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High-spin Multi-quasiparticle Yrast Traps in ^{176}Hf[*]

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ABSTRACT

We have identified several high-K 4- and 6-quasiparticle states between 2.5 and 5 MeV excitation in ^{176}Hf, which are well described by the collective model with axial symmetry. Isomers with $K^{\pi}=14^-$, 19^+ and 22^- form traps at or near the yrast line. The yrast structure changes from the ground band to a $K^{\pi}=16^+$ band at I=16 and again to a $K^{\pi}=22^-$ state at I=22, providing the first demonstration that intrinsic excitations of a heavy deformed nucleus can become yrast.

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The high spin states of deformed nuclei that have been observed to date arise largely from collective rotation, involving the coherent motion of many nucleons. This is true whether the yrast structure remains the ground state band, or develops into decoupled or unpaired bands, as occurs after back-bending. The question arises as to whether few-nucleon degrees of freedom can also play an important role in the structure of nuclei at high spin. This matter is of relevance to nuclear behaviour at spins exceeding $30\hbar$. Indeed, Bohr and Mottelson[1,2] have predicted that in this domain the large angular momentum of yrast states may in some cases be generated by aligning the spins of a few nucleons. Present experimental techniques do not allow us to observe individual levels at such ultra-high spins. Nevertheless, it may be possible to investigate the interplay of collective and few-nucleon motion through the study of discrete levels by judiciously selecting a system in which the intrinsic excitations lie close to the yrast line at relatively low spins (10-$20\hbar$).

Such an investigation entails the study of multi-quasiparticle (qp) configurations in a region of nuclear excitation (2.5-5 MeV) that has hitherto not been explored in detail. It is hence also of interest to determine whether the collective model, which has been remarkably successful at lower spins and energies, is still applicable in this new regime. Specifically, are there still simple intrinsic excitations with well-behaved rotational bands built on them, and are the radiative transitions adequately described? It is also important to ascertain whether K remains a good quantum number. Numerous (heavy ion, xn) studies have identified no high spin isomers which can be associated with band-heads of high K; this may imply a breakdown of a coupling scheme associated with axial symmetry.[2]

A promising system to investigate is ^{176}Hf in which we had previously identified a 401-μsec 4-qp isomer at 2866 keV, in addition to many high-K 2-qp states at lower excitation.[3,4] In the ^{176}Yb(α,4n)^{176}Hf reaction with a 48-MeV alpha beam, the 401-μsec isomer receives ~30% of the (α,4n) cross-section. We have employed a delayed coincidence technique similar to that described in Ref. 3 to isolate the γ-rays populating this isomer. Some of these γ-rays were themselves found to be delayed in separate experiments in which γ-ray, conversion electron[5] and three-parameter γ-γ-t coincidence data were accumulated with the beam pulsed off. In addition, in-beam prompt γ-γ coincidence, γ-ray angular distribution and excitation function data were obtained. Thus, we used a large variety of spectroscopic information to develop the level scheme of Fig. 1. The transition multipolarities and spins have been deduced using K- and L-internal conversion coefficients from direct electron-gamma ratios, total conversion coefficients from intensity balance considerations in delayed spectra, and angular distribution and excitation function data.

Fig. 1 shows the upper portion of the ground band and two other intrinsic rotational bands. One intrinsic band is based on the 401-μsec isomer to which we had previously[4] assigned I $K^{\pi}=14$ 14^{-}; the other band is built on a $I^{\pi}=16^{+}$ level, which is thus a $K^{\pi}=16^{+}$ band-head. The identification of these intrinsic bands was fairly straightforward because of the very regular

rotational energies, spin sequence and γ-decay pattern. The rotational parameters, A and B, where $E=AI(I+1)+BI^{2}(I+1)^{2}$, are 10.8 keV and -2.31 eV for the $K^{\pi}=14^{-}$ band and 6.25 keV and 3.33 eV for the $K^{\pi}=16^{+}$ band. Furthermore, the cascade-crossover ratios and angular distribution data of the intraband transitions yield[6] intrinsic g-factors, $g_{K}=0.57\pm.04$ ($K^{\pi}=14^{-}$) and 0.54 ± 0.05 ($K^{\pi}=16^{+}$), in excellent agreement with the values, 0.57 and 0.50, expected for the 4-qp configurations suggested in Table I. In addition, the energies of the band-heads are in reasonable agreement with expectations based on the energies of the constituent 2-qp states, particularly when residual interactions between quasiparticles are considered.[4,7]

From energy and decay systematics it is clear that the 3080-keV level is not a member of the $K^{\pi}=16^{+}$ band, but is probably the band-head of a $K^{\pi}=15^{+}$ state of 4-qp character (see Table I). The 34-nsec isomerism of the $I^{\pi}=19^{+}$ level at 4377 keV suggests K-forbiddenness and, hence, a $K^{\pi}=19^{+}$ assignment. Since the $I^{\pi}=20^{-}$ and 22^{-} levels at 4766 and 4864 keV decay through the $K^{\pi}=19^{-}$ state (instead of through the energetically favoured 19^{+} member of the $K^{\pi}=16^{+}$ band) they also have very large K and are most likely band-heads with $K^{\pi}=20^{-}$ and 22^{-}, respectively. The occurrence of such very high (≥ 19) K states at the observed energies suggests that the states are of 6-qp character, with probable configurations given in Table I. The proposed configurations provide an explanation for the retarded 43-μsec decay between the $K^{\pi}=22^{-}$ and 20^{-} levels in terms of the $5/2(512)_{n}\rightarrow 1/2(521)_{n}$ transition, which is observed to be slow in neighboring odd-Hf nuclei.[8]

The 6-qp states and the 4-qp rotational bands are observed for the first time. Indeed, there are more high spin states here than have been identified in any other nucleus. The 22^- isomer is the highest spin isomer observed to date. The properties of these highly excited intrinsic states are very well described by the collective model. There is thus no break-down of this model at energies between 2.5 and 5 MeV. In particular, K appears to remain a good quantum number (at least for large K-values), indicating that axial symmetry is preserved.

Inspection of Fig. 1 reveals that the $K^{\pi}=16^+$ band-head lies lower than the 16^+ state of the ground band. The *yrast* structure thus switches character for $I\geq 16$ from the ground band to the members of the $K^{\pi}=16^+$ band. A further change occurs at spin 22 when the I $K^{\pi}=22$` 22^- state becomes *yrast*. Structural changes in the *yrast* line also occur in ^{178}Hf.[9] This demonstrates vividly that the energetically favoured states at high spin do not necessarily arise from collective rotations (ground band) but may instead be associated with few-nucleon structures.

The dominance of high-K multi-qp structures along or near the *yrast* line for $I\geq 16$ has important implications for the electromagnetic decay of the *yrast* states. For instance, the 22^- and 16^+ *yrast* levels de-excite not by collectively enhanced stretched E2 transitions but by slower single-particle transitions. Thus the 22^- isomer at almost 5 MeV is a *yrast* trap, while the $K^{\pi}=19^+$ and 14^- isomers are traps which occur very close to the *yrast* line. There are many similarities between these traps and those which have been predicted[1,2] to occur at ultra-high spin values, when some nuclei are expected to become oblate. Both cases involve the motion of a few nucleons around the symmetry axis, the large spin being generated by alignment of nucleon orbits. (Most of the orbits of present interest

have large Ω. Thus the particle trajectories are concentrated near the equatorial plane, and involve revolutions around the nuclear symmetry axis.)

Bohr and Mottelson[1,2] have recently shown that the energy expended in generating angular momentum by alignment of particle orbits has a rotation-like relationship with spin. Furthermore the effective moment of inertia is that for rigid body rotation about the axis around which the nucleons move. A plot of the energies (from this work and Refs. 3 and 10) of the lowest intrinsic state of each spin in ^{176}Hf as a function of I(I+1) is shown in Fig. 2. The data are distributed about a straight line which represents a moment of inertia $2\mathcal{J}/\hbar^2 = 130\ \text{MeV}^{-1}$. For rigid body rotation about the symmetry axis of an ellipsoid with $\delta=0.28$, the ground state deformation, we have $2\mathcal{J}_3/\hbar^2 = 126\ \text{MeV}^{-1}$, a value close to the above. Although it is tempting to treat the data of Fig. 2 as evidence for the concept[1,2] of a moment of inertia associated with the alignment of single-particle orbits around a symmetry axis, the large effect of pairing interactions in the configurations considered raises serious questions about such an interpretation. The near rigid value of the moment of inertia for the band-heads may be fortuitous, perhaps occurring because of the opposing tendencies of pairing effects (which tend to decrease the effective moment of inertia by increasing the intrinsic energies) and shell effects (viz. the predominance of high-Ω orbitals near the Fermi levels, which lowers the energies of high-K states). Nevertheless the small scatter of the points about the solid straight line of Fig. 2 is quite remarkable and suggests that efforts should be made toward constructing similar plots for other nuclei by identifying high-K qp-states over a wide range of spin.

Although the concept of rotation about a symmetry axis has not been unambiguously demonstrated, many of the other physical concepts introduced by Bohr and Mottelson[1,2] in connection with the behaviour of nuclei in a higher spin domain have found their first demonstration in this study, but at lower spins. This is of significance to the study of nuclei at ultra-high spins.

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TABLE I.--Suggested configurations for 4- and 6-qp states observed in ^{176}Hf.

Band-head Energy (keV)	K^{π}	Configuration[a]
2866	14^-	$7/2_p 9/2_p 7/2_n 5/2_n$
3080	15^+	$7/2_p 9/2_p 9/2_n 5/2_n$
3266	16^+	$7/2_p 9/2_p 7/2_n 9/2_n$
4377	19^+	$7/2_p 9/2_p 7/2_n 9/2_n 5/2_n 1/2_n$
4766	20^-	$7/2_p 9/2_p 7/2_n 9/2_n 7/2'_n 1/2_n$
4864	22^-	$7/2_p 9/2_p 7/2_n 9/2_n 7/2'_n 5/2_n$

[a] Single particle orbitals are: $7/2_p$: 7/2(404); $9/2_p$: 9/2(514); $7/2_n$: 7/2(514); $9/2_n$: 9/2(624); $5/2_n$: 5/2(512); $1/2_n$: 1/2(521); $7/2'_n$: 7/2(633).

FIGURE CAPTIONS

Fig. 1.--Partial level scheme for ^{176}Hf showing 4- and 6-qp excitations and upper portion of ground band. Assignments in parentheses are tentative. Filled circles indicate γ-rays entering and leaving a level in prompt coincidence.

Fig. 2.--Plot for ^{176}Hf of lowest band-head energies for given I (circles) and ground band energies (squares) vs I(I+1). For band-heads, zero point energies for rotation about an axis perpendicular to the symmetry axis have been subtracted as described in Ref. 4. Points for intrinsic states are closely distributed about a straight line with slope corresponding to $2\mathcal{J}/\hbar^2=130\ \mathrm{MeV}^{-1}$; for rigid body rotation about the symmetry axis, $2\mathcal{J}_3/\hbar^2=126\ \mathrm{MeV}^{-1}$.

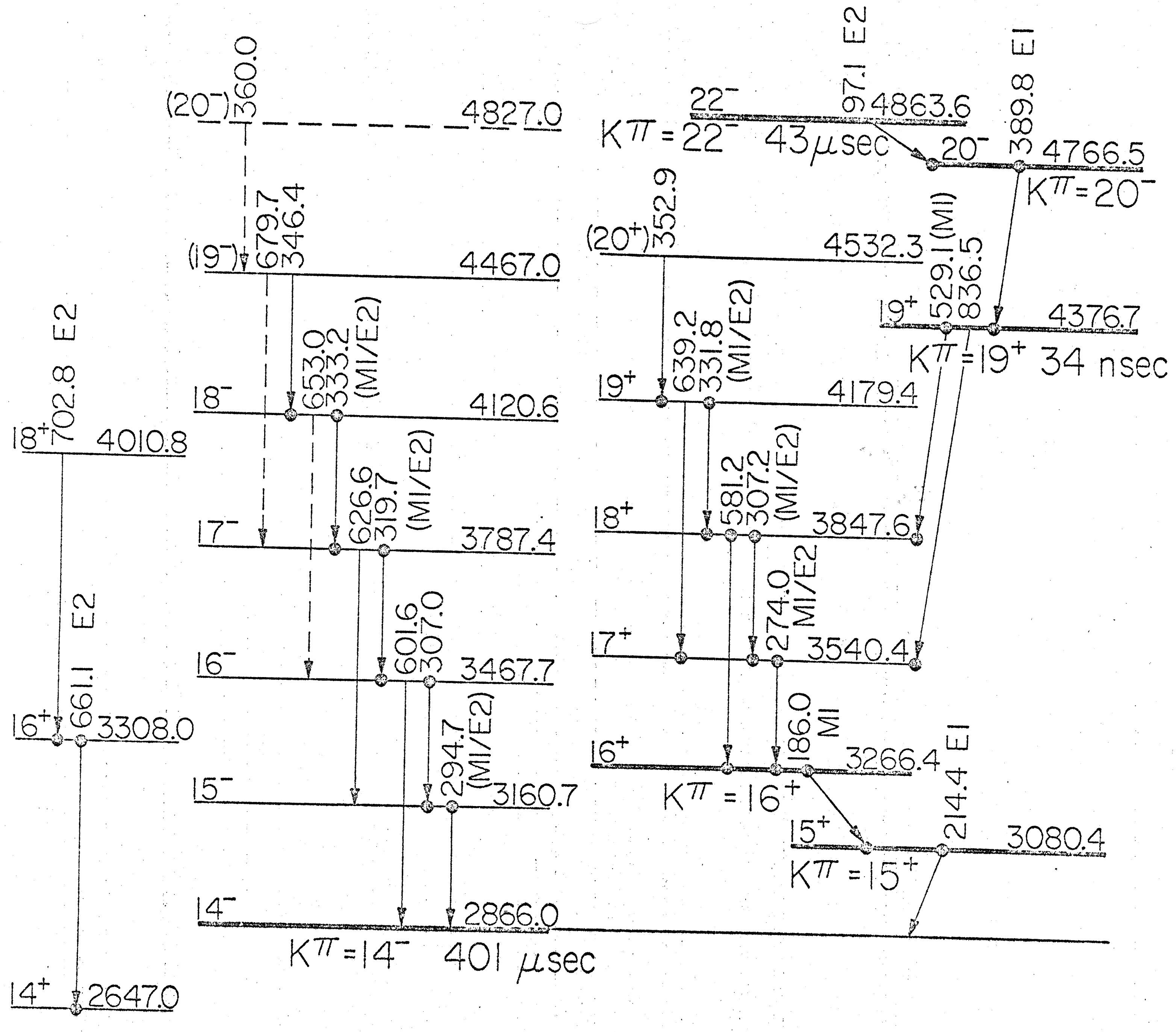
(20⁻) 360.0 4827.0
(19⁻) 679.7 346.4 4467.0
18⁻ 653.0 333.2 (MI/E2) 4120.6
17⁻ 626.6 319.7 (MI/E2) 3787.4
16⁻ 601.6 307.0 3467.7
15⁻ 294.7 (MI/E2) 3160.7
14⁻ 2866.0
Kπ=14⁻ 401 μsec
18⁺ 702.8 E2 4010.8
16⁺ 661.1 E2 3308.0
14⁺ 2647.0
ground band
22⁻ 97.1 E2 4863.6
Kπ=22⁻ 43μsec
20⁻ 389.8 EI 4766.5
Kπ=20⁻
(20⁺) 352.9 4532.3
19⁺ 529.1 (MI) 836.5 43767
Kπ=19⁺ 34 nsec
19⁺ 639.2 331.8 (MI/E2) 4179.4
18⁺ 581.2 307.2 (MI/E2) 3847.6
17⁺ 274.0 MI/E2 3540.4
16⁺ 186.0 MI 3266.4
Kπ=16⁺
15⁺ 214.4 EI 3080.4
Kπ=15⁺
176Hf

Figure 1

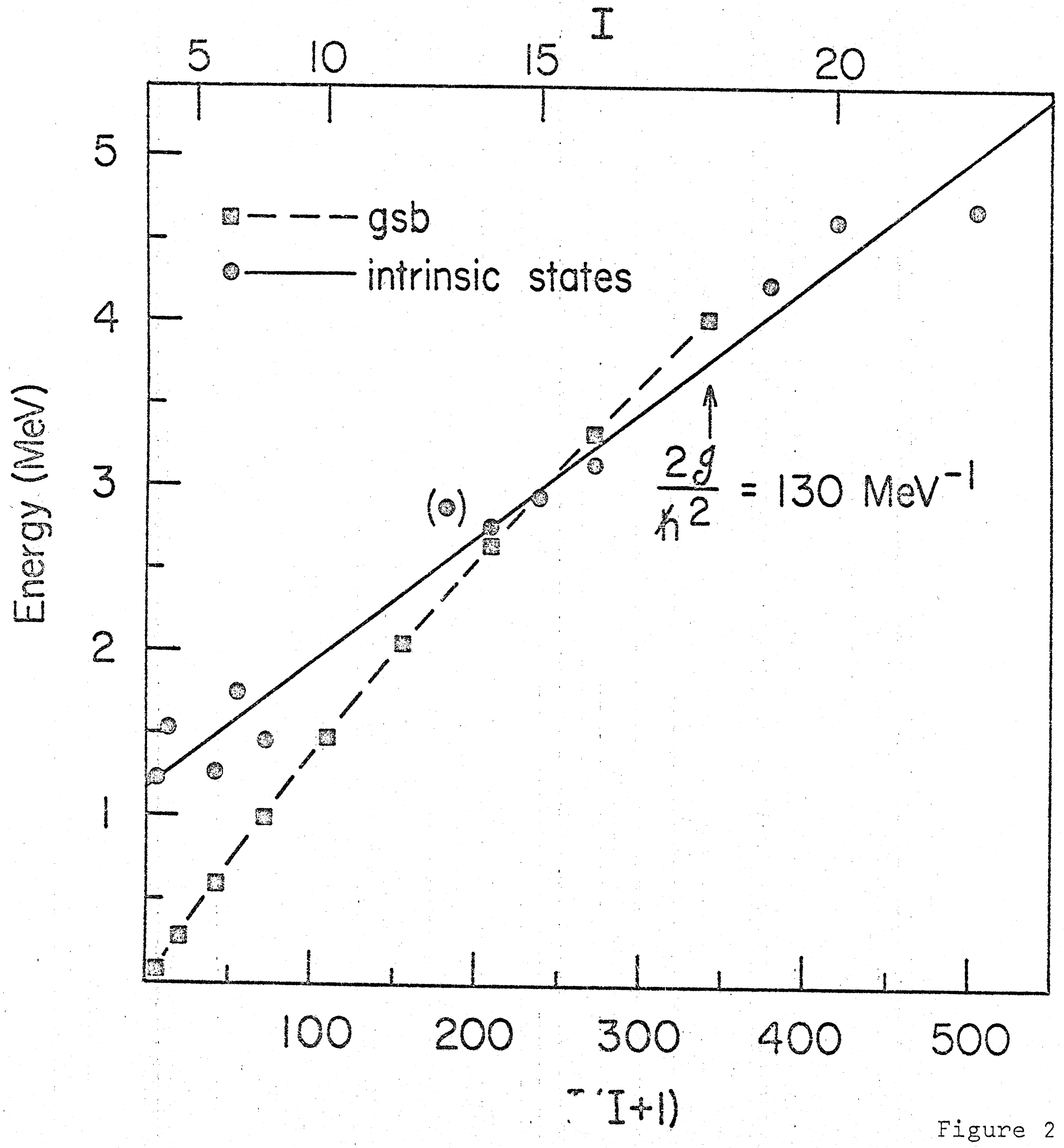
I
5
10
15
20
Energy (MeV)
5
4
3
2
1
gsb
intrinsic states
(●)
$\frac{2\mathcal{J}}{\hbar^2}$ = 130 MeV^{-1}
100
200
300
400
500
I(I+1)

Figure 2