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Second Backbending in ^{158}Er

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(Received 7 September 1977; revised manuscript received 21 September 1978)

By the cranked Hartee-Fock-Bogoliubov method in the pairing $+Q\cdot Q$ model we find that a small second backbending occurs around $J=26$ in ^{158}Er. This is due to the antipairing effect among protons. It is further argued that it is unlikely that further backbends will be seen in any rare-earth rotors after the disappearance of both neutron and proton pairing.

From the many-body point of view, the backbending phenomenon which occurs around $J=12$ in many rare-earth nuclei can be attributed to the decrease of pairing correlation of neutrons. In the cranked Hartree-Fock-Bogoliubov (CHFB) method,[1] which allows for structural changes with the increase in the angular momentum J, an explicit Coriolis term appears and hence the decrease of the pairing gap Δ with J is easily understood. The alternate procedure of axial variations after exact angular momentum projection (VAP) also allows for changes in the intrinsic structure including the pairing degree of freedom. Here as J increases, to minimize the rotational contribution to the total energy, the moment of inertia $\mathscr{I}$ must increase; this is achieved by a decrease in Δ. Both these methods give qualitatively similar results. For ^{158}Er, in quantitative terms, for $J\leq 12$ the VAP results are in better agreement[2] with the experimental data. But, as we had indicated earlier,[2] for larger J values the axial shapes become increasingly inadequate and hence the CHFB method is the only known many-body approach to the yrast states of high J values.

The pair-breaking and -alignment explanation of the backbending phenomenon by Stephens and Simon[3] is considered by some authors as being distinctly different from the antipairing explanation. But this is not so. Breaking of a pair and their alignment does occur, indeed, at the critical J value for which the rotational frequency ω decreases. This is seen in the CHFB[1,4] results. However, we would argue that the Mottelson-Valatin[5] antipairing (though not the complete pairing collapse) is the basic reason for the backbending and the alignment is an important result associated with it. In ^{158}Er for $J\geq 18$ the neutron pairing completely disappears ($\Delta_n=0$); i.e., all the neutron pairs are broken and not just one high-j pair. Hence, in our point of view, we cannot expect any more backbends due to neutron antipairing; but as a result of proton antipairing there can be one more backbend.

Recent experiments[6] on ^{158}Er have revealed a second discontinuity in the yrast sequence around $J=28$. Unfortunately because of some uncertainty it is not yet definite if this is a discontinuity or a backbend. The CHFB results we report below indicate that it is a small backbend due to proton antipairing.

Our CHFB calculations are carried out in the Pal-Faessler-Goodman[4,7,8] basis and the Baranger-Kumar[9] pairing $+Q\cdot Q$ model. $N=4$, 5 and $N=5$, 6 major oscillator shells are used for protons and neutrons, respectively. Other relevant calculational details can be found in Ref. 2.

Rather than the usual plot of $\mathscr{I}$ vs ω^2 we illustrate the results by a $\langle J_x\rangle$ {or $[J(J+1)]^{1/2}$} vs ω plot. The $J\leq 12$ part of this curve is from our earlier VAP calculations[2]; the parts for $12<J\leq 18$ and for $J>18$ are from the previous[2] and the present CHFB work. For $J=24$ and 26, because of a proton pair breaking and alignment, the constraints on $\langle J_x\rangle$ and the proton number are rather difficult to satisfy accurately. Hence

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our results for these J values are not very accurate and this is indicated in Fig. 1 by dots. We are sure of the backbending nature because the very well converged results for $J=22$ and 28 indicate that $\omega_{J=28} < \omega_{J=22}$. The backbends due to proton antipairing are smaller than those first found due to neutrons—we have no qualitative explanation for this.

The exact values of the critical angular momentum are not expected to emerge from CHFB calculations. The method, as we have practiced it, is not free from defects. The pairing $+Q\cdot Q$ model itself may not be as valid for the high-J region as for the low J values. Another point of criticism could be the lack of exact number conservation. Here it should be noted that in the CHFB, for every J value, the Lagrange multiplier $\lambda_{p,n}$ for conserving the proton and neutron numbers, on the average, is adjusted in a self-consistent fashion; hence one would not expect the corrections from this source to be as significant as in some versions of the VAP method. In the latter if $\lambda_{p,n}$ are not determined with respect to J-projected wave functions, then these corrections could become quite significant in some cases[10] such as in ^{166}Yb. We have now repeated the ^{166}Yb calculation, without number projection, by the CHFB method. These results are enumerated in Table I and at $J=10$ we do see a backbend. Thus our expectation that the number-projection corrections are not crucial in the self-consistent CHFB method is borne out.

If the alignment is the basic reason for the backbends, then we may expect[6] many more backbends or discontinuities. On the other hand, if the antipairing is the basic reason, then there cannot be any more backbends after the disappearance of both neutron and proton pairing correlations. In ^{158}Er indications are that for $J\approx 44$ we will find $\Delta_{p=0}$.

In Fig. 1 we also plot $\langle J_x\rangle_n$, the neutron contribution to $\langle J_x\rangle$. All the points on this curve are from the CHFB work. This exhibits a backbend at $J=6$, but thereafter shows almost perfect rotor behavior with a slight tendency towards saturation for the higher J values. Here it is important to realize that for angular frequencies large enough for a proton pair breaking and alignment, the neutrons show no further inclination to cause another backbend. The loss of pairing degree of freedom is obviously the reason. The saturation effect is also seen in the earlier CHF (i.e., without pairing) calculations[11-13]; this is a result of the finiteness of the single-particle basis. By the inclusion of higher-j shells one can build up more neutron angular momentum. But in the absence of pairing we have lost the easy degree of freedom with which $\mathcal{J}$ can be increased drastically and thus produce backbends. Thus, no rare-earth rotor should exhibit backbends after the disappearance of both neutron and proton pairing. Change of shapes and deformation parameters, even in the absence of pairing, can in principle produce changes in $\mathcal{J}$, but these changes can be drastic only if we make very significant changes, like core excitations,[13] in the intrinsic structure and then we would be looking at a very different band. To be doubly sure that the above inference is valid we repeated our ^{158}Er calculations with the

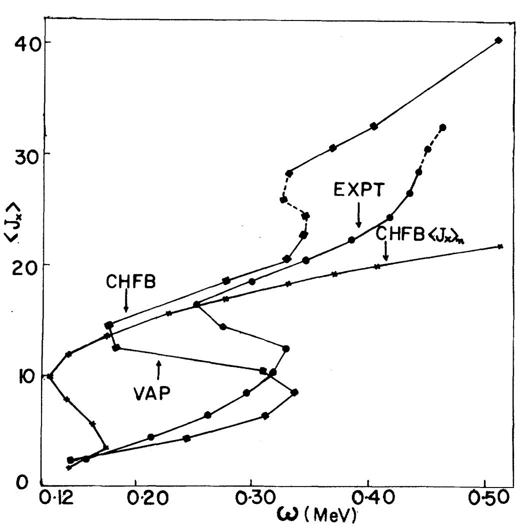

FIG. 1. Semiclassical angular momentum $\langle J_x\rangle$ or $[J(J+1)]^{1/2}$ vs angular frequency.

TABLE I. ω-J values for ^{166}Yb and ^{158}Er from CHFB and CHF calculations, respectively.

J	ω (MeV) CHFB ^{166}Yb	CHF ^{158}Er
2	0.094	0.015
4	0.157	0.029
6	0.195	0.042
8	0.211	0.058
10	0.197	0.078
12	0.195	0.099
14	0.195	0.125
16	0.222	0.152
18	0.257	

pairing switched off. In these CHF results, which are enumerated in Table I, we see no signs of a backbend and indeed this is consistent with the earlier CHF results[12,13] for ^{20}Ne and ^{56}Ni.

We wish to emphasize that our results are not in contradiction to the basic idea of the alignment model.[3,14] At the two critical J values a pair of neutrons and a pair of protons do align. But the antipairing continues to be operative and at two other values of J, larger than these J_c, complete disappearance of both neutron and proton pairings occurs. The alignment model does not describe the latter phenomenon. Amongst all the known methods and models for backbending, the CHFB seems to be the only one capable of describing all the stages in the transition from the paired (BCS) to the completely unpaired state for such large angular momentum values as in the second backbend region. Here we should also point out that within the CHFB framework one can equally well understand the lack of backends at relatively low J values in many of the odd A rotors. Since the CHFB allows for alignment, blocking to alignment (as it does in the alignment model[14]), can also take place. This has been demonstrated by Ring, Mang, and Banarjee.[15] Thus all the existing data and the results reported here and elsewhere[1,2] support the antipairing interpretation. If more than two backbends are ever seen in any rare-earth rotor, a significant modification in the above interpretation would become a necessity.

In view of our results, it would be very interesting to clear up the experimental uncertainity regarding the order of 843- and 855-keV transitions in ^{158}Er and thus decide whether it is a discontinuity or a small backbend.

It is in the demonstration of the importance of the pairing degree of freedom and, thus, in the identification of the basic reason for backbends that we differ from Faessler and Ploszajczak.[16]

We thank the staff of the Computer Centre of Madras Indian Institute of Technology for their excellent help. One of us (S.C.K.N.) acknowledges with thanks the financial support from the Department of Atomic Energy, Government of India through Research Grant No. BRNS/24/74-77.

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Description of the Polarization of ^{12}B Produced in the Reaction ^{100}Mo(^{14}N,^{12}B)^{102}Ru

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(Received 2 August 1978)

The polarization of ^{12}B produced in the reaction ^{100}Mo(^{14}N, ^{12}B)^{102}Ru is explained in a fully quantum mechanical way. It is found that recoil plays a decisive role.

Recently we applied successfully a multistep direct reaction (MSDR) theory to explain continuous spectra of reactions induced by both light[5] and heavy[6] ions. The most important ingredient in making such calculations possible was to recognize that, in calculating continuous cross sec-

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