Unpaired Band Crossings

M. A. Riley[(a)] and J. D. Garrett
The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

J. Simpson
Daresbury Laboratory, Warrington WA4 4AD, United Kingdom

and

J. F. Sharpey-Schafer
Oliver Lodge Laboratory, Liverpool University, Liverpool, United Kingdom
(Received 22 October 1987)

The lack of systematic band crossings at high spin in ^{159,160}Er and the selectivity of the single observed neutron band crossing at $\hbar\omega > 0.37$ MeV in ^{159}Er (i) indicate that static neutron-pair correlations are too weak for the excitation of a pair of quasineutrons, and (ii) can be explained in terms of the expected spectrum of single-neutron states in the absence of static pair correlations.

PACS numbers: 21.10.Re, 27.70.+q

A rotational band is associated with each intrinsic configuration of deformed nuclei. Much of our understanding of the structure of rapidly rotating nuclei is derived from the study of the crossings between such rotational bands (traditionally called "backbends"[1,2]). Most band crossings are associated with the excitation (often termed "alignment") of a pair of quasiparticles[3,4] (see, however, Yang and co-workers[5]). Such *quasiparticle* excitations depend on the existence of pair correlations.[3,6] In the presence of pair correlations the completely paired intrinsic ground state of a nucleus with many valence particles can be described as a "condensate," or vacuum, composed of the superposition of a large number of 0+ pairs.[7] (The quasiparticles are the basic excitations with respect to this vacuum configuration.) In the absence of pair *correlations* this condensate is nonexistent. Therefore, the excitation of a pair of quasiparticles associated with a quasiparticle band crossing disappears in a manner analogous to the disappearance of the enhanced two-particle transfer between correlated nuclear ground states.[8] Indeed the occurrence of such "quasiparticle band crossings" has been suggested[6] and used[9,10] as a test for the existence of static nuclear-pair correlations at large angular momentum.

The absence of pair correlations, however, does not exclude band crossings. Not only can band crossings occur based on the crossing of single-particle (not quasiparticle) levels,[5] but a pair of *particles* with quantum numbers[11] summing to $(\pi = \alpha) = (+,0)$ can replace another $(+,0)$ pair of particles. The first observation of this latter type of "unpaired crossings" is reported in the present Letter.

The advent of large arrays of Compton-suppressed germanium detectors have extended high-spin spectroscopic studies into the region where static pair correlations are quenched.[10,12] The rotating-frame excitation energies[3] (Routhians) e' are shown in Fig. 1 as a function of the rotational frequency $\hbar\omega$, for two of the isotopes, ^{159}Er$_{91}$ (Refs. 13–15) and ^{160}Er$_{92}$ (Refs. 16 and 17), that have been established to the highest spins. In such plots, band crossings (i.e., changes in the intrinsic

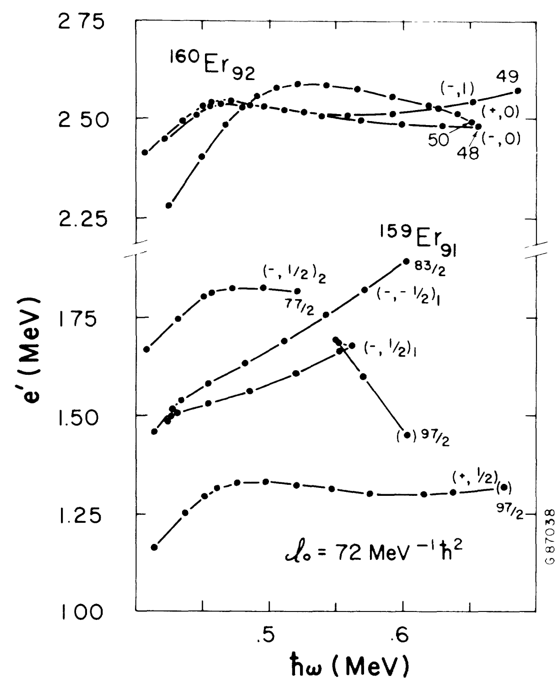

FIG. 1. Experimental Routhians (Ref. 3) for high-spin decay sequences ($\hbar\omega > 0.4$ MeV) in ^{159}Er (Refs. 13–15) and ^{160}Er (Refs. 16 and 17). These Routhians are referred to a configuration with a constant momentum of inertia (J_0) of 72 MeV$^{-1}\hbar^2$. The decay sequences are labeled by the appropriate quantum numbers (Ref. 11) (π,α), and the maximum observed angular momentum is given for each sequence.

nuclear configurations) show up as changes of slope. Those observed at $0.42 < \hbar\omega < 0.48$ MeV correspond to the excitation of the first pair of quasiprotons.[14,16] For $\hbar\omega > 0.48$ MeV only a single band crossing [that at $\hbar\omega = 0.555$ MeV in the $(-,\frac{1}{2})_1$ decay sequence of ^{159}Er] is observed though several bands are established to $\hbar\omega > 0.65$ MeV. This is the only candidate for a "quasineutron band crossing" above $\hbar\omega_c = 0.37$ MeV (see Fig. 2).

Such systematics differ both with the general expectations[3,4,18] and detailed calculations[13,16] of quasineutron excitations for such nuclei. "Quasineutron band crossings," corresponding to the excitation of pairs of both negative-parity (mixture of $h_{9/2}$ and $f_{7/2}$) quasineutrons and additional pairs of $i_{13/2}$ quasineutrons in configurations not yet excited, are expected to occur[19] in the presence of sizable static neutron-pair correlations. Neither can the selective occurrence of the crossing at $\hbar\omega = 0.555$ MeV in the $(-,\frac{1}{2})$ decay sequence of ^{159}Er (see Fig. 1) be explained by the alignment of a pair of quasineutrons[19] or quasiprotons.[20]

The observed band-crossing systematics, however, can be explained in the absence of static neutron-pair correlations. The scheme of single-neutron levels that give such band crossings is shown in Fig. 3. This level diagram also has the general features expected[12,21] for single-neutron states in this mass region: (i) highly aligned (i.e., large negative sloped) positive-parity levels; (ii) less aligned negative-parity levels; (iii) larger energy splitting between opposite signatures of positive-parity levels than for negative-parity levels; and (iv) a lowering of the $\alpha = \frac{1}{2}$ single-neutron levels relative to those with $\alpha = -\frac{1}{2}$. Though the detailed single-neutron spectrum of states depends on the particulars of the deformations and the parametrization of the nuclear potential, the general features for this mass region stated above only require a basically prolate nuclear potential, a sizable spin-orbit splitting and the Fermi level in the lower portion of a major shell. These requirements are expected

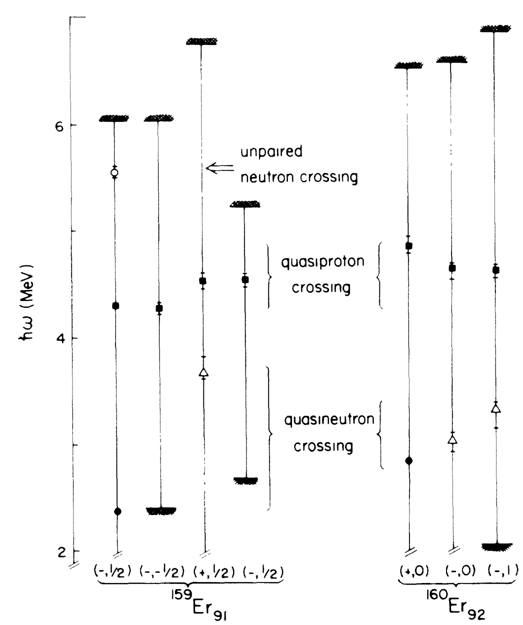

FIG. 2. Summary of band-crossing frequencies $\hbar\omega_c$ for the observed crossings in the decay sequences of ^{159}Er (Refs. 13–15) and ^{160}Er (Refs. 16 and 17). Crossings corresponding to the excitation of the lowest (AB) and second-lowest (BC) pair of quasineutrons are denoted by filled circles and open triangles, respectively. Those corresponding to quasiproton (A_pB_p) alignments are given as squares, and the proposed unpaired neutron crossing is shown as an open circle. The frequency range of the experimental data for each configuration is indicated by the vertical lines. No band crossings are observed for $\hbar\omega < 0.2$ MeV.

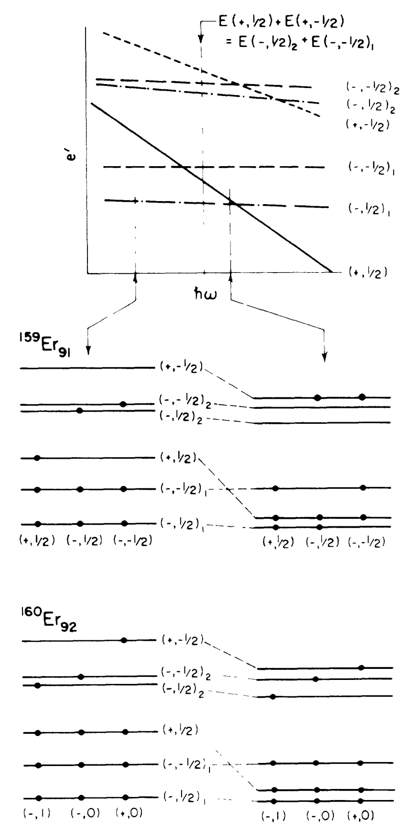

FIG. 3. The scheme of single-neutron levels that in the absence of neutron pair correlations give the observed band crossing in the lowest $(-,\frac{1}{2})$ decay sequence of ^{159}Er and in no other observed decay sequences of ^{159}Er and ^{160}Er is shown in the upper portion. A similarity to calculated single-neutron levels for this mass region (e.g., Refs. 12, 21, and 22) is noted. The explicit occupation is shown for the various low-lying configurations at the specific frequencies indicated in the lower portion of the figure. The exchange of the occupation of the $(-,\frac{1}{2})_2$ and $(-,-\frac{1}{2})_1$ orbitals with the $(+,\frac{1}{2})$ and $(+,-\frac{1}{2})$ orbitals for the lowest-lying $(-,\frac{1}{2})$ sequence in ^{159}Er is associated with the observed band crossing in this decay sequence (see Fig. 1).

to be satisfied in this mass region.

The band crossing in the $(-,\frac{1}{2})$ decay sequence of $^{159}Er_{91}$ is based on the exchange of a pair of neutrons in the levels labeled $(-,-\frac{1}{2})_1$ and $(-,\frac{1}{2})_2$ at smaller rotational frequencies with the pair labeled $(+,\frac{1}{2})$ and $(+,-\frac{1}{2})$ at larger values of $\hbar\omega$. Since both pairs couple to $(\pi,\alpha)=(+,0)$, the parity and signature of the decay sequence remains unchanged. This crossing occurs at the rotational frequency where the condition,

$$e'(+,\tfrac{1}{2})+e'(+,-\tfrac{1}{2})=e'(-,-\tfrac{1}{2})_1+e'(-,\tfrac{1}{2})_2 \qquad (1)$$

is satisfied.

The weak interaction (sharp "backbend") observed between the crossing bands at $\hbar\omega=0.555$ MeV in the $(-,\frac{1}{2})$ decay sequence supports the unpaired band-crossing interpretation described in the preceding paragraph. Interaction strengths between bands differing by two quasiparticles increase with both increasing rotational frequency and decreasing pair gap.[23] Therefore, even though a weakly interacting high-frequency band crossing is not excluded, it is unlikely. Indeed, sharp backbends are rare[22] among the higher-frequency crossings corresponding to the excitation of the second (or higher) pair of quasineutrons (or quasiprotons).

The absence of a similar crossing in the $(-,-\frac{1}{2})$ decay sequence of ^{159}Er, based on the exchange of the $(-,\frac{1}{2})_1$-$(-,-\frac{1}{2})_2$ neutron pair at lower $\hbar\omega$ with the $(+,\frac{1}{2})$-$(+,-\frac{1}{2})$ pair at higher $\hbar\omega$ indicates that the $(-,\frac{1}{2})_1$ single-neutron level must lie somewhat lower in energy than the $(-,-\frac{1}{2})_1$ level. Indeed, a significant splitting in energy is predicted for this configuration independent of sizable variations of the deformation and nuclear potential.[12,21] Such a crossing does not occur in the $(+,\frac{1}{2})$ decay sequence of ^{159}Er and all established sequences of ^{160}Er because of the $(+,\frac{1}{2})$ neutron level is occupied below the band-crossing frequency. Thus the exchange of the $(+,\frac{1}{2})$-$(+,-\frac{1}{2})$ pair with a less-aligned pair of negative-parity states coupled to $(+,0)$ is "blocked."

Additional information on the spectrum of single-neutron states is contained in the crossing between the $(+,0)$ and the $(-,1)$ and $(-,0)$ sequences of ^{160}Er at the largest values of $\hbar\omega$, see Fig. 1. These crossing between sequences with different quantum numbers can be attributed to the crossing of the single-neutron level labeled $(+,\frac{1}{2})$ with those labeled $(-,\frac{1}{2})_2$ and $(-,-\frac{1}{2})_2$ (see Fig. 3). Indeed, the occurrence of such crossings of sequences with different quantum numbers are a necessary condition for the spectrum of single-neutron states required to explain the single selective unpaired band crossing based on an exchange of a pair of particles with quantum numbers coupling to $(\pi,\alpha)=(+,0)$, described in the preceding paragraphs.

In summary, the lack of systematic intraband band crossings and the selectivity of the singularly observed neutron crossing at $\hbar\omega>0.37$ MeV indicate that static neutron-pair correlations are too weak at these rotational frequencies to allow the excitation of a pair of quasineutrons. The pattern of large-frequency crossings, however, can be understood in terms of the expected spectrum of single-neutron states in the absence of static pair correlations. Furthermore, such data yield specific, direct information on the single-particle spectrum of states, e.g., in the present case, the rotational frequency where the condition given in Eq. (1) is satisfied. Such specific information on the spectrum of states is very sensitive to, for example, the details of the nuclear shape and nuclear potential and other possible correlations. Likewise, the interaction strength between unpaired band crossings is an interesting quantity, since such interactions are the basis of rotational damping.[24] Indeed, improved knowledge of such quantities through the measured spectrum of single-particle states will be the result of the spectroscopy of unpaired nuclei which is just now starting.

Discussions with Th. Døssing are acknowledged as is the support of the Danish Natural Science Research Foundation, the United Kingdom Science and Energy Research Council, and the Japanese World Exposition Commemorative Fund. One of us (M.A.R.) acknowledges the award of a Royal Society European Exchange Fellowship.

[a]Present address: Holifield Heavy Ion Facility, Oak Ridge National Laboratory, Oak Ridge, TN 37831.

[1]A. Johnson, H. Ryde, and J. Sztarkier, Phys. Lett. **34B**, 605 (1971).

[2]F. S. Stephens and R. Simon, Nucl. Phys. **A183**, 257 (1972).

[3]R. Bengtsson and S. Frauendorf, Nucl. Phys. **A327**, 139 (1979).

[4]L. L. Riedinger, O. Andersen, S. Frauendorf, J. D. Garrett, J. J. Gaardhøje, G. B. Hagemann, B. Herskind, Y. V. Makovetzky, J. C. Waddington, M. Guttormsen, and P. O. Tjøm, Phys. Rev. Lett. **44**, 568 (1980).

[5]C.-X. Yang, J. Kownacki, J. D. Garrett, G. B. Hagemann, B. Herskind, J. C. Bacelar, J. R. Leslie, R. Chapman, J. C. Lisle, J. N. Mo, A. Simcock, J. C. Willmott, W. Walus, L. Carlen, S. Jonsson, J. Lyttkens, H. Ryde, and P. O. Tjøm, Phys. Lett. **133B**, 39, (1983).

[6]S. Frauendorf, Nucl. Phys. **A409**, 243c (1983).

[7]Aa. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2, pp. 392–395.

[8]R. Broglia, O. Hansen, and C. Riedel, Adv. Nucl. Phys. **6**, 287 (1973).

[9]S. Frauendorf, in *Proceedings of the Fifth Nordic Meeting on Nuclear Physics,* Jyväskylä, Finland, 1984 (Univ. Jyväskylä, Jyväskylä, 1984), p. 19.

[10]J. D. Garrett, in *Selected Topics in Nuclear Structure,* edited by R. Brode and Z. Stachura (Institute of Nuclear Physics, Krakow, 1986), p. 15.

[11]The signature quantum number (denoted α) is associated with a rotation of 180° about the rotational axis (Ref. 3). It is related to the total angular momentum I by $I = \alpha$ (mod 2).

[12]J. C. Bacelar, M. Diebel, C. Ellegaard, J. D. Garrett, G. B. Hagemann, B. Herskind, A. Holm, C.-X. Yang, J.-Y. Zhang, P. O. Tjøm, and J. C. Lisle, Nucl. Phys. **A442**, 509 (1985).

[13]J. Simpson, P. A. Butler, P. D. Forsyth, J. F. Sharpey-Schafer, J. D. Garrett, G. B. Hagemann, B. Herskind, and L. P. Ekstrom, J. Phys. G **10**, 383 (1984).

[14]M. A. Riley, J. Simpson, R. Aryaeinejad, J. R. Cresswell, P. D. Forsyth, D. Howe, P. J. Nolan, B. M. Nyako, J. F. Sharpey-Schafer, P. J. Twin, J. Bacelar, J. D. Garrett, G. B. Hagemann, B. Herskind, and A. Holm, Phys. Lett. **135B**, 275 (1984).

[15]M. A. Deleplanque, J. C. Bacelar, E. M. Beck, R. M. Diamond, J. E. Draper, R. J. McDonald, and F. S. Stephens, Phys. Lett. B **193**, 422 (1987).

[16]J. Simpson, M. A. Riley, J. R. Cresswell, D. V. Elenkov, P. D. Forsyth, G. B. Hagemann, D. Howe, B. M. Nyako, S. Ogaza, J. C. Lisle, and J. F. Sharpey-Schafer, J. Phys. G **13**, 847 (1987).

[17]J. Simpson, M. A. Riley, A. N. James, A. R. Mokhtar, H. W. Cranmer-Gorden, P. D. Forsyth, A. J. Kirwan, D. Howe, J. D. Morrison, and J. F. Sharpey-Schafer, J. Phys. G. **13**, L235 (1987).

[18]L. L. Riedinger, Phys. Scr. **T5**, 36 (1983).

[19]The band crossing corresponding to the excitation of a pair of negative-parity (EF) quasineutrons is allowed in all the positive-parity decay sequences populated in ^{159,160}Er. The next higher allowed positive-parity quasineutron alignment (CD) is allowed only in the ^{160}Er $(+,0)$ decay sequence (S band). The alphabetic labeling of the quasineutrons excited at a band crossing is given, for example, in Refs. 3, 4, and 6.

[20]Above the lowest quasiproton crossings (observed at $0.42 < \hbar\omega < 0.48$ MeV) all configurations have the same single-proton structure; therefore, higher quasiproton band crossings would occur either in all or none of the decay sequences.

[21]T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A436**, 14 (1985), and Phys. Lett. **163B**, 31 (1985).

[22]J. D. Garrett, G. B. Hagemann, and B. Herskind, Annu. Rev. Nucl. Part. Sci. **36**, 419 (1986).

[23]I. Hamamoto, in *Treatis on Heavy-Ion Science,* edited by D. A. Bromley (Plenum, New York, 1985), Vol. 5, p. 313.

[24]B. Lauritzen, T. Døssing, and R. A. Broglia, Nucl. Phys. **A457**, 61 (1986).