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S.C. Pancholi

Exotic Nuclear Excitations

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Foreword

Nuclei are very special objects. They carry energy and angular momentum like any other macroscopic objects. At the same time, being quantum mechanical entities, they carry it in two different ways—as collective rotations and aligned single particle motions. This unique property of nuclei has given rise to range of exotic research topics in nuclear structure studies. Starting with the discovery of rotational alignment and band crossing phenomenon in the early 1970s, several other topics on exotic nuclear excitations are of immense current interest such as rotational alignment and band crossings, magnetic rotation, triaxial strong deformation and wobbling motion and chirality in nuclei.

I am happy that one of my old-time friend and colleague Prof. Suresh C. Pancholi, with his long career in teaching and research in nuclear structure physics at one of the premier Universities in India, the University of Delhi, and at several Laboratories abroad has chosen to bring out this unique monograph. While there is no doubt that this monograph will be a very valuable resource to the young researchers in our universities and institutions, this will also fill a major vacuum in good quality and up-to-date text books across the world in contemporary nuclear physics.

I personally wish all the best for his endeavour.

Bangaluru, India V. S. Ramamurthy
May 21, 2010

Preface

This monograph on high spin physics is geared towards the beginners in research or the young researchers, in the exciting field of high spin nuclear structure physics. New and interesting phenomena have and are being discovered in this field which is providing a microscopic insight into the behaviour of nuclei under the extreme conditions of high excitation energy, highest spins and abnormal neutron-to-proton ratios. The quest for achieving the highest spin states has resulted in remarkable success in this direction. An attempt has been made in this monograph to provide the reader an up-to-date knowledge of some of the recent exotic phenomena at high spins in a collective and consolidated manner. The topics covered are the rotational alignment and bandcrossings, magnetic rotation, triaxial strong deformation and wobbling motion and chirality in nuclei. The earliest discovered is the phenomenon of bandcrossings which is generally known as backbending in nuclei. This discovery led to great excitement and interest in high spin nuclear spectroscopy and has been responsible for the present development so that a very large volume of useful information is available now. Magnetic rotation is a relatively newly discovered phenomenon in which the generation of angular momentum in nuclei is caused by the ‘shears mechanism’. It gives rise to rotation-like magnetic dipole bands in nearly spherical nuclei. Axially symmetric shapes in nuclei are known for the last several decades. Recently, success was achieved in finding the occurrence of stable triaxial shapes in odd-*Z* Lu nuclei at high spins through the observation of wobbling motion at high quadrupole deformation. Although chirality is known in other fields like chemistry, the search for the observation of chirality is being extensively pursued presently in particle physics—in nuclei at moderate spins. Chirality can also provide evidence for the existence of stable triaxial shapes in nuclei.

Due to the monograph nature of this volume, I have purposely left out a number of other very interesting phenomena. These are identical bands, superdeformation and energy correlation in superdeformed states known as C_4 symmetry, hyperdeformation, smooth band termination, enhanced and highly deformed bands, particle–hole excitations, tetrahedral symmetry, isomers at high spins, research area in neutron-rich nuclei providing new physics concepts in nuclear physics in nuclei away from the line of beta stability, etc., to name some of these observations.

The key contributors to this field of research activity are the parallel development of heavy-ion accelerators providing a large variety of heavy-ion beams and gamma detector arrays with large photopeak detection efficiencies. A new avenue in high spin nuclear spectroscopy is now emerging with the development of gamma-ray tracking arrays which are likely to enhance the gamma-ray detection efficiency by several folds.

The emphasis throughout the book has been on a simple and up-to-date treatment of the topics covered. The pre-requisites for a proper appreciation are basic and advanced courses in nuclear physics and nuclear models as well as measurement techniques of observables like gamma-ray energies, intensities, multi-fold coincidences, angular correlations or distributions, linear polarisation, internal conversion coefficients, short lifetime (picosecond range) of excited states, etc. and instrumentation and data analysis methods.

I very gratefully acknowledge the encouragement and support that I received from Professor Deepak Pental, Vice Chancellor, University of Delhi.

The major part of the work on the monograph was carried out at the Inter University Accelerator Centre (IUAC), New Delhi. I am grateful to Dr. Amit Roy, Director, IUAC, and Dr. R. K. Bhowmik, Senior Scientist, IUAC, for providing excellent work atmosphere and allowing me to avail of the facilities.

This work would not have been possible without enthusiastic support that I received from a number of my colleagues and friends in India and abroad. Especially, I would like to acknowledge the advice and comments that I received from Professors Ashok Kumar Jain, Mark Riley and Herbert Hübel. Dr. Anukul Dhal helped me in the preparation of the manuscript. I am thankful to him for the same.

This monograph is based upon the works done by a large number of physicists whose painstaking investigations contributed to the advancement of knowledge. I am indebted to them.

Last but not the least, I thank my family—my wife Rani, daughter Bela, son Vineet, daughter-in-law Ranju and grand-daughter Meghna for their patience, tolerance and perseverance during the course of this project.

The work on the monograph was catalysed and supported by the Department of Science and Technology, under its Utilisation of Scientific Expertise of Retired Scientists Scheme. This is gratefully acknowledged.

New Delhi Suresh C. Pancholi
April 11, 2010

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Chapter 1
Rotational Alignment and Bandcrossings

1.1 Introduction

In the year 1971, in ^{160}Dy [1] nucleus, a discontinuity in the pattern of gamma-ray spectra normally observed in the decay of rotational states, was discovered at angular momentum, $I\sim 14\hbar$. This was interpreted in [2] as due to the decoupling of a pair of high-j nucleons from the rotating nuclear core and subsequent alignment of their angular momenta along the rotation axis at particular rotational frequency. A few years later, in 1977, a second discontinuity was observed in the gamma-ray spectra at angular momentum, $I\sim 28\hbar$ in ^{158}Er [3]. These two were the most significant discoveries in the initial phases of high spin physics. Most of the present day knowledge and the huge amount of information both experimental and theoretical, in a very large number of nuclei at high spins, owe its existence to the interest developed as a result of these discoveries. As will be explained later in this chapter, the rotation alignment of high-j low-Ω pairs of nucleons manifests as bandcrossing (popularly known as 'backending') between rotational bands. This mode of quasiparticle excitation is imposed on the collective nuclear rotational motion.

Since these early discoveries and the quest to populate and investigate nuclei at the highest spins, a number of different types of bandcrossings at high rotational frequencies involving pairs of quasineutrons and pairs of quasiprotons in nuclei in different mass regions, have been found and understood in terms of the cranked shell model (CSM). Such experimental investigations were made possible due to the availability of heavy-ion beams from accelerators and the parallel development of gamma detector arrays with large photopeak detection efficiencies (up to ~9%). In the present chapter, an attempt is made to give the reader a glimpse of this bandcrossing phenomenon through a first order description.

A number of articles which discuss this topic in details exist in the literature [4–11]. A short highly educative movie by Professor Mark Riley and group beautifully explains the phenomenon of rotational alignment and backbending. This can be accessed at: http://www.physics.fsu.edu/TheBackBender/.

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1.2 Rotational Alignment and Bandcrossings

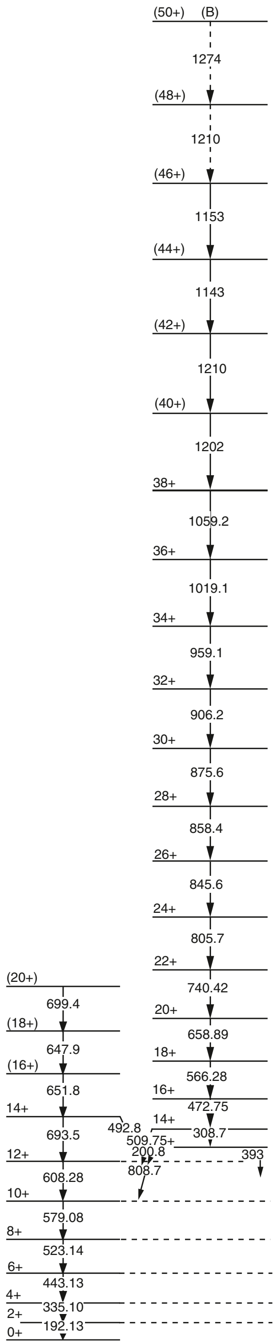
The discovery of the discontinuity in the gamma-ray spectrum mentioned above was observed in an experiment to investigate the high spin states in the even–even nucleus ^{160}Dy, using the ^{160}Gd (α, 4n) reaction at 43 MeV α-particle beam energy by Johnson, Ryde and Sztarkier [1]. The gamma–gamma coincidences were detected in a two 43 cm^3 Ge (Li) detector set-up. From the experimentally measured gamma-ray energies, the effective moment of inertia, $2\mathcal{I}/\hbar^2\{=(4I-2)/[E(I)-E(I-2)]\}$ was calculated and plotted as a function of square of rotational frequency, $(\hbar\omega)^2\{=(1/4)E\gamma^2\}$. This plot exhibited a deviation from the normal monotonous increase of moment of inertia, at $I=14\hbar$ onwards to the highest observed spin of $18\hbar$. The backbending of the moment of inertia generated tremendous interest and excitement. The numerous investigations that followed it, paved the way for the modern era in high spin nuclear structure physics.

The above experimental observation was explained by Stephens and Simon [2] in terms of Coriolis effects on high-j low-Ω particles due to rotational motion of the nucleus. The strong Coriolis force $\omega \cdot \vec{j}$ gradually breaks up the pairing correlations and decouples the particles from the core. It (the Coriolis force) tends to align the particle angular momentum, j with that of the rotor. The alignment tendency is stronger, the larger the value of j for the particle. The maximal aligned spin for two nucleons in a pure-j shell (e.g. a pair of neutrons in $i_{13/2}$ orbital) is $2j-1$ (i.e. $j+j-1$). Therefore, in an even–even rare-earth nucleus, for a pair of $i_{13/2}$ neutrons, an angular momentum of $12\hbar$ can be obtained through the rotation alignment of the pair along the rotation axis. The energy cost for breaking the nucleon pair is about twice the odd–even mass difference (~2Δ). In the situation where the Fermi level is close to the low-Ω orbitals, the alignment will give rise to a 2-quasineutron rotational band. The ground state rotational band and the 2-quasineutron band will cross each other at a certain critical rotational frequency, called the bandcrossing frequency, $\hbar\omega_c$. This will happen as the 2-quasineutron band will drop in energy with respect to the continuation of the ground state band above the crossing frequency (spin) due to the decrease in pairing energy.

A number of other theoretical explanations were provided in several of the works available in literature, e.g. that using the angular momentum projection method [12].

Let us consider, as a typical case, the even–even nucleus ^{158}Er. Figure 1.1 shows the partial level scheme of ^{158}Er [13]. On the left of the figure is shown the positive parity ground state Yrast band with signature $\alpha=0$. This band is fed at spin $I=12\hbar$ by a 2-quasiparticle positive parity $\alpha=0$ band which is also Yrast. The states above spin $12\hbar$ on the left is the continuation of the ground state band. The Yrast 2-quasiparticle band is populated to high spins. In Fig. 1.2 are plotted the spin of the states of the Yrast bands as a function of energy of gamma-rays de-exciting the states. This figure shows two discontinuities in gamma-ray energies, one near $I=14\hbar$ and the other near $I=28\hbar$. In this discussion, particular attention will be given to these

Fig. 1.1 Partial level scheme of ^{158}Er [13]. (Figure with permission reproduced in part from [13])



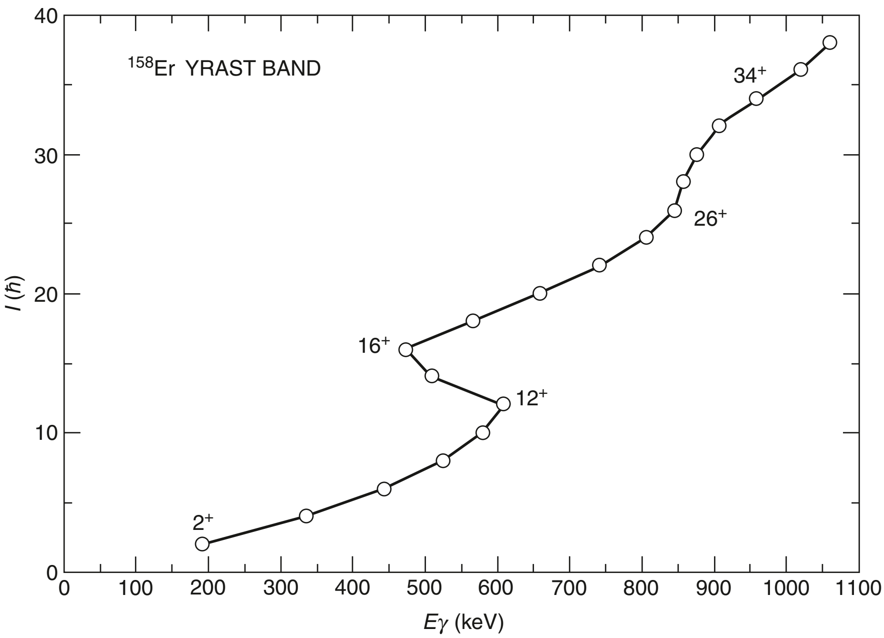


Fig. 1.2 Plot of spin vs. $E\gamma$, for the Yrast rotational band in the even–even ^{158}Er nucleus. (Data from [13])

discontinuities. The rotational bands shown in Fig. 1.1 are interpreted in terms of the CSM to characterize the bandcrossings (the discontinuities) and identify the quasiparticles which contribute to the band. The CSM calculations give the quasiparticle energies, e', in the rotating intrinsic frame (Routhians) and aligned quasiparticle angular momenta, $i_x\hbar$, along the rotation (x) axis. To facilitate comparison between experiment and theory, the values of e' and i_x as a function of rotational frequency, $\hbar\omega$, are extracted from the experimental data. This extraction is done through a transformation prescription which is available in the literature, e.g. [4, 14, 15]. The data for the positive parity Yrast band in ^{158}Er are plotted in Fig. 1.3 [15]. In the bottom panel is the plot of the quasiparticle energies as a function of rotational frequency. The 0-quasiparticle band (the ground state band) is crossed by a 2-quasiparticle band at a bandcrossing frequency, $\hbar\omega_c$=0.272 MeV. This, as we will see in due course is due to the lowest neutron $\nu i_{13/2}$ pair decoupling from the core and aligning their angular momenta along the axis of rotation. In simple terms, this critical frequency can be thought of as the angular frequency of rotation at which the Coriolis plus the centrifugal energies of the high-j low-Ω aligning $\nu i_{13/2}$ neutrons balances the pairing energy of the aligning neutrons. Further on in rotational frequency, another band crosses the 2-quasiparticle band at $\hbar\omega_c$=0.427 MeV. As mentioned earlier, this second bandcrossing in ^{158}Er was first observed in [3]. In the top panel of the figure, i_x is plotted as a function of $\hbar\omega$ from the same data.

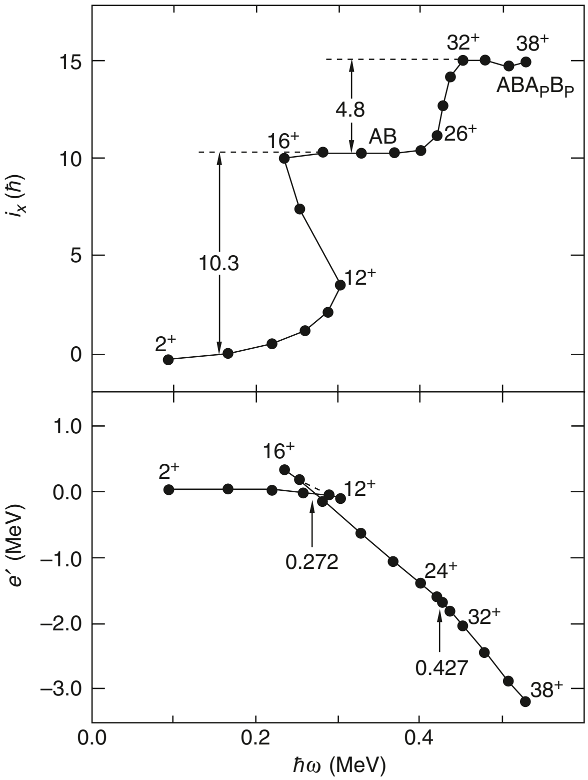


Fig. 1.3 Plots of quasiparticle energies, e', and aligned angular momenta, i_x, versus rotational frequency, $\hbar\omega$, for the Yrast band in ^{158}Er, using $\mathcal{J}_0 = 18.5$ MeV$^{-1}\hbar^2$ and $\mathcal{J}_1 = 85.0$ MeV$^{-3}\hbar^4$ in the parameterization of the ground state band. The bandcrossing frequencies, $\hbar\omega_c$, for the alignments are marked (↑) in the *bottom panel* and the aligned angular momentum gains, Δi_x mentioned in the *upper panel* [15]. (Figure in part reproduced with permission from [15])

This figure shows a typical backbending nature and a second bandcrossing which has a shape between a vertical and a gradual upbender. Also given in the figure are the alignment gains Δi_x (for the first backbending) $= 10.3\hbar$ and for the second bandcrossing $\Delta i_x = 4.8\hbar$.

Let us further characterize these bandcrossings. The experimental values of $\hbar\omega_c$ and Δi_x can be compared with the CSM predictions. Also, the bandcrossings in an even–even nucleus can be interpreted in terms of bandcrossings observed in the neighbouring odd-*N* and odd-*Z* nuclei, on the basis of the Pauli blocking arguments. Following these arguments, we examine the experimental data on bandcrossings in odd-*Z* ^{157}Ho [16] and odd-*N* ^{159}Er [17] nuclei. Plots of experimental values of aligned angular momentum, *i* (same as i_x), as a function of rotational frequency, $\hbar\omega$, for these nuclei are shown in Figs. 1.4 and 1.5, respectively. In ^{157}Ho, the first bandcrossing occurs at $\hbar\omega_c = 0.27$ MeV with an alignment gain of $\Delta i = 9.0\hbar$. This crossing has been identified to be due to the rotation alignment of AB pair of $i_{13/2}$ quasineutrons in the bands based on the lowest energy Ap and Bp proton orbitals. (A, B and Ap, Bp is the nomenclature for nucleon configurations used in the CSM. See Sect. 1.3.1 for details of these notations.) The bandcrossing frequency of

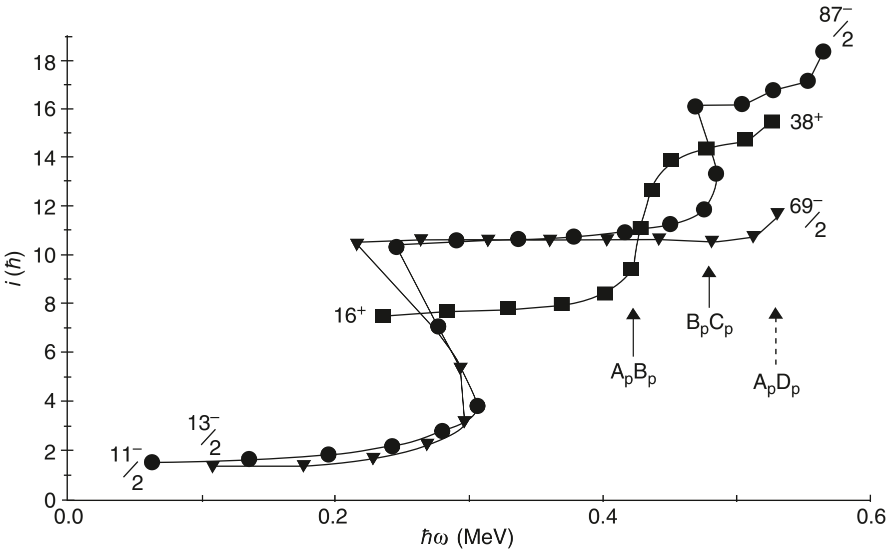


Fig. 1.4 Experimental values of aligned angular momentum, i (same as i_x), as a function of rotational frequency, $\hbar\omega$, for the bands based on Ap (●) and Bp (▼) configurations in the odd-Z nucleus ^{157}Ho [16]. Only data up to $\hbar\omega \sim 0.45$ MeV will be considered in the text. After alignment of 2-quasineutrons, the 3-quasiparticle configuration of these bands is ApAB and BpAB, respectively. A partial alignment plot for ^{158}Er from spin $I=16^{+}$–38^{+} is also shown. Alignments like, ApBp in ^{158}Er and BpCp and ApDp in ^{157}Ho are also marked. (Figure reproduced with permission from [16])

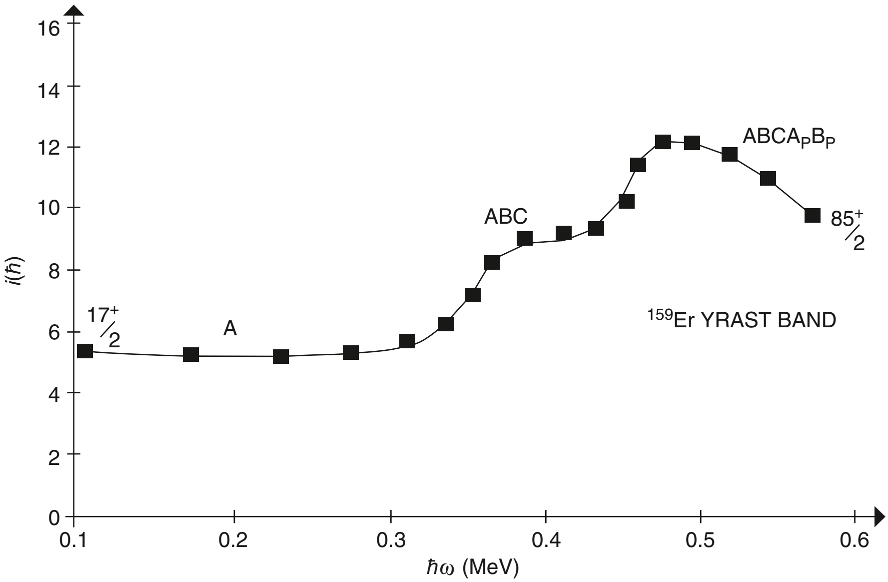


Fig. 1.5 Plot of experimental aligned angular momentum, i (same as i_x), as a function of rotational frequency, $\hbar\omega$, for the positive parity Yrast band in odd-N ^{159}Er nucleus [17]. (Figure in part reproduced with permission from [17])

$\hbar\omega_c$=0.27 MeV and an alignment gain of Δi=9.0$\hbar$ in ^{157}Ho are in agreement with the results $\hbar\omega_c$=0.272 MeV and the alignment gains Δi_x=10.3$\hbar$ for the first bandcrossing in ^{158}Er mentioned above. For ^{159}Er [14, 17], the aligned angular momenta for the bands based on A and B neutron configurations are i_x=5.8$\hbar$ and 4.6$\hbar$, respectively. In Fig. 1.5 [17], the alignment plot only for the A configuration in ^{159}Er is shown. These aligned angular momenta add up to 10.4$\hbar$ as compared to Δi_x=10.3$\hbar$ obtained for the first bandcrossing in ^{158}Er. These results, therefore, firmly establish that the first bandcrossing in ^{158}Er is due to the rotation alignment of the lowest $\nu i_{13/2}$ AB quasineutron pair. In the same alignment plot (Fig. 1.5) in ^{159}Er [17], it is observed that the Yrast band based on A neutron configuration undergoes the first bandcrossing as a gradual upbend at $\hbar\omega_c$=0.355 MeV. This crossing has been interpreted as due to the rotational alignment of the BC quasineutron pair because the AB bandcrossing is blocked as the Yrast band occupies trajectory A. The next gradual/upbend bandcrossing in ^{159}Er is found at a higher rotational frequency of $\hbar\omega_c$=0.453 MeV [17]. This has been interpreted as the alignment of the lowest ApBp quasiproton pair [17, 18]. A similar bandcrossing has also been seen in the Yrast band of the neighbouring N=90 isotone ^{160}Yb at $\hbar\omega_c$=0.42 MeV [15, 19] which has been interpreted as due to the ApBp quasiproton pair. Independently, in the framework of a cranked Hartree-Fock-Bogoliubov (HFB) approach with particle number projection, it was suggested in [20] that this crossing at I=26–30 in ^{158}Er is due to the rotational alignment of a pair of $h_{11/2}$ protons. In [21], through the cranked HFB method in the pairing +Q.Q model, a second backbend around I=26 in ^{158}Er was also predicted due to the anti-pairing effect among protons. Based on these arguments and facts, it can be concluded that the second bandcrossing observed in the Yrast band of ^{158}Er (see Fig. 1.3) is due to the rotational alignment of the $\pi h_{11/2}$ ApBp quasiproton pair.

1.3 Systematics of Bandcrossings

A large body of experimental data exists in literature on bandcrossing(/alignment) frequencies, alignment gains and band interaction strengths for bandcrossings involving different aligning neutron and proton pairs at high spins in nuclei throughout the nuclear chart. Such data have been interpreted by comparison with the predictions of the CSM calculations and successfully and very widely utilized not only in the assignment of nucleon configurations to the crossing bands but also in unfolding the details of nuclear structure. The supportive pair blocking arguments have also proved very useful in data interpretation.

In this section, the nomenclature used in the CSM calculations to define the participating specific quasiparticles in bandcrossings will be outlined. It will be followed by a plot of quasiparticle trajectories (quasiparticle energies, e' in the rotating frame as a function of rotational frequency), as an example and the CSM predictions of bandcrossing frequencies and alignment gains from it. These are required for an understanding of the systematics of bandcrossings described later in this section.

Excellent treatment of the CSM is available, e.g. see [4 and references therein].

1.3.1 Nomenclature for Quasiparticle Trajectories

In the CSM, the quasiparticle energies, e' in the rotating frame (called Routhians[1]), are calculated as a function of rotational frequency, $\hbar\omega$. At $\omega=0$, the levels are labelled by the asymptotic Nilsson quantum numbers $| Nn_z\wedge\Omega |$ and at $\omega\neq 0$, the trajectories can be identified by the quantum numbers, parity (π) and signature (α). The short-hand notation used to label the quasiparticle trajectories in the model is described below. In the region of the neutron $\nu i_{13/2}$ and proton $\pi h_{11/2}$ intruder orbitals and the $h_{9/2}$, $f_{7/2}$ neutron orbitals, the alphabetic labelling convention is used [4, 23, 24]. The notations are: $A=(\pi, \alpha)_n=(+, ½)_1$, $B=(+, -½)_1$, $C=(+, ½)_2$, $D=(+, -½)_2$, for the lowest positive parity quasineutron trajectories from the $i_{13/2}$ intruder orbital and for the negative parity, $E=(\pi, \alpha)_n=(-, ½)_1$ and $F=(-, -½)_1$ quasineutron trajectories from the $h_{9/2}$ and $f_{7/2}$ orbitals respectively. At $\omega=0$, the levels A and B, C and D, E and F and G and H correspond to the Nilsson states [651, 3/2], [660, ½], [532, 3/2] and [521, 3/2], respectively. Similarly, $Ap=(-, -½)_1$, $Bp=(-, ½)_1$ and $Cp=(-, -½)_2$ for the lowest quasiproton trajectories from the mid-shell $h_{11/2}$ ($\Omega\sim 7/2$) orbitals. The subscript '*n*' is the *n*th such aligned quasiparticle.

The experimental rotational band sequences are designated by (π, α) and by their quasiparticle composition. A band may have 0-quasiparticle composition (ground state band) in an even–even nucleus or a 1-quasineutron configuration A, B, C, etc., in an odd-*N* nucleus or a 1-quasiproton Ap, Bp etc., configuration in an odd-*Z* nucleus. The ground state band will have $(\pi, \alpha)=(+, 0)_1$. For 1-quasiparticle bands the (π, α) labelling is given above. Multi-quasiparticle bands may be based on 2-, 3-, 4- and higher quasiparticle configurations. For such bands, the parity, π is the product of the parities of individual quasiparticle orbitals and the signature, α is the sum of the single-quasiparticle values, e.g. AB band will have $(\pi, \alpha)=(+, 0)$. Further, bands of configurations ApAB, BpAB and 0-ABApBp will have $(\pi, \alpha)=(-, -½)$, $(-, ½)$ and $(+, 0)$, respectively.

The total signature, α, of a state is related to the total angular momentum *I* as follows [4]:

$$\alpha=\begin{cases} -1/2 \\ 1/2 \\ \\ 0 \\ 1 \end{cases} \quad \text{if} \quad I=\begin{cases} 3/2, 7/2, 11/2, \ldots \\ 1/2, 5/2, 9/2, \ldots \\ \\ 0, 2, 4, \ldots \\ 1, 3, 5, \ldots \end{cases}$$

[1] The term Routhian is used for excitation energy in the rotating frame, since the transformation from the laboratory to the intrinsic rotating frame is equivalent to Routh procedure [22] for a change of variables in classical mechanics.