectrum of W^{182} is given in Fig. 2. The directional correlation data are given in Table I. This table gives the gamma transitions involved in each correlation measured, the experimental values of A_2 and A_4, and the approximate energy acceptance of each discrimination. The letters $A,B,\ldots H$ which denote the discriminator settings correspond to the letters given in Fig. 2, which give the approximate energy the discriminators accepted. The spin assignments for the excited states and the multipolarities of the gamma rays which were determined by both the angular correlation measurements and the experimental conversion coefficients are given in Table II.

A spin of 2 was assigned to state D by Murray et al. on the basis of their conversion data which showed the 1.222-Mev radiation to be more like $E2$ than either $M1$ or $E1$. If the spin of state D is assumed to be 2, the results of the 1.222 Mev−0.068-Mev correlation yield a spin of 3 for state F. When the experimental values of

TABLE I. Directional correlation results.

Gamma transitions involved	$A_2\pm\epsilon_2$	$A_4\pm\epsilon_4$	Discriminator settings Fig. 2
(Before x-ray—1.222-Mev subtraction) 1.222 Mev−0.068 Mev	+0.164±0.013	−0.026±0.020	H; A
(After x-ray—1.222-Mev subtraction) 1.222 Mev−0.068 Mev	+0.240±0.018	−0.037±0.029	
1.222 Mev−0.264 Mev	+0.076±0.035	+0.016±0.055	H; E
1.231 Mev−0.222 Mev	−0.012±0.014	−0.001±0.020	H; D
1.122 Mev−0.152 Mev	−0.010±0.014	+0.013±0.019	F; C
1.222 Mev−0.152 Mev	−0.037±0.012	+0.003±0.018	H; C
(1.222+1.122) Mev−0.152 Mev	−0.024±0.012	−0.004±0.017	G; C
1.231 Mev−0.100 Mev	+0.037±0.012	−0.002±0.018	H; B
Before background subtraction (0.222+0.229) Mev−0.100 Mev	+0.027±0.011	+0.027±0.016	D; B
After background subtraction (0.222+0.229) Mev−0.100 Mev	+0.034±0.024	+0.013±0.035	
0.222 Mev−0.100 Mev	−0.005±0.038	+0.015±0.055	

[11] R. G. Arns, University of Michigan (private communication).

A_2 and A_4 are plotted on the mixture curve for the sequence 3 (D,Q) 2 (Q) O, connecting levels F, D, and A, the composition of the 0.068-Mev gamma ray is found to be $(89\pm1\%D,\ 11\pm1\%Q)$. This is in fair agreement with the $E1$ assignment for the 0.068-Mev gamma ray which was determined on the basis of the conversion data. However, the assignment of spin 3 to state F is in disagreement with the value (spin 2) which was proposed by Murray et al., and Alaga et al. In such a complicated decay scheme, such as W^{182}, interference from spurious radiations is always a constant source of difficulty. Such interference could cause an error in this correlation. The discriminator which accepted the 0.068-Mev gamma ray undoubtedly accepted a certain fraction of the x rays which are produced by the low-energy gamma rays that are strongly converted. The coincidences between the x rays and the 1.222-Mev gamma rays would add a symmetric component to the correlation function. Therefore, the observed value of the anisotropy of the correlation would be less than the "true" anisotropy. Using the relative intensity of the gamma rays and the conversion coefficients of Murray et al., it was estimated that this symmetric component amounted to approximately 30% of the coincidences collected for the 1.222-Mev$-$0.068-Mev cascade. When this is subtracted out the resultant values of A_2 and A_4 are $A_2=+0.240\pm0.018$; $A_4=0$. These coefficients compare very favorably with the values $A_2=+0.250$; $A_4=0$ which are the values of the coefficients for the sequence $2(D)2(Q)0$. This value of spin 2 for state F is in agreement with the value proposed by Murray et al., and Alaga et al. The dipole assignment for the 0.068-Mev transition is also in agreement with the multipolarity of $E1$ found by Murray et al. It therefore appears that a spin of 2 should be assigned to state F.

Assuming spin of 2 for state D, the 0.152 Mev$-$1.222-Mev correlation data can only be explained by an assignment of spin 3 to state H. The quadrupole content of the 0.152-Mev gamma ray is found to be less than 0.5%. This is in agreement with the work of Murray et al., which showed the 0.152-Mev radiation to be $E1$.

W^{182} being an even-even nucleus has a spin of 0 for its ground state. States B and C were given the spins 2 and 4, respectively. These assignments are in agreement with the $E2$ character of the 0.100 Mev and 0.229-Mev gamma rays as determined from the conversion coefficients and with systematics in this region of the periodic table. Therefore, since the spin of state H has been determined to be 3 the spin sequence involving the 0.152-Mev$-$1.122-Mev gamma rays, connecting states H, D, and B, may be written as $3(D,Q)2(D,Q)2$. Such double mixtures may lead to very ambigious results, especially when the experimental coefficients A_2 and A_4 are small. The complexity of this problem is reduced if the mixture in one of the transitions is known. As previously described, the quadrupole content of the 0.152-Mev gamma ray was determined to be less than 0.5%. Therefore, the first transition is essentially pure dipole and the sequence may be written $3(D)2(D,Q)2$. From the observed values of A_2 and A_4 the quadrupole content for the 1.122-Mev gamma ray is determined to be either 3–11% quadrupole or 94–99% quadrupole. Although the correlation measurements in this case are expected to be quite good there is no information available which allows one to choose between the two values of the quadrupole content which were obtained for the 1.122-Mev gamma ray. Murray et al., from their conversion coefficient measurements, were only able to determine that the 1.122-Mev gamma ray was a mixture of $M1+E2$. Therefore, the correlation data corroborate this result. There is the possibility of interference in the 0.152-Mev$-$1.122-Mev correlation from the intense 1.222-Mev gamma ray. This interference is though to be small. The result of the combined (1.222 Mev, 1.122 Mev$-$0.152 Mev) correlation supports this assumption. In performing the combined correlation the discriminator which selected the high-energy radiations was set symmetrically on the combined 1.222 Mev$-$1.122-Mev peak (see Table I, and Fig. 2.) Since the intensities of these two high-energy gamma rays are approximately equal, the (1.222 Mev+1.122 Mev$-$0.152 Mev) correlation was considered to be composed of 50% of the (1.122 Mev$-$0.152 Mev) correlation and 50% of the (1.222 Mev$-$0.152 Mev) correlation. If 50% of each of these separate correlations are combined the values of the coefficients A_2 and A_4 are $A_2=-0.023\pm0.009$; $A_4=+0.008\pm0.013$. This result is in agreement with the measured combined correlation as given in Table I and therefore it appears that the interference from the 1.222-Mev gamma ray in the 1.122 Mev$-$0.152-Mev correlation is not important. The results of this correlation are therefore assumed to be fairly reliable.

As can be seen from Fig. 1, the 0.264 Mev$-$1.222-Mev correlation must be analyzed as a 1–3 correlation. In such an analysis the multipolarity of the unobserved transition, in this case the 0.068-Mev transition, must be known. When states F and D are assigned spins of 2, the 0.068-Mev transition as was previously discussed, was determined to be nearly pure dipole. The following sequence, connecting states K, F, D, and A, $I(L,L')$-

TABLE II. A comparison of the multipolarities of a few of the transitions from the excited states of W^{182} as determined by conversion coefficients and angular correlation.

Initial and final energy levels	Gamma-ray energy (kev)	Spins of initial and final states	Multipolarity of gamma transitions as determined by conversion coefficients	correlation measurements
FD	67	2–2	$E1$	(essentially pure dipole)
HD	152	3–2	$E1$	$>99.5\%D$; $<0.5\%Q$
DB	1122	2–2	$M1+E2$	89–97%D; 3–11%Q or 1–6%D; 94–99%Q
GB	1231	3–2	$E2$	$98\pm0.5\%D$; $2\pm0.5\%Q$

$2(D)2(Q)0$ was then analyzed. The coefficients for the sequence $4(Q)2(D)2(Q)0$ are $A_2=+0.051$ and $A_4=+0.006$ which in Table I are seen to be in agreement with the experimental values. The assignment of spin 3 to state K also finds agreement with the correlation results. In this case the sequence $3(D,Q)2(D)2(Q)0$ is analyzed and yields a quadrupole content of $(10_{-6}^{+10})\%$ or $(77_{-16}^{+9})\%$ for the 0.264-Mev radiation. The sequence $4(Q)2(D)2(Q)0$ is in agreement with the results of Murray et al., which classified state K by spin 4 and the 0.264-Mev transition as $E2$. However, the sequence $3(23\%D,\ 77\%Q)2(D)2(Q)0$ can not be completely ruled out for lack of agreement with the results obtained from the conversion coefficients, as multipole mixing ratios are not determined with great accuracy by conversion coefficients, i.e., a distinction between pure quadrupole and 77% Q quadrupole would be difficult.

Murray et al. found the 1.231-Mev gamma ray to be $E2$ and the 0.222-Mev gamma ray to be $E1$. If these multipolarities are assumed correct, and in addition if spins of 4, 3, and 2 are assumed for states K, G, and B, respectively, the values of A_2 and A_4 may be calculated for a $4(D)3(Q)2$ cascade. The results are $A_2=-0.018$ and $A_4=0$. The experimental coefficients which were obtained from the 1.231 Mev−0.222-Mev correlation ($A_2=-0.012\pm0.014$, $A_4=-0.001\pm0.020$) are in agreement with these calculated values. However, the experimental coefficients are small and since multipole mixtures in both transitions are possible, nearly any spin sequence with appropriate mixtures in the transitions will result in values of A_2 and A_4 which would be in agreement with the coefficients obtained from experiment.

The only spin assignment for state G which is in agreement with the 1.231 Mev−0.100-Mev correlation data is a spin of 3. The experimental coefficients A_2 and A_4 when plotted on the mixture curve $3(D,Q)2(Q)0$ representing the transitions connecting states G, B, and A, yield a mixture of $(98.5\pm0.5\%D,\ 1.5\pm0.5\%Q)$ for the 1.231-Mev radiation. This analysis of the 1.231-Mev gamma ray is in disagreement with the results of Murray et al., which listed the 1.231-Mev gamma ray as an $E2$ transition. There is the possibility the 1.231 Mev−0.100-Mev correlation has been contaminated by the 1.222 Mev−0.068 Mev coincidences. This latter cascade exhibited a large positive correlation and could conceivably have influenced the 1.231 Mev−0.100-Mev correlation results.

The 0.224 Mev−0.100-Mev correlation function was corrected for the Compton background which is produced by the high-energy gamma rays. It was also corrected for the 4-2-0 correlation which would be expected for coincidences between the 0.229 Mev and 0.100-Mev gamma rays. Because the correlation function after these subtractions was isotropic and since the quadrupole content of the unobserved (1.231 Mev) radiation was not precisely known, no interpretation of this 1–3 correlation was attempted.

DISCUSSION

Interesting observations may be made with regard to the beta transitions from Ta^{182} to the excited states of W^{182}. There are no beta transitions observed from Ta^{182} to states A, B, and C in W^{182}. However, there are strong beta transitions to states F and K, although these beta transitions are much lower in energy than the transitions to states A, B, and C would be. For a given spin value, the transitions to the higher excited states would be expected to proceed with probabilities much less than for the higher energy transitions.

Other interesting observations concern the gamma transitions originating at states D and G and terminating at states A and B. These transitions are either pure quadrupole, or have a large quadrupole content, although dipole radiation is allowed. The absence of an $E2$ transition of 893 kev from level D to the 4+ state at 329 kev seems unusual. It is concerning such observations (relative transition rates to various members of a nuclear rotational band) that the model for deformed nuclei makes precise predictions. W^{182} with its 74 protons and 108 neutrons is expected to exhibit properties of deformed nuclei. Both the number of neutrons and protons differe greatly from the shell which closes with 82 particles.

From measurements of the conversion coefficients Murray et al. were able to classify both the 100 kev and 229-kev transitions occurring between states BA and CB, respectively as $E2$. Since the ground-state spin and parity of all even-even nuclei is 0+, and the transition from the first excited state to the ground state is $E2$, state B must have spin and parity of 2+. If the energy separation between the ground state and first excited state is used to compute the energy of the second excited state (4+) of a rotational band, the 4+ level is found to occur at 333.3 kev. This energy is in good agreement with the observed value of 329.4 kev. It therefore appears that the ground state and first two excited states are members of the ground-state rotational band. On the basis of the conversion coefficients, the level at 1.222 Mev (state D) was assigned spin 2. From both the conversion coefficients and the correlation data level G was found to have spin 3. Assuming these spins for states D and G to be correct and using the expression of Bohr and Mottelson relating the transition rates between states of various rotational bands, the value of $K=2$ for both states was found. (K is equal to the projection of the total angular momentum on the nuclear symmetry axis.) The energy separation of 110 kev between levels G and D is approximately the same separation as is found between the ground state and first excited state. Therefore, since levels G and D have spins 3 and 2, respectively it appears that these two states belong to a second rotational band with $K=2$. Since the 1.222-Mev gamma ray appears to be $E2$ radiation, the positive parity assignment was made to level D. The parities of all members of a rotational band are the same and therefore if states G and D belong to the same rotational band state G must also be a positive parity state. Alaga et al. postulated that states G and D might belong to a "γ-vibrational band."

After correction for x-ray interference the results of the 1.222 Mev−0.068-Mev correlation gave a spin of 2 to level F with the 0.068-Mev gamma ray being classified as dipole radiation. This is in agreement with the assignments which were made on the basis of the conversion coefficients. The results of the 0.152 Mev−1.222-Mev correlation were satisfied by state H having a spin of 3. The 0.152-Mev gamma ray, between states H and D, was found to be mainly dipole radiation ($<0.5\%Q$). The energy separation of 85 kev between states H and F is only about 15% different than the 100-kev separation between states A and B. It therefore appears that states F and H may belong to a third rotational band. Since, on the basis of the conversion coefficients and the correlation results, both the 0.152 Mev and 0.068-Mev gamma rays have been designated as $E1$ transition, negative parity was assigned to both states F and H. Alaga et al. assigned a K value of 2 to these states. Using the observed separation of 85 kev between states H and F, the next excited state in this band is calculated to be at 141.7 kev above state F. Although occurring at 198 kev above state F, state J was assigned by the previous investigators[10] as the $(2, 4, -)$ member of the rotational band which includes F and H. Since the parity of this band is negative, the possibility exists that this band is an octupole vibrational band. There were no directional correlation measurements performed which involved transitions which originated from or terminated at state J. There would have been too great an influence from other radiations to arrive at any reliable results.

Murray et al. assigned the spin and parity as 4− to state K, with an $E2$ assignment for the 0.264-Mev gamma ray. Alaga et al. assigned a K value of 4 to this state. The correlation datum is not only in agreement with a spin of 4 for state K but also with the quadrupole nature of the 0.264-Mev radiation. However, the correlation results could also be satisfied by spins of 4 or 5 for state K.

CONCLUSIONS

The spins of the excited states and the multipolarities of the gammas as determined by the results of directional correlation measurements are in agreement with the values which were determined by Murray et al. on the basis of conversion coefficient measurements. There is only one case where there is disagreement. Murray et al. listed the 1.231-Mev gamma ray as an $E2$ transition. From the correlation data the 1.231-Mev gamma ray appears to be mainly dipole radiation. The spins for the excited states which were determined from the results of the correlation data are also in agreement with the spins predicted by Alaga et al. on the basis of the collective model for spheroidal nuclei. In W^{182} there exists a ground-state rotational band ($K=0$) with three members. Two "rotational-vibrational" bands also appear. There are two members of the $K=2$ even parity band, and three members of the $K=2$ odd parity band. The even parity band might be classified as a "quadrupole" vibrational band. The odd parity band might be classified as an "octupole" vibrational band. The highest excited state had been given the quantum numbers $(4, 4, -)$, and might be the start of a fourth "rotational-vibrational" band. These higher excited states which have been classified as vibrational states could equally well be purely "particle excitation" levels.

The most definite evidence for the vibrational character of the bands would be lifetime measurements of the levels. If the lifetimes were found to be substantially shorter than predicted by the individual particle lifetime formulas, this would constitute strong evidence for some vibrational character for the levels. Such measurements by the present electronic techniques seems impossible, as the expected lifetimes are so short. The theoretical calculated mean lifetimes for an $E2$ transition from the $(2, 3+)$ state at 1.331 Mev—single proton transition to the $(0, 2+)$ state at 0.100 Mev would be approximately 10^{-12} seconds. The same transition if considered as a single phonon (vibrational transition) would have a mean lifetime of 10^{-14} seconds.

Alaga et al., in their discussion of the decay scheme of Ta^{182}, cite as possible evidence for the vibrational character of the band at 1.222 Mev the fact that the rotational moment of inertia for the band is slightly (10%) smaller than that for the ground-state rotational band, whereas a particle-excitation level generally has a greater rotational moment of inertia.

Speculation might arise as to why no $K=0$ bands associated with quadrupole and octupole vibrations are observed in the decay of Ta^{182}, while there are bands observed with $K=2$. Murray et al. labeled level E as having spin and parity value of 1−. This state may be a $K=0$ state. From the proposed decay scheme it seems reasonable to assign $I=K=2$ or 3 to the ground state of Ta^{182}. The beta transitions leading to the ground-state rotational band members would then be expected to be weak and the log ft vaues high. Higher lying states with low spin and $K=0$ would also be populated very weakly by beta transitions, so that radiations from such states probably would have been too weak to be observed. Similar arguments apply when the possible population of high-lying $K=0$ states by gamma radiation from the $K=2$ bands is considered. For instance, a hypothetical $(0, 1, -)$ state around 1-Mev excitation energy might be fed by dipole or quadrupole radiation from the higher excited states. The dipole radiation would be very weak due to K forbiddenness and the quadrupole radiations to this state would be reduced owing to the competition for the quadrupole radiations by the ground-state rotational band. The same type of arguments apply when other members of the high-lying $K=0$ bands are considered.