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Properties of Rotational Bands at the Spin Limit in $A \sim 50$, $A \sim 65$ and $A \sim 110$ Nuclei

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Abstract

There is now widespread evidence for the smooth termination of rotational bands in $A \simeq 110$ nuclei at spins of 40-to-50$\hbar$. The characteristics of these bands are compared to those of bands recently observed to high spin in ^{64}Zn and ^{48}Cr, studied with the 8π γ-ray spectrometer coupled to the Chalk River miniball charged-particle-detector array.

A necessary requirement for establishing nuclear deformation and the associated collective rotational bands at low spin is the presence of a minimal number of valence particles (or particles and holes) outside a closed, spherical shell. The nucleus $^{122}_{54}$Xe$_{68}$, for example, has four protons and 18 neutrons outside the ^{100}Sn doubly closed shell. This combination is sufficient to build up the strong correlations between valence nucleons which are necessary for deformation to occur, and which lead to a collective, rotational band built on the ground-state configuration. In nuclei which lie near closed shells the number of valence particles may be insufficient for collective rotational motion to be the favoured excitation mode producing low-lying states. This is the case for Sn and Sb nuclei ($Z = 50$ and 51, respectively), in which the states of lowest spin and excitation energy arise from combinations of the single-particle orbitals at near-spherical deformation. Nonetheless, if particle-hole excitations across the shell gap are not too costly in energy, it may be possible for the nucleus to deform and consequently for rotational bands to appear at modest spins and excitation energy. These structures are well known in $Z \approx 50$ nuclei [1] where they are known as "intruder-type" bands, since they spring from particle-hole configurations involving orbitals which intrude from high-lying shells. The spectrum shown in Fig. 1 illustrates the yrast intruder band in ^{109}Sb, discovered [2] with the 8π spectrometer at Chalk River and subsequently studied [3, 4] in more detail with the Gammasphere spectrometer. The proton valence configuration in this case consists of an odd $h_{11/2}$ proton coupled to a deformed two-particle-two-hole (2p-2h) excited Sn core, *i.e.*, $\pi h_{11/2} \otimes (g_{9/2}^{-2} \otimes g_{7/2}^{2})$.

In a classical system, this type of rotational motion can continue to arbitrarily high spin. In atomic nuclei, the intrinsic motion of a finite number of nucleons places constraints on the quantum-mechanical observables, in particular the spin of the nucleus. In the modified-oscillator description, the maximum spin possible in a given ground-state band

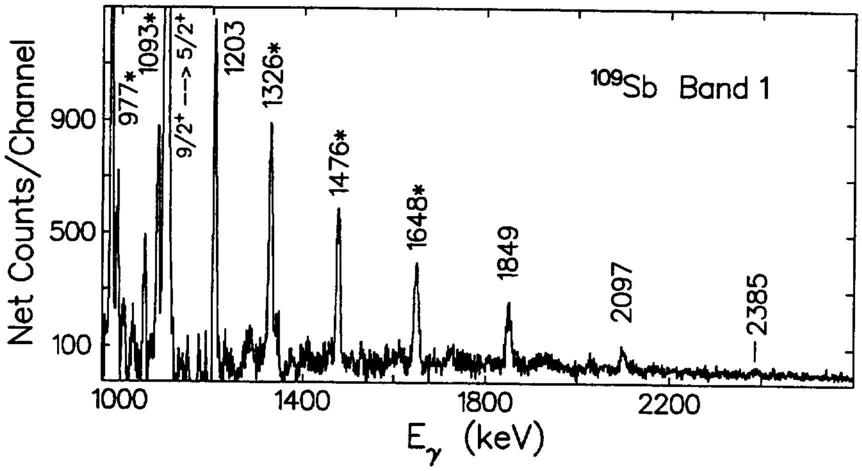

Figure 1: Gamma-ray spectrum of the yrast rotational band in ^{109}Sb. Band members are labelled by energy; gating transitions are denoted by *. From Ref. [2].

can be obtained simply by summing the available oscillator quanta of Nilsson orbitals appearing between the nearest closed shell and the Fermi surface [5]. For heavy nuclei near the middle of closed shells this spin limit is relatively large, of order A of the nucleus [5], and one would expect to observe rotational bands extending to extremely high spins.

Nevertheless, there are a number of cases where the ground-state rotational band appears to be interrupted at only modestly high spins, *e.g.*, $40\hbar$ in ^{158}Er [6], and only $22\hbar$ in the above-mentioned ^{122}Xe [7]. These occurences can be understood as a crossing of the yrast band with a very different sequence of states, terminating in a non-collective state (or states) of maximal spin which is (are) energetically favoured. For this reason, one can refer to such a process as "favoured band termination" [8]. It is often accompanied by sudden changes in the yrast line of the nucleus, as illustrated in Fig. 2 for the positive-parity states in ^{122}Xe.

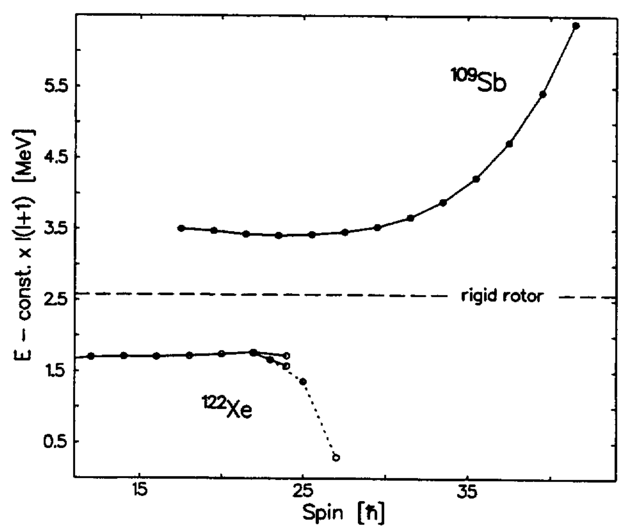

Figure 2: Comparison between the positive-parity states in ^{122}Xe [7] and the yrast intruder band in ^{109}Sb [3, 4]. A rigid-rotor reference, chosen to make the trajectories approximately flat close to spin $20\hbar$, has been subtracted in each case.

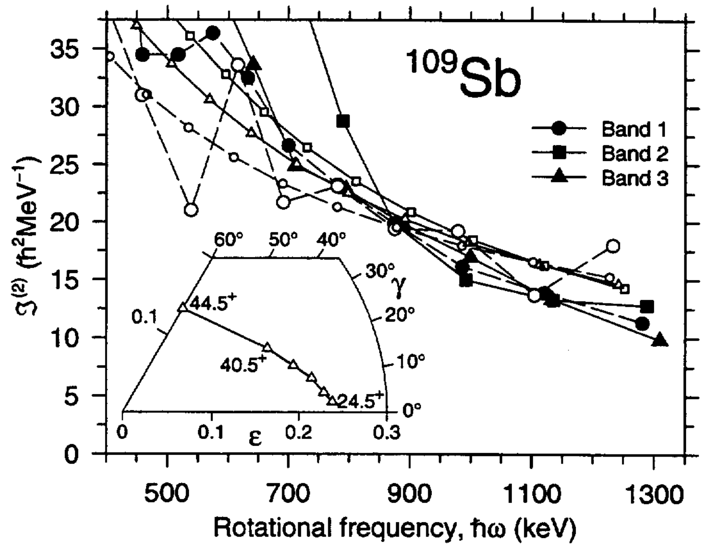

Figure 3: Comparison between experimental (filled) and theoretical (open symbols) $\mathcal{J}^{(2)}$ moments for the three most strongly populated bands in ^{109}Sb. The theoretical values are smoothed by fitting a four-parameter $I(I+1)$ expansion to the 13 highest calculated energies in the band. For one of the bands the unsmoothed values are also shown as larger symbols. Inset: plot of the calculated intrinsic shape of the nucleus as a function of spin, in steps of $4\hbar$, for the rotational band predicted to be yrast at the highest spins observed. At intermediate spins the calculated shape is approximately prolate, while with increasing spin it gradually moves in the direction of increasing γ-deformation, becoming oblate non-collective ($\gamma = 60°$) at termination. From Ref. [8].

The intruder bands of $A \simeq 110$ Sb and Sn nuclei do not undergo the same process. Indeed, inspection of the ^{109}Sb spectrum in Fig. 1 reveals an obvious feature which is inconsistent with the behaviour of ^{122}Xe at high spin: the spacing between consecutive γ-ray peaks is smoothly increasing as a function of increasing γ-ray energy and thus as a function of spin. Consequently, when plotted relative to a rigid-rotor reference energy, as in Fig. 2, the trajectories of ^{109}Sb and ^{122}Xe are quite different.

Another way of illustrating the changes which occur at high spin is to invoke the dynamic moment of inertia, $\mathcal{J}^{(2)} = dI/d\omega \approx 4/\Delta E_\gamma$, as in Fig. 3. This quantity is constant for an ideal rigid rotor, and is sensitive to changes in structure and deformation; an added advantage is that the spins need not be known. The $\mathcal{J}^{(2)}$ moments in Fig. 3 undergo a substantial but smooth decrease with increasing γ-ray energy (and thus with increasing rotational frequency and spin). At the highest spins, the dynamic moments of inertia are only 1/2-to-1/3 the magnitude of the static moments, which are themselves comparable to the rigid-body moments for a deformation $\beta_2 \approx 0.25, \gamma \approx 0°$. Comparison with Nilsson-Strutinsky cranking calculations has led us to conclude that this smooth decrease signifies a continuous transition from high collectivity to a noncollective state [8]. In contrast to the behaviour of ^{122}Xe, this change occurs gradually and with no change in the valence configuration; it is the "smooth termination" of a collective band in which the spin available from the constituent valence nucleons is gradually exhausted. The inset to Fig. 3 illustrates the changes in deformation which are predicted to occur during this process. A detailed description of "smooth band termination" from a theoretical perspective can be found in

Ref. [9]. For ^{109}Sb, as well as for neighbouring ^{108}Sn [10] and ^{110}Sb [11], the agreement between theory and experiment is remarkably good, notably for the latter two which do have firm spin and parity assignments.

The excellent agreement between theory and experiment is satisfying, yet several questions arise. Amongst them are:

- Why don't we see more of this phenomenon, and in different mass regions?
- If there are more cases, what are the similarities and/or differences?
- Can we directly measure the decline in collectivity as a band smoothly terminates?

To begin with, bands with very similar $\mathcal{J}^{(2)}$ features have now been found in 13, possibly 14, $A \simeq 110$ nuclei, as shown in Fig. 4. There is evidence in 4 of these that at least one band has been observed up to the terminating state. Results for ^{110}Sb, which are in very good agreement with theory, are discussed by Lane *et al.* in a contribution to these proceedings. Ragnarsson and Afanasjev discuss the evidence for band termination in the $A = 80$ mass region and in ^{117,118}Xe, also in these proceedings.

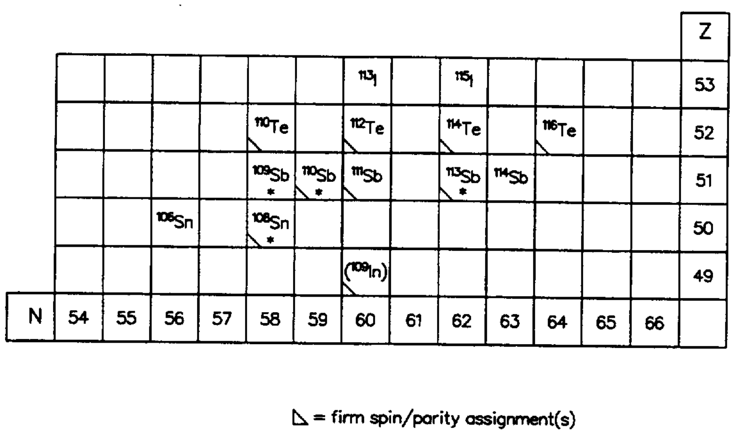

Figure 4: Known cases of smooth band termination in the $A \simeq 110$ mass region. A * denotes nuclei for which there is evidence of at least one terminating state.

Additional information, from lighter nuclei, comes from recent 8π-spectrometer experiments concerning $A \simeq 65$ and $A \simeq 48$ nuclei. As it turns out, the primary conditions for smoothly terminating bands in $A \simeq 110$ nuclei, namely, enough valence particles (and/or holes) to generate collective bands at low spin, but not so many that the terminating spin is out of experimental reach, can be met in nuclei which are close to the $^{56}_{28}\mathrm{Ni}_{28}$ and $^{40}_{20}\mathrm{Ca}_{20}$ doubly closed-shell nuclei. Galindo-Uribarri *et al.* have studied $^{64}_{30}\mathrm{Zn}_{34}$ [12] at high spins, using the ^{40}Ca(^{28}Si,4p) reaction at a beam energy of 115 MeV; the Chalk River miniball array [13], which comprises 44 CsI charged-particle detectors in near-4π geometry, was used to detect the evaporated protons. In this nucleus, for which only non-collective states were previously known, they discovered a strongly coupled excited rotational band which extends from spin $(10)\hbar$ to $(22)\hbar$. The dynamic moment of inertia, shown in Fig. 5, undergoes the gradual decrease to very low values at high frequency which is characteristic of smooth band termination. Theoretical calculations, of the type used so successfully in the $A \simeq 110$ mass region, suggest that the valence proton configuration is $\pi(f_{7/2}^{-1}\otimes g_{9/2}^{1})\otimes p_{3/2}^{2}$, in other words, a 1p-1h proton excitation across the $Z = 28$ spherical shell gap. The six valence neutrons are in orbitals which lie above the corresponding $N = 28$ gap. In this case, it appears that experiment has not reached the point of termination which, according to theory, occurs at spin $26\hbar$.

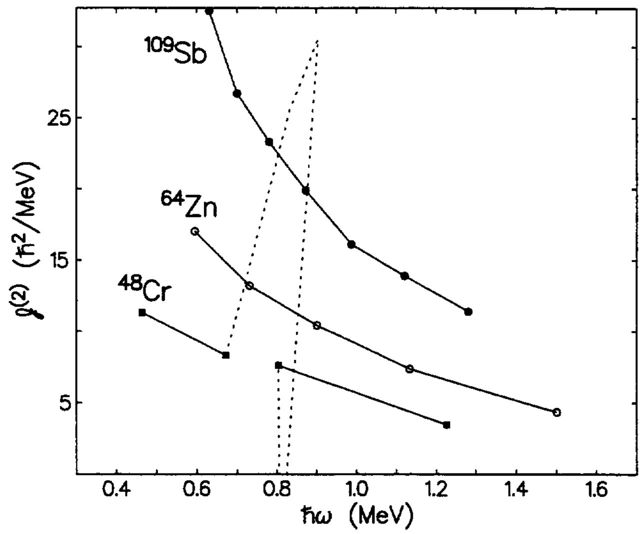

Figure 5: Dynamic moments of inertia for the yrast smoothly terminating bands in ^{109}Sb, ^{64}Zn and ^{48}Cr. The dashed line indicates a band-crossing region in ^{48}Cr (see text).

There is recently obtained data for the $N = Z$ nucleus ^{48}Cr [14], from an 8π-spectrometer experiment which also used the miniball to detect charged particles. The reaction ^{28}Si(^{28}Si,2α) was used at a beam energy of 125 MeV. This nucleus differs from ^{109}Sb and ^{64}Zn in that ^{48}Cr is known to be well deformed in its ground state, and to possess a collective ground-state rotational band. Attention has recently been drawn to the high-spin properties of this nucleus, primarily because it is the first instance in which a "heavy" collective nucleus has been analysed within a microscopic full shell model [15], with the results compared to the mean-field cranking approach used as the standard for interpretating rotational structures in heavier systems. Cameron *et al.* [14] have now observed the ground-state band up to $16\hbar$, which is the limiting spin within a $\pi\otimes\nu$ $f_{7/2}$ shell space. The results have been confirmed [16] by a subsequent experiment with the Ga.S.P. spectrometer. The plot of $\mathcal{J}^{(2)}$ is complicated in this case by a rotational alignment which occurs at a frequency $\hbar\omega = 0.8$ MeV, giving rise to large fluctuations in the dynamic moments. Nevertheless, as shown in Fig. 5, it is clear that the overall trend in the $\mathcal{J}^{(2)}$ values is similar to that shown by the bands in ^{109}Sb and ^{64}Zn.

The similarities between smoothly terminating bands in the three different mass regions are may be summarized as follows:

- The dynamic moments of inertia gradually fall to very low values, 1/2-to-1/3 of the static moments. Another way of describing this is that the level energies *increase* rapidly as termination is approached, giving rise to the term “unfavoured” termination [8].

- Related to this, the γ-ray energies approaching termination become unusually high, approximately 3 MeV.

- Based on theory, the deformation gradually changes from collective prolate (little or no γ-deformation) to single-particle oblate ($\gamma = 60°$), and termination is reached when these bands exhaust the spin available from the valence configuration (*e.g.*, see inset to Fig. 3).

The third question raised above concerns the possibility of a direct measurement of the expected decline in collectivity during termination. Experiments aimed at measuring the lifetimes of these states are difficult. Although the bands are well populated at moderate spin (*e.g.*, the lowest-spin member of band 1 in ^{109}Sb has approximately 30 % of the intensity of the strongest ground-state transition) the intensities drop off dramatically at high spin [3, 4]. In addition, the γ-ray energies are unusually high, approximately 3 MeV, so that detection efficiencies are low and lifetimes are relatively short, even if the highest states have little or no collectivity. So far, the best evidence comes from the lightest nucleus, ^{48}Cr, as shown in Fig. 6. The $B(E2)$ values, as obtained from the Doppler shifts of γ rays emitted from the recoiling residues, reflect considerable collectivity at low spin, in reasonable agreement with shell-model (SM) theory. The fluctuations in the middle of the band are not understood although it has been suggested that they are related to the alignment process mentioned above. At the highest spins, approaching the band's limit, the $B(E2)$ values drop off to a level which corresponds to approximately 5 single-particle units, again in agreement with theoretical predictions. It should be noted that experiments have been recently performed which are designed to measure lifetimes at high spin in heavier nuclei, notably ^{109}Sb and ^{108}Sn, but the results are unavailable at this writing.

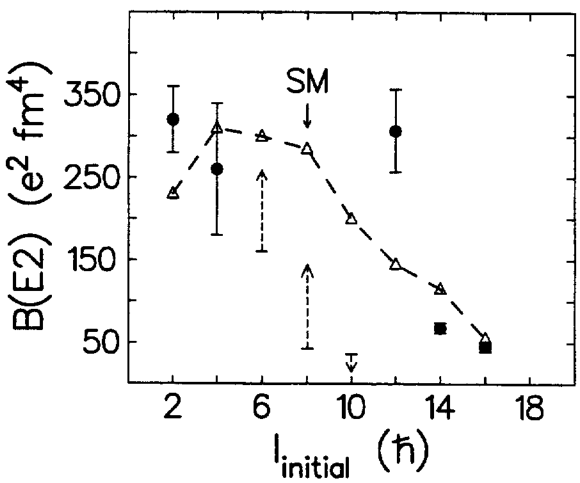

Figure 6: Measured and shell-model calculated (SM) [15] B(E2) values for ^{48}Cr. The data above spin $I = 8$ are taken from Cameron *et al.* [14]. For $I = 6, 8$ and 10, only experimental limits are available.

In summary, there are now a considerable number of examples of smooth band termination in the $A \simeq 110$ region, and, most recently, good evidence for similar occurrences in

^{64}Zn and ^{48}Cr. We anticipate that further experimental results will shed light on the existence of such bands in even more nuclei, and provide direct evidence for the expected loss of collectivity as termination is reached.

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