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NEW FEATURES OF COLLECTIVE NUCLEAR ROTATION AT VERY HIGH FREQUENCY IN ^{109}Sb

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Abstract

Three rotational bands have been discovered in the nucleus ^{109}Sb that extend in angular momentum to $\simeq \frac{81}{2}\hbar$. The rotational frequency at the highest spins reaches $\hbar\omega \simeq 1.4$ MeV, the highest frequency so far observed in a heavy nucleus. With increasing frequency the collective moments of inertia of all three bands smoothly diminish to unexpectedly low values, $\mathcal{J}^{(2)} \sim 13\ \hbar^2\mathrm{MeV}^{-1}$, approximately one third the rigid-body value, and, contrary to expectations, the moments of inertia become nearly equal to one another and to those of rotational bands in the core nucleus ^{108}Sn.

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Nuclei near the $Z = 50$ (Sn) closed proton shell exhibit both collective and non-collective features. Despite the stability of spherical shapes at low excitation [1], collective rotational structures exist in both $Z = 50$ and $Z = 51$ (Sb) nuclei at higher excitation energy. These structures involve the promotion of protons from the proton $g_{9/2}$ orbital to the $g_{7/2}$ orbital, which is energetically favourable for prolate deformation $\beta_2 \sim 0.2$ [1]. Particle-hole (p-h) excitations involving these orbitals give rise to $\Delta I = 1$ collective bands in the Sb isotopes [3], and to $\Delta I = 2$ collective bands in the Sn isotopes [2, 4]. More complex structures occur in ^{117}Sb [6] and ^{113}Sb [7] involving couplings of 2p-2h excitations to higher lying orbitals. These interesting features near the $Z = 50$ closed shell motivated us to study the isotope ^{109}Sb. Three $\Delta I = 2$ rotational bands were observed to high angular momentum, $I \simeq \frac{81}{2}\hbar$; one of the bands exhibits the highest rotational frequencies observed to date in heavy nuclei, $\hbar\omega \sim 1.4$ MeV. The dynamic moments of inertia, associated with collective properties of the rotating nucleus, gradually diminish to $\mathcal{J}^{(2)} \sim 13\ \hbar^2\text{MeV}^{-1}$ at high frequency, which is about a third of the rigid-body value. The high-frequency $\mathcal{J}^{(2)}$ moments are very closely related to each other and to those of rotational bands in the core nucleus, ^{108}Sn. The purpose of this Letter is to present and discuss these unexpected features, which, we suggest, represent the first observation of a smooth progression from a collective band to a non-collective terminating state.

High-spin states in ^{109}Sb were populated via the ^{54}Fe(^{58}Ni,3p) reaction, with a 243-MeV ^{58}Ni beam provided by the Tandem Accelerator SuperConducting Cyclotron (TASCC) facility at Chalk River Laboratories. Experiments were performed with both

[1]A diagram of the calculated single-particle levels around $Z = 50$ may be found in Fig. 1 of Ref. [2].

thin self-supporting and Au-backed target foils. Approximately 172×10^6 (self-supporting target) and 89×10^6 (backed target) γ-γ events were collected with the 8π γ-ray spectrometer, which comprises 20 Compton-suppressed HPGe detectors and a spherical shell of 71 BGO detectors. The event trigger required a suppressed HPGe 2-or-higher-fold coincidence together with a K-fold coincidence in the BGO ball, where $K^{BGO} \geq 11$. In sorting the data to construct E_γ-E_γ coincidence matrices, a fold threshold of $K^{BGO}_{min} = 15$ was used. A three-dimensional coincidence cube was constructed with no constraint on the BGO-ball fold. Two- and three-dimensional data analysis techniques, described elsewhere [8], were used to determine the level structure of the nucleus.

Figure 1 shows a partial level scheme of ^{109}Sb. The ground state was assumed to have spin-parity $\frac{5}{2}^+$ [9]. For the sake of clarity, only a subset of the observed low-spin states, those populated by the decay of the $\Delta I = 2$ rotational bands, are shown. The low-spin portion of the scheme is irregular, and characteristic of multi-quasiparticle excitations in a near-spherical shape. Not shown, for reasons of space, are several $\Delta I = 1$ rotational-band structures, which are observed to spins $\simeq \frac{39}{2}\hbar$. They are most likely built on deformed 2p-1h structures involving the proton $g_{9/2}$ orbital (*cf.* Ref. [3]).

The focus of this Letter is the three $\Delta I = 2$ structures, bands 1 to 3, which extend to high spin, *cf.* Fig. 2. The spins, parities and excitation energies of these states cannot be fixed because transitions linking them to states of known spin and parity were not observed. The assignments shown are based on decay patterns (*cf.* Fig. 1) and theoretical predictions discussed below. The spin values have an uncertainty of $\pm 2\hbar$ ($\pm 3\hbar$) for band 1 (bands 2 and 3).

We estimate the intensities of the bottom transitions in the three bands to be $13\pm2\%$, $10\pm2\%$, and $7\pm2\%$ of the reaction channel for Band 1, 2, and 3, respectively. Band 1 is the most intense and is likely yrast [2] in the range $\sim 25 \leq I \leq 40\hbar$. Cranked Strutinsky calculations [10] with a Woods-Saxon potential predict that the lowest lying structure in this spin range should correspond with proton $h_{11/2}$ coupled to the ^{108}Sn deformed core (proton 2p-2h $g^2_{7/2} \otimes g^{-2}_{9/2}$) at a deformation $\beta_2 \sim 0.2$, This "intruder" orbital (*eg.* [7]) is characterized by a large single-particle angular momentum aligned to the rotation axis, and its occupation gives rise to the high-spin yrast bands observed in heavier Sb nuclei [7, 11]. The suggested parity and sequence of spins is consistent with those expected for the $h_{11/2}$ orbital, namely $(-,-\frac{1}{2})$.

There are two possible interpretations of bands 2 and 3. One explanation involves the deformed 2p-2h state, from which one of the protons is promoted to the next available $h_{11/2}$ orbital. Excited bands involving this structure have been reported [2] in ^{108}Sn. Nonetheless, calculations suggest that the $Z = 51$ energy gap is much larger than the spacing between neutron orbitals for $N \simeq 58$, at the appropriate deformation and frequency; therefore, we expect that in ^{109}Sb excitation of neutrons would be more favourable than promotion of protons across the gap. In this explanation, the configuration of bands 2 and 3 would be the neutron p-h structure $h_{11/2} \otimes g^{-1}_{7/2}$ coupled to band 1. Either scenario leads to two signature-partner bands with parity and signature $(+,+\frac{1}{2})$ and $(+,-\frac{1}{2})$, with the latter predicted to become favoured in energy at high frequency. The intensity of band 3 relative to that of band 2 rises with increasing frequency, and so we have associated it

[2] *i.e.* comprises the set of lowest levels of a given spin I

with $(\pi, \alpha) = (+, -\frac{1}{2})$.

With the backed-target data we have performed a Doppler-shift (DSAM) analysis of the γ-ray centroid shifts observed in the $\pm 37°$ rings of HPGe detectors, to extract an average quadrupole moment for band 1. The data were analysed with the prescription used in Ref. [12], in which a constant quadrupole moment was assumed. The time-history of sidefeeding into the band was assumed to be identical to that passing down the band. The fractional shifts were well reproduced by an average $Q_0 = 3.1 \pm 0.5$ eb (see inset to Fig. 2), corresponding with a prolate deformation $\beta_2 \simeq 0.2$ for axial symmetry (γ-deformation of 0°). Cranked Strutinsky calculations of the total routhian surfaces predict $Q_0 = 3.5$ eb for an axially symmetric shape, for the spin range over which we have measured shifts. If the nuclear shape were non-axial with $\gamma \sim 10° - 20°$, the theoretical Q_0-value would decrease by 10-to-25%.

A number of unusual features are evident in the ^{109}Sb intruder bands at high spin. Firstly, the energies of the top-most transitions are extremely high, including a γ ray in band 2 with an energy of 2725 ± 5 keV (Fig. 2 inset) corresponding to the highest rotational frequency ($\hbar\omega \simeq E_\gamma/2$) observed to date in a heavy nucleus. Such rapid rotation raises interesting questions. For instance, the single-particle spectrum of states is radically altered by extreme rotation, in that it causes the juxtaposition at the Fermi surface of orbitals which are usually far removed from each other. This is analogous to the effects of extreme deformation. Consider the neutron $i_{13/2}$ orbital, which, according to cranked-shell model calculations, approaches the Fermi surface at $\hbar\omega \geq 1.3$ MeV in ^{109}Sb. This same orbital is observed as a highly deformed intruder configuration in $A \sim 130$

nuclei ($\beta_2 \sim 0.35$) and as part of the core in superdeformed $A \sim 150$ nuclei ($\beta_2 \sim 0.6$). In addition, such rapid rotation probes the limits of the cranking model (*eg.* see final paragraph), which has been so successful in explaining the observed features of rotating nuclei at frequencies $\hbar\omega < 1$ MeV.

The inertial properties of these bands (Fig. 3) are unusual. For $\hbar\omega < 0.8$ MeV, strong fluctuations appear in the dynamic moments of inertia. These are associated with band crossings predicted by the cranked shell model and observed in heavier Sb isotopes, such as the alignment of $h_{11/2}$ neutrons and $g_{7/2}$ protons [7]. By contrast, for $\hbar\omega > 0.8$ MeV the dynamic moments for the three bands converge and follow a smooth decline. The absence of band crossings at high rotational frequencies is interesting since crossings would be expected in at least some of these bands. For example, cranked-shell model calculations which include pairing predict crossings due to the alignment of $h_{11/2}$ protons and $g_{7/2}$ neutrons in the frequency range $0.7 < \hbar\omega < 1.2$ MeV. We suggest, therefore, that at frequencies $\hbar\omega > 0.8$ MeV static pairing correlations have greatly diminished or even disappeared. Similar observations have been made in A$\sim$160 nuclei [13].

A new feature is the extent of the decline in the dynamic moments of inertia at high frequency. This can be directly observed in Fig. 2, where the spacing between successive γ-ray peaks increases in the high-energy portions of the spectra. The dynamic moments of inertia, which are associated with the collective properties of the nucleus, are given by $\mathcal{J}^{(2)} = dI/d\omega \sim 4/\Delta E_\gamma$, and at the highest spins are typically $\sim 13\ \hbar^2\text{MeV}^{-1}$. The kinematic moments of inertia ($\mathcal{J}^{(1)} = I/\omega$) lie near the rigid-body value, $\sim 36\ \hbar^2\text{MeV}^{-1}$ for $\beta_2 = 0.2$. If the nucleus were a perfect, collective rotor, the two moments would be identical. In a standard interpretation, the large difference between $\mathcal{J}^{(2)}$ and $\mathcal{J}^{(1)}$ implies that a remarkably large fraction of the nuclear spin arises from the alignment of single-particle spin to the rotation axis. We suggest that each of these bands is built upon one configuration in which with increasing spin, the spin vectors of the valence particles gradually align, inducing a progressive change from a prolate towards an oblate shape, with accompanying smoothly-changing transition energies. This behaviour is very different from that of bands in other nuclei which have been described as terminating. On the one hand, in ^{158}Er [14] the $\mathcal{J}^{(2)}$ values show little change at high spin, but there is evidence for a decrease in the collective transition rates. On the other hand, yrast sequences in the nearby $^{115-123}$I isotopes are much more irregular [15], presumably because for spins below the termination other states compete and mix with the terminating sequence.

The possibility of a termination occuring smoothly over a range of spins was indeed suggested in Ref. [16], along with the resulting divergence between $\mathcal{J}^{(2)}$ and $\mathcal{J}^{(1)}$ in the manner observed here, but the extremely low values of $\mathcal{J}^{(2)}$ seen in ^{109}Sb were not predicted. It was assumed that it would be very difficult to observe such a termination, since the band would rise steeply in energy and the final states would lie high above the yrast states. Nevertheless, if at moderate spins the band is greatly favoured over other configurations then the last few units of spin could be gained at relatively high cost in energy and the states still remain close to yrast at the termination point. Preliminary calculations [17] indicate that this is likely the situation for the three bands in ^{109}Sb, and that these bands have reached or are very close to their termination. Such a change in structure could be associated with changes in the γ-ray transition rates. But even though the fractional Doppler shifts have been measured for transitions up to spin $\simeq \frac{67}{2}^-$, the present data are not sensitive to the collectivity of the top-most states in the band.

The final intriguing feature of the $\mathcal{J}^{(2)}$ moments of inertia in ^{109}Sb which we wish to consider is their near equality, both to one another and to the three known bands in the core nucleus ^{108}Sn (Fig. 3). This is very surprising, since intruder orbitals with a small K-quantum number, *eg.* proton K=$\frac{1}{2}$ $h_{11/2}$, neutron K=$\frac{3}{2}$ $h_{11/2}$, are thought [18, 19] to be the *least* likely to result in identical moments of inertia. It is interesting to note, that if, under extreme rotation, the asymptotic limit for individual low-K orbitals, $\mathcal{J}^{(2)}_{orb} = (dI/d\omega)_{orb} \sim 0$ is approached, the $\mathcal{J}^{(2)}$ moments for different bands with the same deformation will be very similar. Even so, the resemblance is striking, since no account is taken of the expected polarization of the deformed mean field by the low-K orbitals.

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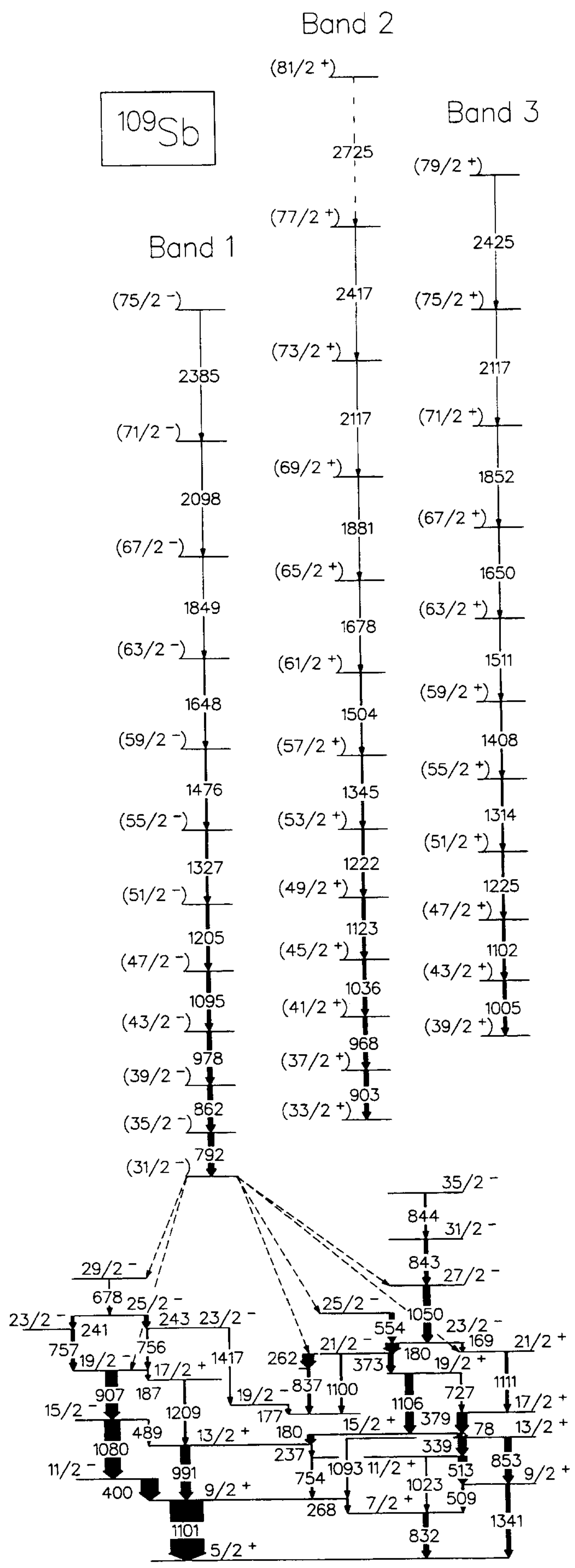
Figure Captions

Fig. 1. Partial level scheme of ^{109}Sb from the present work. Transition energies are marked in keV. Although the discrete transitions connecting bands 1, 2 and 3 have not been observed, the feeding pattern of band 1 into the spherical states has been determined and is indicated by dashed lines. The feeding patterns for bands 2 and 3 are less well determined, but they both clearly populate levels up to the $\frac{35}{2}^-$ state shown. As discussed in the text, the excitation energies of the three bands are not known.

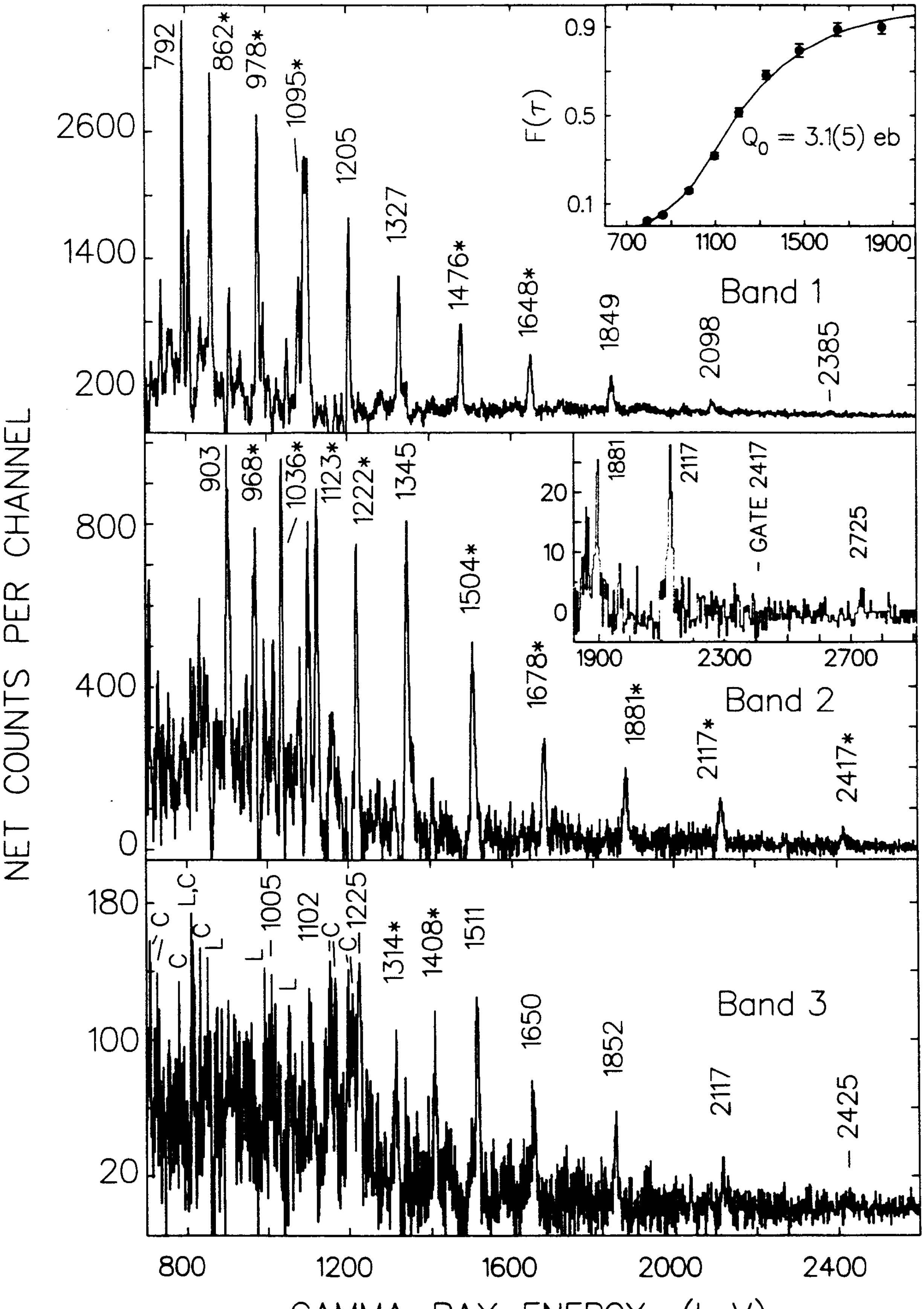
Fig. 2. Sum of γ-ray spectra gated on transitions within $\Delta I = 2$ rotational bands in ^{109}Sb. Peaks not labelled by their energy correspond to out-of-band decays, transitions between spherical states or contaminant γ rays. Gating transitions are marked by an asterix, and a background spectrum has been subtracted in each case. There are no transitions which isolate band 3 cleanly; for that spectrum the contaminant peaks and transitions between low-spin states are marked by C and L, respectively. The uncertainties in the transition energies range from 0.3 keV (net peak counts > 2000, $E_\gamma \leq 1000$ keV) to 5 keV ($E_\gamma > 2200$ keV). Insets: *Upper panel:* fraction of the full Doppler shift of γ rays in band 1 as a function of γ-ray energy. The solid line corresponds to the best-fit Q_0 value of 3.1 *e*b. *Middle panel:* high-energy portion of the γ-ray spectrum gated on the 2415-keV peak, showing the $(81/2^+) \rightarrow (77/2^+)$ transition in band 2.

Fig. 3. Upper panel: dynamic ($\mathcal{J}^{(2)}$) moments of inertia for the intruder bands in ^{109}Sb. The kinematic ($\mathcal{J}^{(1)}$) moment for band 1, which assumes the spins shown in Fig. 1, is

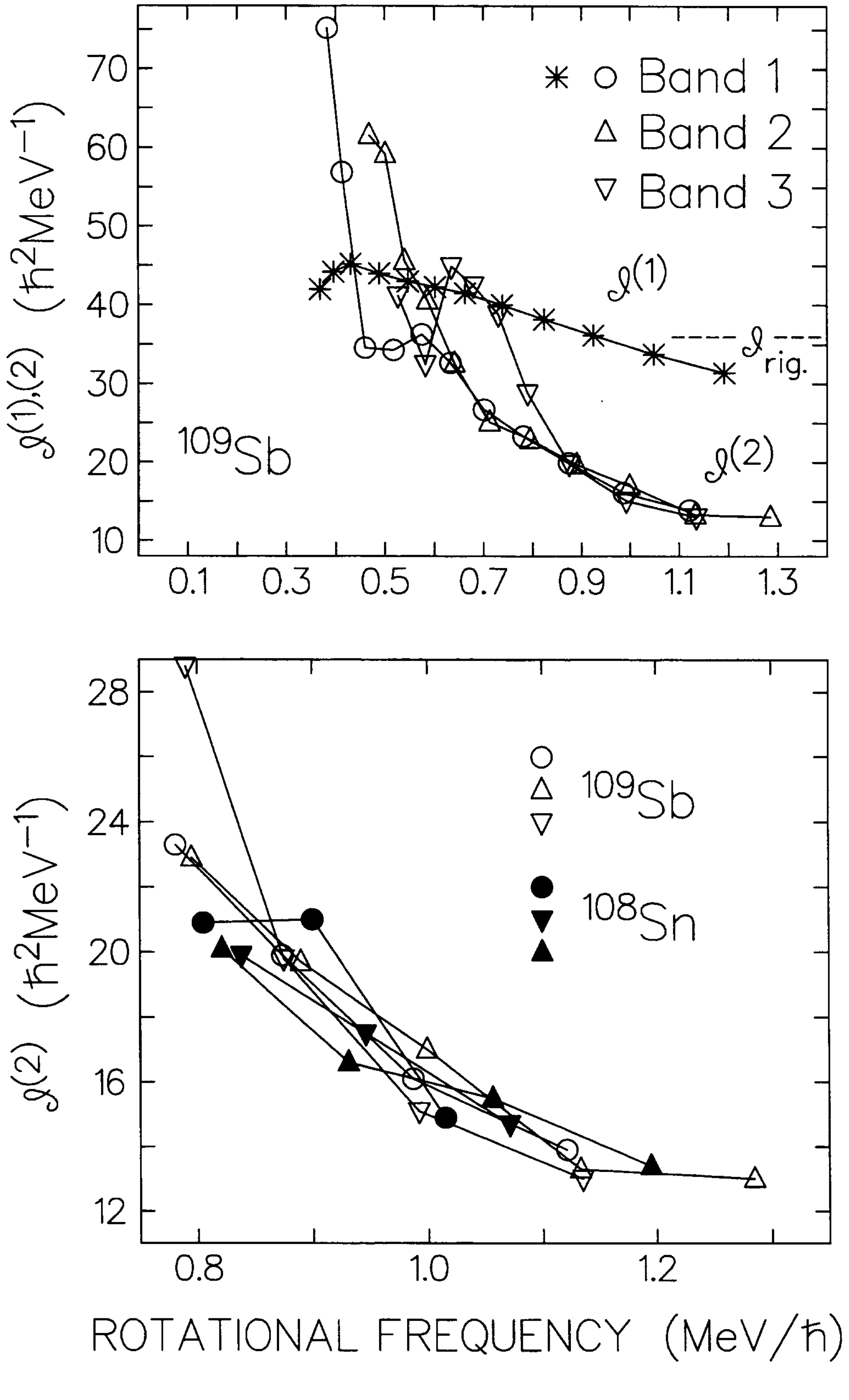
also shown. A dashed line indicates the rigid-body value for a deformation of $\beta_2 = 0.2$. Lower panel: $\mathcal{J}^{(2)}$ moments on an expanded scale, showing the close similarity amongst the six known intruder bands in $N = 58$ nuclei.



109Sb
Band 1
Band 2
Band 3
(75/2 −)
2385
(71/2 −)
2098
(67/2 −)
1849
(63/2 −)
1648
(59/2 −)
1476
(55/2 −)
1327
(51/2 −)
1205
(47/2 −)
1095
(43/2 −)
978
(39/2 −)
862
(35/2 −)
792
(31/2 −)
(81/2 +)
2725
(77/2 +)
2417
(73/2 +)
2117
(69/2 +)
1881
(65/2 +)
1678
(61/2 +)
1504
(57/2 +)
1345
(53/2 +)
1222
(49/2 +)
1123
(45/2 +)
1036
(41/2 +)
968
(37/2 +)
903
(33/2 +)
(79/2 +)
2425
(75/2 +)
2117
(71/2 +)
1852
(67/2 +)
1650
(63/2 +)
1511
(59/2 +)
1408
(55/2 +)
1314
(51/2 +)
1225
(47/2 +)
1102
(43/2 +)
1005
(39/2 +)
35/2 −
844
31/2 −
843
27/2 −
29/2 −
678
25/2 −
23/2 −
241
243
23/2 −
757
756
19/2 −
17/2 +
1417
187
907
15/2 −
1209
489
1080
13/2 +
11/2 −
991
400
9/2 +
1101
5/2 +
25/2 −
1050
554
23/2 −
169
21/2 +
262
21/2 −
373
180
19/2 +
837
1100
1111
19/2 −
727
177
1106
17/2 +
379
15/2 +
180
78
13/2 +
237
339
853
1093
11/2 +
513
754
1023
9/2 +
268
7/2 +
509
1341
832



NET COUNTS PER CHANNEL
GAMMA-RAY ENERGY (keV)
Band 1
792
862*
978*
1095*
1205
1327
1476*
1648*
1849
2098
2385
F(τ)
Q_0 = 3.1(5) eb
Band 2
903
968*
1036*
1123*
1222*
1345
1504*
1678*
1881*
2117*
2417*
1881
2117
GATE 2417
2725
Band 3
L,C
1005
1102
1225
1314*
1408*
1511
1650
1852
2117
2425



Band 1
Band 2
Band 3
$\mathcal{J}^{(1)}$
$\mathcal{J}_{rig.}$
$\mathcal{J}^{(2)}$
^{109}Sb
$\mathcal{J}^{(1),(2)}$ ($\hbar^2$MeV^{-1})
^{109}Sb
^{108}Sn
$\mathcal{J}^{(2)}$ ($\hbar^2$MeV^{-1})
ROTATIONAL FREQUENCY (MeV/$\hbar$)