5. Pairing correlations and band termination at the highest spins*

5.1. Introduction

The evolution of the superfluid properties of the nucleus with increasing angular momentum is of considerable interest. At low spins, the nucleus displays well-established superfluid properties with nucleons teaming up in time-reversed orbits, or Cooper pairs. But collective rotation of the nucleus tries to break these correlated fermions apart, the Coriolis anti-pairing effect. With increasing rotational frequency and particle alignments it was thought that a transition out of the superfluid paired phase may occur, in an analogous manner to the quenching of superconductivity by a sufficiently high magnetic field (the Meissner effect). However, while it now seems that the occurrence of such a phase change is somewhat more complex in nuclei than at first thought, "the question of how does rotation affect the pairing correlations at very high spin is still an important and unfinished business" (Nobel Laureate, Ben Mottelson, NBI, September 1997).

One test for the existence of static pairing correlations at large angular momentum is through the study of band crossings. In regions of spin where pairing is significant, band crossings are expected to occur at a similar rotational frequency in all rotational bands where the associated alignment is not blocked. In the absence of pairing, a rotational band based on a particular single-particle configuration can be crossed by another rotational band based on a different but more energetically favourable configuration. The rotational frequencies at which such rearrangements occur are specific and highly dependent on the details of the single-particle spectrum of states. Thus, one characteristic of the decline of static pairing correlations would be the observation at high angular momentum of band crossings not correlated in rotational frequency.

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5.2. High spin spectroscopy

Nuclei in the mass $A \sim 160$ region present the best opportunity to observe and investigate the very highest nuclear spins possible in a chain of isotopes or isotones. They are the best cases to probe the ultimate angular-momentum limit for discrete nuclear states, beyond which the huge rotational forces cause the nucleus to fission. EUROBALL is the ideal instrument to perform this ultra high spin spectroscopy.

Using EUROBALL, very high spin states (I = 50-60$\hbar$) have been observed in the transitional nuclei ^{159}Er – ^{162}Er [136]. The positive parity, even spin (+, 0), the negative parity, odd spin (–,1) and even spin (–,0) bands in ^{160}Er were established up to $I^{\pi} = 54^{+}$, 51^{-} and 54^{-}, respectively. In ^{161}Er, three bands are observed well above spin 50$\hbar$. In the positive parity, positive signature (+,+½) band a discontinuity in the regular rotational behaviour occurs at $109/2^{+}$ and a splitting into two branches occurs at $97/2^{-}$ in the negative parity, positive signature (–,+½) band. The (–,–½) band continues in a regular fashion to $115/2^{-}$, tentatively ($119/2^{-}$). In ^{162}Er the (+,0) yrast band is observed to continue smoothly up to 60^{+} (see Figure 5.1) and the (–,0) and (–,1) bands have been extended from 30^{-} to 34^{-} and from 31^{-} to 49^{-}, respectively.

The high spin experimental spectra were compared with both a simple model involving the occupation of specific single neutron states in the absence of neutron pair correlations and with more detailed cranked Nilsson-Strutinsky calculations in which both proton and neutron pairing correlations are neglected. The very high spin domain was found to comprise a series of unpaired rotational bands. Excellent agreement between the experiment and theory for the relative energy of the bands at high rotational frequency and for the observation and interpretation of the band crossings in the (+,+½) and (–,+½) sequences in ^{161}Er was obtained. This work provided, for the first time, strong evidence for the demise of both proton and neutron static pairing correlations at these ultra high spins. It is also worth noting that the nucleus ^{159}Er was the first one to establish an unpaired band crossing in the (–,+½) sequence, i.e. at $\hbar\omega \sim 0.55$ MeV [137]. The simple model predicts another such crossing in the (–,–½) sequence at higher rotational frequency and indeed the Euroball data shows good evidence for this crossing at $\hbar\omega \sim 0.62$ MeV.

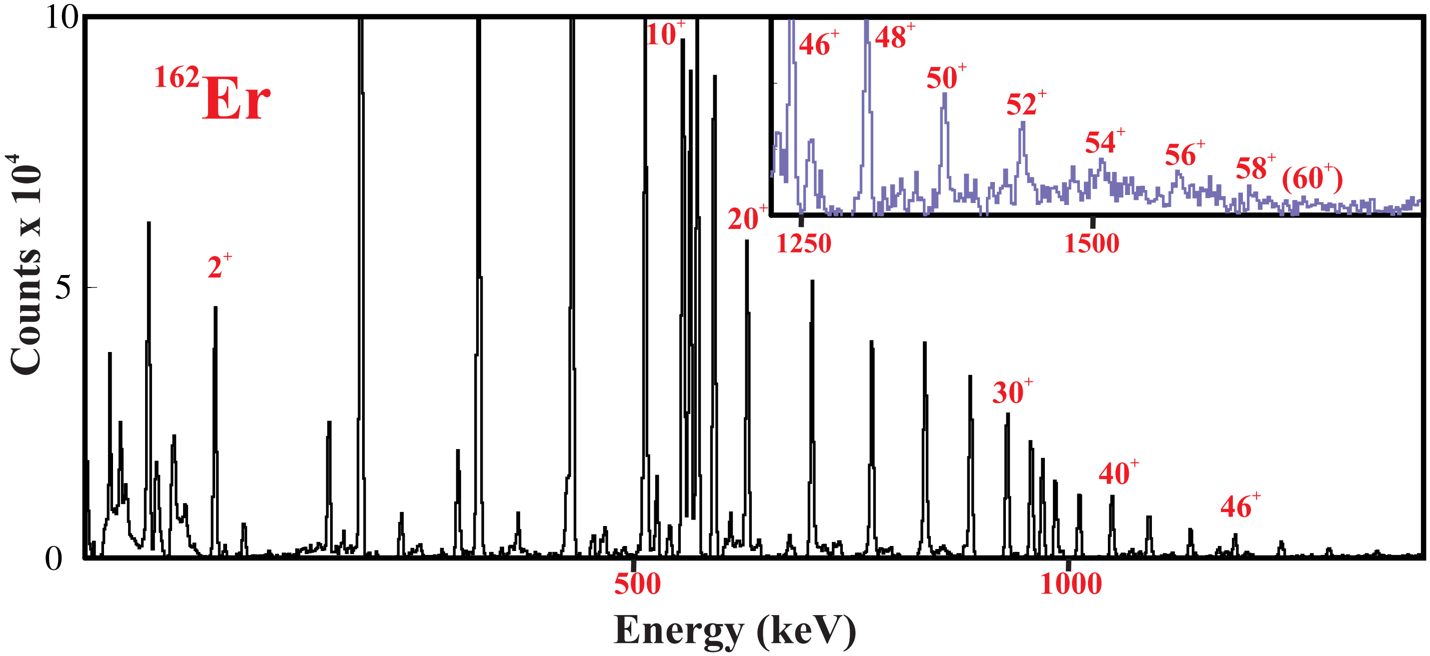

Figure 5.1: *EUROBALL spectrum showing the yrast band in* ^{162}*Er up to spin 60ħ.*

5.3. Termination of rotational bands

Two types of band termination have been observed to occur in nuclei. The first involves the crossing, in terms of excitation energy, of deformed collective rotational states and oblate non-collective single-particle states, the latter becoming favoured at high-spins. This is often called "abrupt" band termination. The second type, which has been called "smooth" or "soft" band termination, results when, for a given configuration, a deformed collectively rotating nucleus gradually changes its shape from a near-prolate to a non-collective oblate shape at termination. Detailed discussions of band termination can be found in the review article by Afanasjev et al. [138]. Experiments have been carried out to study both of these phenomena at EUROBALL.

The transitional erbium isotopes exhibit perhaps the classic examples of the angular momentum induced abrupt prolate-collective to oblate non-collective shape change at high spin in heavy nuclei [138,139]. This band termination effect, which is a consequence of the finite number of valence particles outside the $Z = 64$ and the $N = 82$ core has been traced in a range of Er isotopes using EUROBALL.

In ^{159}Er there is clear evidence for the first time of the fully aligned band terminating state in the (+,+½) sequence at $101/2^+$ (see Figure 5.2). This state corresponds to a fully aligned $[\pi(h_{11/2})^4]_{16}{}^+ \otimes [\nu\ (i_{13/2})^3\ (h_{11/2},\ f_{7/2})^6]_{69/2}{}^+$ configuration and is formed by adding one extra favoured $i_{13/2}$ $(9/2^+)$ neutron to the classic favoured band terminating state at spin $46\hbar$ in ^{158}Er [140]. In the heavier isotopes these non-collective states are predicted to move to higher excitation energy with respect to the yrast line, which is consistent with the experimental observations.

Some of the best examples of smoothly terminating bands have been found in the *A~110* mass region [138]. In the Sn nuclei these structures are mainly based on two-particle-two-hole (2p-2h) proton excitations across the *Z=50* shell gap. Examples have also been found in Sb, Te, I and Xe nuclei where the configurations involve 3p-2h, 4p-2h, 5p-2h and 6p-2h proton excitations respectively.

Using EUROBALL, evidence has been found in ^{73}Br and the odd-*A* Lanthanum isotopes for smoothly terminating bands which do not involve proton particle-hole excitations. In ^{73}Br [141] a negative parity band was observed up to its terminating spin of $63/2\hbar$. This was the first terminating band to be identified in the *A~70* mass region. Following comparison with unpaired cranked Nilsson-Strutinsky calculations the band was assigned a *[43,73]* configuration relative to a ^{56}Ni core. The notation used is $[p_1,p_2,n_1n_2]$ where $p_1(n_1)$ is the number of protons (neutrons) in the $p_{3/2},f_{5/2}$ orbitals and $p_2(n_2)$ represents the number of protons (neutrons) in the $g_{9/2}$ orbitals.

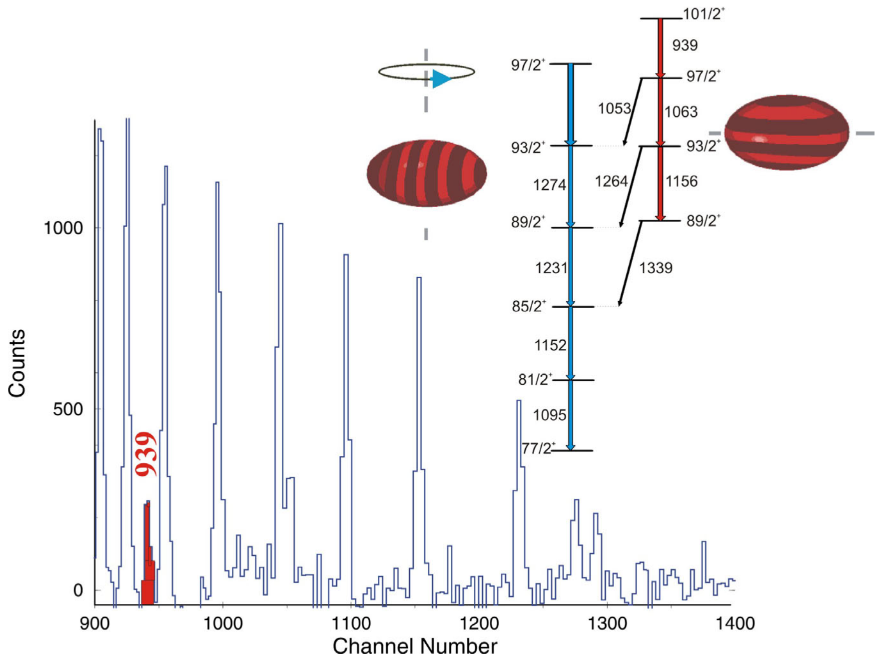

Figure 5.2: *EUROBALL spectrum and level scheme for the top of the (+, +1/2) band in ^{159}Er. The 939 keV gamma ray is the transition depopulating the fully aligned band termination state at $101/2^+$.*

The existence of smoothly terminating structures in the highly-deformed bands in *A~130* nuclei was predicted some time ago by Afanasjev and Ragnarsson using cranked Nilsson-Strutinsky calculations [142]. However, because the terminating spins were expected to be very high (e.g. >70ħ in ^{132}Ce) it was believed that it would be too difficult to observe such states. Recent EUROBALL studies have revealed the first hint for smooth band termination behaviour in the yrast highly deformed band in ^{132}Ce [143]. Figure 5.3 shows the experimental results for this along with the results of unpaired cranked Nilsson-Strutinsky (CNS) calculations. Experimentally, two starting spin values are shown since the decay to the normal-deformed yrast states has not yet been established. Below spin 60ħ the band has been assigned a *[24,422]* = $\pi[g_{9/2}^{-2}h_{11/2}^{4}]\otimes\nu[h_{11/2}^{-4}(h_{9/2}f_{7/2})^{2}i_{13/2}^{2}]$ configuration relative to a ^{132}Sn core, whilst above this spin calculations suggest that an $h_{11/2}$ neutron is promoted into an $h_{9/2}/f_{7/2}$ orbital, which raises the termination spin for the resulting $\pi[g_{9/2}^{-2}h_{11/2}^{4}]\otimes\nu[h_{11/2}^{-5}(h_{9/2}f_{7/2})^{3}i_{13/2}^{2}]$ configuration from 78ħ to 82ħ. Although the present calculations reveal some discrepancies with the data, such as the crossing point for the two structures discussed above, the behaviour of the kinematic and dynamic moments of inertia (panel a) and the rigid rotor plot (panel b) suggests that the experimental band is approaching termination. These results reveal important insight into the microscopic structure of highly-deformed collective bands in this region.

In the odd mass La isotopes with *A=127,129,131* the normal-deformed structures (ε_2~0.2) have been extended to very high spins (~37-44ħ) using EUROBALL and found to have the characteristics of smoothly-terminating bands [144,145]. This provided the first evidence for such behaviour in normal-deformed bands in this mass region. In these nuclei, however, the structures were found not to involve $g_{9/2}$ holes, which are observed to play an important part in the A~110 mass region and in the highly-deformed bands in the Ce isotopes. They are based on protons and neutrons in the $d_{5/2}$,$g_{7/2}$, $h_{11/2}$ valence orbitals with additional neutrons in the $s_{1/2}$ and $d_{3/2}$ orbitals.

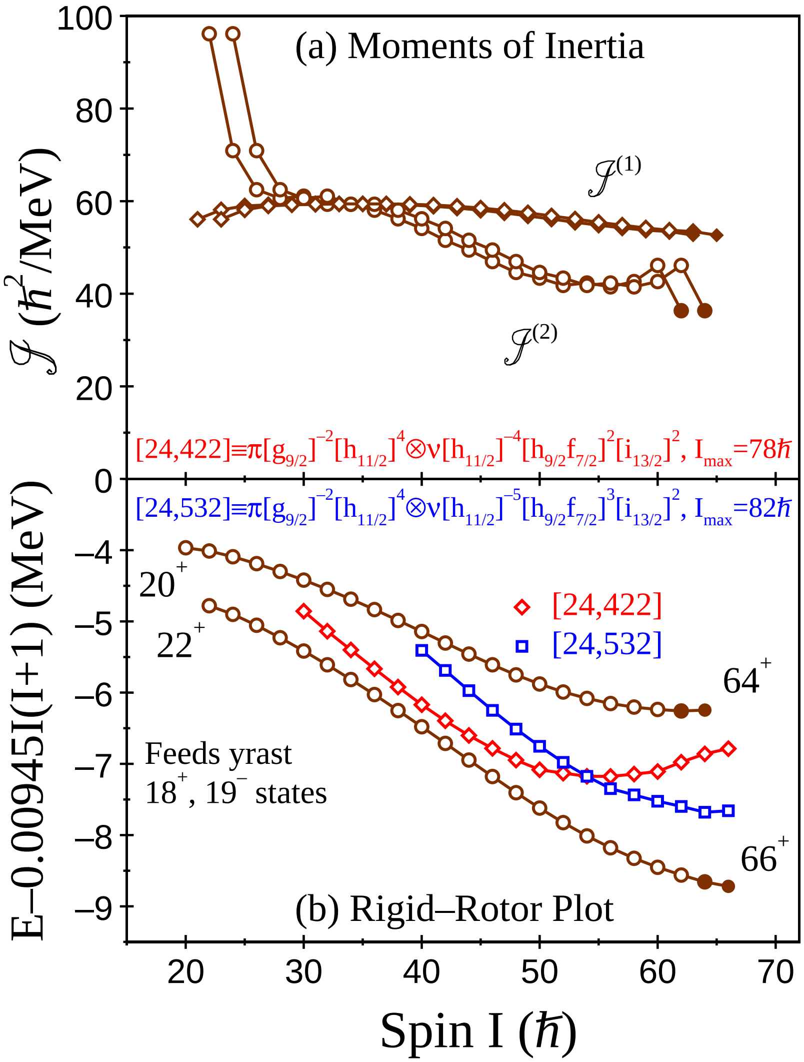

Figure 5.3: *(a) Experimental kinematic and dynamic moments of inertia and (b) energy relative to a rigid rotor reference energy for the yrast highly-deformed band in* ^{132}*Ce. The experimental results are shown for two different starting spin values. Also shown in panel (b) are the theoretical configurations calculated within the CNS model.*

5.4. Summary

Experiments with EUROBALL have allowed, for the first time, detailed spectroscopy to be carried out in the spin 50ħ to 60ħ regime in a range of Er isotopes. This has enabled us to gain some insight into the behaviour of the atomic nucleus in the absence of static pairing correlations and to investigate shape competition at the very highest excitation energy and angular momentum. Further experiments in this area will be required since it is important to investigate band crossing frequencies in a range of nuclei. It will be exciting to continue the experimental quest to even higher spins (~60-70ħ) in this region of nuclei where many aligned oblate states and numerous unpaired crossings are predicted to occur. It is also of fundamental interest to find the actual limit of discrete nuclear states before the large rotational forces cause the nucleus to fission.

Abrupt band termination is now a well established phenomenon in a few nuclei in various mass regions. One of the best areas to study this phenomenon is in the A~160 region, where it has been possible to establish evidence for single-particle states and their configuration at high spin (~40ħ) and high excitation energy (~40 MeV). Such work is vital for fixing the location of the single-particle orbitals. One interesting question that remains in this area is; what lies beyond band termination? In other words, what structures feed these special terminating states. At the present time studies are continuing in the Er nuclei to investigate whether such structures involve a breaking of the ^{146}Gd core or if they are fed from a semi-continuum of states based on proton and neutron particle-hole excitations.

EUROBALL has provided evidence for smooth band termination in new regions (A~70 and 130) of the Segrè chart. These results, along with those from other arrays such as GAMMASPHERE, have helped to establish that this phenomenon is observed when a well defined configuration is followed to very high-spin, and is a natural consequence of the alignment of all the valence nucleon spin vectors within the configuration with the initial axis of rotation. The properties of such bands can be well reproduced by unpaired cranked Nilsson-Strutinsky calculations. Comparison of such calculations with the available data suggests that for structures that involve particle-hole (p-h) excitations the states within the smoothly terminating bands have rather pure wavefunctions. However, in ^{73}Br and the odd-mass La isotopes, where the configurations do not involve particle-hole excitations, the structures do not seem to evolve as smoothly. This may reflect the fact that the wavefunctions of the states in these bands are less pure than those resulting from the 2p-nh bands in the mass 110 region, for example. The EUROBALL spectrometer has also provided the first hints that smooth band termination may also occur at the highest spins in the yrast highly deformed band in ^{132}Ce. Further work will, however, be required to establish whether termination is achieved.