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EVIDENCE FOR REDUCED NEUTRON PAIRING CORRELATIONS IN ^{165}Yb

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ABSTRACT:

Three rotational sequences in ^{165}Yb have been extended to high spins by using the ^{130}Te (^{40}Ar,5n) and ^{150}Nd(^{20}Ne,5n) reactions. Evidence is presented for a reduction of the neutron pairing correlations at the highest rotational frequencies ($\hbar\omega$ > 0.40 MeV), but no quantitative measure of this reduction can be made.

Discrete lines studies of rapidly rotating nuclei have focused on band crossings corresponding to the alignment of high-j, low-Ω quasiparticles.[1] In the yrast sequence of the N=90 even-even isotones ^{158}Er[2] and ^{160}Yb[3,4], which have a moderate quadrupole deformation ($\varepsilon_2 \sim 0.2$), two band crossings have been established at angular frequencies $\hbar\omega$ = 0.27 and 0.41 MeV. These crossings are interpreted as the alignment of a pair of $i_{13/2}$ quasineutrons(1) and a pair of $h_{11/2}$ quasiprotons.[5] The present letter reports data for several configurations in an odd-N nucleus, ^{165}Yb (N=95), which has a somewhat larger deformation and so delays the quasiproton crossing to a higher rotational frequency. As a result the rotational sequences based on a specific neutron configuration can be studied to higher frequency than in the lighter, less deformed nuclei. In fact, the quasiproton band crossing has been observed at $\hbar\omega$ = 0.48-0.50 MeV in the two N=96 isotones ^{168}Hf[6,7] and ^{170}W[8] with ε_2 = 0.24-0.25.

Rotational decay sequences in ^{165}Yb established in previous studies[9] have been extended to higher angular momentum by using the ^{130}Te(^{40}Ar,5n) and ^{150}Nd(^{20}Ne,5n) reactions.[10] The 185 MeV ^{40}Ar and 102 MeV ^{20}Ne beams were provided by the 88-inch cyclotron of the Lawrence Berkeley Laboratory. The combination of the ^{20}Ne beam and a thin ^{150}Nd target (~ 1mg/cm^2) proved to be the best compromise between populating the evaporation residues with large angular momentum and reducing the Doppler broadening for γ-ray energies higher than 700 keV.

In this experiment γ-γ coincidences were obtained from an array of five Ge(Li) detectors, four of them set at 153° with respect to the beam direction. An additional coincidence was required with one or more of five 7.6 x 7.6 cm NaI detectors used as a multiplicity filter. Angular distribution measurements were obtained from the fifth Ge(Li) detector positioned alternatively at 0° and 87°. Due to the complexity of the γ-ray singles spectra, the multipolarities of the weaker γ-rays were deduced from events in this detector in coincidence with at least one of the 153° detectors and one of the NaI detectors. They are in agreement with those established previously[9] where such a comparison can be made. The extension of the $(\pi,\alpha) = (-,1/2)$ and $(-,-1/2)$ sequences is based on the relative intensities of the transitions in the γ-γ coincidence data.[10] In the $(+,1/2)$ sequence, the 815 keV transition is observed in coincidence with the 895 keV transition as well as with both the 832 and 864 keV transitions. These latter transitions, however, are not observed in coincidence with the 734 keV transition, and the 728 and 815 keV transitions are of nearly equal intensity in the 832 and 864 keV gates.[10] Thus, two 815 keV transitions are placed in the level scheme (Fig. 1). The experimental results are analyzed in the next few paragraphs and then will be discussed.

The component of the total angular momentum aligned with the rotation

$$I_x = \sqrt{(I+1/2)^2 - K^2} \qquad (1)$$

is presented in Fig. 2 as a function of the angular frequency

$$\hbar\omega(I) = \frac{E(I+1) - E(I-1)}{I_x(I+1) - I_x(I-1)} \qquad (2)$$

for four rotational sequences in ^{165}Yb together with similar values for the yrast sequence of the neighboring even-even isotopes ^{164}Yb[11] and ^{166}Yb.[12] For $\hbar\omega > 0.28$ MeV in the negative-parity bands of ^{165}Yb and after the blocked band crossing at $\hbar\omega \sim 0.36$ MeV in the positive-parity band, I_x is observed to increase linearly with the frequency for these seniority-three configurations. The rise is not as linear for the seniority-two configurations in the even-even ^{164,166}Yb, but is linear for $\hbar\omega > 0.38$ MeV in ^{168}Hf,[6] the isotone of ^{166}Yb.

The kinematic moments of inertia

$$\mathcal{J}^{(1)}/\hbar^2 = \frac{I_x}{\hbar\omega} \qquad (3)$$

are presented as a function of the frequency in Fig. 3a. At large rotational frequencies ($\hbar\omega > 0.3$ MeV) the $\mathcal{J}^{(1)}$ values for the seniority three ($v = 3$) sequences in ^{165}Yb are only slightly frequency dependent. In the frequency region where such data exist for the $v=2$ yrast sequences in ^{164,166}Yb, the $\mathcal{J}^{(1)}$ values are slightly smaller than those of the $v=3$ configurations. However, all $\mathcal{J}^{(1)}/\hbar^2$ values, if extrapolated, seem to converge at the largest rotational frequencies to values close to 65 MeV^{-1}. This is only slightly lower than that of the moment of inertia of a deformed ($\varepsilon_2 = 0.24$) rigid rotor, $\mathcal{J}_{rig.}/\hbar^2 = 73$ MeV^{-1}.

The dynamic moments of inertia

$$\mathcal{J}^{(2)}_{\text{band}}/\hbar^2 = \frac{dI_x}{\hbar d\omega} = \frac{I_x(I+1) - I_x(I-1)}{\hbar[\omega(I+1) - \omega(I-1)]} \tag{4}$$

are shown as a function of the frequency in Fig. 3b. They are much more sensitive to changes in the local structure than $\mathcal{J}^{(1)}/\hbar^2$, but are nearly constant for the negative-parity states for $0.36 < \hbar\omega < 0.44$ MeV.

The excitation energies in a rotating frame (Routhians or e') calculated relative to a reference configuration with a moment of inertia equal to $61.2\,\hbar\ \text{MeV}^{-1}$ (corresponding to the moment of inertia of the "linear" region of the I_x versus $\hbar\omega$ plots in Fig. 2).

$$e'(\omega) = E(\omega) - \hbar I_x \omega + \frac{1}{2}\, 61.2\hbar^2\omega^2 \tag{5}$$

are shown in Fig. 4a for the four bands in ^{165}Yb and in Fig. 4b for two bands in ^{164,166}Yb. $E(\omega)$ is the energy above the ground state in the laboratory frame. It should be noted that for $\hbar\omega > 0.4$ MeV the yrast configuration in Fig. 4a has negative parity.

From the experimental results a striking feature that emerges is the nearly constant value of $\mathcal{J}^{(1)}$ above $\hbar\omega = 0.36$ MeV for all three configurations in ^{165}Yb. Two other mathematically equivalent ways to say this are $\mathcal{J}^{(2)}_{\text{band}}$ is nearly equal to $\mathcal{J}^{(1)}$ and the I_x vs. $\hbar\omega$ curve is approximately straight with an intercept near zero. In order to understand this behavior we can begin by considering the properties of a system with no pairing correlations, because the three quasi-neutrons and high rotational frequency are expected to result in a strong reduction of pairing. With no pairing (neutron or proton), $\mathcal{J}^{(1)}$ should average to the deformed rigid-rotor value, but should not be constant due to the occurrence of particle alignments which cause jumps in $\mathcal{J}^{(1)}$. All C.S.M. calculations of high-spin nuclear behavior[13,14] predict that part of the angular momentum will continue to come in these sudden alignments leaving significantly less available for the collective motion. Between alignments $\mathcal{J}^{(2)}_{band}$ should therefore be less than $\mathcal{J}^{(1)}$ (around 1/2 to 2/3 on average), causing $\mathcal{J}^{(1)}$ to drop slowly. Thus $\mathcal{J}^{(1)}$ is expected to oscillate around the rigid-rotor value. If the shape, deformation, and configuration are frozen, $\mathcal{J}^{(2)}_{band}$ itself is expected to decrease slowly as the more easily available angular momentum is used up, but that is a higher order effect.

This described behavior is not very similar to that observed. However, there are no quasi-protons in the observed bands of ^{165}Yb, so that the proton pairing correlations are almost surely not quenched. This means that the protons will contribute less angular momentum at a given frequency, resulting in an $\mathcal{J}^{(1)}$ lower than the rigid-body value (as observed). It also means that the proton pairing will be continuously reduced by the Coriolis interaction (Coriolis anti-pairing) as $\hbar\omega$ increases. This will, by itself, contribute to an increased $\mathcal{J}^{(2)}_{band}$ value, and together with the lowered $\mathcal{J}^{(2)}_{band}$ expected after the (neutron) alignments, could give a nearly constant $\mathcal{J}^{(2)}_{band} \sim \mathcal{J}^{(1)}$ as observed. If so, this is a somewhat accidental cancellation of two opposite tendencies. But other examples are known where $\mathcal{J}^{(2)}_{band} \sim \mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}_{band}$ is quite constant over a wide range of frequency. Thus there may be more fundamental reasons for this behavior, but they are not apparent in present C.S.M. calculations. The above discussion requires that the neutron pairing be rather low, but gives no quantitative measure of it. It should also be noted that the moments of inertia of the seniority three neutron states in ^{165}Yb are larger, but only slightly so, than the seniority two states of the neighboring even-even ^{164,166}Yb, indicating possibly not much further decrease in neutron pairing correlations with an additional unpaired particle.

A different type of argument that the neutron pairing is greatly reduced at large $\hbar\omega$ in ^{165}Yb comes from the feature that at high frequency the yrast configuration has negative parity. Cranked-Shell-Model calculations[15] for ^{165}Yb (and heavier Yb's) predict positive-parity configurations to lie lowest for neutron-pairing gaps as small as 200 keV; only for values of Δ_n smaller than that does a negative-parity-configuration become yrast for $\hbar\omega \geq 0.4$ MeV. However, the strength of this argument is weakened by the circumstance that such states are predicted to be yrast even with full neutron-pairing correlations for the lighter Yb nuclei at $\hbar\omega < 0.4$ MeV,[16] and it is not clear how accurately the calculations can make a dividing line for such behavior at ^{165}Yb. In addition, there is some question as to the influence of the octupole vibrations on the lowest negative-parity states.

But on balance, this feature is another result arguing for strongly reduced neutron correlations.

Finally, we can make a measurement of the change in the total pairing correlation energy as a function of high rotational frequency. Consider the difference between the Routhian of the two-quasineutron band AB and the sum of its one-quasineutron constituents, $\delta = e'_{AB} - e'_A - e'_B$, with reference states chosen such that the lowest real state in both even and odd nuclei has $e' = 0$ at $\omega = 0$. At $\omega = 0$, δ is a measure of the neutron pairing correlation energy, being roughly equal to twice the odd-even mass difference. For non-zero ω, with the assumption that the only change is the loss in neutron and proton pairing and not, for example, a change in deformation,

$$\begin{aligned}\delta = &+ \varepsilon'(n,\omega,AB) - \varepsilon'(n,\omega{=}0,0) - \varepsilon'(n,\omega,A) + \varepsilon'(n,\omega{=}0,g) \\ &- \varepsilon'(n,\omega,B) + \varepsilon'(n,\omega{=}0,g) - \varepsilon'(p,\omega,0) + \varepsilon'(p,\omega{=}0,0)\end{aligned} \quad (6)$$

Here $\varepsilon'(p,\omega,0)$ and $\varepsilon'(n,\omega,A)$ are (negative) pairing correlation energies at rotational frequency ω for protons and neutrons in the zero quasiparticle and one-quasineutron configuration A, respectively, and $\varepsilon'(n,\omega{=}0,g)$ is the pairing energy of the odd-mass ground state at $\omega{=}0$. The first six terms are the changes in neutron pairing, but the last two represent changes in the proton pairing. Although the total pairing energy falls steeply with ω (Fig. 4c), it is not, in general, possible to separate the effects of the neutrons and of the protons although calculations show that the major effect in the range of ω we have observed experimentally is due to loss of neutron pairing. However, it should be noted that at still larger ω, where the proton as well as the neutron pairing has been quenched, all the terms will approximately cancel but for $\varepsilon'(p,\omega=0,0)$, leaving a large negative value of order $-1/2\ g_p\Delta_p^2$. Thus the (extrapolated) crossing of the horizontal axis in Fig. 4c is not the value of ω where the neutron pairing vanishes, but comes early depending upon the relative quenching of the neutron and proton pairing. But clearly by $\omega=0.36$ the neutron pairing has been greatly diminished.

Thus there are a number of features about the high-spin states in ^{165}Yb for $\hbar\omega$ = 0.3-0.5 MeV that suggest that the neutron pairing correlations are substantially reduced. Although it cannot be ruled out by the experiments performed so far that part of the effects are not due to a shape change, such a deformation change is not predicted theoretically for this frequency range.[17,18] However, the nearly equal and (large) constant values of $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ observed in this and in other recent studies at high rotational frequencies pose a real challenge; such a situation is not expected from simple theory for the unpaired system, and too many examples are accumulating to believe it is accidental. Future experiments (observation of the next few states) and better calculations that simultaneously take into account changes with pairing and deformation may solve this problem, but it is possible that some physics is missing from the picture.

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Figure Captions

Fig. 1. Level scheme of ^{165}Yb populated by the ^{150}Nd (^{20}Ne,5n) and the ^{130}Te (^{40}Ar,5n) reactions. The number between parenthesis are the relative intensities of the γ transitions obtained with the ^{20}Ne reaction.

Fig. 2. Plot of I_x vs. $\hbar\omega$ for four rotational bands in ^{165}Yb and the yrast sequences in $^{164,166}Yb$.

Fig. 3. (a) Plot of $\mathcal{J}^{(1)}/\hbar^2$ vs. $\hbar\omega$ for four rotational bands in ^{165}Yb and the yrast bands in $^{164,166}Yb$

(b) Plot of $\mathcal{J}^{(2)}/\hbar^2$ vs. $\hbar\omega$ for three bands in ^{165}Yb and the yrast bands in $^{164,166}Yb$

Fig. 4. (a) Plot vs. $\hbar\omega$ of Routhians relative to the $\mathcal{J} = 61.2\ \hbar^2\ MeV^{-1}$ reference for four rotational bands in ^{165}Yb

(b) Plot vs. $\hbar\omega$ of Routhians relative to the same reference for two different 2-particle configurations in ^{164}Yb and ^{166}Yb together with the constructed 2-particle Routhians in ^{165}Yb.

(c) Plot vs. $\hbar\omega$ of δ, the difference between the average of the 2-particle Routhians in the even-even nuclei and the sum of $\varepsilon'_A + \varepsilon'_B$ in ^{165}Yb.

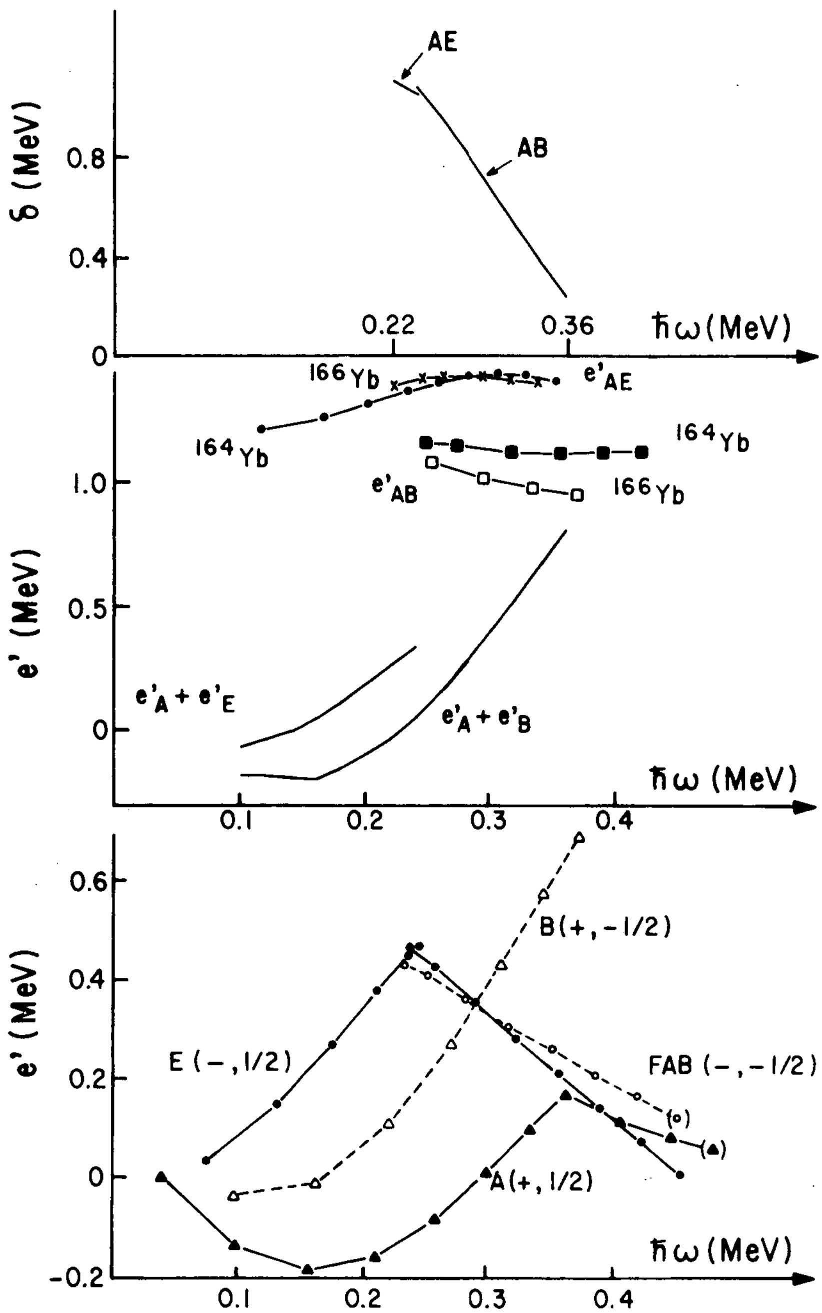

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Fig. 1

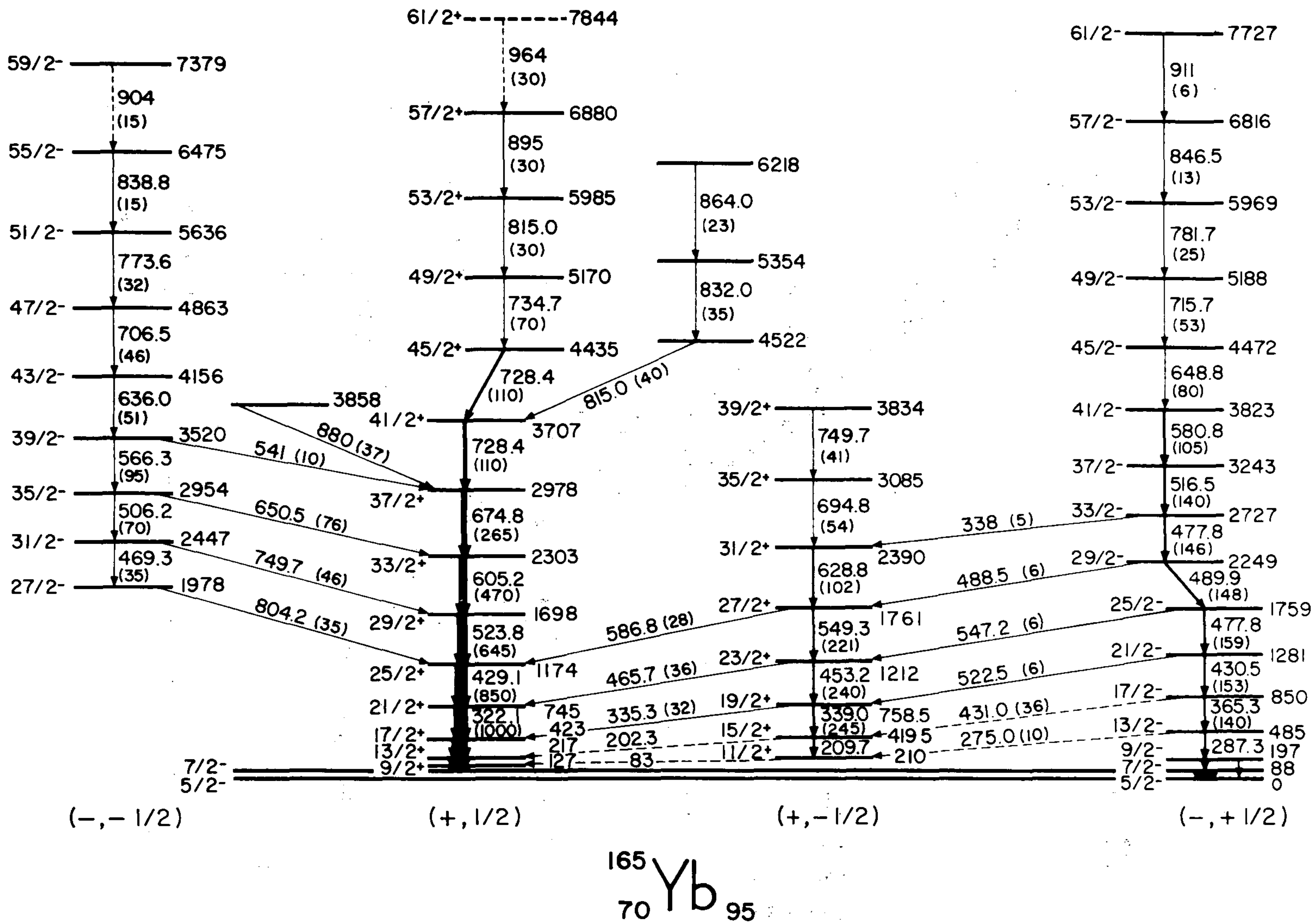

Fig. 2

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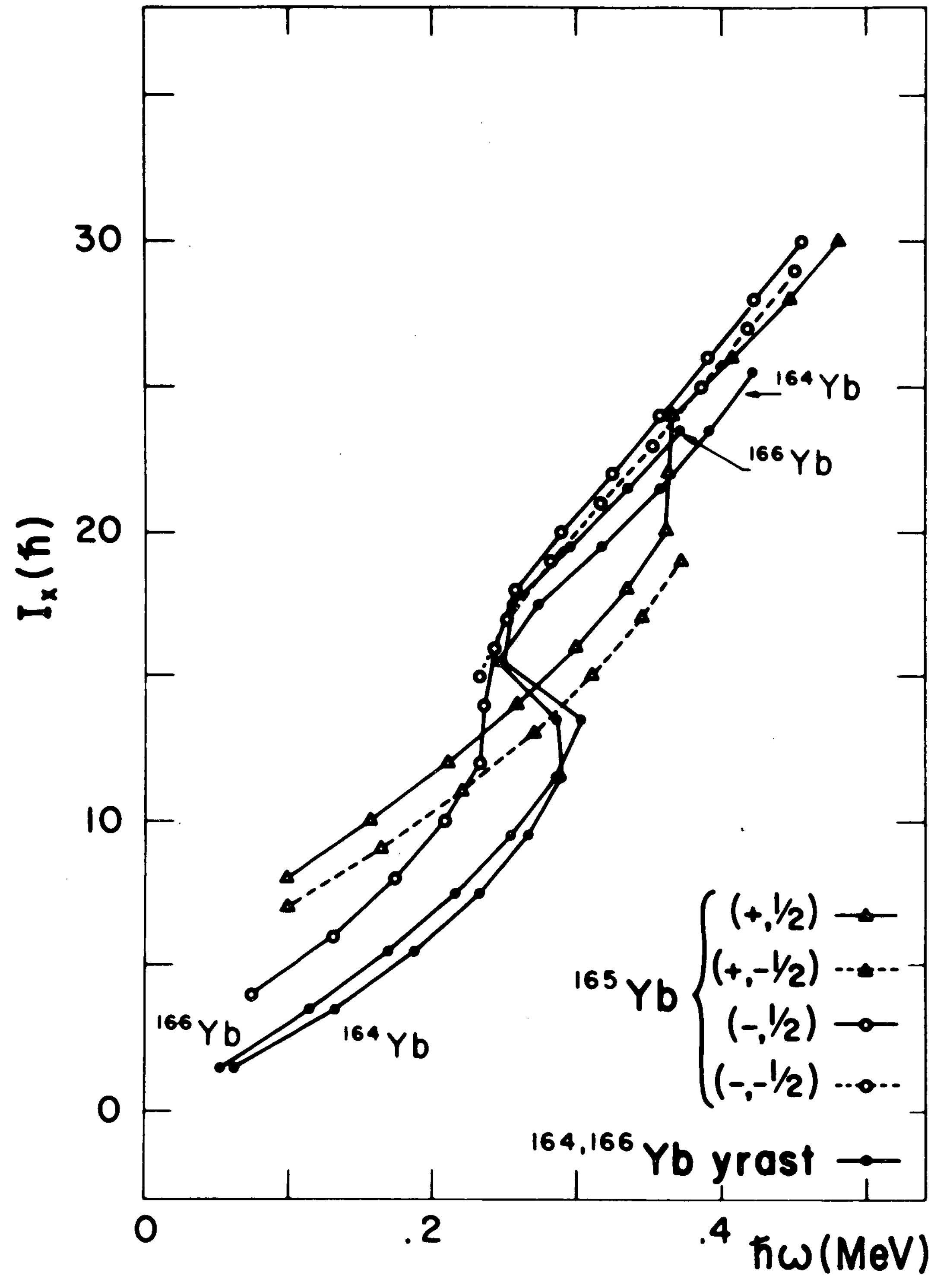

XBL 841-410

Fig. 3

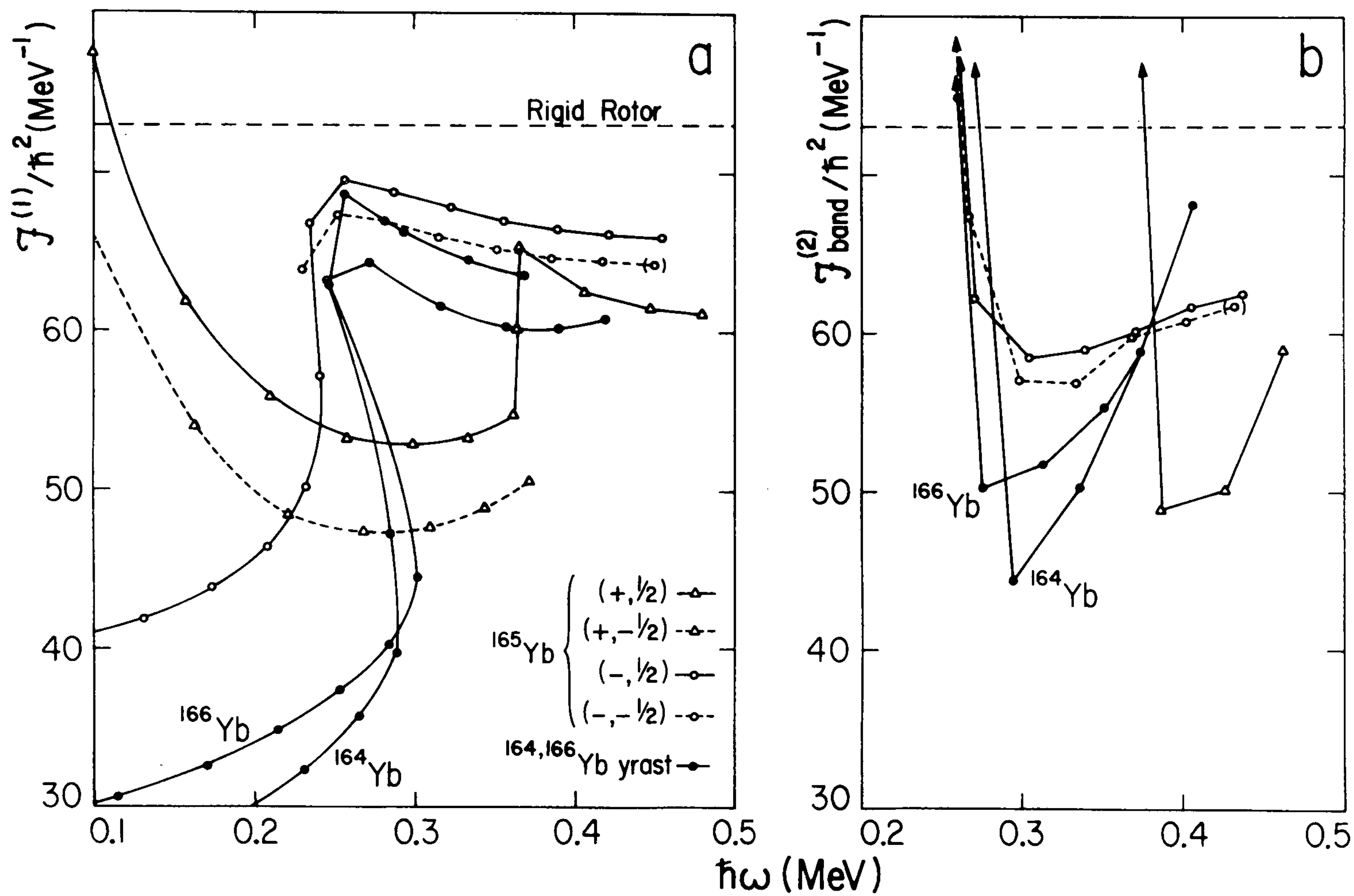

Fig. 4

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