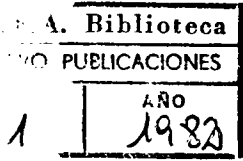


Structure and decay of the highly mixed  $13/2^+$  states in  $^{171}\text{Er}$

A. J. Kreiner,\* P. D. Bond, C. Baktash, J. Barrette, C. E. Thorn, and M. T. Collins

Brookhaven National Laboratory, Upton, New York 11973

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The previously unknown structure and decay of the lowest two  $13/2^+$  levels in  $^{171}\text{Er}$  have been studied following the  $^{170}\text{Er}(^{16}\text{O}, ^{15}\text{O})$  reaction via a particle-gamma coincidence measurement utilizing a quadrupole-dipole-dipole-dipole spectrometer. Properties of the these levels, which are highly mixed in  $K$ , are compared to quasiparticle plus rotor model calculations which reproduce the general features of the particle and gamma-ray data well.

[ NUCLEAR REACTIONS  $^{170}\text{Er}(^{16}\text{O}, ^{15}\text{O})^{171}\text{Er}$ ,  $E = 120$  MeV; measured particle gamma coincidence; deduced level energies, decay scheme. ]

INTRODUCTION

The low-lying positive parity levels in odd mass, neutron rich Er nuclei, which are due almost exclusively to the  $i_{13/2}$  neutron orbital, are not well known. This situation, which is in sharp contrast with the well studied low-lying negative parity states,<sup>1</sup> has been due at least in part to the lack of a mechanism to populate selectively high  $j$  single particle states. It has been recently shown, however, that there is a great selectivity in populating such levels for neutrons in heavy ion ( $^{16}\text{O}, ^{15}\text{O}$ ) and ( $^{12}\text{C}, ^{11}\text{C}$ ) reactions.<sup>2</sup> In particular, the two lowest lying  $13/2^+$  levels in erbium nuclei, nominally belonging to the  $7/2^+$  [633] and  $9/2^+$  [624] bands, were identified in that work. The systematic movement of these  $13/2^+$  levels through the Er isotopes indicated that they would be nearly degenerate in  $^{171}\text{Er}$  were it not for the Coriolis interaction. This presents the intriguing possibility of experimentally studying two states which are as mixed in  $K$  as possible. In the present experiment the gamma decay of the lowest two  $13/2$  levels in  $^{171}\text{Er}$  has been investigated using a particle gamma coincidence technique, and additional evidence is obtained that the earlier spin identification was correct. In addition, other members of the lower band have been identified, the predominant modes of decay have been measured, and it is established that the  $7/2^+$  [633] quasiparticle level lies lower in energy than the  $9/2^+$  [624] level, in contrast to an earlier conjecture.<sup>3</sup> Quasiparticle plus rotor model

calculations have been made and are compared to the experimental findings.

EXPERIMENTAL TECHNIQUE

A target of  $^{170}\text{Er}$  enriched to 97% and of about  $100 \mu\text{g}/\text{cm}^2$  areal density was bombarded with a 120-MeV beam of  $^{16}\text{O}$  particles from the Brookhaven tandem facility. Outgoing  $^{15}\text{O}$  ions were momentum analyzed by the quadrupole-dipole-dipole-dipole (QDDD) spectrometer and identified in the focal plane by a dual volume  $\Delta E$ - $E$  proportional counter. Gamma rays in coincidence with those particles were detected at  $130^\circ$  (which is roughly normal to the Er recoil direction) by an intrinsic Ge detector at a distance of about 10 cm. The rate in this detector, which included a negligible contribution from the well-shielded beam dump 70 cm downstream, was kept at about 25 kHz during the run. The data were event-mode recorded on tape so that in subsequent analyses gates could be placed on the  $^{15}\text{O}$  particle group, on the position of the particle along the focal plane, and on the time spectrum.

The  $^{171}\text{Er}(^{16}\text{O}, ^{15}\text{O})$  angular distributions are bell shaped and centered at about  $42^\circ$  in the laboratory. The  $^{15}\text{O}$  particle spectrum, taken at the peak of the angular distribution with a spectrometer solid angle of 12 msr, is shown in Fig. 1 and indicates a particle resolution of about 200 keV. The peaks at 620 and 960 keV were previously identified<sup>2</sup> as  $13/2^+$  states and are the subjects of this paper.

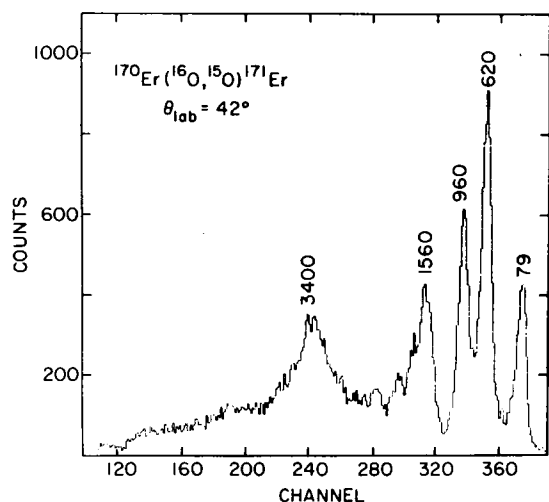


FIG. 1. Position spectrum along the focal plane of  $^{15}\text{O}$  particles following the  $^{170}\text{Er}(^{16}\text{O}, ^{15}\text{O})^{171}\text{Er}$  reaction. Peak energies are given in keV.

The time spectrum of gamma rays in coincidence with  $^{15}\text{O}$  particles is shown in Fig. 2. The resolution (FWHM) of the sharp peak is on the order of 40 nsec, much of which is due to the different times of flight through the spectrometer for different angles of entry. The rather long tail on the right hand side is due to events in the Ge detector which have a poor collection time and are primarily the result of low energy gamma rays.

The gamma-ray spectra in coincidence with 620- and 960-keV particle peaks are shown in Fig. 3. The spectra shown are those following subtraction of random coincidence spectra. A striking feature

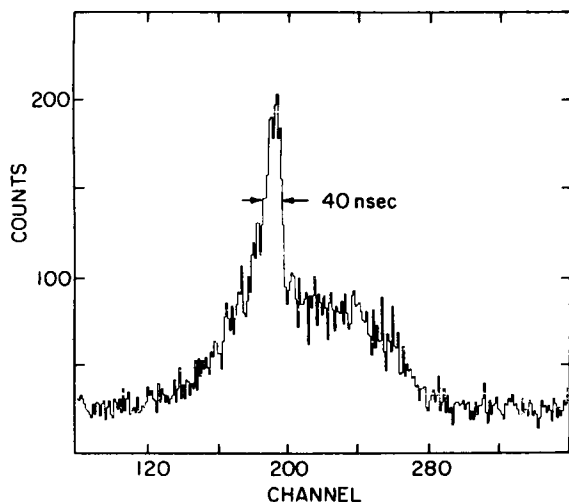


FIG. 2. Time spectrum of coincidence events between  $^{15}\text{O}$  particles and gamma rays detected in a Ge detector. See text for explanation of the tail on the spectrum.

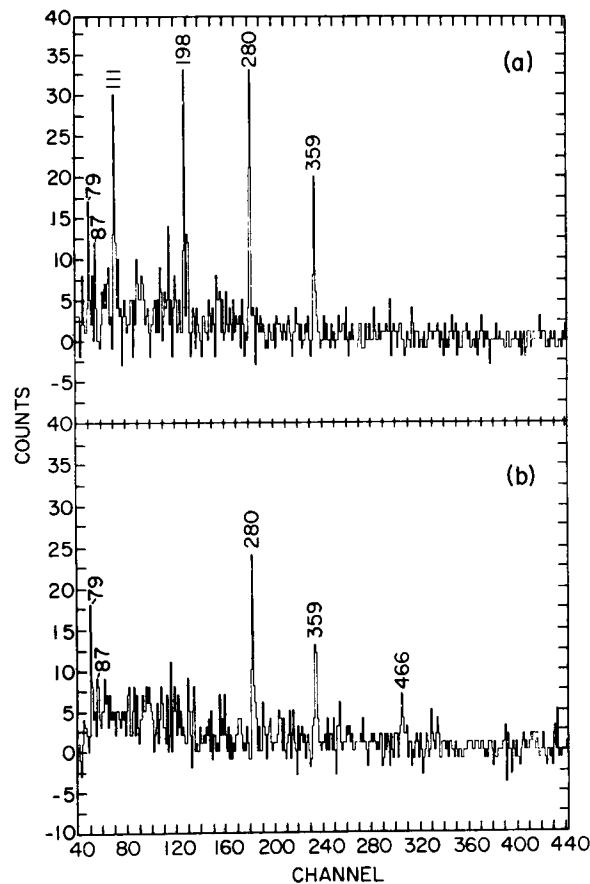


FIG. 3. Gamma-ray spectra in coincidence with (a) the 620-keV particle peak and (b) the 960-keV particle peak. Spectra corresponding to random coincidences have been subtracted.

of the data (Fig. 3) is that there are more strong gamma rays in coincidence with the particle peak corresponding to lower excitation energy. The gamma-ray spectrum in coincidence with the particle peak at 79 keV is of little interest because only a single, highly converted gamma ray is emitted to the ground state. The coincidence spectra for higher lying peaks will be presented elsewhere.

## RESULTS

### 620-keV peak

Particle identification restricts the excitation energy of this peak to  $620 \pm 20$  keV above the ground state. This  $13/2^+$  level had been previously identified<sup>3</sup> at 616 keV by the  $(d,p)$  reaction with an uncertainty of roughly  $\pm 10$  keV. Four strong gamma rays are seen in coincidence with the 620-keV

particle peak [Fig. 3(a)]: 111, 198, 280, and 359 keV. There is also a hint of weaker transitions at 87 and 201 keV. The 111- and 198-keV gamma rays cannot follow one another in cascade with the 359-keV gamma ray because the summed energy of 668 keV would be too high in  $^{171}\text{Er}$  to correspond to the level energy determined from the particle spectrum. The additional observation that the 111- and 198-keV peaks do not occur in coincidence with the higher  $13/2^+$  peak while the 280- and 359-keV gammas do is strong evidence that the 111- and 198-keV gamma rays originate directly from the  $13/2^+$  state at 620 keV, and the 280- and 359-keV gamma rays originate from levels closer to the ground state.

If we tentatively assume that the energy of this  $13/2^+$  level is 616 keV,<sup>3</sup> then there should also be levels at 505 and 418 keV which correspond to the 111- and 198-keV transitions. Since  $^{171}\text{Er}$  is a good rotational nucleus, the most likely assignments for the spins of these levels are  $11/2^+$  and  $9/2^+$ , respectively. The 280- and 359-keV gamma rays could not arise from the decay of any of the levels at 616, 505, or 418 keV to known levels in  $^{171}\text{Er}$ , so it is natural to propose that there is a  $7/2^+$  level at 359 keV which decays by  $E1$  radiation both to the  $5/2^-$  ground state and to the  $7/2^-$  state at 79 keV.

This lower positive parity band is expected to be compressed in energy so that some gamma rays will have very low energies, and hence, be highly converted; thus not all gamma decays within the band will be seen. The decay of the level at 505 keV would occur primarily via a highly converted 87-keV  $M1$  transition to the 418 level, which in turn decays via an even more converted 59-keV  $M1$  transition to the 359-keV level. There is, in fact, evidence for the 87 keV transition in Fig. 3. The 505 keV level could also decay via an  $E2$  transition of 146 keV to the 359 keV level but it is not seen. For the levels above the  $7/2^+$  level the predominant decay is expected to be in band, but they could, in principle, decay via  $E1$  radiation out of the band. There is a weak indication of a 201-keV gamma ray, which might correspond to decay of the  $11/2^+$  state to the known  $11/2^-$  state of 304 keV,<sup>1</sup> but except for the energy matching there is no other evidence for such an assignment.

The deduced scheme for the strong transitions of the 616-keV level in  $^{171}\text{Er}$  is shown in Fig. 4. This decay scheme is clearly only valid for the most intense routes and some qualification must be given to the assignments of level energies. Since the

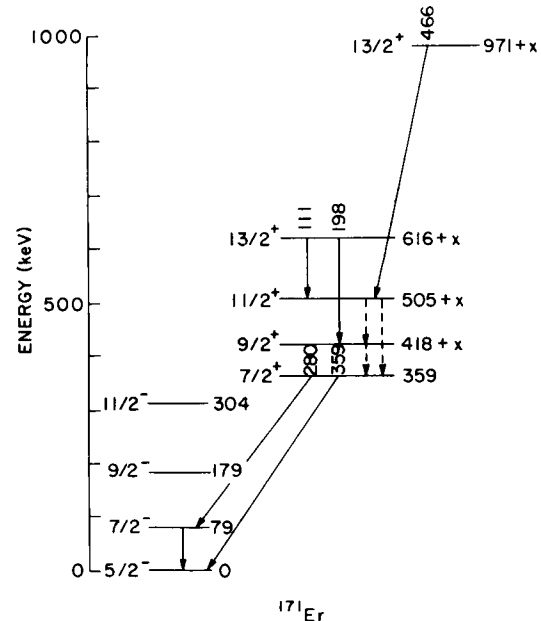


FIG. 4. Derived level scheme for the lowest positive parity bands in  $^{171}\text{Er}$ . The energies of the transitions are given above them. Dashed lines indicate unobserved transitions. See text for explanation of  $x$ .

lower  $7/2^+$  state decays to the ground state, its energy is known to about 1 keV. The levels at 418 and 505 keV, however, were derived only on the basis of gamma decays from a proposed level at 616 keV. While the relative spacing of these levels is determined to about 1 keV, none of them decay to a known level so their absolute energies have a common uncertainty of  $x$  keV, where  $x$  is on the order of 10 keV (the uncertainty established by the particle spectrum).<sup>3</sup> If the weak 201-keV transition observed in coincidence with the 620-keV peak could be assigned to the  $11/2_1^+ \rightarrow 11/2_1^-$  decay, then  $x = 0$ . Firmer grounds, however, are needed to establish the precise energies of these levels, specifically, coincidence measurements involving conversion electrons.

A  $9/2^+$  state at 378 keV was proposed, in Ref. 3 but there is no evidence for it from this experiment. In deriving the decay scheme (Fig. 4) the strong suppression of low spin states shown in Ref. 2 for the ( $^{16}\text{O}$ ,  $^{15}\text{O}$ ) reaction is important as both 198- and 279-keV gamma rays are present in the decay of  $^{171}\text{Er}$  low spin negative parity states. The energy resolution of the  $^{15}\text{O}$  spectrum (Fig. 1) is poor enough that it is not possible to rule out some small contribution from the  $9/2^-$  level at 645 keV from this spectrum alone. However, it was shown

that the corresponding level in the other Er isotopes is populated very weakly with the ( $^{16}\text{O}, ^{15}\text{O}$ ) reaction.<sup>2</sup>

The decay of the lower  $13/2^+$  level in  $^{171}\text{Er}$  (Fig. 4) might be expected to be similar to that of the corresponding level in the isotone  $^{173}\text{Yb}$ . The electron capture decay of  $^{173}\text{Lu}$  into  $^{173}\text{Yb}$  feeds a  $9/2^+$  level at 412 keV and a  $7/2^+$  level at 351 keV.<sup>1</sup> The decay of the  $7/2^+$  level proceeds by 273- and 351-keV  $E1$  gamma rays to the first excited and ground states, respectively, a situation analogous to what is observed in  $^{171}\text{Er}$ . In  $^{173}\text{Yb}$ , however, there apparently is another strong branch to the  $9/2^-$  level which is not seen in  $^{171}\text{Er}$ .

#### The 960-keV peak

This  $13/2^+$  state was first identified in Ref. 2 at an excitation energy of  $960 \pm 20$  keV. Decay of levels corresponding to this upper positive parity band are expected to be considerably more complicated than the lower positive parity band because the out-of-band transitions can be  $M1$  or  $E2$  rather than  $E1$ . The highly mixed character of these positive parity bands adds further complexity.

Despite this complexity the most striking aspect of the gamma ray coincidence spectrum [Fig. 3(b)] is the observation of only one reasonably strong gamma ray (at 466 keV) other than the 280- and 359-keV gamma rays which correspond to decay from the postulated  $7/2^+$  state at 359 keV. Since the 280- and 359-keV gamma rays appear strongly, it is clear that almost all of the decay of this upper  $13/2^+$  state eventually proceeds through the lower positive parity band. The 466-keV transition energy implies that it must be an interband transition. This transition cannot be  $13/2_2^+ \rightarrow 13/2_1^+$  because it would place the second  $13/2^+$  level at  $\approx 1082$  keV, an energy not allowed by the particle spectrum. In fact, the lowest  $13/2^+$  level is not populated strongly by decay from any other state since there is no evidence for the 111- or 198-keV gamma rays. The sum of level and gamma-ray energies also eliminates the possibility of the transition being  $13/2_2^+ \rightarrow 9/2_1$ . It is very unlikely that the 466 keV transition originates from the  $11/2_2^+$  or  $9/2_2^+$  levels in the second band because no strong transitions corresponding to decay to these levels from the  $13/2_2^+$  state are observed. Thus, the only transition not eliminated by the data is  $13/2_2^+ \rightarrow 11/2_1^+$ .

Since the other members of the upper band are not populated directly through transfer<sup>2</sup> nor suffi-

ciently through subsequent gamma decay, they cannot be identified in this experiment. The same qualifications made about the level energies of the lower band shown in Fig. 4 must be made here. The level identified in the particle spectrum near 960 keV has an uncertainty of about 20 keV, but since this level does decay directly to the  $11/2^+$  level at  $505+x$  keV with an energy difference of 466 keV, its energy should be  $971+x$  keV. Further experiments are needed to determine the value of  $x$ .

#### DISCUSSION

Calculations for the two positive parity bands discussed here were performed following the procedure described (for example) in Ref. 4. No attempt to get a best fit to experiment was made. The full quasiparticle-plus-rotor Hamiltonian was diagonalized within the basis space of all Nilsson orbitals of  $\nu i_{13/2}$  parentage. In order to perform such a calculation, several parameters have to be selected, for which there is no unique prescription. The deformation value which was used,  $\beta=0.32$ , corresponds to that obtained from the  $B(E2)$ 's of the  $2^+$  states of neighboring even-even Er nuclei.<sup>1</sup> The other parameters of the Nilsson potential were taken as  $\kappa=0.05$  and  $\mu=0.4476$ .<sup>5</sup> The pairing gap ( $\Delta=650$  keV) is of the order of the odd-even mass difference reduced by the blocking of an orbital near the Fermi surface.<sup>4</sup> The neutron Fermi level  $\lambda$  was considered an adjustable parameter (within reasonable limits) and was allowed to vary between the positions of the  $\Omega=7/2$  and  $9/2$  components of the  $i_{13/2}$  Nilsson multiplet (the adopted value lies about halfway between those two orbitals). This is a very plausible choice considering the systematics of  $7/2^+$  [633] and  $9/2^+$  [624] bands discussed in Ref. 2.

As far as the rotor is concerned, the only parameter to be determined is the moment of inertia which was also considered adjustable, since the properties of the associated even-even core are likely to be affected by the presence of the high- $j$  odd quasiparticle. The value for the rotational parameter  $A = \hbar^2/2\mathcal{I}$  used was 0.0084 MeV. The calculated level scheme for the two positive parity bands discussed here is shown in Fig. 5. The amplitudes  $a_K^I$  for the lowest two highly mixed positive parity bands are shown in Table I. It is clear from Table I that  $^{171}\text{Er}$  is very nearly a case of pure two state mixing.

TABLE I. Calculated mixing amplitudes  $a_K^I$  for the two lowest lying positive parity bands of  $\nu i_{13/2}$  parentage. Also shown are the  $U_K$  values.

I \ K	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{7}{2}$	$\frac{9}{2}$	$\frac{11}{2}$	$\frac{13}{2}$
	$7/2_1$	0.000	0.005	0.083	0.997		
$9/2_1$	0.001	0.010	0.113	0.921	0.372		
$9/2_2$	-0.000	-0.005	-0.053	-0.368	0.928		
$11/2_1$	0.001	0.014	0.137	0.882	0.450	0.028	
$11/2_2$	-0.001	-0.010	-0.085	-0.443	0.890	0.066	
$13/2_1$	0.002	0.019	0.159	0.856	0.489	0.045	0.001
$13/2_2$	-0.002	-0.016	-0.114	-0.478	0.866	0.095	0.003
$U_K$	0.078	0.094	0.141	0.359	0.962	0.994	0.998

The effect of the Coriolis interaction in compressing the lower band and expanding the upper band from their unperturbed positions is clear in Fig. 5. The  $B(E2)$  and  $B(M1)$  values determined from the calculation have been used together with the energy factors from the experiment (where known) to calculate gamma-ray transition probabilities for the two  $13/2^+$  states. A comparison of the experimental and calculated relative gamma-ray branching ratios, shown in Fig. 5, demonstrates that the decay of the lower  $13/2^+$  state is rather well reproduced.

However, the most important merit of the calculation is to provide a natural explanation for the fact that the second excited  $13/2_2^+$  state ( $\approx 900$  keV in the calculation) seems to decay directly to the lower positive parity band, a situation which appears to be fairly independent of the exact values

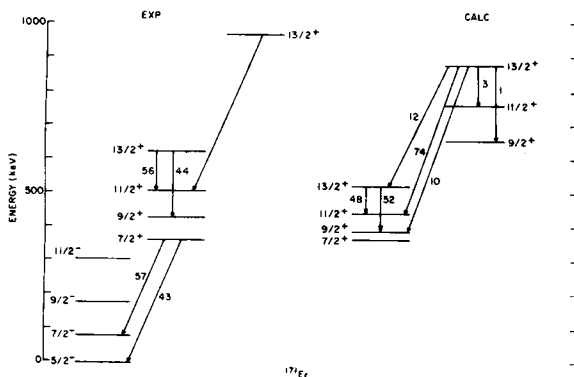


FIG. 5. Comparison of calculated and experimental level schemes with relative branching ratios of gamma-ray transitions. The theoretical level scheme has been adjusted so the  $7/2^+$  level agrees with experiment.

of the parameters used. The reason that the  $13/2_2^+ \rightarrow 11/2_1^+$  transition is by far the strongest single decay path for the  $13/2_2^+$  state is that the reduced transition matrix elements of the  $M1$  operator within the upper band and out of the band into the lower one are of similar size. In lowest order the in-band  $M1$  transitions proceed through the diagonal part ( $\Delta K=0$ ) of the operator and the out-of-band ones go through the transverse ( $\Delta K=1$ ) parts. In the present case both are of comparable magnitude since both bands have the same high- $j$   $i_{13/2}$  parentage. Hence, the out-of-band transitions dominate because of the much larger energy factor contributing to the transition probability. Of course, in the case at hand the bands are highly mixed, but this qualitative description holds. The matrix elements of the  $M1$  operator are closely related to those of the Coriolis operator so that a precise knowledge of the decay pattern of the second (and higher) excited bands of the  $i_{13/2}$  system would provide additional valuable information.

The relative intensity of the 466 keV line compared to the sum of the 280- and 359-keV lines is about 35%, which is in disagreement with the calculated intensities shown in Fig. 5. At least part of the discrepancy may be due to the fact that the energy levels in the higher band are not known, so neither the correct gamma ray intensity nor the conversion electron intensity can be calculated correctly. In addition, parameter changes (e.g.,  $\beta$  and  $\hbar^2/2\mathcal{I}$ ) in the calculation produce some variation in the  $B(M1)$  and  $B(E2)$  values. While both of these factors change the fraction of the total decay of the  $13/2_2 \rightarrow 11/2_1$  transition, it nevertheless

remains the dominant route.

The calculation also provides a natural explanation as to why the  $11/2_1 \rightarrow 7/2_1$  transition does not appear strongly in the data. Its calculated intensity is only 7% of the total decay of the  $11/2$  state and thus it would not easily be seen. The  $E1$  transition probabilities connecting the positive parity bands to the ground state band have not been calculated because they depend on very small parts of the wave functions and are thus unreliable.

The assignment of the  $7/2^+$  state at 359 keV clearly means that the  $7/2^+$  [633] quasiparticle level is at a lower excitation energy than the  $9/2^+$  [624] level in  $^{171}\text{Er}$ , in contrast to the tentative conclusion of Ref. 3. That conclusion was based on the fact that the  $7/2^+$  [633] orbital should be filled, and thus, states of its rotational band would not be populated strongly in a stripping reaction. (Note in Fig. 1 that the lower  $13/2^+$  state is more strongly populated.) The last line in Table I gives the calculated emptiness factors,  $U_{K=\Omega}$ , which indicate that indeed the  $\Omega=7/2$  orbit is nearly filled while the  $\Omega=9/2$  orbit is nearly empty. Without the Coriolis interaction the expected population of the corresponding  $13/2^+$  states would be  $(U_{7/2}/U_{9/2})^2 \approx 0.14$ , which is clearly not what is seen in the data. However, because of Coriolis mixing, the relative population of each  $13/2^+$  level is determined<sup>6</sup> approximately by  $|\sum_K a_K^I U_K|^2$  (since  $C_{j=13/2}^K \sim 1$ ). This drastically changes the expected population of these  $13/2$  states. The ratio of populations [ $(13/2_1)/(13/2_2)$ ], obtained by using the values from Table I and correcting for the

expected  $Q$  dependence of reaction theory,<sup>2</sup> is 1.2, which is in good agreement with the experimental particle yield ratio of 1.4. This agreement of particle data and theory is another indication that the structure of these levels is rather well understood.

## SUMMARY

The previously unknown structure and decay of the lowest two  $13/2^+$  states in  $^{171}\text{Er}$  has been deduced from a particle gamma coincidence measurement. The highly mixed nature of the lower two positive parity bands has been established, and quasiparticle plus rotor model calculations have successfully reproduced the general features of both the particle and gamma-ray data. It has been established that the  $7/2^+$  [633] quasiparticle level lies lower in energy than the  $9/2^+$  [624] level in  $^{171}\text{Er}$ . Measurements of conversion electrons in coincidence with particles would help to establish the energies of some of the levels more precisely.

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\*Present address: Comision Nacional de Energia Atomica, Departamento de Fisica, Libertador 8250, 1429 Buenos Aires, Argentina.

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<sup>4</sup>A. J. Kreiner, Phys. Rev. Lett. **42**, 829 (1979).

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<sup>6</sup>See, for example, B. Elbek and P. D. Tjoem, Adv. Nucl. Phys. **3**, 259 (1969).