PHYSICAL REVIEW C VOLUME 45, NUMBER 1 JANUARY 1992

Convergence of the moments of inertia in *f-p-g* shell nuclei

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(Received 12 June 1991)

A survey of the kinematic moments of inertia of $A \approx 80$ nuclei shows a tendency to converge toward the rigid-body values of 20 to 25 $\hbar^2$/MeV at rotational frequencies above 0.6 MeV/$\hbar$. The moments of the even-even isotopes approach the convergence zone from much lower values. The farther from the center of the shell, the lower the initial values are and the more rapid is the rise. By contrast, the moments of inertia of the odd-odd nuclei start from higher values and decrease into the convergence zone. The values for odd-A nuclei are generally intermediate, usually starting somewhat below the final value and increasing into the 20 to 25 $\hbar^2$/MeV region. The quadrupole deformations inferred from lifetimes in the even-even nuclei show no systematic change with spin, in contrast to the moments of inertia.

PACS number(s): 21.60.Ev, 27.50.+e

I. INTRODUCTION

One of the most striking characteristics of collective nuclear structure is the spontaneous breaking of spherical symmetry, leading to a variety of deformed nuclear shapes. Two questions particularly relevant to this process concern the relative importance of various deformation driving forces and the level of reliability and model independence of techniques for determining nuclear shapes.

A number of factors have been proposed as deformation driving agents, including proton-neutron (p-n) interactions, rotation, and single-particle orbitals. An empirical approach to evaluating the role of p-n interactions involves examining various measures of deformation as a function of the number of "active" p-n pairs, using quantities such as N_pN_n or $N_pN_n/(N_p+N_n)$. Such surveys [1–6], which have emphasized the better known low-lying states, have shown a reasonably systematic increase of deformation with N_pN_n. This is also true [7] of the lighter f-p-g shell nuclei if care is taken to minimize the effects of shape coexistence.

An increasing wealth of spectroscopic data makes it more feasible to investigate the systematics of nuclear deformation among structures with considerably higher angular momentum. A recent study [8] of the moments of inertia of $Z = 64$–78 nuclei has raised interesting questions concerning the variation of deformation and collectivity with N_pN_n. While the moments of inertia for low-spin states increase with increasing N_pN_n, they remain remarkably constant for high-spin states.

Further questions about the variation of deformation across a shell are raised by laser-induced hyperfine structure measurements [9] of the $\frac{9}{2}^+$ isomers in ^{81,85}Rb. While the deformation measured for ^{81}Rb^m, $\beta_2 = 0.27$, is consistent with the N_pN_n ($= 54$) systematics (and with that inferred from lifetime measurements in the rotational band built on the isomer), the similar value ($\beta_2 = 0.26$) reported for ^{85}Rb^m ($N_pN_n = 18$) is not.

The present investigation was undertaken to provide some empirical answers to these questions by examining the systematics of the moments of inertia of f-p-g shell nuclei as a function of spin and position in the shell.

II. MOMENTS OF INERTIA AND DEFORMATION

The normal or kinematic moment of inertia $J^{(1)}$ is often used as a measure of deformation or collectivity in nuclear rotational bands. It can be inferred directly from the level scheme for any rotational band [10] and should be independent of spin for a rigid rotor. Classically, in terms of the spin I and excitation energy E of states in the band,

$$J^{(1)} = I/(dE/dI). \tag{1}$$

The rotational frequency ω is also classically related to this derivative:

$$\omega = dE/dI. \tag{2}$$

The derivative can be estimated by the ratio of finite differences of energies and spins between two adjacent levels:

$$\frac{dE}{dI_x} = \frac{E(I+1)-E(I-1)}{I_x(I+1)-I_x(I-1)}, \tag{3}$$

where I_x is the component of the angular momentum perpendicular to the symmetry axis and is given approximately by

$$I_x(I) = \sqrt{(I+\hbar/2)^2 - K^2}. \tag{4}$$

K is the projection of the angular momentum onto the symmetry axis.

Equations (1)–(4) provide a recipe within the cranking model for inferring the kinematic moment of inertia from experimental data. The prescription will provide a set of values for any sequence of states with spins increasing by $2\hbar$. These are the quantities under discussion. The interpretation of whether they represent moments of inertia depends on other evidence as well. This is similar to the spirit of studying the ratios of excitation energies, even though the ratios mean different things in different models.

An example of the variation of the moments of inertia with N_pN_n is shown in Fig. 1 for the even Se [11–16], Kr [17–26], Sr [27–32], and Zr [33-36] isotopes. The arrows indicate the direction of increasing neutron number N. Since N_p and N_n are counted as the number of particles below midshell (28–39) and holes above (39–50), two nuclei can have the same value. The trend of the moments of inertia $J^{(1)}$ inferred from the 0^+ and 2^+ yrast states is generally increasing with N_pN_n. However, there is some scatter in the points and only partial symmetry about midshell, $N = 39$. Most importantly, the value of $J^{(1)}$ reaches only half that expected for a rigid rotor.

The graph of moments of inertia inferred from the 4^+ and 6^+ states (also shown in Fig. 1) shows a similar increase with N_pN_n but is displaced upward by almost a factor of 2. Without exception, every $J^{(1)}$ value is significantly higher than the corresponding one based on the 0^+-2^+ states. These two graphs give some indication of the limitations of surveys based on the lowest-spin states

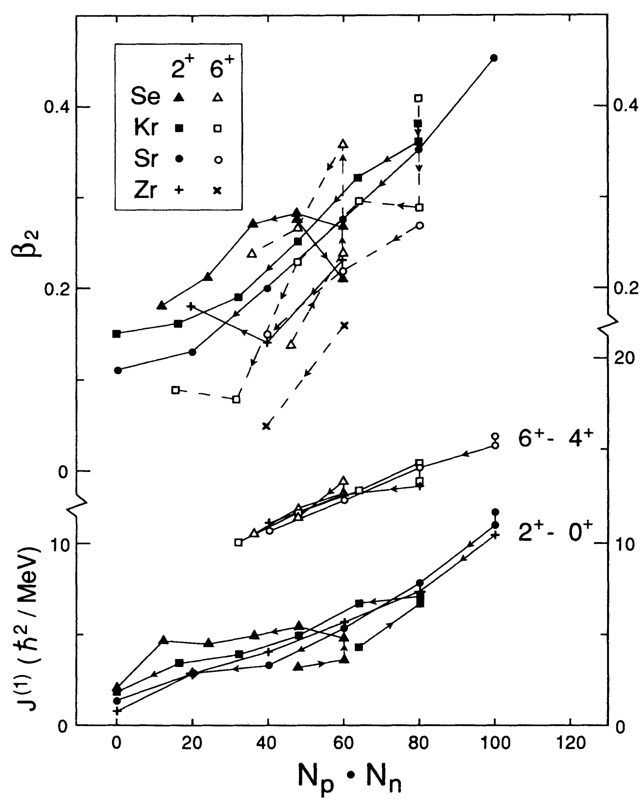

FIG. 1. The kinematic moments of inertia of the even Se, Kr, Sr, and Zr isotopes as a function of N_pN_n. Values are shown based on the 2^+-0^+ and on the 6^+-4^+ energy differences. Arrows indicate the direction of increasing neutron number N. Also shown on the top portion of the figure are the quadrupole deformations β_2 derived from the lifetimes of the 2^+ and 6^+ states using an axially symmetric rotational model.

as well as a major problem with using higher-spin states. Namely, even states of spin 6^+ are either not known or not associated with the yrast decay sequence for one third of the nuclei. Nor is the loss of information randomly distributed. Not surprisingly the higher-spin states are most poorly known for those nuclei closest to shell closures with small N_pN_n values.

The variation of the moments of inertia with spin indicates that the level energies deviate from those of a rigid rotor. This variability suggests the need for other measures of collectivity and deformation. A more direct determination can be made of the magnitude of the quadrupole deformations β_2 from the transition quadrupole moments Q_t assuming axial symmetry using

$$\beta_2 = -7\sqrt{\pi/80} + (49\pi/80 + 7\pi Q_t/60 Z r_0^2 A^{\frac{2}{3}})^{\frac{1}{2}} \quad (5)$$

with r_0=1.2 fm. The magnitude of Q_t can be calculated from the mean lifetime τ of the transition from J_i to J_f of energy ΔE using the rotational model formula

$$Q_t^2 = 60\hbar^6 c^5/[< J_i K 20 \mid J_f K >^2 \tau(\Delta E)^5]. \quad (6)$$

Although the determination of β_2 values from lifetimes is model dependent, the process can also be viewed as simply a means of scaling the measured quadrupole transition strengths $B(E2)$. That is, the values of β_2, like those of $J^{(1)}$, are directly related to experimental measurements, but their literal interpretation as deformations or moments of inertia must be taken with caution. In particular the transition quadrupole moments tend to underestimate the intrinsic or diagonal quadrupole moments in the region of a band crossing where the initial and final states may represent different admixtures of the crossing structures.

In spite of the variability of the moments of inertia, the β_2 values indicate a considerable to high degree of deformation in many of these nuclei. The β_2 values determined from the 2^+ and 6^+ states are also shown in Fig. 1. Many of the nuclei have substantial deformations with β_2 exceeding 0.2 and extending above 0.4 in one case. Like the moments of inertia, the inferred deformations increase with N_pN_n. However, there is no evidence that they increase with spin. In fact, the average values of β_2 based on the lifetimes of the 6^+ states might even be lower.

A. Even-even nuclei

Because of this variability, it is instructive to examine more systematically how the moments of inertia depend on spin or rotational frequency [37]. Such a survey is shown in Fig. 2 for the yrast band of the even-even nuclei. The increasing trend of $J^{(1)}$ is quite evident. The systematics are best illustrated by the behavior of the Sr isotopes. At low spins $J^{(1)}$ increases with frequency for each isotope, but the rate of increase is larger for those nearer the shell closure at $N = 50$; i.e., the lower the initial $J^{(1)}$ value, the more rapid its increase with frequency. The result of these two trends is a tendency for the $J^{(1)}$ values to converge to a common value at higher

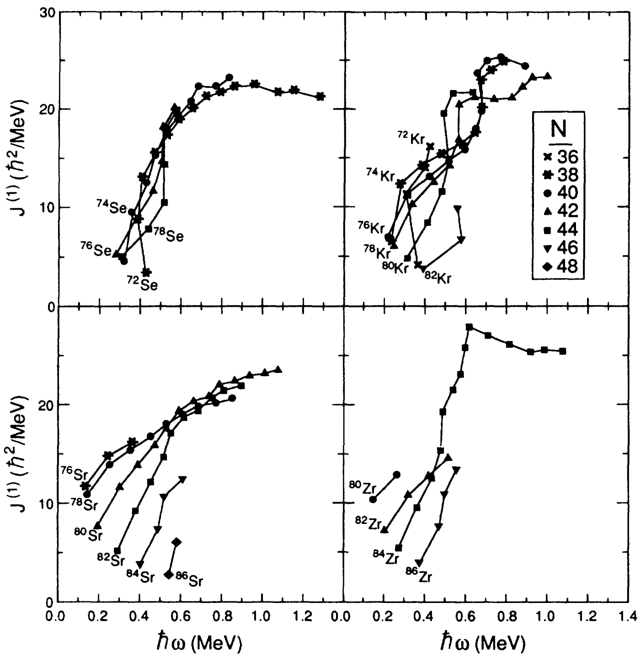

FIG. 2. The kinematic moments of inertia as a function of rotational frequency ω for the even Se($Z = 34$), Kr($Z = 36$), Sr($Z = 38$), and Zr($Z = 40$) isotopes.

frequencies.

The trend for the moments of inertia to start lower but increase more rapidly as N approaches 50 also appears to hold for the Zr isotopes, although only ^{84}Zr is known to relatively high spins. There is evidence for this trend in the Kr and Se isotopes, but it is somewhat obscured by shape coexistence and some sharp band crossings. The principal effect which has been attributed to shape coexistence [17,38–40] is an increase in the energy spacings of the lowest levels compared to extrapolations from the higher levels. In Fig. 2 this results in a reduced value of $J^{(1)}$ and increased frequency ω for the affected states. The effect becomes more pronounced for lower masses. If the lowest point for ^{74,76,78}Kr were shifted to align with the next 2 or 3 points, the graphs for Kr would look much more like those of Sr. Similarly, the Se graphs would resemble those of Sr much more if "corrected" for shape coexistence.

Regardless of whether the distortions attributed to shape coexistence represent a separate mechanism which can be corrected away, all the moments of inertia in Fig. 2 rise and tend to converge to values between 20 and 25 $\hbar^2$/MeV at high frequencies. This is the range of values expected for a rigid rotor for masses of 75 to 85 and deformations of 0.1 to 0.4. While none of the known data violate this statement, many of the bands are not known to high spins.

The β_2 values determined from the lifetimes can also be examined for similar trends. These are shown in Fig. 3. Fewer lifetimes are known and their uncertainties are much larger. It is difficult to discern what, if any, trend is present in these data. However, the β_2 values certainly do not increase rapidly with ω as do the $J^{(1)}$ values, nor is there any indication of saturation or convergence. For

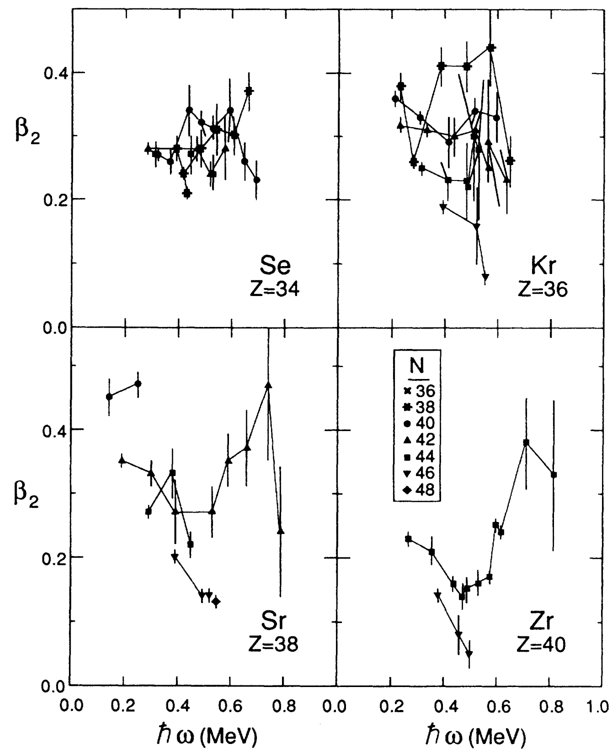

FIG. 3. The axial quadrupole deformations β_2 derived from the lifetimes as a function of rotational frequency.

example, the $J^{(1)}$ values for Se increase by a factor of 4 to 5, whereas the β_2 values vary up and down by less than a factor of 2 over the same frequency range. Hence, the measured transition strengths do not confirm a systematic increase of deformation with increasing rotational frequency.

B. Odd-odd nuclei

A different pattern is seen in the few odd-odd nuclei whose rotational structure is known. The moments of

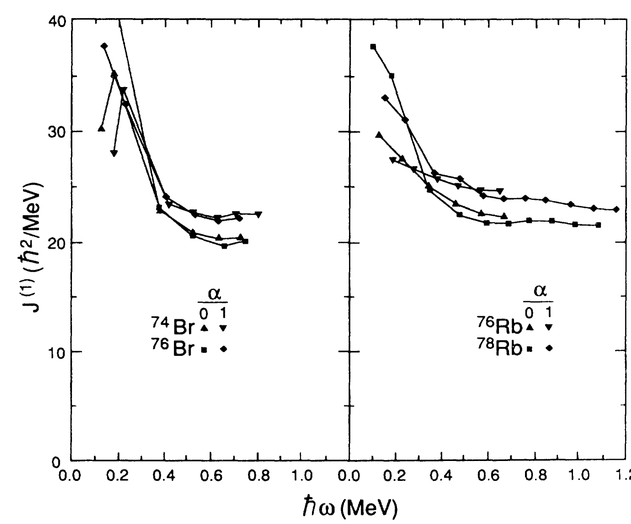

FIG. 4. The kinematic moments of inertia as a function of rotational frequency for the odd-odd Br and Rb isotopes.

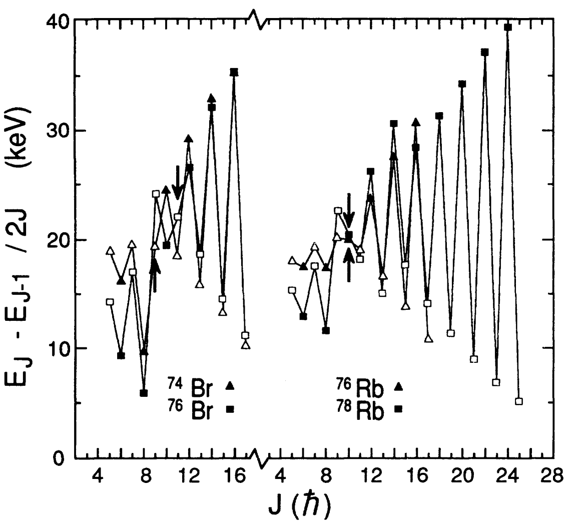

FIG. 5. Energy differences between states of opposite signature as a function of spin for the odd-odd Br and Rb isotopes. Solid (open) symbols are used for even (odd) J to clearly show the phase reversals which occur at the arrows.

inertia in the yrast bands of these Br [41–43] and Rb [44] isotopes are shown in Fig. 4. In contrast to the even-even nuclei, $J^{(1)}$ falls from a high value and appears to level out at between 20 and 25 $\hbar^2$/MeV. That is, the behavior of the moments of inertia of even-even and odd-odd nuclei is opposite at low spins or frequencies but all converge to the same range at frequencies above 0.6 MeV/$\hbar$. This, at least, is true at the present level of experimental knowledge.

There is other experimental evidence for a difference in structure between the low- and high-spin states in ^{74,76}Br and ^{76,78}Rb. The energy differences between states of opposite signature are shown in Fig. 5. This graph clearly shows the signature splitting in the energy levels as an alternating pattern of high and low values. The interesting effect is that at the arrows [spins (9–11)$\hbar$] the phase of the signature splitting reverses. Kreiner and Mariscotti [45] have shown from a two noninteracting particles plus rotor calculation that the phase reversal can arise because part of the increasing angular momentum at low energies can come from recoupling the $\pi g_{9/2} \times \nu g_{9/2}$ quasiparticles to higher spin, whereas above spin 9 it can come only from collective rotation. Hence, the high $J^{(1)}$ values at low spins may be related to variable quasiparticle alignment.

C. Odd-*A* nuclei

The situation is somewhat intermediate in the odd-even nuclei. As shown in Figs. 6 and 7, the moments of inertia in the $g_{9/2}$ yrast bands of the odd proton nuclei (Br [46–49], Rb [50–53], and Y [54–57]) are relatively constant, while those of the odd neutron nuclei (Se [58–61], Kr [62–65], Sr [66–70], and Zr [71–73]) generally rise, sometimes with sharp alignments. However, the range of variation is less than among the even-even nuclei and most also converge to the 20–25 $\hbar^2$/MeV range. The value for ^{83}Zr is somewhat above this range, and that for one signature of ^{83}Sr does not appear to be rising toward convergence, but only 3 points are known.

A rising trend is seen in all the lowest negative parity bands (usually $K^\pi = \frac{3}{2}^-$). Generally these are not known as far up in spin, so that it is harder to determine whether they are approaching a convergence at high frequencies or continuing to increase.

III. DISCUSSION AND SUMMARY

The kinematic moments of inertia, or at least the quantities derived from the energy spacings which correspond to the moments of inertia for rotors, show some interesting systematics among the yrast decay sequences of *f-p-g* shell nuclei. Most important is the tendency to converge to rigid-body values of 20 to 25 $\hbar^2$/MeV at rotational frequencies above 0.6 MeV/$\hbar$. Those for the even-even nuclei increase from much lower values, while those for

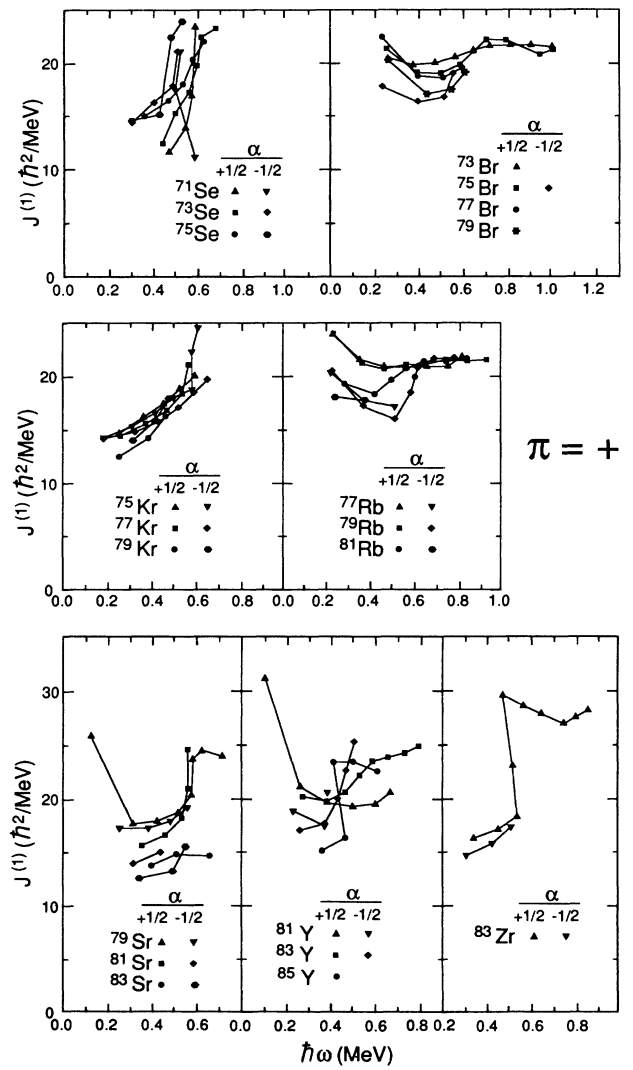

FIG. 6. The kinematic moments of inertia as a function of rotational frequency for the positive parity yrast bands in the odd-*A* nuclei.

the few odd-odd nuclei known decrease from higher values toward the convergence zone. The moments of inertia for odd-even nuclei are somewhat intermediate, often rising moderately into the 20 to 25 $\hbar^2$/MeV zone.

A certain amount of caution must be applied to a survey such as this, since the experimental data are rather incomplete at higher spins. Additional data may confirm or contradict the trends which appear at present. The higher-spin states are harder to observe in weakly deformed nuclei, perhaps leading to a bias favoring only the more deformed nuclei. The convergence seems best established for the even-even nuclei and the few odd-odd ones known. There is not much information on the odd nuclei above 0.6 MeV/$\hbar$. While the moments of inertia for some odd nuclei, such as the Br isotopes, show a rather clear convergence, those for other isotopes, such as Se, rise steeply to the last known point.

However, the evidence for a convergence of the moments of inertia towards the rigid-body value seems clear enough to raise a number of questions about the trend. Supporting evidence comes from the even-even $Z = 64$–78 nuclei, where Espino and Garrett [8] have shown that $J^{(1)}$ based on the 2^+-0^+ energy spacing varies from 5 to 40 $\hbar^2$/MeV, whereas that based on the 22^+-20^+ spacing ranges only from 55 to 65 $\hbar^2$/MeV—approximately the rigid-body value. Quasiparticle alignment must play an important role since the behavior of $J^{(1)}$ at low spins depends so much on whether 0, 1, or 2 unpaired particles are involved. Some of the increases in $J^{(1)}$ are rather sharp, indicating a relatively rapid pair alignment. The anomalous signature splitting in the odd-odd Br and Rb isotopes below the maximum possible spin for two unlike $g_{9/2}$ nucleons and the particle-rotor calculations [45, 74] interpreting this as an alignment effect also point to the importance of alignment on the observed behavior of the moments of inertia.

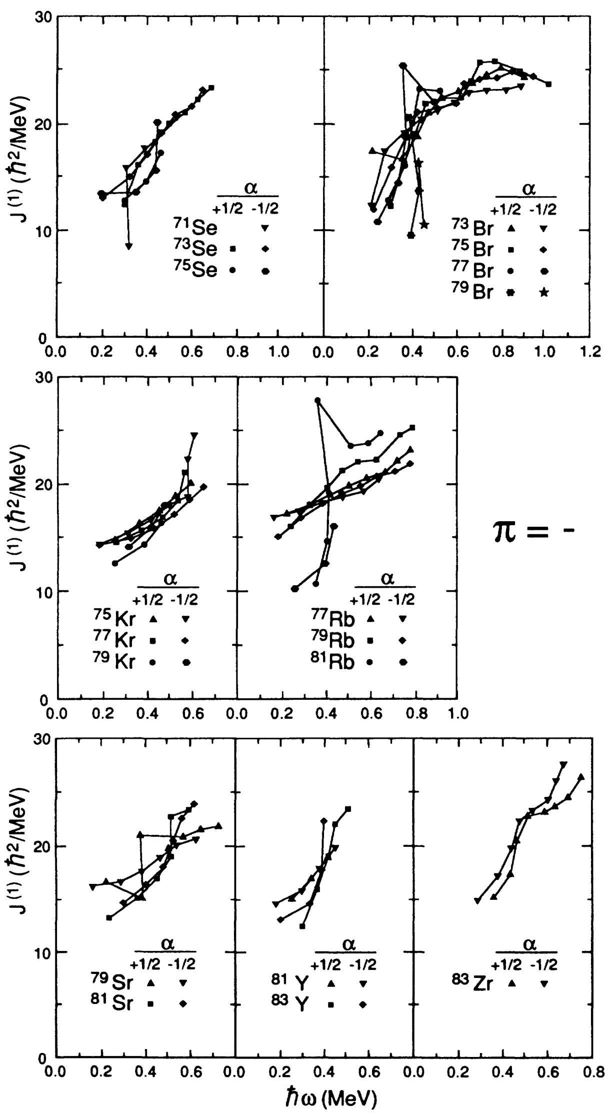

FIG. 7. The kinematic moments of inertia as a function of rotational frequency for the lowest negative parity bands in the odd-A nuclei.

The dynamic moments of inertia $J^{(2)}$ are often compared with the kinematic moments $J^{(1)}$ for evidence of rigid rotation. Because of their derivative nature, the dynamic moments accentuate variations in the kinematic moments and tend to vary significantly in these nuclei. The values of $J^{(2)}$ have not been displayed since their variations often obscure trends and few level schemes have been measured well into the convergence region. There is a tendency for the values of $J^{(2)}$ to approach those of $J^{(1)}$ at frequencies above 0.8 to 1.0 MeV/$\hbar$, and the implications for rigid rotation have been pointed out in individual cases [35].

Other questions raised by the trends in $J^{(1)}$ are the relation between deformation and the moment of inertia and the variation of each of these quantities across the shell. Espino and Garrett have commented on the very different behavior of $J^{(1)}$ with N_pN_n for low- versus high-spin states in rare-earth nuclei. The convergence of the f-p-g shell moments of inertia towards a common value at high spins implies the same conclusion—that although $J^{(1)}$ varies systematically with N_pN_n at low spins, it becomes almost independent of N_pN_n at high spins.

The lifetimes provide information about deformations. Because nuclear lifetimes are harder to measure, they are not known nearly so accurately as are the excitation energies, nor for as many levels. The deformations β_2 deduced from the 2^+ and 6^+ lifetimes and shown in Fig. 1 vary with N_pN_n much as does $J^{(1)}$. This supports the conclusion that the nuclear deformation, at least for the low-lying states, increases substantially toward the middle of the shell. However, there is no trend like that seen for $J^{(1)}$ of the inferred β_2 values changing consistently with spin. Of course this statement is limited by the decreasing quantity and quality of the lifetime data at high spin and the relationship between lifetimes and β_2 values. The quoted uncertainties in the lifetime values are often large and the observed variations are sometimes even larger. It is not clear whether the variations result from such effects as structural changes or nonaxial shapes which change the relation between β_2 and lifetimes or from difficulties in the measurements such as feeding corrections or stopping powers.

While this survey indicates interesting trends in the existing data, it also suggests a need for more experimental work. Very few rotational bands in odd-A nuclei are known above a rotational frequency $\hbar\omega$ of 0.8 MeV, not much is known about odd-odd nuclei, and the yrast bands of many even-even nuclei are not known in the convergence region, especially for the Zr isotopes. The question of how much shape information can be learned from the moments of inertia places a greater emphasis on lifetime measurements. The number of lifetimes which have been reported is rather limited, but perhaps most important is the large asystematic variation seen. Although the experimental problems are challenging, there is a strong need for more accurate lifetime measurements of high-spin states.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation. Informative discussions with P. Cottle, J. Garrett, A. Leviatan, W. Nazarewicz, M. Riley, and I. Talmi are gratefully acknowledged.

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