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BRIEF REPORTS

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Second proton and neutron alignments in the doubly-odd nuclei ^{154,156}Tb

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High-spin states in the doubly-odd nuclei ^{154,156}Tb have been populated in two separate experiments using the ^{36}S$+^{124}$Sn reaction at different beam energies (160 and 175 MeV). The yrast structures of both nuclei were extended to much higher spin ($I \leqslant 48\hbar$) than previously known and several quasiparticle alignments have been identified. These include the second neutron alignment and a clear delineation of the second proton crossing in ^{156}Tb. Systematics of these crossings for odd-Z nuclei and comparisons with results of cranked shell model calculations are discussed. [S0556-2813(99)03302-6]

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An important theme in high-spin studies has been the investigation of the rotational alignment of specific pairs of quasiparticles. The observation of the associated band crossings have, for example, provided detailed information concerning configuration assignments, deformations, and pairing correlations. In the present work, the level structures of ^{154,156}Tb ($Z=65$) have been considerably extended to higher angular momenta and band crossings have been observed for the first time in both of these light rare-earth isotopes. In ^{156}Tb, it has been possible to firmly delineate the alignment of the second most favored pair of protons. This crossing and its systematic observation in neighboring nuclei provides strong evidence for the persistence of significant proton pairing correlations at high spin ($I \approx 30-40\hbar$). Trends in both the second proton and neutron crossing frequencies can now be established for odd-Z nuclei. These trends can then be compared with cranked shell model predictions. This work is part of a systematic study of the terbium nuclei from $N=88-92$ [1–4].

High-spin states in ^{154,156}Tb were populated by two separate experiments using the ^{36}S$+^{124}$Sn reaction with different beam energies. The weak $p5n$ reaction channel ($\sim 1\%$ of the total fusion cross section) leading to ^{154}Tb was observed with a 175 MeV beam bombarding a target consisting of a 1 mg/cm^2 layer of ^{124}Sn evaporated onto 15 mg/cm^2 of Au. With a reduced beam energy of 160 MeV and two thin (0.35 mg/cm^2) stacked ^{124}Sn targets, states in ^{156}Tb from the $p3n$ channel (also $\sim 1\%$ of the total fusion cross section) were populated. Both experiments were performed at the 88-Inch Cyclotron facility at the Lawrence Berkeley National Laboratory using the Gammasphere spectrometer [5]. In the former experiment, 67 Compton-suppressed detectors were used, while 93 suppressed detectors were operated in the latter. The data from the two experiments were sorted into separate $E_\gamma \times E_\gamma \times E_\gamma$ coincidence cubes and analyzed using the program LEVIT8R [6]. The $4n$ (^{156}Dy [7]), $5n$ (^{155}Dy [8,9]), and $6n$ (^{154}Dy [10]) neutron evaporation channels dominated the reaction and have been or will be reported elsewhere.

The most recent high-spin spectroscopic information on ^{154,156}Tb was published in Ref. [11]. In this work, the positive-parity $\nu i_{13/2} \otimes \pi d_{5/2}$ [$AE_p(F_p)$ using the quasiparticle labeling scheme of the standard cranked shell model [12,13]] and the yrast negative-parity $\nu i_{13/2} \otimes \pi h_{11/2}$ [$AA_p(B_p)$] bands were observed up to spin (19^+) and (22^-) in ^{154}Tb, and to spin (23^+) and (24^-) in ^{156}Tb, respectively. Figure 1(a) displays a summed coinci-

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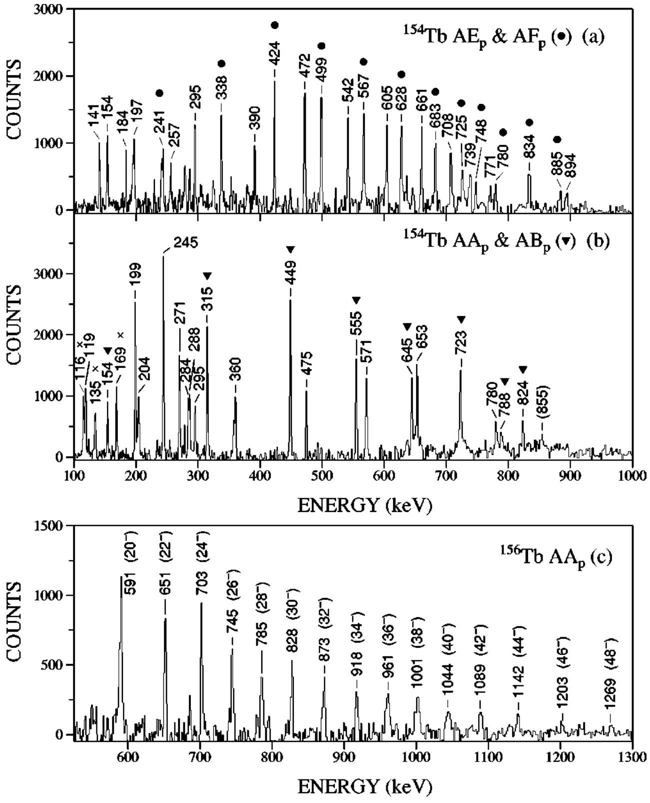

FIG. 1. (a) Summed coincidence spectrum for the $AE_p(F_p)$ band in ^{154}Tb. The $E2$ transitions in the $AF_p(+,0)$ signature are denoted by filled circles. (b) Summed coincidence spectrum for the $AA_p(B_p)$ band in ^{154}Tb. The $E2$ transitions in the $AB_p(-,1)$ signature are denoted by filled triangles. Peaks marked with a $\times$ correspond to transitions depopulating the (9^-) state to other low-spin levels [11]. (c) Summed coincidence spectrum for the extended portion of the $AA_p(-,0)$ signature in ^{156}Tb. Spin assignments for the depopulated states are given for each transition (see text for details).

dence spectrum for the strongly coupled, positive-parity band in ^{154}Tb from the present work. The level scheme for ^{154}Tb is shown in Fig. 2. Using the spin assignments of Ref. [11] for the low-spin states, it can be seen that the $AE_p(F_p)$ structure has been extended to $I^\pi=(32^+)$. A summed coincidence spectrum for the negative-parity $AA_p(B_p)$ band is shown in Fig. 1(b), which is now established to $I^\pi=(28^-)$. Note that no linking transitions between these two structures have been observed in either Ref. [11] or the present work, and as a result their relative energies are not known.

Only one signature (AA_p) of the $\nu i_{13/2}\otimes\pi h_{11/2}$ band was extended to higher spin in ^{156}Tb. However, as can be seen in Fig. 1(c), it is now observed to very high rotational frequencies ($\hbar\omega>0.6$ MeV). Since the signature partner was not observed to higher spin than what was previously known, a level scheme for this band has been omitted here. The original spin assignment given in Ref. [11] was called into question by the systematic study of $\nu i_{13/2}\otimes\pi h_{11/2}$ bands in the $A\approx160$ region [14]. It was suggested in Ref. [14] that the spin of this band should be increased by $2\hbar$. This increase in the band head spin has been adopted here and thus the 1269 keV transition depopulates the (48^-) state, which is the highest normal deformed spin state observed in an odd-odd nucleus for this mass region.

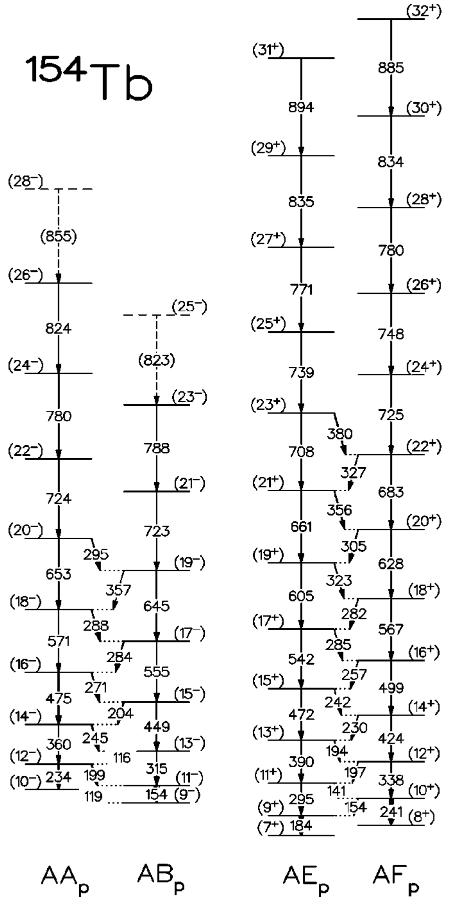

FIG. 2. The level scheme of ^{154}Tb derived from the present work. Tentative transitions or levels are denoted with dashed lines. Relative excitation energies are not known (see text).

Figure 3(a) displays the alignment of the ^{154}Tb bands versus rotational frequency. The $\alpha=-\frac{1}{2}$ signature of the $\pi h_{11/2}$ band (A_p) in ^{153}Tb [3] is also shown for reference. A Harris parametrization [15] was used where the values $\mathcal{J}_0=12\ \hbar^2/\mathrm{MeV},\mathcal{J}_1=90\ \hbar^4/\mathrm{MeV}^3$ were chosen from previous work on ^{153}Tb [3]. Neither the $AA_p(B_p)$ nor the $AE_p(F_p)$ excitations in ^{154}Tb undergo the AB crossing observed in the A_p band of ^{153}Tb due to the Pauli blocking of the unpaired $i_{13/2}$ neutron. However, an alignment of $\sim5\hbar$ does occur in the $AE_p(F_p)$ band at a frequency of $\hbar\omega_c\approx0.37$ MeV. The beginning of a band crossing is also evident in the $AA_p(B_p)$ band for $\hbar\omega_c>0.41$ MeV. The alignment of the second most favored pair of $i_{13/2}$ neutrons (BC) is likely responsible for both occurrences. Figure 4 presents the BC crossing frequencies (open symbols) for the odd-Z Tb, Ho, and Tm nuclei. Just as in ^{154}Tb, the $AA_p(B_p)$ bands in ^{156}Ho [16] and ^{158}Tm [17] undergo this neutron alignment at ~0.40 MeV. Morrison *et al.* [22] have reported that both experiment and theory indicate that the BC alignment occurs at lower frequencies as the deformation increases within an isotonic chain. The earlier crossing in the $AE_p(F_p)$ band of ^{154}Tb (denoted by the $\otimes$ data point in Fig. 4) may therefore suggest that this configuration corresponds to a larger deformation than the negative-parity band. In fact cranked shell model calculations [12] indicate that an increase in deformation of $\Delta\beta_2=0.01$ decreases the crossing frequency $\hbar\omega_c$ by $0.02-0.03$ MeV. This behavior is consistent with the

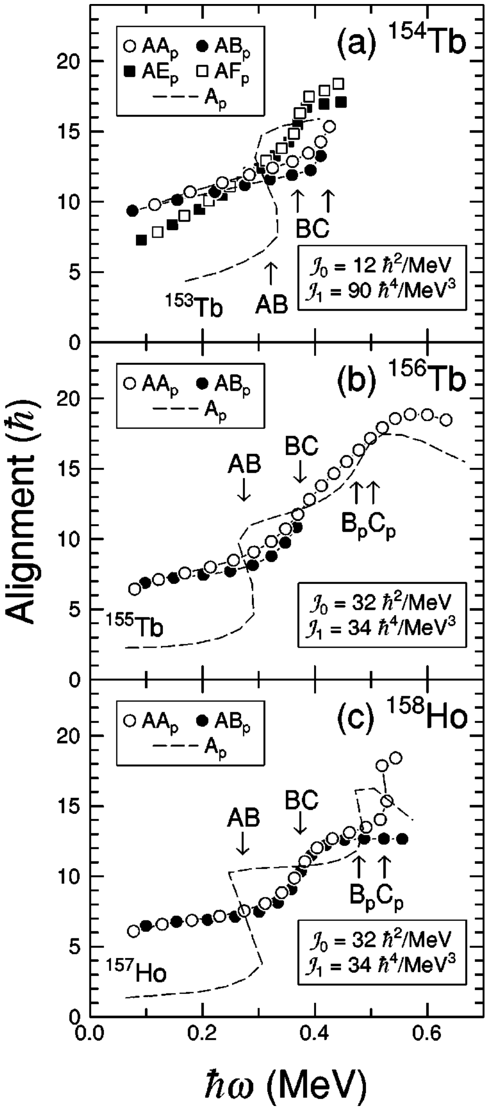

FIG. 3. Rotational alignments of the denoted bands in (a) ^{154}Tb, (b) ^{156}Tb, and (c) ^{158}Ho [18]. The $\alpha=-\frac{1}{2}$ signature (A_p) of the $\pi h_{11/2}$ bands in (a) ^{153}Tb [3], (b) ^{155}Tb [4], and (c) ^{157}Ho [19] are given for reference. Open symbols represent the $\alpha=0$ signature while closed symbols denote the $\alpha=1$ signature.

$E_p(F_p)$ bands in ^{155}Tb [4] and ^{157}Tb [2], where evidence was found that bands based on these same protons are associated with slightly larger deformations than those based on the $A_p(B_p)$ excitation.

One may also observe the systematic trend of the BC crossing as a function of neutron number in Fig. 4. All of the open symbols come from bands containing at least the A neutron and A_p proton, except the ⊗ data point as discussed above. A sharp decrease in the crossing frequency is found as N increases from 89 to 90, which is very similar to that observed for the AB crossing frequencies of $N=88$ and 90 nuclei [2,23]. It is generally understood that decreasing the neutron number from $N=90$ will move the neutron Fermi surface further away from the low-Ω, intruder $i_{13/2}$ neutrons [23]; thus causing the significant jump in $\hbar\omega_c$. As seen in Fig. 4, the cranked shell model (dashed line) is able to reproduce these data satisfactorily. The calculations presented were performed for Ho nuclei and deformation parameters

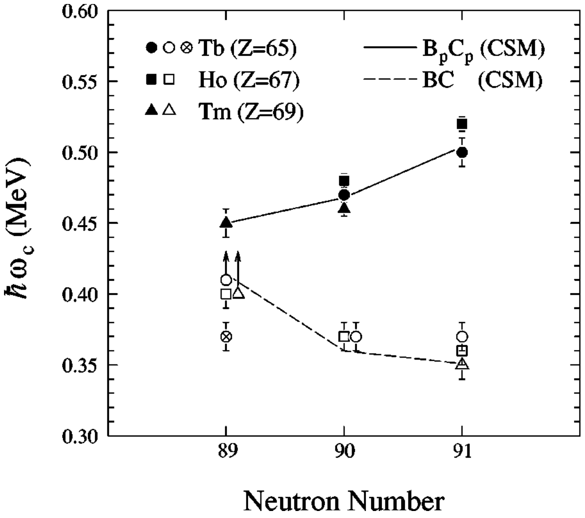

FIG. 4. Crossing frequencies of the BC and B_pC_p alignments as a function of neutron number. The open (solid) symbols represent the BC (B_pC_p) crossing. Cranked shell model calculations, described in the text, are displayed in the plot as the dashed (solid) line for the $BC(B_pC_p)$ crossing. Data for nuclei not presented in this work were taken from Refs. [4] (^{155}Tb), [16,18,19] ($^{156-158}$Ho), and [17,20,21] ($^{158-160}$Tm).

for the $N=90$ nucleus were taken from Ref. [24], while average values for the neighboring even-N nuclei from the same reference [24] were used for the $N=89$ and 91 nuclei. An attenuation factor of 0.9 has also been applied to the calculated frequencies, which used the full pairing strength for both neutrons ($\Delta_n\approx1.1$ MeV) and protons ($\Delta_p\approx1.1$ MeV).

The rotational alignment of the AA_p band in ^{156}Tb is presented in Fig. 3(b) along with its signature partner (AB_p) and the A_p band in ^{155}Tb [4]. The commonly used Harris parameters $\mathcal{J}_0=32\ \hbar^2$/MeV and $\mathcal{J}_1=34\ \hbar^4$/MeV^3 were invoked as a reference. The AB crossing is blocked in the negative-parity band in ^{156}Tb, but for $\hbar\omega>0.30$ MeV a gain of $\sim11\hbar$ in alignment can be seen, which is interpreted as resulting from two nearby crossings. Once again, the BC crossing, which occurs at a frequency of $\hbar\omega_c\approx0.37$ MeV, is observed. From the alignment profile of the A_p band in ^{155}Tb, a crossing due to the alignment of the second most favored pair of protons (B_pC_p) should be expected for a frequency $\hbar\omega>0.45$ MeV. Typically, $\sim5\hbar$ is gained when these protons decouple [see Figs. 3(b) and 3(c)]. Therefore, adding this amount to the expected $\sim5\hbar$ of alignment from the BC neutrons would be consistent with the total alignment seen in Fig. 3(b). This is also comparable with the crossings in ^{158}Ho [18], see Fig. 3(c), where a weaker interaction strength is observed in this second proton alignment.

A plot of all the known B_pC_p crossing frequencies in the $A\approx160$ region is shown in Fig. 4 (solid symbols). A systematic increase in $\hbar\omega_c$ with neutron number is observed. Cranked shell model calculations were performed in exactly the same manner as described above and the results are shown in Fig. 4 as the solid line. Once again, the model reproduces the experimental data well. It should also be noted that the model correctly predicts the larger interaction strength in the Tb nuclei as compared with the Ho nuclei for the B_pC_p alignment [see Figs. 3(b) and 3(c)]. The small deviations in crossing frequency for the $N=90$ nuclei (see Fig. 4) suggest that the proton Fermi level does not greatly affect the second proton crossing frequency. The increase in $\hbar\omega_c$ with N is most probably due to the increase in deformation.

In summary, the level schemes of ^{154,156}Tb have been extended to much higher spins. The alignments observed in the level sequences can be understood in the cranked shell model. Systematic trends for both the BC and B_pC_p crossing frequencies in odd-Z nuclei were discussed in terms of changes in deformation and in the location of the Fermi surface. The systematic observation of the B_pC_p crossing also provides strong evidence for the persistence of significant proton pairing correlations at high rotational frequencies and spins in light rare-earth nuclei.

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