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$h_{11/2}$ band in ^{159}Tm and the second yrast crossing in ^{158}Er and ^{160}Yb

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All the members of the $h_{11/2}$ rotational structure have been observed in $^{159}_{69}$Tm up to spin $\frac{49}{2}^+$. The alignments of these bands relative to the core nuclei $^{158}_{68}$Er$_{90}$ and $^{160}_{70}$Yb$_{90}$ are presented. These data provide additional evidence that the second backbend of the yrast structure of the core results from an $(h_{11/2})^2$ proton alignment.

[NUCLEAR REACTIONS ^{148}Sm(^{14}N,3n)^{159}Tm, $E = 68$ MeV; measured γ-γ coin, $\gamma(\theta)$. ^{159}Tm deduced levels.]

The second crossing in the yrast structure which has been found in the even-even $^{158}_{68}$Er and $^{160}_{70}$Yb nuclei,[1–3] is absent in the neighboring $^{156}_{66}$Dy and $^{164}_{72}$Hf nuclei.[4,5] The calculations of Faessler and Plozajczak[6] and Bengtsson and Frauendorf[7] have suggested that this crossing results from an alignment of $h_{11/2}$ protons, in addition to the $i_{13/2}$ neutrons aligned at the first crossing. In order to test this prediction, the present paper reports on the rotational structure of the $h_{11/2}$ proton in $^{159}_{69}$Tm. The gain in aligned angular momentum (Δi) has been extracted from the experimental data and compared with the theoretical prediction. With this Δi one may calculate the gain in alignment at the second backbend in the neighboring even-even nuclei.

The detailed studies by Riedinger *et al.*[3] showed the presence of three crossing frequencies in the rotational bands of ^{160}Yb. The first and second at $\hbar\omega_{c_1} \approx 0.27$ and $\hbar\omega_{c_2} \approx 0.36$ MeV were associated with the breaking of an $i_{13/2}$ pair and its alignment with the rotation of the core. The reason for the third crossing at $\hbar\omega_{c_3} \approx 0.42$ MeV is the object of the present study. The experimental data for ^{159}Tm will be compared with the data for ^{158}Er and ^{160}Yb and the theoretical predictions.

The ^{148}Sm(^{14}N,3n)^{159}Tm reaction was used with 68 MeV beams from the McMaster University tandem accelerator. The targets were ~ 1 mg/cm^2 thick and backed by ^{208}Pb. In order to enhance the higher spin states in the cascade, coincidences among an array of five Ge(Li) detectors were gated by additional γ rays detected in six NaI detectors. Angular distributions of the γ rays were measured and were also gated

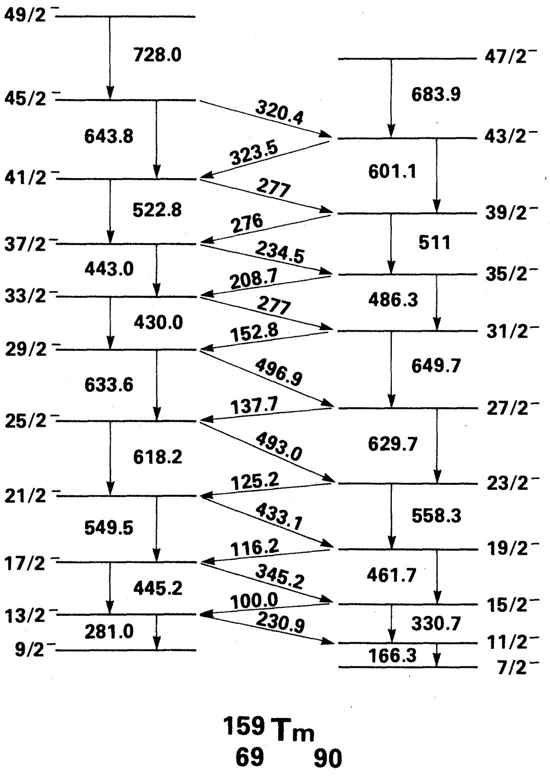

FIG. 1. Partial level scheme for ^{159}Tm showing the $h_{11/2}$ bands. The excitation energy of the $\frac{7}{2}^-$ member is > 13 keV and probably < 80 keV. Transitions to the $\frac{5}{2}$ ground state (Ref. 11) have not been observed.

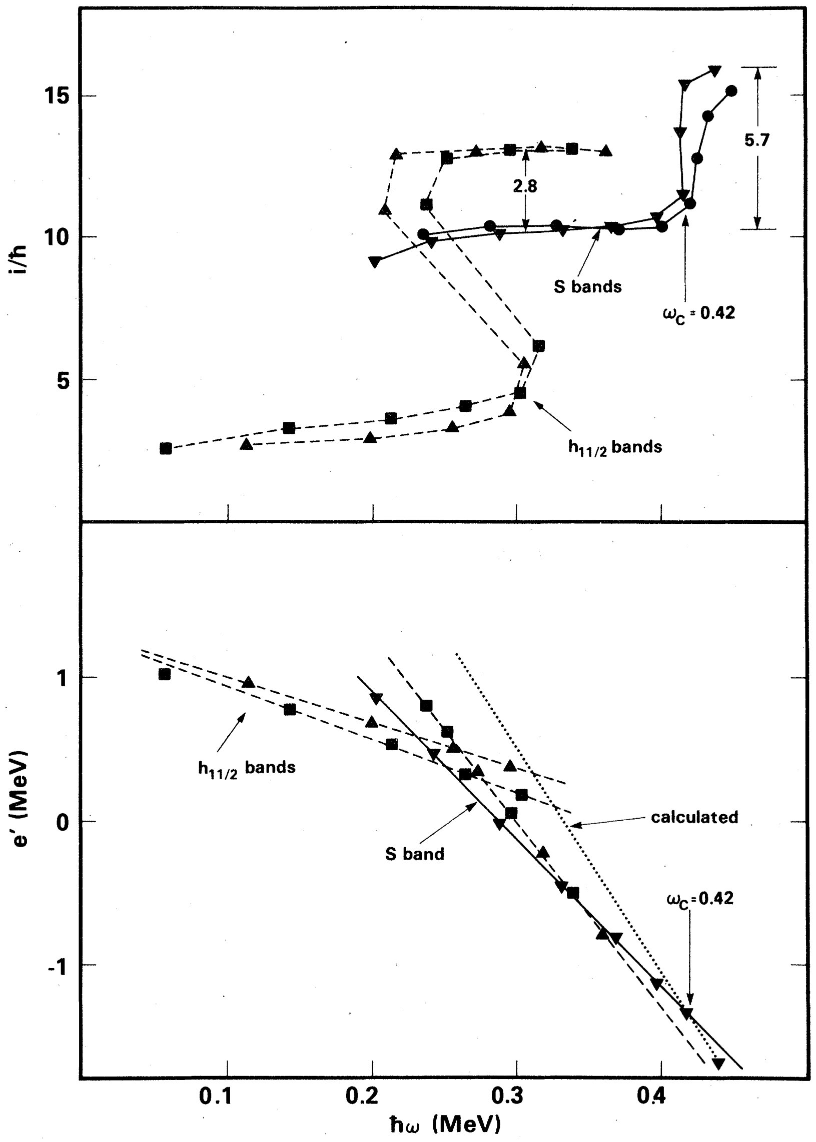

FIG. 2. In the upper part, the aligned angular momentum of the $h_{11/2}$ bands (▲, ■) is compared with that for the S bands in ^{158}Er(●) (Ref. 1) and ^{160}Yb(▼) (Refs. 3 and 5). All the calculations are based on $\mathcal{J}_0 = 18$ MeV^{-1} and $\mathcal{J}_1 = 90$ MeV^{-3}. After the backbend, the $h_{11/2}$ band has an alignment of $2.8\hbar$ in addition to the alignment of the S band. In the lower part, the experimental Routhians are shown for these bands. The dotted line is a calculation of the predicted excitation energy of the $(h_{11/2})_p{}^2(i_{13/2})_n{}^2$ band.

through the use of the NaI array.

The analysis of the 150×10^6 coincidences revealed the presence of a number of bands and crossings. The $h_{11/2}$ structure was identified with the yrast sequence and the low spin members continue the smooth trend observed in the lighter $N = 90$ odd-proton nuclei. The level scheme representing only the $h_{11/2}$ structure is illustrated in Fig. 1. The presence of two band sequences with $\Delta I = 2$ and different signatures[8,9] may be seen. These bands, which are connected by strong $\Delta I = 1$ transitions, both undergo decreases in transition energy similar to the behavior of the yrast structure of the neighboring even-even nuclei.

The meaning of these data is most clearly understood by calculating the aligned angular momentum, i, as a function of the rotational frequency, $\hbar\omega$. The prescription for the calculation of these quantities has been explained in Refs. 8 and 9. The parameters for the Harris expansion[10] were taken as the average of those for the neighboring even-even nuclei, $\mathcal{J}_0 = 20$ MeV^{-1} for ^{158}Er and $\mathcal{J}_0 = 16$ MeV^{-1} for ^{160}Yb and $\mathcal{J}_1 = 90$ MeV^{-3}. Although it is not critical to the calculation, the bands were assumed to have $K = \frac{7}{2}$.

The alignments of the $h_{11/2}$ bands in ^{159}Tm and the yrast sequences in ^{158}Er and ^{160}Yb are shown in the upper part of Fig. 2. The choice of $\mathcal{I}_0 = 18$ MeV^{-1} has the fortuitous consequence of producing a constant i for the S bands, i.e., the $(i_{13/2})_n{}^2$ bands in the core nuclei. The value of $i = 10.3\hbar$ represents the alignment gain at the first backbend. It can be seen that up to $\hbar\omega \approx 0.30$ the $h_{11/2}$ sequences have a slowly varying alignment. This may be a true gain in alignment at higher rotational frequencies or may result from an inadequacy of the angular momentum expansion.

Since the $i_{13/2}$ quasiparticle is not blocked for these bands, one expects a band crossing at $\hbar\omega_{c_1}$. Indeed one finds that these bands backbend at precisely the same frequency (0.27 MeV/$\hbar$) as the even-even nuclei, showing that the odd proton has not affected these crossings. Beyond this backbend the difference in alignment between the bands with different signatures, α, has disappeared. The reason for this signature splitting is not understood.

Since after the backbend the structure of these bands is $(h_{11/2})_p(i_{13/2})_n{}^2$, it is most straightforward to compare their alignments to that of the S band, $(i_{13/2})_n{}^2$. As may be seen, the $h_{11/2}$ proton contributes an additional alignment of $2.8\hbar$ in both bands. Thus the gain in alignment that the yrast structure should experience at the second backbend is $5.6\hbar$ which is in good agreement with the value of $5.7\hbar$ observed in ^{160}Yb and the calculation of $6.0\hbar$ made in Ref. 7.

Although this represents a good confirmation that the second yrast crossing results from the alignment of a pair of $h_{11/2}$ protons, one can carry the analysis further by constructing the $(h_{11/2})_p{}^2(i_{13/2})_n{}^2$ band and seeing if such a band is consistent with a crossing at $\hbar\omega_{c_3} = 0.42$ MeV. Again, following the procedures outlined in Ref. 7, one may calculate the quasiparticle energies in the rotating frame (the experimental Routhian), i.e., $e'(\omega) = E'(\omega) - E_g'(\omega)$. This is the energy, $E'(\omega)$, of a state as observed in a frame rotating with an angular velocity ω, relative to the excitation energy, $E_g'(\omega)$, of the even-even core. The slope of the e' vs $\hbar\omega$ curve is given by $-i$.

The lower part of Fig. 2 shows a plot of e' vs $\hbar\omega$ for the $h_{11/2}$ bands in ^{159}Tm and the S band in ^{160}Yb. The discontinuities in the lines for the $h_{11/2}$ bands occur, of course, at the backbend in these bands at $\hbar\omega_c \approx 0.27$ MeV. The alignment of the $(h_{11/2})_p{}^2(i_{13/2})_n{}^2$ band has been calculated by adding the additional alignment of $2.8\hbar$ for each proton, to the known alignment of the S band. This gives a total alignment of $15.9\hbar$ for the four quasiparticle band. A band with this alignment is shown in Fig. 2, crossing the S band at $\hbar\omega_{c_3} = 0.42$ MeV. If this were extrapolated back to $\omega = 0$, it would have an excitation energy of 2.36 MeV relative to the S band. This relative excitation energy at $\omega = 0$ should be represented by the proton energy gap, $2\Delta p$, plus a contribution due to the excitation energy of the $h_{11/2}$ bands. The Δ_p extracted by this method is $1.10 \leq \Delta_p \leq 1.18$. (The range arises from an uncertainty in the excitation energy of the $h_{11/2}$ band.) The value of Δ_p found from the odd-even mass differences is 1.26 for ^{160}Yb and 1.20 for ^{158}Er. Since this simple picture does not include any contributions which should arise from interactions among the quasiparticles, the agreement is consistent with the interpretation that the second backbend results from a crossing of the $(b_{11/2})_p{}^2(i_{13/2})_n{}^2$ band with the S band at $\hbar\omega_{c_3} = 0.42$ MeV.

It might be possible to use these bands to study crossings at still higher frequencies. Crossings arising from the $h_{9/2}$ neutron band should appear at $\hbar\omega_{c_4} \approx 0.5$ MeV. Since the $(h_{11/2})_p{}^2$ crossing is blocked in ^{159}Tm, one should observe these bands continuing through the $\hbar\omega_{c_3}$ crossing and reach the $\hbar\omega_{c_4}$ crossing at a spin of $\approx \frac{65}{2}\hbar$. This is equivalent to the spins which have already been studied in the neighboring even-even nuclei and should be obtainable using present techniques.

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