Signature-Dependent Proton Alignments at High Rotational Frequency and the Persistence of Proton Pairing Correlations

J. Simpson, P. D. Forsyth, D. Howe, B. M. Nyakó,[(a)] M. A. Riley, and J. F. Sharpey-Schafer
Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool L69 3BX, United Kingdom

and

J. Bacelar, J. D. Garrett, G. B. Hagemann, B. Herskind, and A. Holm
The Niels Bohr Institute, University of Copenhagen, DK-2100, Copenhagen, Denmark

and

P. O. Tjøm
Institute of Physics, University of Oslo, Oslo, Norway

(Received 21 January 1985)

Band crossings are observed in the yrast $\alpha = -\frac{1}{2}$ and $+\frac{1}{2}$ negative-parity decay sequences in ^{157}Ho at $\hbar\omega = 0.48$ and ≈ 0.54 MeV, respectively. These band crossings are interpreted as the alignment of the second and probably the third pair of $h_{11/2}$ quasiprotons. This is the first identification of delayed crossings involving the second aligning nucleon. These crossings show that sizable proton-pair correlations must remain for these configurations up to high rotational frequencies $\hbar\omega \approx 0.5$ MeV.

PACS numbers: 23.20.Lv, 21.10.Re, 27.70.+q

Soon after the interpretation of "backbending"[1] in even-even deformed rare-earth nuclei as a crossing near spin $I \approx 14$ between the ground-state rotational band and a band based on an aligned pair of high-j quasineutrons,[2] a second backbend was observed[3] in the yrast sequence of ^{158}Er at larger angular momentum $I \approx 28$. This second band crossing was interpreted[4] as the alignment of a pair of $h_{11/2}$ quasiprotons. Recently, it has been definitely established that this second band crossing corresponds to quasiproton alignment by observation of this crossing in the neighboring odd-N isotopes[5,6] and by no observation of it in the neighboring odd-Z isotones.[5,7]

Quasiparticle alignments are rich in nuclear structure information. They provide insight into the quasiparticle structure of the levels[8] and give information on the pairing force[9] and the deformation of the nucleus.[6] Additional information on the shape of the nucleus can be obtained from the interaction $|V|$ between the bands at the crossing[10,11] and from the degree of signature splitting before and after a crossing.[7,12] Of particular importance is the effect of quasiparticle alignments and the rotational forces on the pairing energy. This has been a topic of much discussion.[13–18] Current expectations[15,19] are that proton-pair correlations should remain large up to rotational frequencies $\gtrsim 0.5$ MeV in contrast to neutron-pair correlations which are thought to be greatly reduced. Observation of proton alignments at very high rotational frequency would enable this to be corroborated. The place to look for such band crossings is in odd-proton nuclei where the first proton crossing is blocked by the single unpaired proton and subsequent alignments may take place analogous to the delayed neutron alignments observed in odd-neutron nuclei.[8,20] To date no delayed band crossing involving the second aligning particle has been observed. The development of a new generation of gamma-ray spectrometers allows discrete line spectroscopy to be taken to much higher rotational frequency and angular momentum into the region where these alignments are expected. In the present work alignment of the second and probably the third most alignable pairs of quasiprotons is observed in ^{157}Ho in the lowest-energy signature[21] $\alpha = -\frac{1}{2}$ and $+\frac{1}{2}$ rotational sequences respectively at rotational frequencies above 0.45 MeV. The consequences of these crossings with regard to proton-pair correlations and cranking calculations are discussed.

The present data were obtained by bombarding five stacked thin foils of ^{124}Sn (total thickness 1.75 mg/cm^2) with a 160-MeV ^{37}Cl beam from the tandem accelerator at the nuclear structure facility at Daresbury Laboratory. Gamma rays were detected in the array TESSA2[22] which consists of six escape-suppressed germanium spectrometers (ESS's) and a fifty-element bismuth germanate (BGO) "crystal ball" which measures the total energy and number of gamma rays (multiplicity) in the gamma-ray cascade. A total of 24×10^6 events were recorded when two or more ESS's and at least one BGO were in coincidence. The decay scheme shown in Fig. 1 was deduced from the γ-γ-BGO coincidence spectra. The positive and negative signatures ($+\frac{1}{2}$ and $-\frac{1}{2}$) of the $h_{11/2}[523\frac{7}{2}]$ rotational structure are known from previous work[23] up to $I^\pi = \frac{49}{2}^-$ and $\frac{47}{2}^-$, respectively. The present work ex-

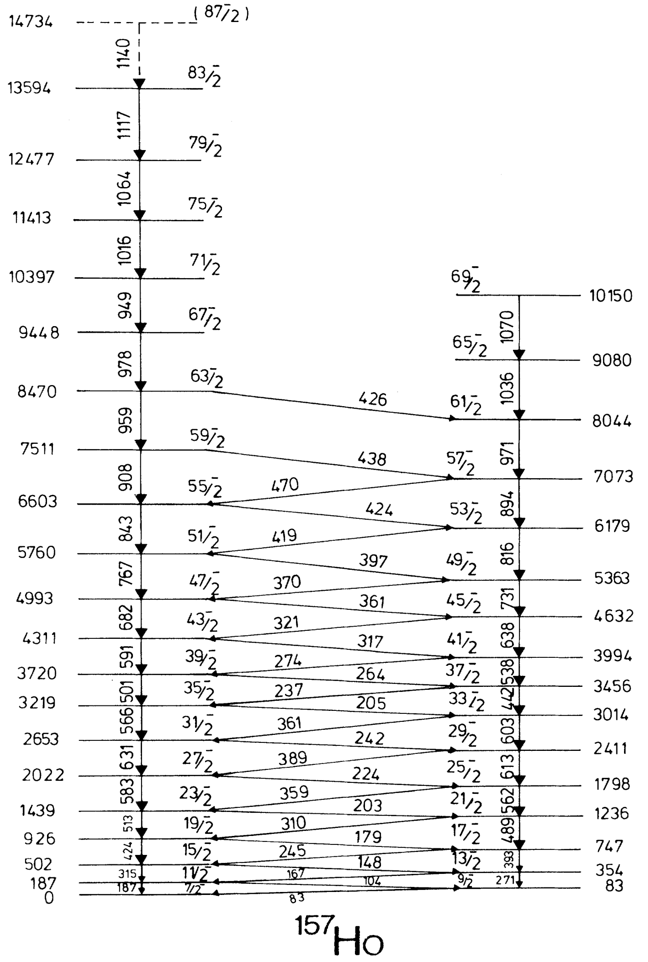

FIG. 1. The level scheme for ^{157}Ho deduced following the ^{124}Sn(^{37}Cl,4n) reaction at at beam energy of 160 MeV. Excitation and transition energies are given in kiloelectronvolts.

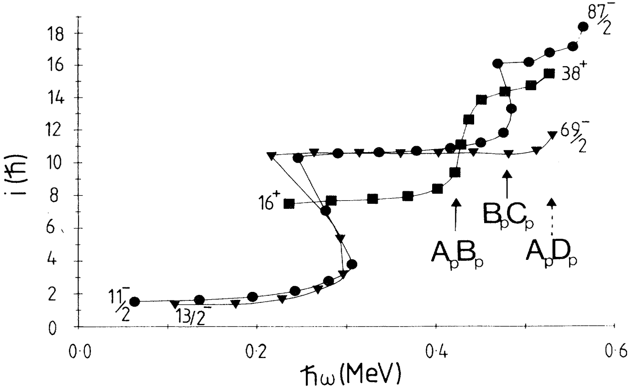

FIG. 2. The experimental aligned angular momentum i against rotational frequency $\hbar\omega$ for the bands observed in ^{157}Ho. The bands are labeled by the constituent quasiparticles in each band. Also plotted is the yrast band in ^{158}Er for the 16^+ to 38^+ states.

tends the $\alpha = +\frac{1}{2}$ sequence up to $\frac{69}{2}^-$ and the $\alpha = -\frac{1}{2}$ sequence up to $\frac{83}{2}^-$. The 1140-keV γ-ray is tentatively assigned as the $\frac{87}{2}^- \rightarrow \frac{83}{2}^-$ transition. Relative intensities of the γ rays assigned to a band were measured at $\theta = 30°$ and 90° which showed that their angular distributions are consistent with the in-band γ rays being stretched $E2$ transitions.

In Fig. 2 the experimental aligned angular momentum[10] i is plotted as a function of the rotational frequency $\hbar\omega$. Also plotted is the aligned angular momentum for the yrast band in ^{158}Er[24,25] for the 16^+ to 38^+ states. In the extraction of i the reference subtracted was based on the Harris formula[26] which has as parameters $\mathscr{J}_0$ and $\mathscr{J}_1$. Values of $\mathscr{J}_0 = 32.1\hbar^{-1}$ MeV^2 and $\mathscr{J}_1 = 34.0\hbar^{-3}$ MeV^4 were adopted in the present work. These values were chosen to give nearly constant alignment for the $\alpha = +\frac{1}{2}$ three-quasiparticle configuration (B_pAB) in ^{157}Ho (see below). In the following discussion the convention for the labeling of the quasineutron orbitals is that given in Ref. 8 where for neutrons, A and B are the lowest-energy positive-parity orbitals of either signature. For protons we label the four lowest-energy orbitals as $A_p = (\pi,\alpha)_n = (-, -\frac{1}{2})_1$, $B_p = (-, +\frac{1}{2})_1$, $C_p = (-, -\frac{1}{2})_2$, and $D_p(-, +\frac{1}{2})_2$, where n denotes the nth such quasiproton orbital. At low rotational frequency ($\hbar\omega \lesssim 0.25$ MeV) the cascades are along the rotational bands based on the two signatures originating at $\omega = 0$ from the $h_{11/2}[523\frac{7}{2}]$ single-quasiproton intrinsic configuration. At $\hbar\omega \approx 0.27$ MeV both signatures of the single-quasiproton bands in ^{157}Ho are crossed by bands based on three-quasiparticle configurations in which a pair of $i_{13/2}$ quasineutrons (AB) have aligned. Thus these bands are composed of two aligned quasineutrons (AB) and a single quasiproton (A_p or B_p). The alignment of the most alignable pair of quasiprotons (A_pB_p), which is observed in the yrast band of ^{158}Er at $\hbar\omega = 0.43$ MeV,[24,25] see Fig. 2, is blocked in both sequences and is not observed. However, another band crossing is established at $\hbar\omega = 0.48$ MeV in the $\alpha = -\frac{1}{2}$ rotational sequence and the beginning of a crossing is observed at $\hbar\omega \approx 0.54$ MeV in the $\alpha = +\frac{1}{2}$ rotational sequence. The large shift in band-crossing frequencies between the $\alpha = \pm\frac{1}{2}$ decay sequences argues against the alignment of a completely new pair of quasineutrons or quasiprotons, e.g., $\pi(h_{9/2})$, $\pi(i_{13/2})$, $\nu(h_{9/2})$, or $\nu(i_{13/2})$, since such crossings would occur at roughly the same rotational frequency. Also, since the crossing at 0.48 MeV in the $\alpha = -\frac{1}{2}$ sequence (A_pAB configuration) is not observed in the $\alpha = +\frac{1}{2}$ sequence (B_pAB configuration) then this alignment must involve the quasiproton B_p. Therefore this crossing at 0.48 MeV is the alignment of the second most alignable pair of quasiprotons, namely B_pC_p.

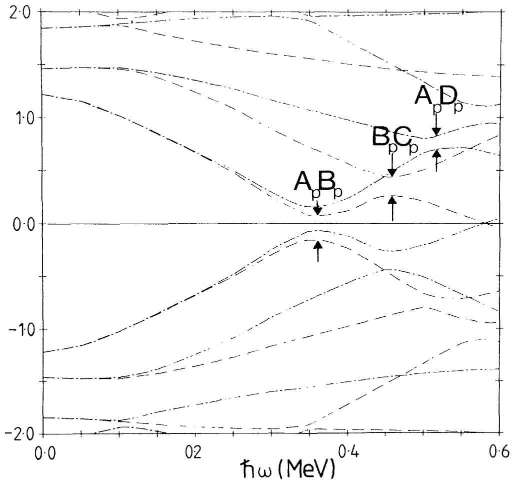

FIG. 3. Cranked-shell-model calculations of the rotating-frame excitation energy e' against rotational frequency $\hbar\omega$ for the lowest-energy negative-parity quasiproton orbitals in ^{157}Ho. The parameters used in this calculation were $\epsilon_2 = 0.21$, $\epsilon_4 = -0.018$, $\gamma = 0°$, and $\Delta_p = 1.2$ MeV.

Similar delayed crossings involving $i_{13/2}$ quasineutrons have been observed at much lower rotational frequency in nuclei in this region.[8,20] In the same manner the start of an upbend in the $\alpha = +\frac{1}{2}$ sequence at $\hbar\omega \approx 0.54$ MeV can probably be interpreted as the alignment of the third most alignable pair of quasiprotons, namely A_pD_p. However, there is also an onset of an alignment at a similar rotational frequency in the yrast band in ^{158}Er (see Fig. 2) and to some extent in the $\alpha = -\frac{1}{2}$ five-quasiparticle configuration in ^{157}Ho. Therefore the interpretation that this crossing is the A_pD_p alignment is speculative.

The interpretation of these high-frequency crossings in the negative-parity sequences in ^{157}Ho as the alignment of the second and third most alignable pairs of quasiprotons agrees will with cranked shell-model (CSM) calculations.[10] Figure 3 shows the negative-parity quasiproton Routhians calculated using the CSM for ^{157}Ho. The parameters used in the calculation of the quasiproton trajectories were $\epsilon_2 = 0.21$, $\epsilon_4 = -0.018$, $\gamma = 0°$, and $\Delta_p = 1.2$ MeV. Using these parameters the B_pC_p and A_pD_p proton crossing frequencies are predicted to occur at 0.47 MeV and 0.53 MeV, respectively. For the B_pC_p crossing an alignment gain of $7.0\hbar$ is predicted compared to the experimental value of $5.7\hbar$. Therefore, with a reasonable choice of input parameters $(\epsilon_2, \epsilon_4, \gamma, \Delta)$ the CSM can still give qualitative agreement with the quasiproton alignments up to $\hbar\omega \approx 0.5$ MeV. In the absence of proton pairing the highly alignable, low-Ω $h_{11/2}$ proton orbitals are occupied in the holmium isotopes since the Fermi surface for $Z = 67$ is near the $\Omega = \frac{7}{2} h_{11/2}$ orbital. Therefore, such crossings require substantial pair correlations to scatter pairs of protons from the low-Ω $h_{11/2}$ orbitals producing low-Ω $h_{11/2}$ quasiproton states which align under rotation. Within the CSM with the deformation parameters $(\epsilon_2, \epsilon_4, \gamma)$ kept to reasonable values it is found that the pairing gap needs to be at least 0.9 MeV ($\Delta_p \gtrsim 0.9$ MeV) for the alignments observed to be reproduced. These data are the first demonstration that proton-pair correlations exist at such high rotational frequencies. Such observations imply that the rotationally induced reduction in pair correlations is dominantly associated with particle alignment rather than a gradual decrease with increasing rotational frequency.

In summary, the band crossings observed at high rotational frequencies in the negative-parity decay sequences of ^{157}Ho are associated with the alignment of the second and probably the third most alignable pair of quasiprotons. Interpreting these as delayed quasiproton crossings completes the analogy between quasiprotons and the lower-frequency quasineutron crossings in the nuclei in this region. These crossings require significant pair correlations (using the CSM $\Delta_p \gtrsim 0.9$ MeV) to remain for these configurations up to $\hbar\omega \approx 0.5$ MeV.

This work was supported by the United Kingdom Science and Engineering Research Council (SERC) and the Danish Natural Science Research Council. Two of us (M.A.R. and D.H.) acknowledge the receipt of SERC postgraduate studentships. The authors wish to thank the crew of the Nuclear Structure Facility for supplying the beam, J. R. Cresswell and C. D. Wooff for software support, and all those involved in the operation of TESSA2.

---

[a] Permanent address: Institute of Nuclear Research of The Hungarian Academy of Sciences, H-4001, Debrecen pf 51, Hungary.

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

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

[3] I. Y. Lee, M. M. Aleonard, M. A. Deleplanque, Y. El-Masri, J. O. Newton, R. S. Simon, R. M. Diamond, and F. S. Stephens, Phys. Rev. Lett. **38**, 1454 (1977).

[4] A. Faessler and M. Ploszajczak, Phys. Lett. **76B**, 1 (1978).

[5] R. Holtzmann, J. Kuzminski, M. Loiselet, M. A. Van Hove, and J. Vervier, Phys. Rev. Lett. **50**, 1834 (1983).

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

[7] A. J. Larabee, L. H. Courtney, S. Frauendorf, L. L. Riedinger, J. C. Waddington, M. P. Fewell, N. R. Johnson, I. Y. Lee, and F. K. McGowan, Phys. Rev. C **29**, 1934 (1984).

[8] 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).

[9] J. D. Garrett, O. Andersen, J. J. Gaardhøje, G. B. Hagemann, B. Herskind, J. Kownacki, J. C. Lisle, L. L. Riedinger, W. Walús, N. Roy, S. Jönsson, H. Ryde, M. Guttormsen, and P. O. Tjøm, Phys. Rev. Lett. **47**, 75 (1981).

[10] R. Bengtsson and S. Frauendorf, Nucl. Phys. **A327**, 139 (1979), and **A314**, 27 (1979).

[11] A. Faessler and M. Ploszajczak, Phys. Rev. C **22**, 2609 (1980).

[12] S. Frauendorf and F. R. May, Phys. Lett. **125B**, 245 (1983).

[13] B. R. Mottelson and J. G. Valatin, Phys. Rev. Lett. **5**, 511 (1960).

[14] S. G. Nilsson and O. Prior, K. Dan. Vid. Selsk. Mat. Fys. Medd. **32**, (1961).

[15] K. Tanabe and K. Sugawara-Tanabe, Phys. Lett. **135B**, 353 (1984).

[16] U. Mutz and P. Ring, J. Phys. G **10**, L39 (1984).

[17] R. Bengtsson and H.-B. Håkansson, Nucl. Phys. **A357**, 61 (1981).

[18] R. Bengtsson and J. Zhang, Phys. Lett. **135B**, 358 (1984).

[19] S. Frauendorf, in Proceedings of the Fifth Nordic Meeting on Nuclear Physics, Jyväskylä, Finland, 1984 (to be published), p. 19.

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

[21] Signature is the quantum number associated with invariance under rotation of 180° about an axis perpendicular to the nuclear symmetry axis. It is related to the spin by $I \equiv \alpha \bmod 2$; hence in an odd-A nucleus bands of $\alpha = +\frac{1}{2}$ contain $I = \frac{1}{2}, \frac{5}{2}, \frac{9}{2}, \frac{13}{2}, \ldots$ spin sequences and $\alpha = -\frac{1}{2}$ contain $I = \frac{3}{2}, \frac{7}{2}, \frac{11}{2}, \ldots$ spin sequences.

[22] P. J. Twin, P. J. Nolan, R. Aryaeinejad, D. J. G. Love, A. H. Nelson, and A. Kirwan, Nucl. Phys. **A409**, 343c (1983).

[23] G. B. Hagemann, J. D. Garrett, B. Herskind, G. Sletten, P. O. Tjøm, A. Henriquez, F. Ingebretsen, J. Rekstad, G. Løvhøiden, and T. F. Thorsteinsen, Phys. Rev. C **25**, 3224 (1982).

[24] J. Burde, E. L. Dines, S. Shih, R. M. Diamond, J. E. Draper, K. H. Lindenberger, C. Schück, and F. S. Stephens, Phys. Rev. Lett. **48**, 530 (1982).

[25] J. Simpson, M. A. Riley, J. R. Cresswell, P. D. Forsyth, D. Howe, B. M. Nyakó, J. F. Sharpey-Schafer, J. Bacelar, J. D. Garrett, G. B. Hagemann, B. Herskind, and A. Holm, Phys. Rev. Lett. **53**, 648 (1984).

[26] S. M. Harris, Phys. Rev. B **138**, 509 (1965).