Submitted to Comments on Nuclear and
Particle Physics

LBL-5034
Preprint c.1

NUCLEI AT HIGH ANGULAR MOMENTA

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June 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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Two developments have recently attracted attention to high-spin states in nuclei. The first was the discovery[1] in 1971 of a pronounced irregularity around spin 16ħ (called backbending) in the otherwise very regular behavior of the rotational energy spacings in some even-even rare-earth nuclei. Consideration of the cause of this backbending led to the realization that the whole sequence of yrast states (the lowest-energy state for each spin value) is particularly simple and interesting. This sequence is effectively terminated when the states become unstable to fission, or perhaps in some cases to particle evaporation, which occurs at angular momenta around 70 or 80ħ for nuclei in the middle of the periodic table, and at lower angular momenta both above and below this region. Although these states may have high excitation energies, there is no excess over that required to carry the angular momentum so that they are otherwise cold and expected to have simple configurations characteristic of the response of nuclear matter to the addition of angular momentum. The second development in this area has to do with the yrast states above the backbend region. In compound-nucleus reactions, heavy-ions can bring in angular momentum up to the limit that any nucleus can hold, and experimental techniques to study the resulting very high-spin states are now evolving rapidly. This has recently produced[2] the first information about states with spins as high as 50ħ, indicating that the whole range of nuclear angular momenta is now open to study.

The individual yrast states in a number medium and heavy nuclei are known up to about 20ħ, and none are presently known beyond 24ħ. This limit is imposed by the present methods of producing these states. The energies[3,4] of the yrast states for the even-even nucleus ^{164}Yb are plotted against spin in Fig. 1. The behavior is reasonably smooth and approximately parabolic as expected from the rotational $I(I + 1)$ relationship. However, around $I = 14$ there is a change in slope, and if these same data are plotted as (essentially) moment of inertia against the square of the rotational frequency, then the usual backbending plot shown in the insert results. Here the change in slope appears very clearly as a reduction in the rotational frequency (backbend), and such behavior is seen in many, but not all, rare-earth nuclei, and also in some cases outside this region.

It is now rather clear that the backbend is due to an intersection of the ground-state rotational band with another band having a larger effective moment of inertia. The dotted and dashed lines in Fig. 1 show the probable extensions of the two bands, which are not observed in this case, but both of which have been identified in the two 90-neutron nuclei, ^{154}Gd and ^{156}Dy, and one of which has been seen in several other cases.[5] Very recently the extension of the ground band beyond the backbend has been seen in ^{164}Er following Coulomb excitation[6] with ^{136}Xe projectiles, and this represents a promising new method to study the backbending region. There are four cases in the rare-earth region where sufficient information is now available to obtain the interaction matrix elements between the two bands, and these are all in the 10-100 keV range. The nature of these new bands that carry angular momentum with the least expenditure of energy around I = 20ℏ is of considerable interest, and at least three possibilities have been seriously considered. These three mechanisms are also important in the regions of higher angular momentum.

One possibility for the new bands in that their larger moment of inertia ia due to a larger deformation of the nucleus. Such shape changes will surely be important at sufficiently high angular momenta, and there already is some information about them in the spin regions of interest. The deformation of the nucleus, β, is generally inferred from the nucleus quadrupole moment, which in turn is obtained most readily from the collective B(E2) values. Studies of these B(E2) values in the ground-state rotational bands of well deformed rare-earth and actinide ($\beta \approx 0.3$) rotors consistently show[5] no increase up to the highest measured spins (at present ~20ℏ). The B(E2) values near or in the backbend region seem, if anything, to be slightly smaller than the values at lower spins. On the other hand, nuclei along the lower edge of the rare-earth region ($N \approx 90$) where $\beta < 0.3$, do show B(E2) values increasing with spin,[7] and, therefore, presumably some centrifugal stretching. The data do not extend high enough in spin to tell if these nuclei stretch beyond the value $\beta \approx 0.3$ characteristic of the heavier rare-earth rotors, but this seems unlikely. Thus it appears that the medium and heavier nuclei are soft toward deformation out to $\beta \approx 0.3$, where the shell structure characteristic of the spherical region is smeared out, and then tend to resist further stretching.

A more dramatic example of a shape change is seen in the very neutron-deficient Hg isotopes. Here a backbend at very low spin values (only 4 in ^{186}Hg and ^{184}Hg) is associated with a large increase in B(E2) value.[8] It thus appears to correspond to a sudden change from a nearly spherical shape, $\beta \sim 0.1$ to a strongly deformed one, $\beta \sim 0.25$. Recent work[9] shows this backbend is due to a crossing of the ground band with a deformed band. Nuclear potential-energy calculations[10] are entirely consistent with this behavior as they show a deformed minimum dropping in energy with decreasing neutron number in the Hg nuclei, until it lies at about the same energy as the nearly spherical ground-state minimum in ^{184}Hg. These calculations do not indicate a second more-deformed minimum (or even shoulder) for the rare-earth region. Thus, although backbending can, in special circumstances, occur due to a shape change, it seems unlikely that those in the rare-earth region have this cause.

Another possibility for the upper bands is that they have no pairing correlations, and thus have a rigid-body moment of inertia ($2\mathcal{J}/\hbar^2 \sim 140$ on Fig. 1). A sudden collapse of the pairing correlations at a critical rotational frequency was suggested in 1960 by Mottelson and Valatin.[11] Backbending at first seemed to be the realization of this possibility, even though on such a picture one would not <u>a priori</u> expect a reduction of the rotational frequency nor the subsequent decrease of the moment of inertia which often occurs after the backbend. It is clear that the rotation will reduce the pairing correlations since it removes the (time-reversal) degeneracy of the paired nucleons.

A perfect rotor would give a horizontal line in the insert to Fig. 1, and the observed slope at moderate and low spin values is very likely to be due mainly to this effect of the rotation on the pairing. This increase in moment of inertia is not generally accompanied by a corresponding increase in B(E2) value (deformation), which is consistent with its being caused by a pairing reduction. The calculations suggest that the pairing correlations should be quenched somewhere between 20 and 30ħ resulting in the rigid-body moment of inertia, and the data do not seem inconsistent with this. However, it is not clear that this quenching will be accompanied by any sudden change in properties.

A third method for carrying angular momentum efficiently in the upper band is the alignment of individual high-j nucleons. In the rare-earth region two $i_{13/2}$ neutrons can be aligned with the rotation axis to produce 12ħ in this direction, and the Coriolis interaction provides a driving force toward such an alignment. The initial calculation of such an effect showed that it could produce backbending behavior,[12] and subsequent calculations[13] suggested that this alignment is more likely than a pairing collapse in this respect. Furthermore, two additional factors support alignment as the cause of backbending. First, the above mentioned band interaction matrix elements of 10-100 keV can be understood[6] as Coriolis matrix elements, strongly reduced by the much lower core rotational angular momentum in the aligned band compared with the ground-state band. Secondly, backbending is also observed in rotational bands of odd-mass nuclei, but in the light rare-earth region it is inhibited when (and only when) the odd particle is an aligned $i_{13/2}$ neutron. Such a blocking suggests that the aligned $i_{13/2}$ neutron is involved in the band causing the backbending. In the heavier tungsten and osmium nuclei it is the $h_{9/2}$ proton that blocks the backbend, and in the Ba region it is the $h_{11/2}$ proton. In each case the orbital is involved in backbending when alignment is energetically most favorable (nearly empty for these prolate shapes). The evidence is becoming rather strong that alignment is the cause of most backbending This same rotation-alignment concept has also been useful in understanding the states of odd-mass nuclei,[14] especially those with smaller deformations and thus higher rotation frequencies. In such cases it seems that a coupling scheme where the particle angular momentum, j, is quantized along the rotation axis may be applicable to many of the low-lying states. Thus the alignment of single-particle and rotational angular momenta appears to be important for several different types of high-spin states.

It is now of interest to view the entire range of angular momenta possible for nuclei. Such a view is given schematically in Fig. 2, which is due to Bohr and Mottelson.[15] This is a plot of energy vs angular momentum for a nucleus of mass around 160. The lower, approximately parabolic, line is the yrast line so that there are no levels in the nucleus at energies below this. The upper line gives the fission barrier which normally sets the upper limit to the study of nuclear levels. The intersection of these two lines gives an effective maximum angular momentum possible for such a nucleus, although the study of the states by gamma-ray emission might terminate earlier if the highest yrast states were particle unstable. Nuclei in this rare-earth region have prolate shapes near the ground state as a result of the shell structure. The hatched region around the ground state indicates the region where the pairing correlations are expected to exist. This region is expected to terminate around I = 20, as has been discussed, and while the experimental data confirm a steady decrease in the pairing with increasing spin, no termination has yet been identified.

Some insight into the behavior above 20ħ in Fig. 2 can be obtained from the equilibrium shape of a liquid drop.[16] A rigidly rotating, charged liquid drop prefers an oblate shape until shortly prior to the point where it fissions. The large moment of inertia associated with oblate shapes minimizes the total energy of the system in the same way that the earth's rotation gives rise to such a shape. While a nucleus cannot rotate in a classical sense about a symmetry axis, it has been shown[17] that the trajectory of states obtained by aligning the angular momenta of individual particles along the symmetry axis (deformation-aligned states) is the same, on the average, as that which would be obtained by rigid rotation of the system about that axis. In contrast to the prolate case, discussed above, this means that the deformation-aligned states generally lie lower than the rotation-aligned states in oblate nuclei. Thus if the shell effects were negligible, the nucleus at high angular momentum would be oblate and the angular momentum would be carried by aligned individual nucleons. There would be no collective motion and thus no enhanced B(E2) values. This corresponds to the region labeled C in Fig. 2, and is proposed to occur at the higher angular momenta, when the classical liquid-drop effects dominate the shell effects. It has been suggested[15] that this region might be identified experimentally by the occurrence of isomeric states which arise due to the absence of smooth rotational-band structures. However, no such isomers have been identified up to the present time, and the most recent calculations[18] suggest that such isomers may be rare.

At the very highest spins the liquid-drop estimates suggest that the nucleus will stretch rapidly into very deformed triaxial shapes leading to fission. The increase in deformation and moment of inertia is predicted to be so rapid that the rotational frequency well decrease and a "super-backbend" will occur. It is interesting that the liquid-drop estimates (and more recent ones[18] including shell effects) predict only small increases (if any at all) in deformation up to ~10$\hbar$ prior to this fission limit (60 or 70$\hbar$ for rare-earth nuclei). The observations extend only up to ~20$\hbar$ but in that range they are consistent with this expectation. The super-backbend is, therefore, expected to occur over a very limited region in spin, but it should be detectable if this region is as large as ~10$\hbar$, and searches for it are in progress.

Between the prolate ground-state region and the oblate high-spin region just discussed the nuclei are expected to go through triaxial shapes. In such a case the possibility of a wobbling motion, in addition to rotation about the axis with the largest moment of inertia, has been suggested by Mottelson[19] to give rise to a series of closely spaced parallel rotational bands, labeled A in Fig. 2. In this region of spins there is experimental evidence[20] suggesting that a number of parallel bands do exist, having enhanced B(E2) values. Furthermore, the observed backbend in the rare-earth deformed region seems most likely to correspond to two aligned high-j nucleons, whose orbits would indeed represent a triaxial bulge in these prolate nuclei. Thus, there is some evidence to support the behavior suggested in Fig. 2. However, the extent of the triaxiality and the spacing and nature of the parallel bands are not known at the present time.

As discussed previously, the backbend most likely corresponds to a particular pair of high-j nucleons aligning their angular momenta with the rotation axis, and thus represents a small "shell" effect. One might expect further shell effects of this type as bands based on other aligned high-j orbitals cross under the previous yrast band. This situation is labeled B in Fig. 2 and offers the hope of additional structure at these spins in the nuclear spectra. Whether these crossings will show up as additional backbending or be averaged out to a more classical centrifugal behavior is not clear at the present time.

Part of the present excitement connected with these high-spin states comes about because the ideas outlined above can be tested experimentally. Almost all the present information on high-spin states has come from heavy-ion compound-nucleus reactions, where angular momenta well over $100\hbar$ could be introduced. The de-excitation of the products from such reactions show strong individual gamma-ray lines from states with $I \lesssim 20\hbar$. The study of such lines over the last 10-12 years has produced a wealth of information on the individual states of many nuclei at spins around and below $20\hbar$, and led to the discovery of backbending. But above $20\hbar$ it appears that the population is spread out over so many levels that no single one can be isolated for study using presently available techniques. The choices have thus been to develop new techniques to pick out the study these very weakly populated levels, or to devise methods to study the unresolved (the so-called "continuum") spectrum. At the present time the latter possibility seems to be progressing more rapidly.

Several recent developments in the experimental study of the continuum spectra have brought it to the point of giving information on moments of inertia for states have spins up to 60ħ. First, events having high angular momentum must be selected, and two methods to accomplish this have been devised. One of to record the continuum spectrum in coincidence with the discrete lines at the bottom of the cascade. This gives a continuum spectrum for each channel (number of neutrons, protons, and/or alpha particles evaporated), and it has been found that the angular momentum is fractionated, with the highest values in those channels where the fewest particles are evaporated. The other way to select high angular-momentum events is to record the continuum spectrum in coincidence with an array of many detectors, sometimes called a "multiplicity filter". Since a relationship (not unexpected) between the number of gamma rays emitted and the initial angular momentum of the nucleus has been reasonably well established, a selection of events were the most array detectors fired simultaneously corresponds to a high angular-momentum selection. It is not yet clear which of these methods will prove to be more useful. In either case, the continuum spectrum is recorded in detectors located a large ($\sim$50 cm) distance from the target in order to differentiate neutrons from gamma-rays by their time of flight. The observed gamma-ray pulse-height spectrum also has to be "unfolded" to give the primary gamma-ray energy spectrum, and for this reason the best response function (highest proportion of full-energy events) is desirable, leading to the present choice of large NaI detectors. Eventually detectors with much better response functions (for example, some type of electron spectrometer) might prove advantageous.

The spectra obtained with these techniques have two general features: a high-energy exponential tail and a more intense lower-energy "bump". The high-energy tail seems likely to correspond to the first few statistical gamma rays emitted before the yrast line is reached. Such an exponential spectrum with about the observed slope (temperature) was predicted by Grover and Gilat[21] in 1967. The bump probably corresponds to collective (stretched E2) transitions along the yrast region. This conclusion is supported by the angular distribution of the gamma-rays, and by the observed shape variations of the bump with angular-momentum input. If this bump indeed represents transitions along, and parallel to, the yrast line, then its endpoint, height, and shape variations contain detailed information about the nuclear moments of inertia up to the highest angular momenta in the channel and several methods to extract this information have been devised. The results[2] for the nucleus ^{162}Yb are shown in Fig. 3 which is the same type of plot as the insert in Fig. 1. The data from the continuum spectra are shown as the large points in Fig. 3 and they extend up to transition energies of 1.4 MeV, $(\hbar\omega)^2 \approx 0.5$, and to spins of ~50$\hbar$. Two independent methods were used to obtain these points, one of which (diamonds in Fig. 3) is sensitive to local variations in the moment of inertia, and can, therefore, be used to search for backbends or any other irregularities in the moments of inertia. The data in Fig. 3 are not yet very detailed in this respect, and show mainly just the approach to the rigid-body value of the moment of inertia. Studies of this type are just beginning but they can give information over to the whole angular-momentum region shown in Fig. 2 and for nuclei in any mass region.

It is now clear that nuclei respond to increasing angular momentum; changes begin to occur from the very beginning, and some major modifications in the structure of most nuclei happen by spin $20\hbar$. Calculations have recently suggested still more dramatic structural changes at higher angular momenta, and the experimental techniques to identify these events seem to be at hand or developing rapidly. This promises continued progress in our understanding of this dimension of nuclear matter.

ACKNOWLEDGEMENT

This report was done with support from the U. S. Energy Research and Development Administration.

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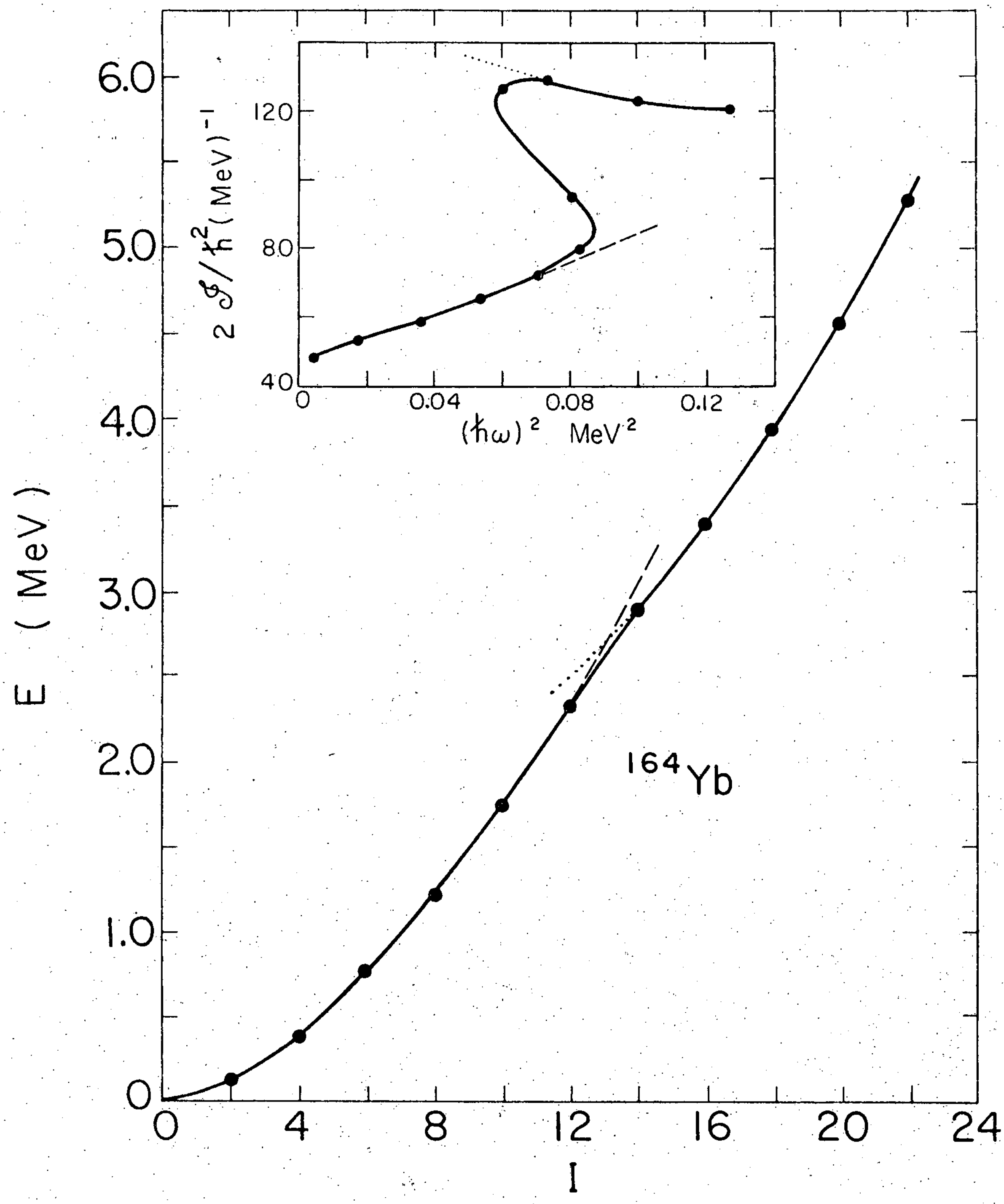
FIGURE CAPTIONS

Fig. 1. A plot of energy vs I for the ground-band rotational levels in ^{164}Yb. The insert shows the same data in the type of plot generally used to show backbending behavior, where $2\mathcal{J}/\hbar^2 = (4I - 2)/E_t$ and $(\hbar\omega)^2 = (E_t/2)^2$, with $E_t = E_I - E_{I-2}$.

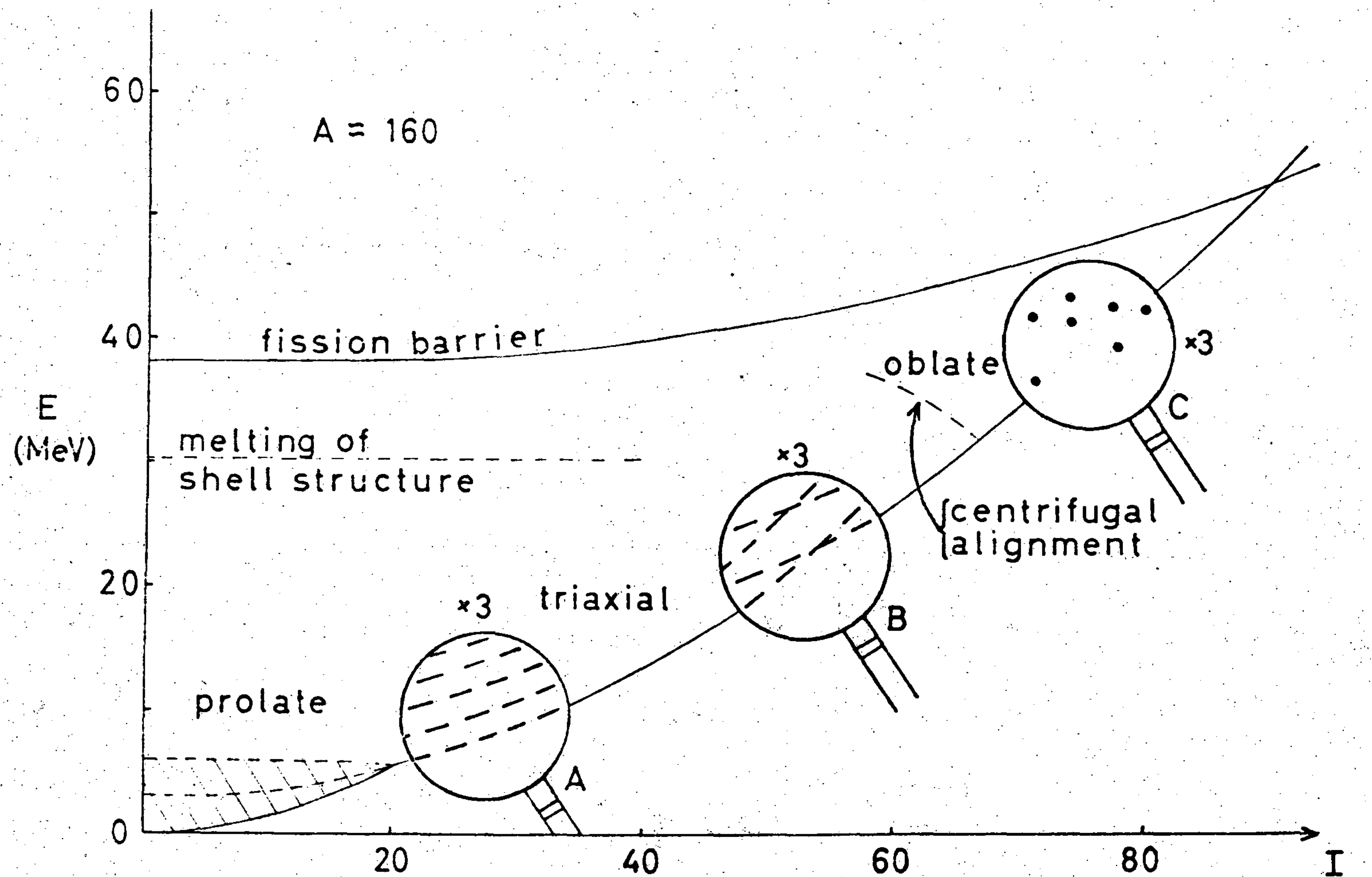
Fig. 2. Nuclear phases as a function of angular momentum and excitation energy (schematic). The fission barrier as a function of I is taken from the liquid drop calculations.[16] For I > 80, these calculations give a triaxial equilibrium shape, which would imply another regime with collective rotational band structure, but this feature has not been included in the present figure. The enlargements show possible level structures in the neighborhood of the yrast line.

Fig. 3. Backbending plot for ^{162}Yb. The small solid dots correspond to the known low-spin states of ^{162}Yb, whereas the open circles are for the isotone ^{160}Er. The large dots correspond to values derived by the integral method[2] from the reaction, 181 MeV ^{40}Ar + ^{162}Te. The triangle and square come from 157 MeV ^{40}Ar + ^{126}Te and 87 MeV ^{16}O + ^{150}Sm spectra using the same method. The diamonds are values from the differential method[2] applied to the 181 MeV ^{40}Ar case. The horizontal dashed line is the moment of inertia of a rigid sphere with A = 162.



XBL 766 3015

Fig. 1



XBL 764-971

Fig. 2

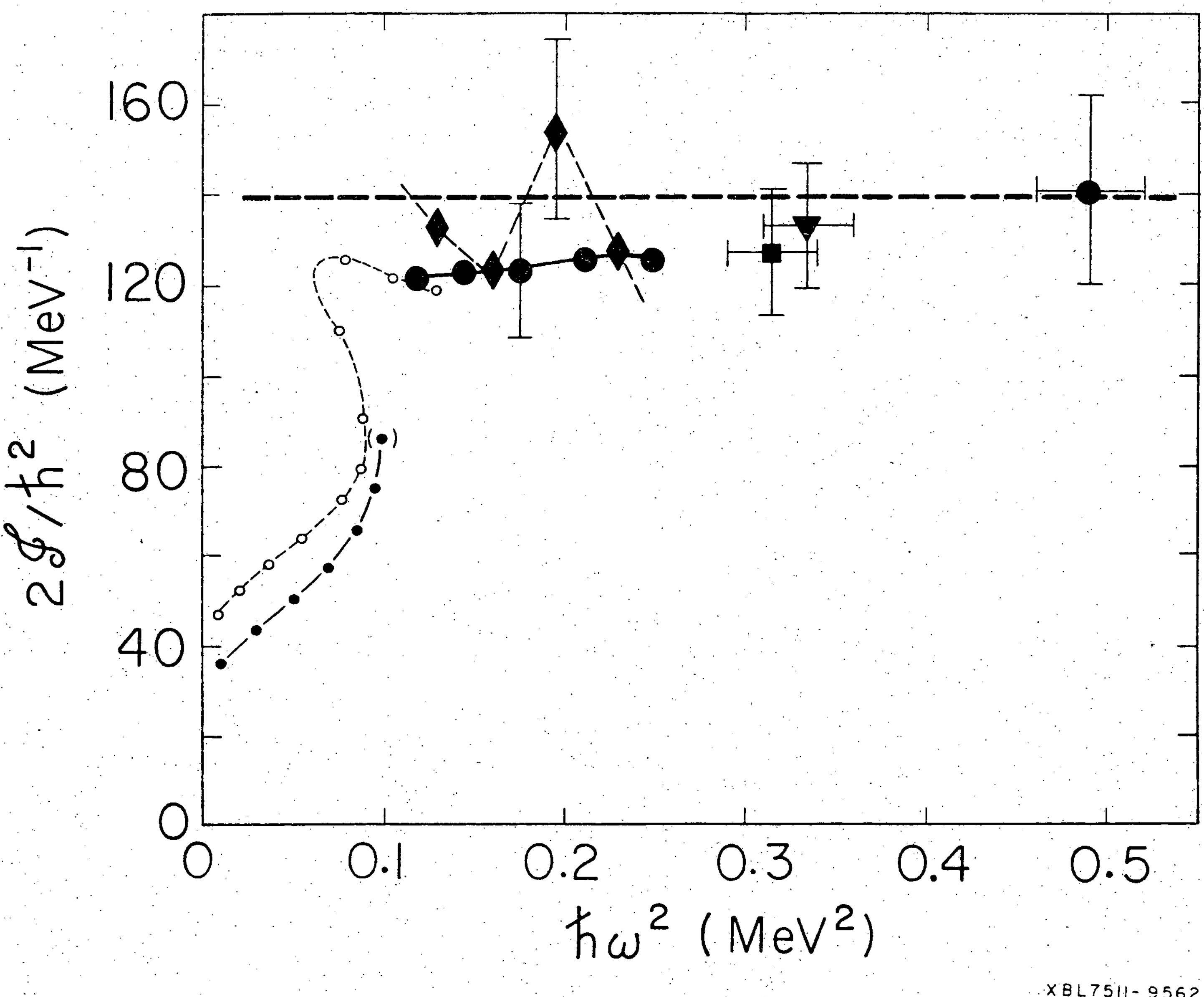

160
120
80
40
0
0
0.1
0.2
0.3
0.4
0.5
$2\mathscr{J}/\hbar^2$ (MeV^{-1})
$\hbar\omega^2$ (MeV^2)
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Fig. 3

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