Evidence for Decreased Pairing Energies in Odd-N Nuclei from Band-Crossing Frequencies

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An odd-even neutron-number dependence of the alignment frequency of the first pair of $i_{13/2}$ quasineutrons in rare-earth nuclei is established. This effect is explained by a reduction of the neutron pairing-correlation parameter Δ_n for odd-N systems as compared to seniority-zero configurations in even-N nuclei.

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The cranked shell model has been successful in reproducing many of the spectroscopic properties of the near-yrast region of deformed nuclei up to $I \approx 30$ assuming a constant, large pairing-correlation parameter, Δ.[1-3] It is expected, however, that pairing should decrease with increasing angular momentum. The present Letter addresses this problem. Experimental evidence is reported for an odd-even neutron-number dependence of the angular frequency at which it is energetically more favorable for the first pair of $i_{13/2}$ neutrons to be aligned. Such a behavior can be explained by a reduction of the neutron pairing-correlation parameter, Δ_n, for the odd-N system as compared to the seniority-zero neutron configurations in even-N nuclei. The reduction in Δ_n presumably is the result of the "blocking" of the pairing contribution from a quasineutron orbit near the Fermi surface, and therefore is expected to be a function of the number of unpaired neutrons.

To establish the angular frequency, $\hbar\omega$, at which it is energetically favorable for a quasineutron pair to be aligned, it is convenient to express the information contained in the level schemes in terms of $\hbar\omega$ and the experimental excitation energy in a rotating frame,[1,2] e', or the Routhian. Nonrotational features, interpreted as band crossings, are apparent from the variation of e' as a function of $\hbar\omega$ for a specific cascade—see Fig. 1. The band-crossing frequencies, $\hbar\omega_c$, are well defined in such a plot. In even-even rare-earth nuclei the lowest-frequency band crossing corresponds to the crossing of the ground-state band with the aligned two-quasineutron "S band." This band crossing, which corresponds to the alignment of a pair of $i_{13/2}$ quasineutrons,[4] is responsible for the "backbends" observed in the yrast sequence of even-even rare-earth nuclei. A band crossing corresponding to the alignment of the same two quasineutrons can be observed in the low-lying negative-parity bands of the odd-N nuclei.[2] Here a band based on negative-parity, sin-

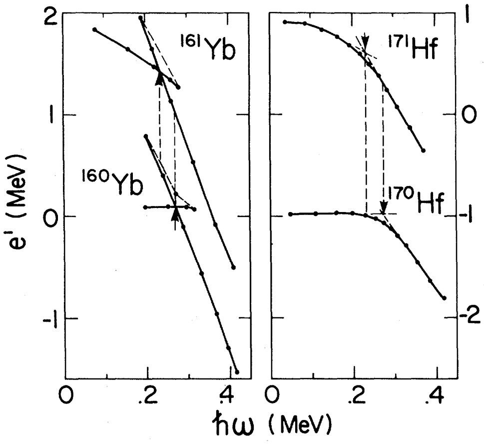

FIG. 1. Experimental Routhian, e', as a function of $\hbar\omega$ for the yrast bands of ^{160}Yb and ^{170}Hf and the lowest negative-parity bands of ^{161}Yb and ^{171}Hf indicating the definition of $\hbar\omega_c$ for weakly interacting bands (^{160,161}Yb) and strongly interacting bands (^{170,171}Hf). The ordinate scale on the left- and right-hand sides applies to even- and odd-mass nuclei, respectively.

gle quasineutrons crosses a three-quasineutron band involving the unpaired, negative-parity quasineutron as well as the same two $i_{13/2}$ quasineutrons, which are the configuration of the S band in the even-even nuclei.

Experimental band crossing (or alignment) frequencies have been obtained for a large number of Er,[5] Yb,[3,6] Hf,[7] and W[8] nuclei. The systematic behavior of $\hbar\omega_c$ is shown as a function of neutron number in Fig. 2. Throughout the $N=90$–102 mass region the $\hbar\omega_c$ corresponding to the alignment of the first pair of quasineutrons *is systematically lower* for odd-N nuclei than for even-even nuclei. This systematic variation of $\hbar\omega_c$ between odd- and even-N nuclei is not a result of the technique of defining $\hbar\omega_c$ from the experimental Routhians. The crossing frequencies are nearly independent of the Harris parameters[2] used to remove the excitation energy of the rotating core. If a nonzero value of K is assumed for the S band, the magnitude of the odd-even variation of $\hbar\omega_c$ would be even larger.

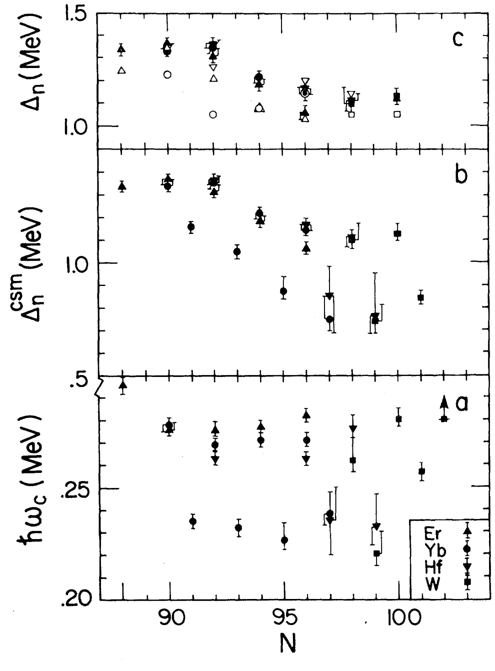

FIG. 2. (a) Systematics of $\hbar\omega_c$ for yrast bands in even-mass nuclei and for the lowest negative-parity band in odd-N nuclei. (b) Values of Δ_n^{CSM} necessary to reproduce the $\hbar\omega_c$'s in CSM calculations. The error bars only reflect uncertainties in the definition of the $\hbar\omega_c$'s and do not include model-dependent uncertainties resulting from the CSM calculations. (c) A comparison of Δ_n^{CSM} for even-N systems (solid symbols) with Δ_n^{oe} (open symbols) obtained from odd-even mass differences.

For odd-Z rare-earth nuclei the level schemes are not established sufficiently high in $\hbar\omega$ to define the crossing frequency from experimental Routhians. Some information, however, is available[9] for ^{169}Lu. For this $N=98$ nucleus the slope of e' changes sufficiently slowly with $\hbar\omega$ so that it is possible to obtain information on $\hbar\omega_c$ from the plot of the alignment ($i\equiv -de'/d\omega$) as a function of $\hbar\omega$. For the $[541]\frac{1}{2}$ proton band in ^{169}Lu$_{98}$ the $di/d\omega$ for given $\hbar\omega$ in the "crossing region" is nearly identical to that of its isotone ^{170}Hf$_{98}$ and is quite different from that for the neighboring odd-N system ^{171}Hf$_{99}$; see Fig. 3. A similar conclusion can be made from a comparison of i vs $\hbar\omega$ for bands in ^{165}Tm[10] with that of the appropriate bands in the neighboring even-even and odd-N nuclei.

The angular frequency of the alignment of the first pair of neutrons is less for odd-N nuclei than for even-N nuclei. These alignment or band-crossing frequencies, however, are nearly constant for isotones and for a number of even-even rare-earth nuclei of different Z, N, and deformations. Cranked shell model (CSM) calculations (see Fig. 4) indicate that such systematics may be explained by a reduction of the neutron pairing-correlation parameter, Δ_n, for the odd-N nuclei, presumably the result of the "blocking" of the

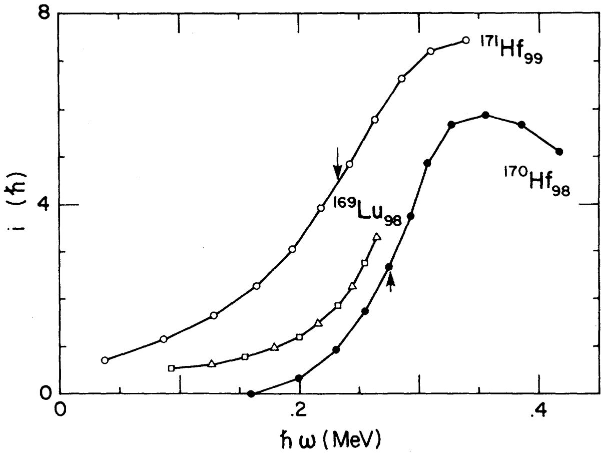

FIG. 3. Comparison of the alignments of the yrast bands in ^{169}Lu (favored and unfavored portions indicated by squares and triangles, respectively) and ^{170}Hf with that of the lowest negative-parity band of ^{171}Hf. The yrast band in ^{169}Lu aligns at frequencies comparable to that of the ^{170}Hf yrast band. For reference, the values of $\hbar\omega_c$ obtained from crossings in e' vs $\hbar\omega$ plots (see Fig. 1) are shown for ^{170,171}Hf by arrows.

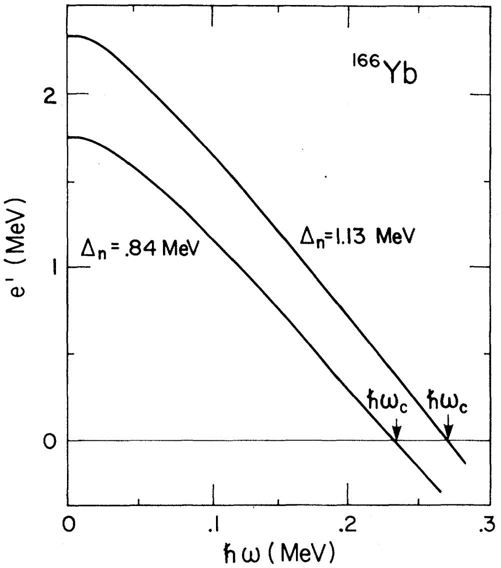

FIG. 4. Cranked shell-model two-quasiparticle Routhians as a function of $\hbar\omega$ for ^{166}Yb calculated with two different values Δ_n, indicating the shift in $\hbar\omega_c$ for a change in Δ_n.

pairing contribution from a quasineutron orbit near the Fermi surface. The values of Δ_n which reproduce the observed band crossings in CSM calculations, Δ_n^{CSM}, are shown in Fig. 2(b). In these calculations the deformations, ϵ_2 and ϵ_4, were varied according to the prescription of Bengtsson[11] and the Fermi surface was chosen to reproduce the correct neutron number. The change in the predicted alignments of the quasineutron orbits between $N=90$, where the $[660]\frac{1}{2}^+$ Nilsson configuration dominates, and $N=96$, where the Fermi surface is between the $[642]\frac{5}{2}^+$ and the $[633]\frac{7}{2}^+$ configurations, produces a decrease of Δ_n^{CSM} with mass number, which is superimposed on the odd-even variation resulting from the odd-even variation of $\hbar\omega_c$. It is emphasized that Δ_n^{CSM} is a parameter in the CSM calculations and, therefore, is not only model dependent, but also depends on the values of the other parameters in the calculations. Even the magnitude of such Δ_n^{CSM} values, however, becomes plausible when compared to Δ_n's obtained from the odd-even mass differences, Δ_n^{oe}—see Fig. 2(c). For $N=98$–102, where the deformations are stable, the values of Δ_n^{CSM} for even-even nuclei agree with Δ_n^{oe}. For $N=90$–94, where deformations are rapidly changing and where the nuclear masses are not known but are taken from systematics, there is no detailed agreement; however, the general decrease in the magnitude of Δ_n with increasing N is reproduced. The increased magnitude of Δ_n near $N=90$, which is the result of a local increase in the number of states near the Fermi surface, is reproduced in BCS calculations.[12]

Evidence for a reduction of Δ_n in odd-N nuclei as compared to seniority-zero bands in even-even nuclei also has been obtained from the analysis of moments of inertia, α-decay intensities, and two-neutron transfer cross sections.[13] It is difficult, however, to obtain quantitative results from the analysis of the moments of inertia and two-neutron transfer due to additional contributing effects. An ≈30% reduction in Δ_n is indicated from α-decay intensities for actinide nuclei, but such studies are not possible for rare-earth nuclei. The reduction of Δ_n due to the "blocking" of the appropriate orbit near the Fermi surface is calculated[12] to be ≈200 keV.

The present results indicate that it also would be necessary to use a reduced Δ_n in CSM calculations for multi-quasineutron configurations in even-N nuclei. The value of Δ_n apparently does not depend upon the proton number. Therefore, no problem is involved in the use of a full-strength pairing-gap parameter in CSM calculations to reproduce the second "backbend" in the yrast band, if the explanation of this feature is the alignment of a pair of quasiprotons.

In summary, an empirical odd-even neutron-number dependence of the angular frequency for the alignment of the first pair of $i_{13/2}$ quasineutrons is established. This behavior is explained by a reduction of Δ_n for odd-N systems as compared to the seniority-zero neutron configurations in even-N nuclei. A comparison of the magnitudes of the CSM Δ_n necessary to reproduce the crossing frequencies with values of Δ_n from odd-even mass differences indicates that it may be possible to obtain quantitative values of Δ from the crossing frequencies of quasiparticle bands. The agreement between Δ_n^{CSM} and Δ_n^{oe} also indicates that Δ_n is not strongly dependent upon $\hbar\omega$ for values of $\hbar\omega < \hbar\omega_c$. The loss in neutron pairing apparently is associated with neutron alignment and independent of proton alignment. It should be possible to reproduce the observed odd-even neutron-number systematics of the band-crossing frequencies in self-consistent calculations.

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