Eur. Phys. J. A **1**, 267–274 (1998)

THE EUROPEAN PHYSICAL JOURNAL A

High-K quasiparticle structures in ^{159}Er and ^{160}Er

J. Simpson[1], M.A. Riley[2], R.W. Laird[2], D.J. Hartley[2], F.G. Kondev[2], J. Sweeney[3], A.N. Wilson[4,13], S.J. Gale[4], M.A. Bentley[5], A.M. Bruce[6], R. Chapman[7], R.M. Clark[8,14], D.M. Cullen[9,15], P. Fallon[10], P.D. Forsyth[4], S.J. Freeman[11,16], P.M. Jones[4,17], J.C. Lisle[3], A.O. Macchiavelli[10], J.F. Sharpey-Schafer[4,18], A.G. Smith[3], J.F. Smith[4,19], D.M. Thompson[3]

[1] CCLRC, Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, UK
[2] Department of Physics, Florida State University, Tallahassee, FL 32306, USA
[3] Schuster Laboratory, University of Manchester, Manchester, M13 9PL, UK
[4] Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 7ZE, UK
[5] School of Sciences, Staffordshire University, Stoke on Trent, ST4 2DE, UK
[6] Department of Mechanical and Manufacturing Engineering, University of Brighton, Brighton, BN2 4GJ, UK
[7] Department of Physics, University of Paisley, Paisley, PA1 2BE, UK
[8] Department of Physics, University of York, Heslington, York, YO1 5DD, UK
[9] Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[10] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA
[11] Niels Bohr Institute, Tandem Accelerator Laboratory, DK-4000 Roskilde, Denmark

Received: 19 November 1997
Communicated by B. Herskind

Abstract. A series of new strongly coupled high−K, multi−quasiparticle structures have been observed in the light erbium transitional nuclei, ^{159}Er and ^{160}Er. The interpretation of these bands is discussed within the framework of the cranked shell model. These sequences, when taken together with the existing quasiparticle excitations, form a near complete set of low−lying, multi−quasiparticle structures on which a coherent series of aligned angular momentum, band crossing and blocking arguments can be based. The measured B(M1)/B(E2) ratios are compared with geometrical calculations to test the proposed configuration assignments.

PACS. 23.20.Lv Gamma transitions and level energies – 27.70.+q $150 \leq A \leq 189$

The light rare-earth transitional region near N ≈ 90 was one of the early testing grounds for the cranked shell model [1−4]. The investigation of the behaviour of the observed band structures with increasing rotational frequency, their aligned angular momentum properties and the variety of band crossings that occur helped place the cranked shell model on a firm footing. In addition to the rich variety of band structures, the light A ≈ 160 Er nuclei form an isotopic chain in which the highest−spin states in normal deformed nuclei have been observed [5−10]. The majority of the excited rotational bands that have been reported are based on low−K quasineutron excitations. The present work reports on the observation of six strongly–coupled bands in ^{159}Er and ^{160}Er which are interpreted as being based on high−K quasiparticle excitations. High−K structures have also been observed in ^{157}Er [5], ^{158}Er [12], ^{161}Er [13], ^{162,163}Er [14] and ^{164}Er [15]. These bands, when taken with the other quasiparticle structures observed in ^{159}Er and ^{160}Er, represent a near complete set of low lying quasiparticle excitations which provide a stringent test of the cranked shell model. This enables the investigation and interpretation of many different quasiparticle configurations from their alignment properties and band crossings systematics.

High-spin states in ^{159}Er and ^{160}Er were populated by the reaction ^{116}Cd(^{48}Ca,5n,4n)^{159,160}Er at a beam energy of 215 MeV. The tandem Van de Graaff accelerator at the Nuclear Structure Facility, Daresbury Laboratory

Present Addresses
[13] Department of Physics, University of York, Heslington, York, YO1 5DD, UK
[15] Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 7ZE, UK
[16] Schuster Laboratory, University of Manchester, Manchester, M13 9PL, UK
[17] Department of Physics, University of Jyväskylä, P.O.Box 35, FIN-40351, Finland
[18] National Accelerator Centre, Faure, P.O. Box 72, ZA- 7131, South Africa
[19] Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3800, USA

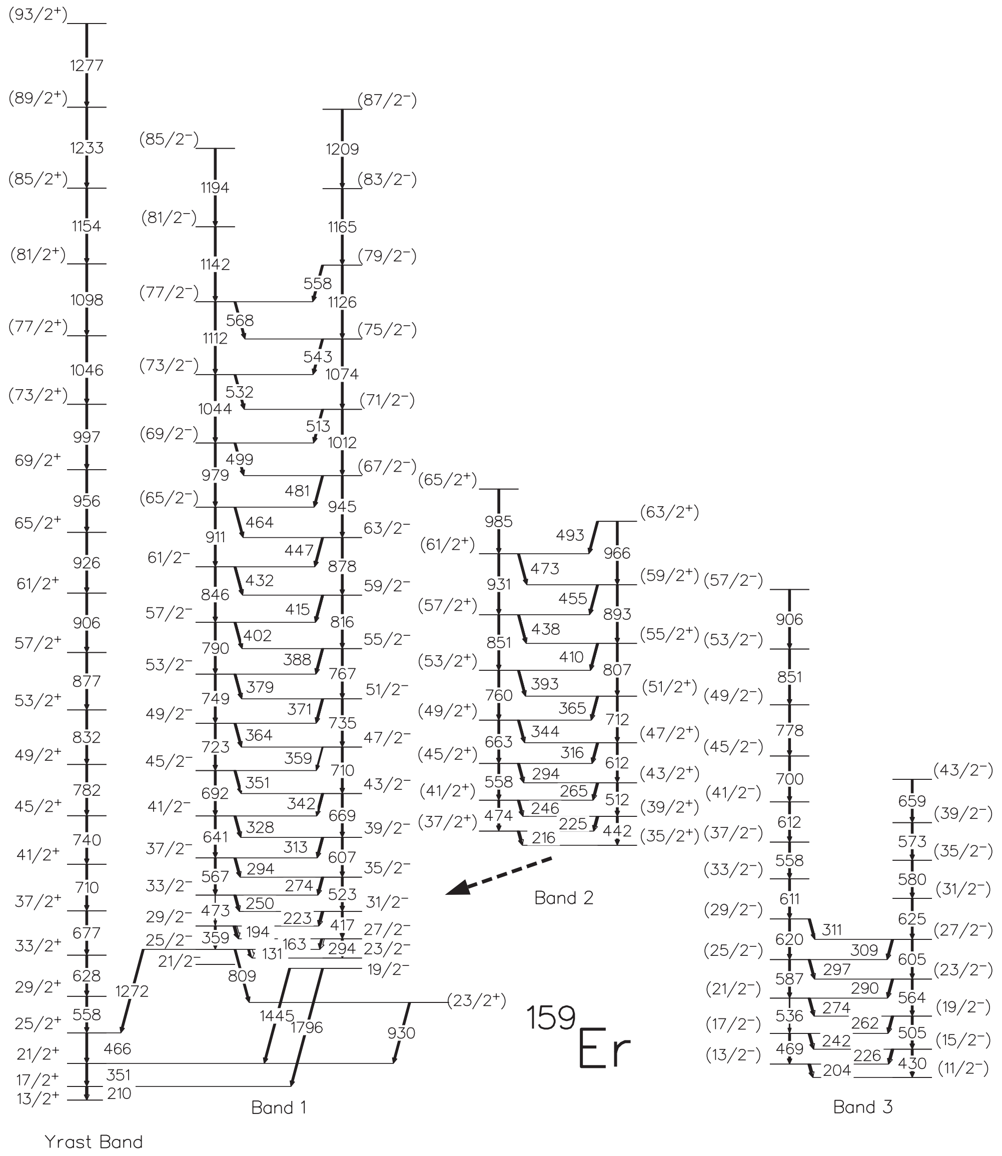

Fig. 1. Partial level scheme including the strongly–coupled bands observed in ^{159}Er. Energies are given in keV. Tentative assignments are in parentheses

provided the beam. The target consisted of two stacked thin foils of ^{116}Cd, each of thickness 500μgcm^{-2}. Gamma rays were detected by the EUROGAM spectrometer [16, 17] with 44 escape-suppressed spectrometers [18]. A total of 6.5 x 10^8 Compton suppressed coincident events were collected with the trigger requirement that at least six unsuppressed Ge detectors were in coincidence. After unpacking the higher fold events, the data yielded a total of 3.4 x 10^9 (γ^3) suppressed coincidences. In the analysis the (γ^3) and (γ^4) data were used to produce γ^2 coincidence matrices with one or two γ rays, respectively, being used to select a particular structure of interest. In addition, γ^3 cubes were created from all possible unpacked triple coincidences and analysed using the software packages LEVIT8R [19] and Ana [20].

Figures 1 and 2 show the partial level schemes, including the strongly–coupled bands and the yrast states, in ^{159}Er and ^{160}Er, respectively. Figures 3 and 4 show examples of the coincidence spectra for the strongly–coupled bands in ^{159}Er and ^{160}Er, respectively. The strongly–coupled bands are very weakly populated, being typically ≤2% of the strongest transition in each particular nucleus. Also the decay path to the yrast states in most cases is very fragmented. This makes their placement in the level scheme very difficult. In addition, high−K structures are expected to have hindered decays to the low−K yrast structures, which may result in isomeric band heads. This experiment used thin, unbacked targets and was therefore not sensitive to isomeric decays. However, the firm connection of the bands to the yrast states is not critical for interpretation of the quasiparticle configurations for the structures. It was not possible to obtain angular correlation information from the data since the bands are too low in intensity. States in band 1 in ^{159}Er had previously been assigned spin values [7] and these are used in figure 1. Spin and parity assignments of the other bands are based on systematics of quasiparticle structures in the region and the suggested configuration assignments.

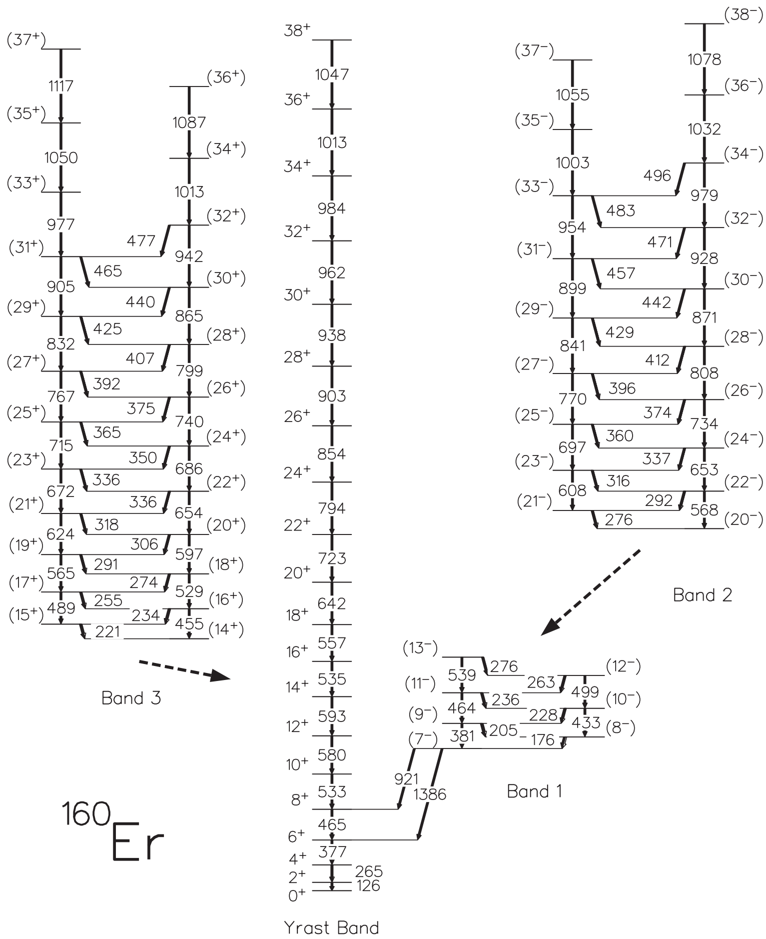

Fig. 2. Partial level scheme including the strongly–coupled bands observed in ^{160}Er. Energies are given in keV. Tentative assignments are in parentheses

Band 1 in ^{159}Er has previously been observed [7] up to spin $\frac{79}{2}$. Each signature has been extended to higher spin by two transitions in this work. This band decays mainly by the 1272 keV γ ray to the yrast $\frac{25}{2}^{+}$ state. Several other decays are known from this band to the yrast states, see figure 1 and [7]. Bands 2 and 3 are observed for the first time in this work. Band 2 has 7 transitions in each signature and the data indicates that it decays mainly to band 1, although the exact nature of this connection could not be firmly established. Band 3 in ^{159}Er has 8 transitions in one signature partner of the band and 11 in the other. Again, the details of the connection to the known states could not be definitely established although the data suggests that the bandhead is at low spin and excitation energy in ^{159}Er.

Three sequences, labelled band 1, 2 and 3, are observed in ^{160}Er for the first time in this work. Band 1 decays mainly via a 1386 keV transition to the 6^+ yrast state and a 921 keV transition to the 8^+ yrast state. It is assumed, based on their relative intensity and high energy, that these decays are stretched E1 transitions. Therefore, the lowest state established in band 1 is (7^-). This band is populated by a further strongly–coupled band, band 2, which is tentatively established up to (38^-). The decay path connecting these two bands is very complex and could not be definitely established. This arises since both signatures experience a band crossing in this frequency region which is interpreted as the $i_{\frac{13}{2}}$ AB neutron alignment (see discussion below). Band 3 comprises 11 in-band decays in each signature and the data indicates that it decays to the yrast states at spin $\approx$ 12-14$\hbar$.

Figure 5 shows the alignment (as defined in [1,2]) as a function of rotational frequency for the strongly–coupled bands in ^{159}Er and ^{160}Er. For comparison, the alignment for selected bands with well-established quasiparticle configurations within these nuclei [4,8,9] are also shown. A representative cranked shell model calculation for ^{160}Er can be found in [11] and a standard cranked shell model analysis of the previously observed structures in ^{159}Er and ^{160}Er can be found in refs. [4,8,9]. The rotational frequencies of the observed gain in alignment for specific quasineutron or quasiproton pairs in these or neighbouring nuclei are also indicated. The quasiparticle labelling scheme, based on the convention of reference [3], is given in Table 1.

Harris reference parameters [21] of $\Im_0 = 32$ MeV$^{-1}\hbar^2$ and $\Im_1 = 34$ MeV$^{-3}\hbar^4$ have been chosen since these values give a constant alignment for the positive-signature yrast band in ^{157}Ho above the first $i_{13/2}$ (AB) neutron crossing. In this configuration (ABB_p) both the first (A_pB_p) and second (B_pC_p) $h_{11/2}$ proton crossings, and the second (BC) and third (AD) $i_{13/2}$ neutron crossings are blocked.

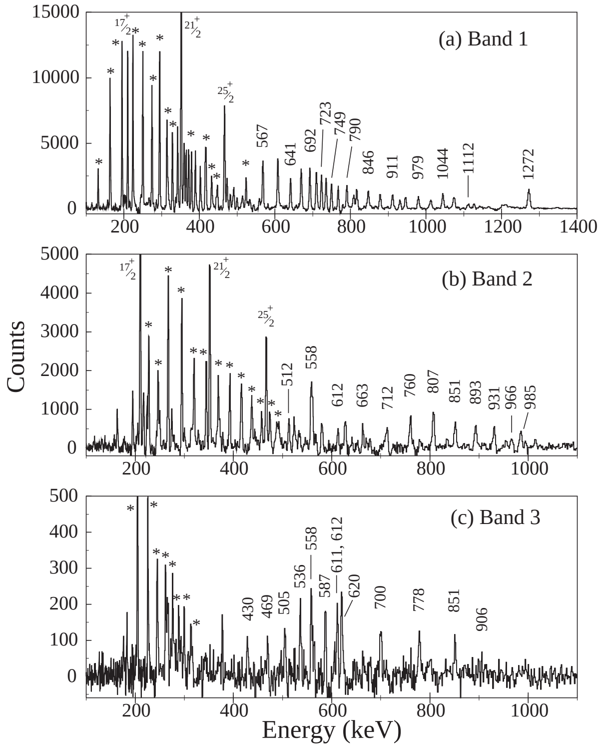

Fig. 3. Transitions in coincidence with **a** band 1, **b** band 2 and **c** band 3 in ^{159}Er. Selected dipole transitions in the bands are labelled by a $*$ and selected in−band quadrupole transitions by their energy. The yrast states are indicated by the spin−parity of the initial state. Transition energies are given in keV. The spectra are generated by requiring relevant pairs of γ rays and projecting out the resulting γ rays in coincidence

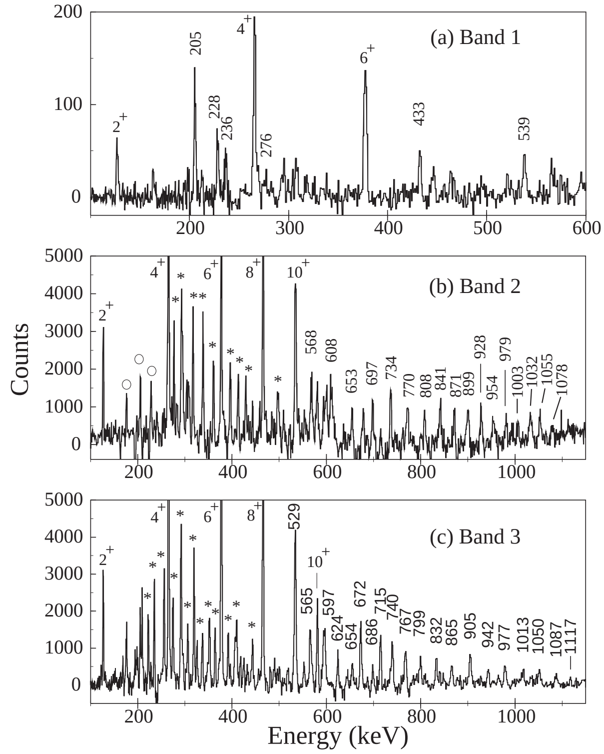

Fig. 4. Transitions in coincidence with **a** the 1386 and 176 keV γ rays, **b** band 2 and **c** band 3 in ^{160}Er. Selected dipole transitions in the bands are labelled by a $*$ and selected in band quadrupole transitions by their energy. The yrast states are indicated by the spin-parity of the initial state. Transition energies are given in keV. The spectra for bands 2 and 3 are generated by requiring relevant pairs of γ rays and projecting out the resulting γ rays in coincidence. Transitions in band 1 in coincidence with band 2 are denoted by ◯ in (b)

Therefore, this band is a good reference for discussing the high-frequency behaviour of quasiparticle structures in neighbouring Er nuclei. The investigation of the aligned angular-momentum behaviour of the high−K bands, together with a knowledge of the high−K configurations expected near the Fermi surface in neighbouring $_{66}$Dy and $_{67}$Ho [22,24] nuclei enables specific quasiparticle configurations to be assigned to the new Er high−K structures.

In this region of nuclei, excitations based on the high−K, $h_{\frac{11}{2}}[505]\frac{11}{2}$ neutron orbital (XY), have been observed in both odd−N and even−N $_{64}$Gd [23] and $_{66}$Dy [22] isotopes, ^{157}Ho [24], ^{161}Er [13] and ^{163}Er [14]. It therefore seems reasonable that bands based on this highly oblate orbital will be present in the lighter Er nuclei. However, the smaller deformation of the Er isotopes compared with its lower Z neighbours [25] means that such bands will be further from the yrast line and hence of lower intensity, since this orbital moves away from the Fermi surface with decreasing deformation. In neighbouring odd−Z nuclei, strongly–coupled bands built on the π $h_{\frac{11}{2}}[523]\frac{7}{2}$ (A_pB_p) and $g_{\frac{7}{2}}[404]\frac{7}{2}$ (E_pF_p) orbitals are also well established at the yrast line [24]. Any strongly–coupled two quasiproton bands in Er nuclei may therefore be expected to involve a quasiparticle excitation into both of these orbitals. Due to the larger splitting between the two $\pi h_{\frac{11}{2}}$ signatures, the lowest energy strongly–coupled, two quasiproton band is expected to have the configurations A_pE_p and A_pF_p, subsequently labelled $A_pE_p(F_p)$. A detailed theoretical discussion of these quasiproton configurations (excitation energies, deformations, alignments and band crossing properties) calculated for ^{158}Er, can be found in [26].

Figure 5 shows that the alignment properties of the three strongly–coupled bands in ^{159}Er are quite different. Band 1 starts with an initial additional alignment of $\approx 2\hbar$ compared with the yrast (A) configuration. This band does not undergo the first $i_{\frac{13}{2}}$ AB neutron alignment which is established in the lowest energy negative parity band E [4] at $\hbar\omega \sim$0.24 MeV. However, it does undergo an alignment at $\hbar\omega \sim$0.33 MeV which is interpreted as the BC crossing. This crossing is well established in this region (e.g. [23]). The band does not experience the A_pB_p crossing at $\hbar\omega \sim$0.45 MeV. These facts are consistent with the interpretation that band 1 is based on the configuration $A\otimes A_pE_p(F_p)$ at low frequency and $ABC\otimes A_pE_p(F_p)$ at high frequency. This is in agreement with the previous assignment [7]. In the neighbouring nucleus ^{157}Er one strongly–coupled band has been observed and is also in-

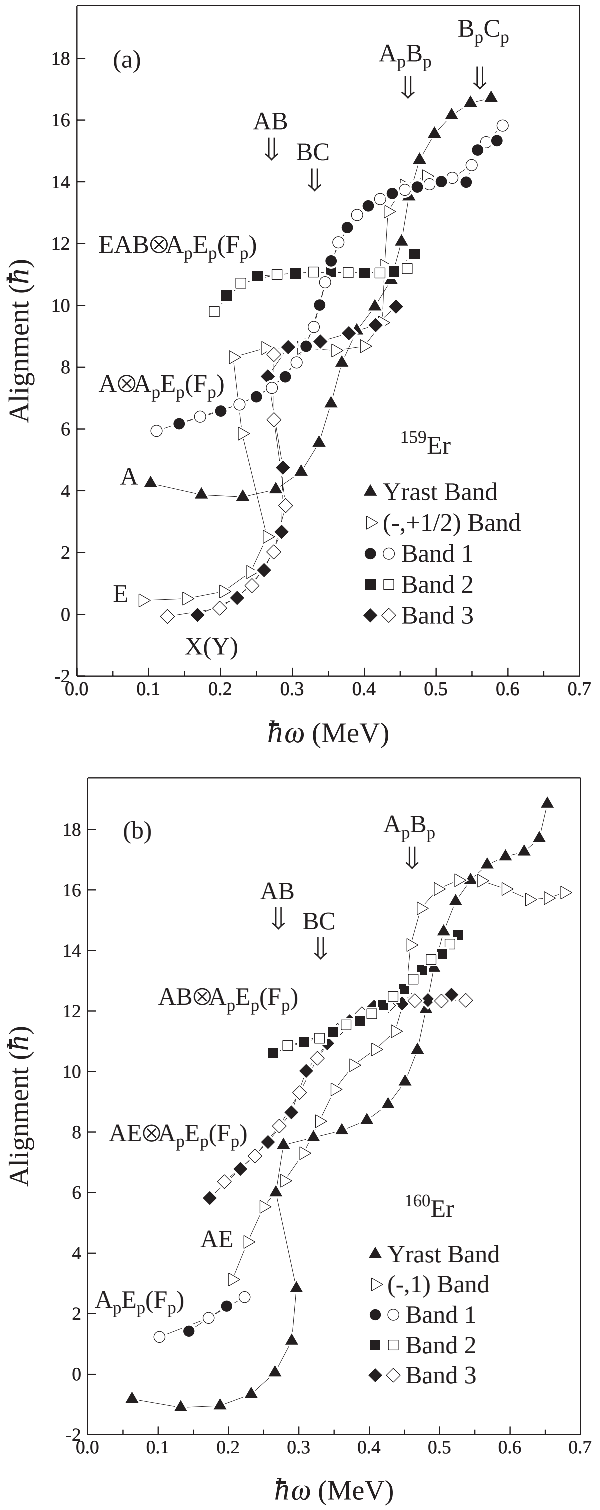

Fig. 5. Experimental alignments versus rotational frequency $\hbar\omega$ for bands in **a** ^{159}Er and **b** ^{160}Er. Selected bands of known configuration are shown for comparison. The bands are labelled at low frequency by their initial quasiparticle configuration and band crossings are labelled at the appropriate rotational frequencies. Harris parameters of $\Im_0 = 32$ MeV$^{-1}\hbar^2$ and $\Im_1 = 34$ MeV$^{-3}\hbar^4$ were used. *Open* and *closed symbols* denote the opposite signatures

Table 1. Quasiparticle labelling scheme. π = parity and α = signature

	Label	$(\pi,\alpha)_n$	Nilsson quantum numbers at $\hbar\omega = 0$
Quasineutrons	A	$(+,+1/2)_1$	$i_{\frac{13}{2}}\,[651]\frac{3}{2}$
	B	$(+,-1/2)_1$	$i_{\frac{13}{2}}\,[651]\frac{3}{2}$
	C	$(+,+1/2)_2$	$i_{\frac{13}{2}}\,[660]\frac{1}{2}$
	D	$(+,-1/2)_2$	$i_{\frac{13}{2}}\,[660]\frac{1}{2}$
	E	$(-,+1/2)_1$	$h_{\frac{9}{2}}\,[521]\frac{3}{2}$
	F	$(-,-1/2)_1$	$h_{\frac{9}{2}}\,[521]\frac{3}{2}$
	X	$(-,+1/2)_2$	$h_{\frac{11}{2}}\,[505]\frac{11}{2}$
	Y	$(-,-1/2)_2$	$h_{\frac{11}{2}}\,[505]\frac{11}{2}$
Quasiprotons	A_p	$(-,-1/2)_1$	$h_{\frac{11}{2}}\,[523]\frac{7}{2}$
	B_p	$(-,+1/2)_1$	$h_{\frac{11}{2}}\,[523]\frac{7}{2}$
	E_p	$(+,-1/2)_1$	$g_{\frac{7}{2}}\,[404]\frac{7}{2}$
	F_p	$(+,+1/2)_1$	$g_{\frac{7}{2}}\,[404]\frac{7}{2}$

terpreted as having this configuration [5]. At the highest frequency ($\hbar\omega \sim 0.56$ MeV) both signatures show another gain in alignment, which is interpreted as the start of the alignment of the second pair of $h_{\frac{11}{2}}$ protons, namely B_pC_p [27].

The fact that band 2 in ^{159}Er has some initial curvature and begins just below the known AB crossing frequency suggests the band is at least a 3 quasiparticle band involving the aligned AB neutron pair. This band does not undergo the AB, BC or A_pB_p crossings. These alignment properties suggest that this band has the configuration EAB⊗$A_pE_p(F_p)$. The difference in alignment, see Fig. 5, between this band and the known EAB configuration is the same as between band 1(A⊗$A_pE_p(F_p)$) and the yrast band (A configuration). This serves as a check on the suggested spin assignments.

Band 3 clearly experiences an alignment gain of $\approx 9\hbar$ at $\hbar\omega \sim$0.28 MeV. This is interpreted as the first $i_{13/2}$ AB neutron crossing. One signature of this band is observed to high rotational frequency and at the highest frequency ($\hbar\omega \sim$0.44 MeV) there is evidence for the start of a further gain in alignment which is interpreted as the first $h_{\frac{11}{2}}$ (A_pB_p) proton crossing. These alignment properties are consistent with this band being based on the $\nu\ h_{\frac{11}{2}}[505]\frac{11}{2}$ orbital, X(Y), which has a bandhead energy of 428.8 keV and lifetime 0.59μsec [28]. This long lifetime accounts for

Table 2. Parameters used in calculation of B(M1)/B(E2) ratios in ^{159,160}Er

Band	Configuration	$K^{\pi\, a)}$	Ω_1^π	i_1	$g_{\Omega 1}$	Ω_2^π	i_2	$g_{\Omega 2}$	Ω_3^π	i_3	$g_{\Omega 3}$	Ω_4^π	i_4	$g_{\Omega 4}$
^{159}Er	Q_0=6.5 *e*b	g_R=0.32												
Band 1	A⊗A_pE_p	$17/2^-$	$7/2^+$	0.5	0.64	$7/2^-$	2.3	1.33	$3/2^+$	5.3	−0.26			
Band 2	EAB⊗A_pE_p	$17/2^+$	$7/2^+$	0.5	0.64	$7/2^-$	2.3	1.33	$3/2^-$	1.9	−0.17	0	9.4	−0.26
Band 3	X(Y)	$11/2^-$							$11/2^-$	0.5	−0.24			
^{160}Er	Q_0=7.0 *e*b	g_R=0.32												
Band 1	A_pE_p	7^-	$7/2^+$	0.5	0.64	$7/2^-$	2.3	1.33						
Band 2	AB⊗A_pE_p	7^-	$7/2^+$	0.5	0.64	$7/2^-$	2.3	1.33	0	9.4	−0.26			
Band 3	AE⊗A_pE_p	10^+	$7/2^+$	0.5	0.64	$7/2^-$	2.3	1.33	$3/2^+$	5.3	−0.26	$3/2^-$	1.9	−0.17
neutron crossings														
	AB	0							0	9.4	−0.26			
	BC	2^+							2^+	7.6	−0.26			

a) $K=\sum_i \Omega_i$

the non-observation of the bandhead decay in this experiment. The AB neutron crossing observed in this band (0.28 MeV) is at slightly higher frequency than that observed in the negative parity band based on the ν [521]$\frac{3}{2}$ orbital, E (at 0.24 MeV) [4]. This would be expected because of the slightly higher deformation produced by the hole in the oblate driving [505]$\frac{11}{2}$ orbital together with configuration dependent pairing effects which both cause a delayed crossing. This phenomenon was first discussed by Garrett et al. [13].

In order to test the configuration assignments the ratio of the reduced transition probabilities B(M1)/B(E2) can be measured. These can be deduced from a measurement of the (I→ $I-1$) to (I→ $I-2$) branching ratios within the strongly–coupled bands. These ratios contain important information on the configuration of the bands and the band crossings that occur. Comparisons are made with the theoretical predictions for specific configurations using the semi-classical geometrical model [29,30]. The parameters used in the B(M1)/BE2) calculations and a summary of the configuration assignments are given in Table 2.

Figure 6 shows the experimentally extracted B(M1)/ B(E2) ratios for the strongly–coupled bands in ^{159}Er. The predictions for possible configurations in ^{159}Er are shown. The ν $h_{\frac{11}{2}}$[505]$\frac{11}{2}$ X(Y) assignment to band 3 is confirmed in this analysis and the configurations for bands 1 and 2 are consistent with the proposed assignments.

In ^{160}Er, the three bands again have different alignment properties, see Fig. 5. The alignment properties of band 2, including the fact that the BC crossing is not observed, are consistent with a configuration of AB⊗$A_pE_p(F_p)$. This band decays directly to band 1, which has an alignment of $2\hbar$. Band 1 is interpreted as having the $A_pE_p(F_p)$ configuration and the connection between bands 1 and 2, which was observed but not firmly established in the data, is interpreted as the AB neutron crossing. A band based on the AX(Y) configuration is also expected in ^{160}Er and band 1 could be interpreted as this configuration. Both of these suggested assignments have a bandhead spin of 7, which is consistent with the lowest spin state observed experimentally. However, the relatively high B(M1)/B(E2) ratios measured for this band are only consistent with the $A_pE_p(F_p)$ assignment, see Fig. 7. It is interesting to note that band 1 in ^{160}Er is proposed to have the same configuration as the 7^- band in ^{164}Er [15]. The bandhead of the latter is known to be isomeric with a half-life of 22.7 ns [15] and its decay mainly proceeds via a high energy E1 transition (1371 keV) in a similar way to that observed in ^{160}Er (1386 keV). Assuming that these transitions have equal strength the half-life of the 7^- state in ^{160}Er can be estimated to be less than 18 ns, a limit which is consistent with the intensity flow through the 7^- state.

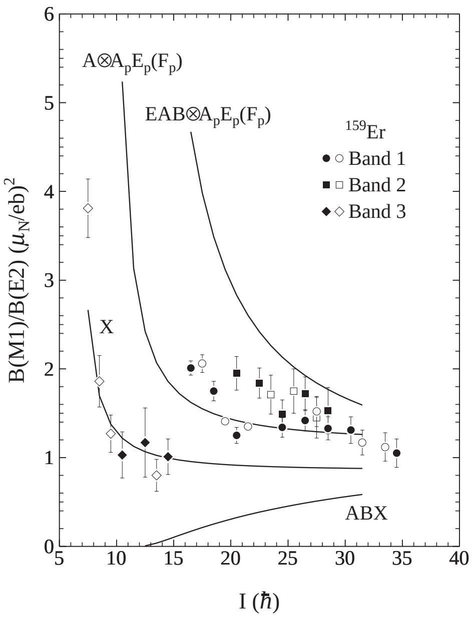

Fig. 6. Experimental B(M1)/B(E2) ratios as a function of spin for ^{159}Er. Comparison is made with the theoretical predictions for the proposed configurations using the geometrical model [27,28]. The parameters used in the calculations are given in Table 2

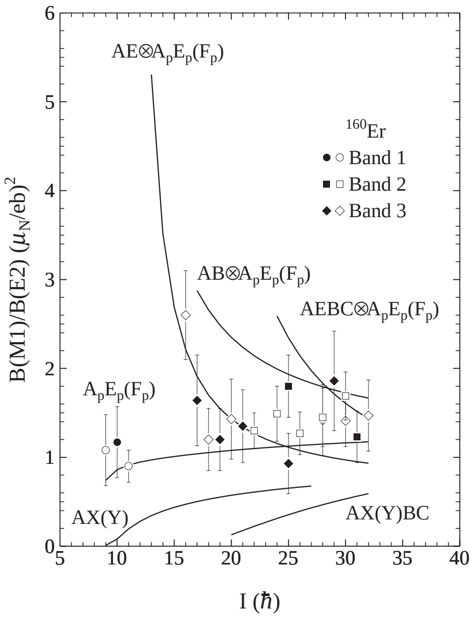

Fig. 7. Experimental B(M1)/B(E2) ratios as a function of spin for ^{160}Er. Comparison is made with the theoretical predictions for the proposed configurations using the geometrical model [27,28]. The parameters used in the calculations are given in Table 2

Band 3 has a gain in alignment of $\sim 4-5\hbar$ at $\hbar\omega \sim 0.35$ MeV which is interpreted as the BC neutron crossing. In addition, the band does not undergo the A_pB_p crossing which suggests that this band is based on the AE⊗ $A_pE_p(F_p)$ configuration at low spin and the AEBC⊗ $A_pE_p(F_p)$ at high spin. This is consistent with the assigned spins for the states in this band. The measured B(M1)/B(E2) ratios for bands 2 and 3 are consistent with the theoretical predictions for these configurations, see Fig. 7.

In summary, six strongly–coupled bands have been observed in ^{159}Er and ^{160}Er. These bands are interpreted as being based on multi−quasiparticle excitations involving the high−K, π $g_{\frac{7}{2}}[404]\frac{7}{2}$ or ν $h_{\frac{11}{2}}[505]\frac{11}{2}$ orbitals. The behaviour of these structures in terms of their alignment and band crossing properties has been discussed and serves as an excellent example of the application of the cranked shell model to the understanding of the behaviour of high spin nuclear states. In addition, these assignments have been found to be in agreement with theoretical expectations of the measured B(M1)/B(E2) transition strength ratios. It is interesting to note that other bands based on configurations involving high−K orbits are expected at slightly higher excitation energy in both nuclei. For example, in ^{159}Er the A⊗$B_pE_p(F_p)$ configuration and in ^{160}Er the AB⊗$B_pE_p(F_p)$ and AX(Y) configurations are expected. The new generation of gamma−ray spectrometers should allow the observation of these excited configurations and fix those discussed in this work firmly into the level schemes. Further studies of the residual interactions between the quasiparticles could then be investigated.

Support for this work was provided by the UK Engineering and Physical Sciences Research Council EPSRC and the National Science Foundation, the State of Florida. Eurogam was funded jointly by the EPSRC and the Institute for Nuclear and Particle Physics, IN2P3, France. RMC, SJG, PMJ, JFS, JS (Sweeney) and DMT acknowledge receipt of UK Science and Engineering Research Council SERC postgraduate studentships and ANW an EPSRC postgraduate studentship. PF and AOM acknowledge support from the office of Energy Research, Division of Nuclear Physics of the U.S. Department of Energy under contract number DE-AC03-765F00009. Software support from D.C.Radford, R.W.MacLeod and H.Q.Jin is greatly appreciated. JS (Simpson) and MAR acknowledge the receipt of a NATO Collaborative Research Grant.

References

1. R. Bengtsson and S. Frauendorf, Nucl. Phys. **A 327** (1979) 139
2. R. Bengtsson and S. Frauendorf, Nucl. Phys. **A 314** (1979) 27
3. L.L. Riedinger, O. Andersen, S. Frauendorf et al., Phys. Rev. Lett. **44** (1980) 56
4. J. Simpson, P.A. Butler, P.D. Forsyth et al., J.Phys. G **10** (1984) 383
5. S.J. Gale, J. Simpson, M.A. Riley et al., J.Phys. G **21** (1995) 193
6. J. Simpson, M.A. Riley, S.J. Gale et al., Phys. Lett. **B327** (1994) 187
7. M.A. Deleplanque, J.C. Bacelar, E.M. Beck et al., Phys. Lett. B **193** (1987) 422
8. J. Simpson, M.A. Riley, J.R. Cresswell et al., J.Phys. G **13** (1987) 847
9. J. Simpson, M.A. Riley, A.N. James et al., J.Phys. G **13** (1987) L235
10. M.A. Riley, J.W. Roberts, J. Simpson et al., J.Phys. G **16** (1990) L67
11. R. Bengtsson, S. Frauendorf and F.R. May, *Atomic Data and Nuclear Data Tables* **35** (1986) 15
12. M.A. Riley, J. Simpson, F.G. Kondev et al., to be published and Ph.D Thesis, University of Liverpool 1985 (unpublished)
13. J.D. Garrett, G.B. Hagemann, B. Herskind et al., Phys. Lett. B **118** (1982) 297
14. G.B. Hagemann, H. Ryde, P. Bosetti et al., Nucl. Phys. **A 618** (1997) 199 and private communication
15. R.A. Bark, P. Bosetti, G.B. Hagemnann et al., Z. Phys. A **359** (1997) 5
16. F.A. Beck, Prog. Part. Nucl. Phys. **28** (1992) 443
17. P.J. Nolan, Nucl. Phys. **A 520** (1990) 657c
18. C.W. Beausang, S.A. Forbes, P. Fallon et al., Nucl. Instrum. and Meth. **A 313** (1992) 285
19. D.C. Radford, Nucl. Instrum. and Meth. **A 361** (1995) 297
20. W. Urban, University of Manchester Nucl. Group Ann. Rep 199 2-3
21. S.M. Harris, Phys. Rev. B **138** (1965) 509

22. M.A. Riley, J. Simpson, J.F. Sharpey-Schafer et al., Nucl. Phys. **A 486** (1988) 456
23. J.D. Morrison, J. Simpson, M.A. Riley et al., J.Phys. G **15** (1989) 1871
24. D.C. Radford, H.R. Andrews, G.C. Ball et al., Nucl. Phys. **A 545** (1992) 665
25. W. Nazarewicz, M.A. Riley and J.D. Garrett, Nucl. Phys. **A 512** (1990) 61
26. T. Bengtsson, Nucl. Phys. **A 512** (1990) 124
27. J. Simpson, P.D. Forsyth, D. Howe et al., Phys. Rev. Lett. **54** (1984) 1132
28. J.R. Leigh, R.M. Diamond, K.H. Maier et al., UCRL-20426 (1970) p. 18 and H.Strusny, H.Tyrroff, E.Herrmann et al., Nucl. Phys. **A 242** (1975) 30
29. F. Dönau and S. Frauendorf, *Proc. Conf. on High Angular Momentum Properties of Nuclei, Oak Ridge, 1982 ed N R Johnson (New York: Harwood)* p143
30. F. Dönau, Nucl. Phys. **A 471** (1987) 469