Yrast transition strengths in ^{76}Br

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Levels in ^{76}Br have been populated through the ^{48}Ti(^{32}S,3*pn*) reaction at 106 MeV. The yrast ($K=4^+$) band has been extended to angular momentum 21$\hbar$. Lifetimes were measured for seven levels by means of the Doppler shift attenuation method. Above the 10^+ level the band behaves as a near-rigid rotor. The measured $B(E2)$ values are observed to decrease with increasing rotational frequency.

I. INTRODUCTION

The high-spin structure of the odd-odd bromine isotopes has been studied for many years, initially in order to determine the very complex low-lying isomeric structure and in recent years in order to observe high-spin rotational bands.[1–6] Much progress has been made, but many facets of the structure of these nuclei remain to be determined.

Previous work on ^{76}Br has established the existence of rotational bands built on the ground state ($I=1^-$) and low-lying isomers of spin 4^+ and 4^- (Refs. 5 and 6). The 4^+ band is yrast from the band head at 103 keV upwards. The first several levels (Fig. 1) evidence an irregular pattern. However, Döring *et al.*[6] showed that above spin 9^+ and up to spin 13^+ the yrast band begins to emerge as a more regular rotor.

We have extended the 4^+ band to tentative spin 21^+, and have determined lifetimes for a number of levels. It appears that above spin 9^+ the $K=4^+$ band is a good example of the doubly-blocked $g_{9/2}$ band, with no evidence of band crossings or of shape change in the region of angular velocity observed.

II. EXPERIMENTAL METHODS AND RESULTS

A. $\gamma\gamma$ coincidence measurements

The fusion evaporation reaction ^{48}Ti(^{32}S,3*pn*) was used to populate high spin states in ^{76}Br. A thick natural Ti target was bombarded with a 106 MeV ^{32}S beam from the Florida State University Tandem-Linac facility. The observation of ^{76}Br represented about 10 percent of more than 6×10^8 two-fold coincidences from the target, the majority of which were ^{77}Kr and ^{74}Br events. The results for these nuclei will be reported elsewhere.[7]

An array of four BGO Compton-suppressed detectors was used to measure $\gamma\gamma$ coincidences from the target. Three detectors were placed at 95° and the fourth was placed at 18°. The forward angle detector was used to determine lifetimes of the high-spin states by means of the Doppler shift attenuation method. A sum of 95°–95° coincidence gated spectra is shown in Fig. 2. This spectrum demonstrates the dramatic decrease in intensity above the 1114 keV ($13^+\rightarrow11^+$) transition. This effect, which is typical of fusion evaporation yields to high-spin levels in odd-odd nuclei in this mass region, is poorly understood and contributes to the difficulty in extending level schemes to high spins.

B. Transition energies, intensities, and multipolarities

For the levels up to spin 13^+ our results for the yrast band ($K=4^+$) in large measure confirm those previously reported. Table I summarizes the transition energies, intensities, spin assignments, and mean lifetimes for the extended yrast band. For the long-lived ($\tau>2$ ps) transitions energies are accurate to 0.2 keV. However, in thick target measurements the sensitivity to angle for short-lived transitions results, for our detector distances (6.5 cm), in transition energies that are uncertain by up to several keV for higher-lying transitions, as noted in Table I.

Gamma rays corresponding to stretched $E2$ transitions from levels with $J>14$ have been assigned on the basis of coincidence relations, which however are not always definitive in the presence of strong interference from transitions in ^{77}Kr and ^{74}Br, as well as appreciable amounts of a number of other reaction products. Additional constraints on assignments were relative intensities and coincidence intensity ratios (effective DCO values). The transitions assigned as $E2$ ($\Delta I=2$) have, in the approximation $W(\theta)=W_0(1+A_2P_2)$, positive A_2 values in the range 0.3–0.6. Transitions assigned as $M1+E2$ ($\Delta I=1$) are clearly distinguished by their negative A_2 values; in all cases the gating transition was $\Delta I=1$. These procedures are less certain for the unfavored even-spin levels above spin 10. Above spin 11 in the yrast band no $\Delta I=1$ transitions can be unambiguously assigned.

C. DSA lifetimes

Line shapes for 18° spectra gated by the 95° detectors were analyzed by means of the Doppler shift attenuation technique for the 432 keV ($9^+ \rightarrow 8^+$), 823 keV ($10^+ \rightarrow 8^+$), 873 keV ($11^+ \rightarrow 9^+$), 1114 keV ($13^+ \rightarrow 11^+$), 1326 keV ($15^+ \rightarrow 13^+$), 1496 keV ($17^+ \rightarrow 15^+$), and 1655 keV ($19^+ \rightarrow 17^+$) transitions (Table I). The codes FIT1 and FITS were used, as described in detail earlier.[8,9] Corrections for cascade feeding according to the deduced decay scheme, and sidefeeding as discussed below were included. Best-fit DSA spectra are shown in Fig. 3 for the 1114 and 1496 keV transitions.

It is interesting to note the role of the $\Delta I = 1$ transitions in extending the range of levels accessible to DSA lifetime determination. In particular the dominance (90% of total intensity) of the 432 keV $9^+ \rightarrow 8^+$ transition allows the accurate extraction of an $E2$ lifetime of almost 10 ps for the 9^+ level. This is also the case to a lesser degree for the 10^+ level.

D. The role of sidefeeding

A problem for lifetime determinations in the mass-80 region is the assessment of sidefeeding from the continuum. A considerable literature has developed on this question,[10–15] which is a difficult one because direct observation of the sidefeeding component is not practical. Despite many careful measurements, no consensus has yet emerged. This problem is exacerbated for the highest spins we report here. No estimates of sidefeeding times for $I > 13$ have been reported, apart from the very helpful Monte Carlo calculations of Cristancho and Lieb,[16] which however are sensitive to assumptions about continuum lifetimes near the entry energy in the residual nucleus, as well as to the assumed width of the region of enhanced transition strengths near yrast in the discrete spectrum.

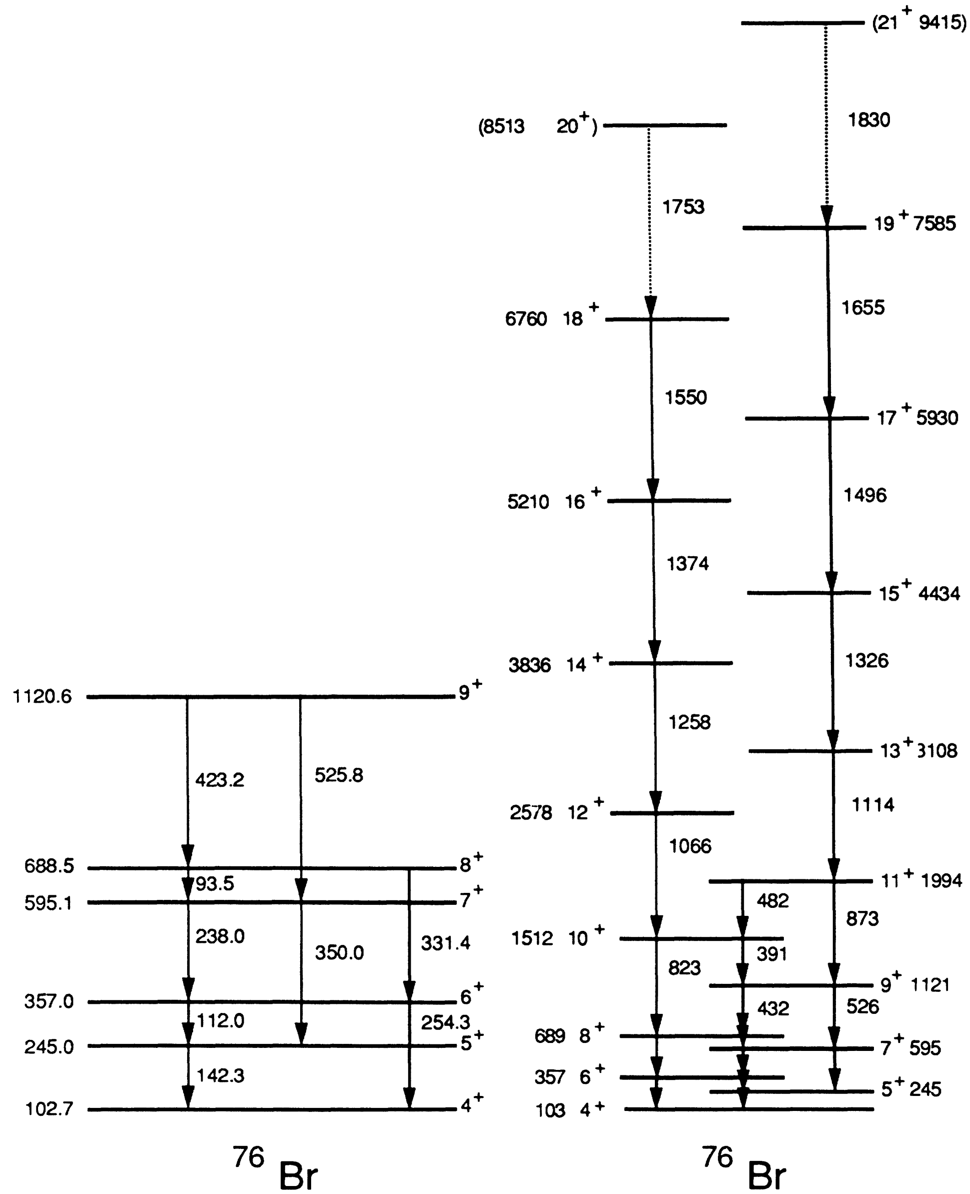

FIG. 1. The lower portion of the level scheme for ^{76}Br from previous work is shown on the left. The level scheme for ^{76}Br from previous work ($I^\pi \leq 13^+$) and as deduced from the present work ($I^\pi \geq 13^+$) is shown on the right.

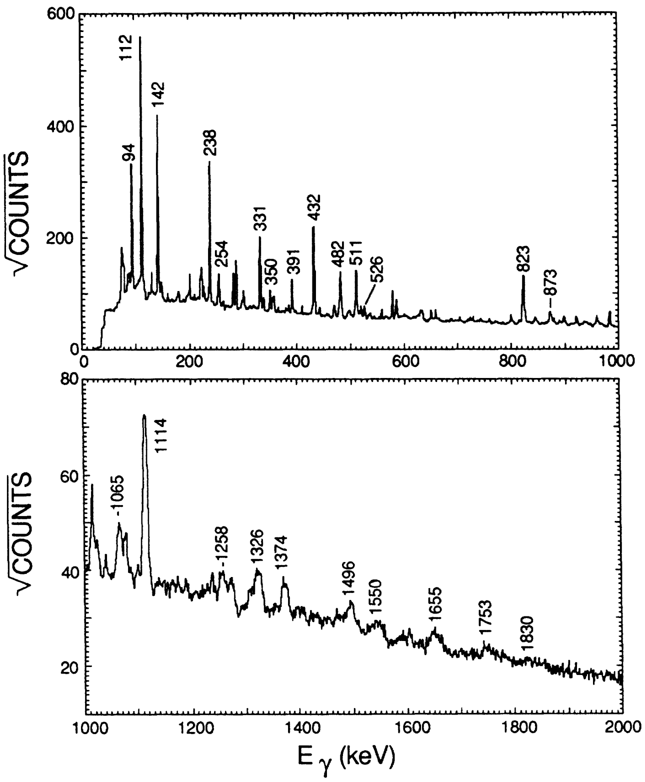

FIG. 2. The spectrum of γ rays observed at 95° in coincidence with the sum of 95° gates set at 142, 238, 94, and 331 keV.

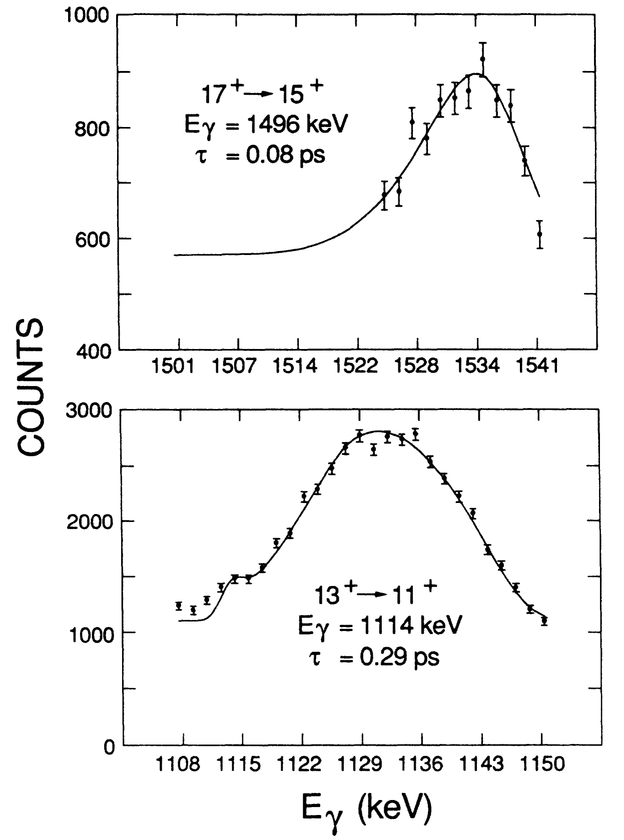

FIG. 3. DSAM fit at 18° to the coincidence spectrum for the 1496 keV transition is shown at the top. DSAM fit at 18° to the coincidence spectrum for the 1114 keV transition is at the bottom.

TABLE I. Excitation energies, transition energies, spin-parity assignments, relative intensities, lifetimes, continuum feeding lifetimes (assumed), $B(E2)$ values, and nominal deformations for the yrast band. Errors in the last digit are shown in parentheses.

E_x (keV)	E_γ (keV)	I^π	Relative intensity	τ (ps)	τ_f^a (ps)	$B(E2)$ (e^2fm^4)	β_2^b
1121	526.0(2)	9^+	13(1)				
	423.3(2)	9^+	118(12)	0.85(9)	1.10	2386^{300}_{200}	0.44
1512	823.4(5)	10^+	132(13)	0.70(8)	0.78	2430^{300}_{200}	0.42
	391.3(5)	10^+	35(3)				
1994	873(1)	11^+	32(3)	0.30(5)	0.45	1713^{300}_{200}	0.34
	482(1)	11^+	68(7)				
2578	1066(1)	12^+	28(4)				
3108	1114(1)	13^+	100(10)	0.29(3)	0.08	1634^{200}_{100}	0.32
3836	1258(2)	14^+	18(3)				
4434	1326(2)	15^+	27(4)	0.16(4)	0.07	1245^{400}_{200}	0.27
5210	1374(3)	16^+	21(3)				
5930	1496(3)	17^+	22(3)	0.08(4)	0.029	1362^{500}_{300}	0.28
6760	1550(4)	18^+	12(3)				
7585	1655(4)	19^+	13(3)	<0.08	0.015	>822	>0.22
8513	1753(5)	20^+					
9145	1830(5)	21^+	8(3)				

[a]Continuum feeding lifetimes.
[b]Assumes $\gamma = 0$ (see Sec. III B for discussion).

Our approach has been to extrapolate the roughly exponential trend of reported sidefeeding lifetimes deduced from DSA fits. The slopes obtained by Cristancho and Lieb were also taken into account in obtaining values for high spins. The sidefeeding values tabulated in Table I however were obtained without including the relatively high values reported for ^{77}Rb (Ref. 14). The deduced DSA lifetimes obviously are sensitive to the handling of sidefeeding. Nevertheless, for deformed $\Delta I = 2$ bands, as long as sidefeeding lifetimes are not appreciably larger than the lifetime of the next level above that in question, the effect of sidefeeding is not large. That is the case for our choices of sidefeeding times.

III. THE YRAST BAND IN ^{78}Br

A. Absence of evidence for band crossing

The present study extends the $K = 4^+$ band to tentative spin 21^+ for the dominant odd-spin component and to tentative spin 20^+ for the weaker even-spin component. Figure 1 shows the decay scheme for this band.

The trend to a rather pure rotor at about spin 9^+ which was reported by Döring *et al.*[6] is observed in the present experiment to continue with no evidence of band crossings. In Fig. 4(a) the kinematical moments of inertia of both odd and even spins are seen to remain constant at about 23 MeV^{-1}, which is close to the rigid body value for this nucleus. Stronger evidence for emergence of quasirigid rotation is seen in the dynamical moments of inertia [Fig. 4(b)] where, with only a relatively slight variation for the unfavored even spins, values near the rigid body value are observed. The absence of band crossings above $\hbar\omega = 0.2$ MeV is clearly shown in the constancy of the aligned angular momentum [Fig. 4(c)] calculated for a $K = 4$ band with Harris parameters of $J_0 = 23.6\hbar^2\ \text{MeV}^{-1}$ and $J_1 = -2.4\hbar^4\ \text{MeV}^3$ derived from the band itself.

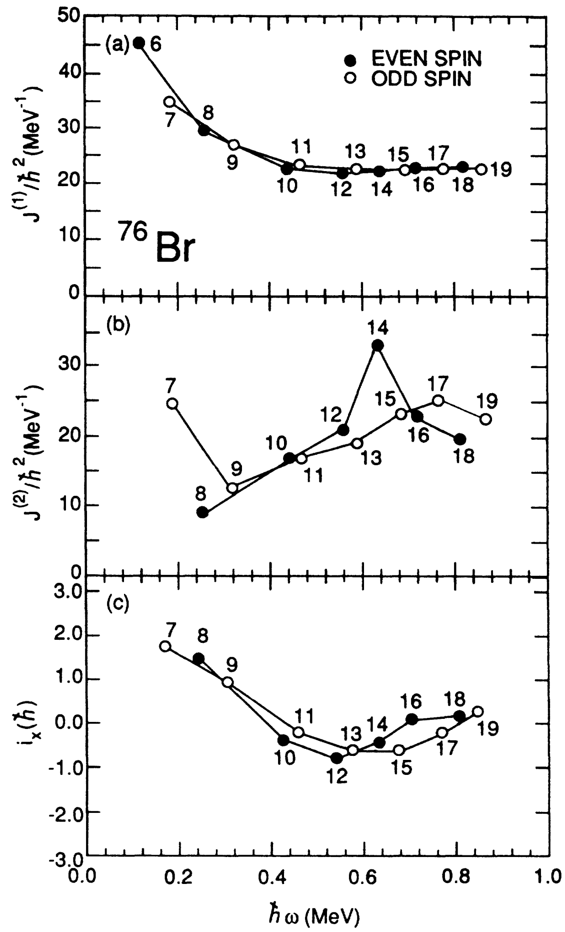

FIG. 4. (a) Kinematical moments of inertia $J^{(1)}$ for the yrast band in ^{76}Br as a function of rotational frequency. (b) Dynamical moments of inertia $J^{(2)}$ for the yrast band in ^{76}Br as a function of rotational frequency. (c) Aligned angular momentum i_x for the yrast band in ^{76}Br as a function of rotational frequency.

B. $B(E2)$ values and deformation

The lifetime determinations and branching ratios obtained in the present experiment yield the $B(E2, I \rightarrow I-2)$ values tabulated in Table I and plotted in Fig. 5. The $B(E2)$ values for the $\Delta I = 2$ portion of the odd-spin band correspond to a quadrupole deformation of about 0.30, which is typical of this part of mass-80 region. However, the $B(E2)$ values tend to decrease for increasing spins.

Three possible explanations for decreasing $B(E2)$ values with increasing excitation have been proposed. In the case of a band crossing, a change in shape can be expected; this has been observed, for example, in ^{83}Zr (Ref. 15). In the present case the constancy of the kinematic and dynamical moments of inertia $J^{(1)}$ and $J^{(2)}$ argue against band crossing at high rotational velocities. A second possible explanation, appropriate when the kinematic moment of inertia is constant, is a change in triaxiality of the nuclear shape.[12] Garrett *et al.*,[17] however, have recently argued that the constancy of $J^{(1)}$ is no guarantee of constant deformation, since $J^{(1)}$ may tend to increase when quasiparticle deformation is decreasing. This effect has been observed experimentally in the rare

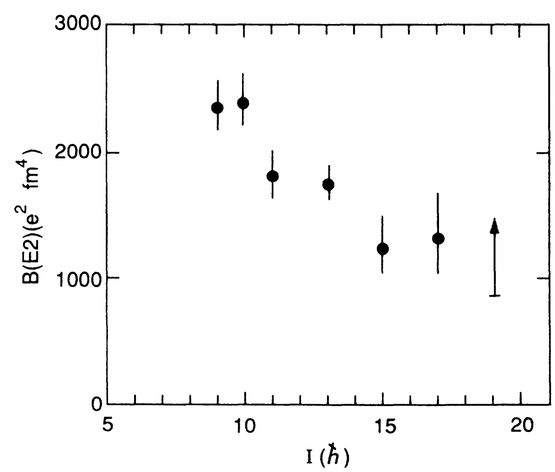

FIG. 5. $B(E2)$ values for the yrast band in ^{76}Br as a function of spin.

earth region,[18] and has been obtained theoretically there as well.[19] Further investigation of this phenomenon is clearly warranted.

C. Configurations for ^{76}Br

The deformation $|\beta_2| \simeq 0.3-0.4$ observed in the present experiment is typical of nuclei over much of the $fpg_{9/2}$ region. Positive parity $g_{9/2}$ orbitals can be combined to give prolate bands with $I < 6^+$. The yrast band in ^{76}Br is built on a 4^+ level; there is no problem in accounting for a $K = 4^+$ band as $g_{9/2}$. Positive parity 2*qp* states made from 2 *fp* orbitals allow $I \leq 5^+$; however, the energy gap for protons should push such a positive-parity band head to higher excitation.

For oblate deformation of $\beta_2 \simeq -0.3$ for ^{76}Br, 2*qp* $g_{9/2}$ bands are possible with $I \leq 8^+$. Oblate deformation positive-parity band heads with two negative-parity orbitals could only have $I \leq 2^+$, unless the $j = \frac{11}{2}^-$ intruder state were allowed. The latter would imply quite large oblate deformation. Also, the large energy gaps for both neutron and proton negative-parity states argue for $g_{9/2}$ character for low-lying oblate bands.

IV. DISCUSSION AND CONCLUSIONS

A. Near-rigid rotation at high spins in the mass-80 region

The principal result of the present experiment is a rotational band which at high spins shows little variation from a pure rotational energy pattern to quite high rotational frequencies, and with both kinematical and dynamical moments of inertia close to rigid body values. Since the remarkable experiment of Price *et al.*[20] for ^{84}Zr, evidence for bands with $J^{(1)}$ and $J^{(2)}$ essentially equal and constant has continued to accumulate across the mass region. The effect typically is most marked for just one band in each nucleus, and the near-rigid rotor pattern usually is not found at low spins. In addition to the present study, particularly clear examples in this mass region are reported for ^{72}Se (Refs. 11 and 12), ^{72}Br (Ref. 21), ^{73}Br (Ref. 12), ^{74}Br (Ref. 7), and ^{76,78}Kr (Refs. 22 and 23). Additional examples might include ^{77}Rb (Ref. 14), where an upturn in the dynamical moment of inertia is observed at $\hbar\omega \cong 0.6$ MeV, ^{79}Rb (Ref. 24), ^{81}Y (Ref. 25), ^{83}Y (Ref. 26); still others could be cited. Near-rigid rotation is observed in even-even, odd, and odd-odd nuclei, with $34 < Z < 40$ and $37 < N < 44$ at least.

This phenomenon has been discussed in terms of blocking effects for the $g_{9/2}$ deformed orbitals by Lühmann *et al.*,[14] who speculate that the combination of constant moment of inertia and large $B(E2)$ values to high spin might be evidence for the Mottelson-Valatin effect.[27] Clearly, microscopic calculations will be required to determine the structure in detail. It will be interesting to see how far quasirigid rotation can be traced at the upper and lower bounds of the $fpg_{9/2}$ region. For a number of nuclei for which high-spin ($I > 12$) studies have not been reported, there is evidence for bands with kinematic moments of inertia near the rigid body value. Extension of the level schemes to high spin in these cases no doubt will reveal further examples of near-rigid rotors.

B. Structure of low-lying levels in odd-odd bromine isotopes

The first several levels in the $K = 4^+$ band of ^{76}Br show a compression and variation from the essentially pure rotational pattern which is seen at higher spins. This effect, which is seen in one form or another for odd-odd bromine isotopes from ^{72}Br to ^{82}Br, is not fully understood. The nonrotational pattern of low-lying levels has been attributed to configuration mixing, for the more neutron-deficient bromine isotopes,[21] and to reduced deformation, for the more massive isotopes.[28] The large $B(E2)$ values obtained for the 9^+ and 10^+ levels in ^{76}Br are interesting in this connection.

For ^{76}Br the yrast levels with spin 4 to 9 were earlier discussed as a possible example of the "semidecoupled" band in the nomenclature of Kreiner and Mariscotti.[29] A semidecoupled band in an odd-odd nucleus retains some evidence of a decoupled low-Ω quasiparticle, as evidenced by even-odd staggering of the level energies. Although such bands have been reported for more massive nuclei, no evidence for the persistence of such structure to high spins has been found in the mass-80 region. As further lifetimes are reported in this mass region, progress in understanding the low-lying levels can be expected.

C. Non-yrast bands

Good-statistics experiments designed to allow determination of yrast structure to $I = 20$ and above are also likely to make possible the observation of the weaker bands with more complex structure. Many examples of non-yrast states that may represent incipient side bands have been reported, but relatively few have been followed sufficiently far to allow full characterization of their structure. Measurement of lifetimes for non-yrast bands is particularly important.

In spite of the difficulties posed by the complexity of the level schemes, the odd-odd nuclei in this mass region—and indeed in general, as Kreiner *et al.*[30] have recently discussed—offer the possibility of demonstrating a variety of configurations and of providing information about band crossing and blocking effects that will be important for a full understanding of the underlying structure.

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