Identification of pseudospin partner bands in ^{108}Tc

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High-spin structures in the neutron-rich ^{108}Tc nucleus have been reinvestigated by measuring the prompt γ-rays from spontaneous fission of ^{252}Cf. A previously known collective band has been extended up to higher spin states and a new side band has been identified. These doublet bands are proposed as pseudospin partner bands with configurations $\pi 1/2^+[431] \otimes \nu[\widetilde{312}\,5/2^+, 3/2^+]$, which is a first identification in $A \sim 100$ region. The particle-rotor model (PRM) was applied to calculate levels and $B(M1)/B(E2)$ ratios of the bands in ^{108}Tc. The calculated results are in good agreement with the experimental values.

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I. INTRODUCTION

In studies of nuclear structure, the pseudospin is an interesting topic both theoretically and experimentally [1–8]. In the pseudospin concept, the single particle orbitals with $j = l + 1/2$ and $j = (l + 2) - 1/2$ lie very close in energy and can therefore be labeled as pseudospin doublets with quantum number $\widetilde{N} = N - 1, \widetilde{l} = l - 1$, and $\widetilde{s} = s = 1/2$ [3]. In deformed case, the Nilsson states labeled by the asymptotic quantum numbers $[Nn_Z\Lambda]\Omega$ have pseudo-Nilsson equivalents $[\widetilde{N}\widetilde{n}_Z\widetilde{\Lambda}]\widetilde{\Omega}$, where $\widetilde{N} = N - 1, \widetilde{n}_Z = n_Z, \widetilde{\Lambda} = \Lambda \pm 1$, and $\widetilde{\Omega} = \Omega = \widetilde{\Lambda} + \widetilde{\Sigma}$, where $\widetilde{\Sigma} = \pm 1/2$ [9]. In the experimental study of deformed nuclei, the pseudospin symmetry shows a pair of doublet bands with nearly degenerate energies, which have been observed in several nuclei, such as, ^{128}Pr [6], ^{186}Ir [7], and ^{195}Pt [8].

In this paper, we report on new high spin states in neutron-rich ^{108}Tc nucleus in $A \sim 100$ region. The pseudospin partner bands have been observed. In previous repots, some high spin levels in ^{108}Tc were investigated by our group [10], and some low excitation states were identified by β-decay studies [11].

II. EXPERIMENT AND RESULTS

Since ^{108}Tc lies in the $A \sim 100$ neutron-rich region, it is difficult to study the high-spin states of these neutron-rich nuclei by using the usual heavy ion nuclear reaction. A practical method is to measure the prompt γ-rays of the spontaneous fission of ^{252}Cf [12]. The experiment was carried out at the Lawrence Berkeley National Laboratory. Prompt γ-γ-γ coincidence studies were performed with the Gammasphere detector array, which, for this experiment, consisted of 102 Compton-suppressed Ge detectors. A ^{252}Cf source of strength $\sim$60 μCi was placed at the center of the Gammasphere. A total of 5.7×10^{11} triple- and higher fold γ-coincidence events were collected. The coincidence data were analyzed with the RADWARE software package [13]. Detailed information of the experiment can be found in other articles [12,14,15].

By carefully examining many coincidence relationships and the transition intensities, a new high spin level scheme of ^{108}Tc has been established, as shown in Fig. 1. The collective bands observed are labeled on the top of the scheme. The results of our analysis such as the γ transition energies and the relative transition intensities are presented in Table I. The transition intensities have been normalized to that of the 176.5 keV γ-ray.

From Fig. 1 one can see that there are two collective bands in ^{108}Tc observed in this work. The two signature branches, A and B in band (1), and C and D in band (2) are also labeled in the figure. In Ref. [10], the absolute energies of all levels in ^{108}Tc were not determined. Here we have determined them based on comparison with the earlier β-decay work [11]. At low spins, two levels at 86.1 and 106.2 keV along with the deexcitation γ-transitions 86.1 and 106.2 keV in Fig. 1 have been reported in Ref. [11]. So the present level scheme is found to be connected to these two levels, and the other level energies can be determined as shown in Fig. 1. Band (1) has been updated. All the transitions in the band (1) reported in Ref. [10] are confirmed, except for the 601.1 keV one above the 1457.5 keV level, which is not observed in the present work. In Ref. [10], band (1) was assigned to be based on the 453.8 keV level. Here we have added a new transition 248.7 keV between the 579.3 and 330.6 keV levels and a new transition 330.6 keV between the 330.6 and 0.0 keV levels in the low spin states. Thus the band head level of band (1) is changed to a 330.6 keV level. At high spins, we added three new levels at 2156.4, 3005.9, and 3188.3 keV along with four new transitions 480.5, 698.9, 829.7, and 849.5 keV in this band. Band (2) based on the 412.5 keV level is newly established

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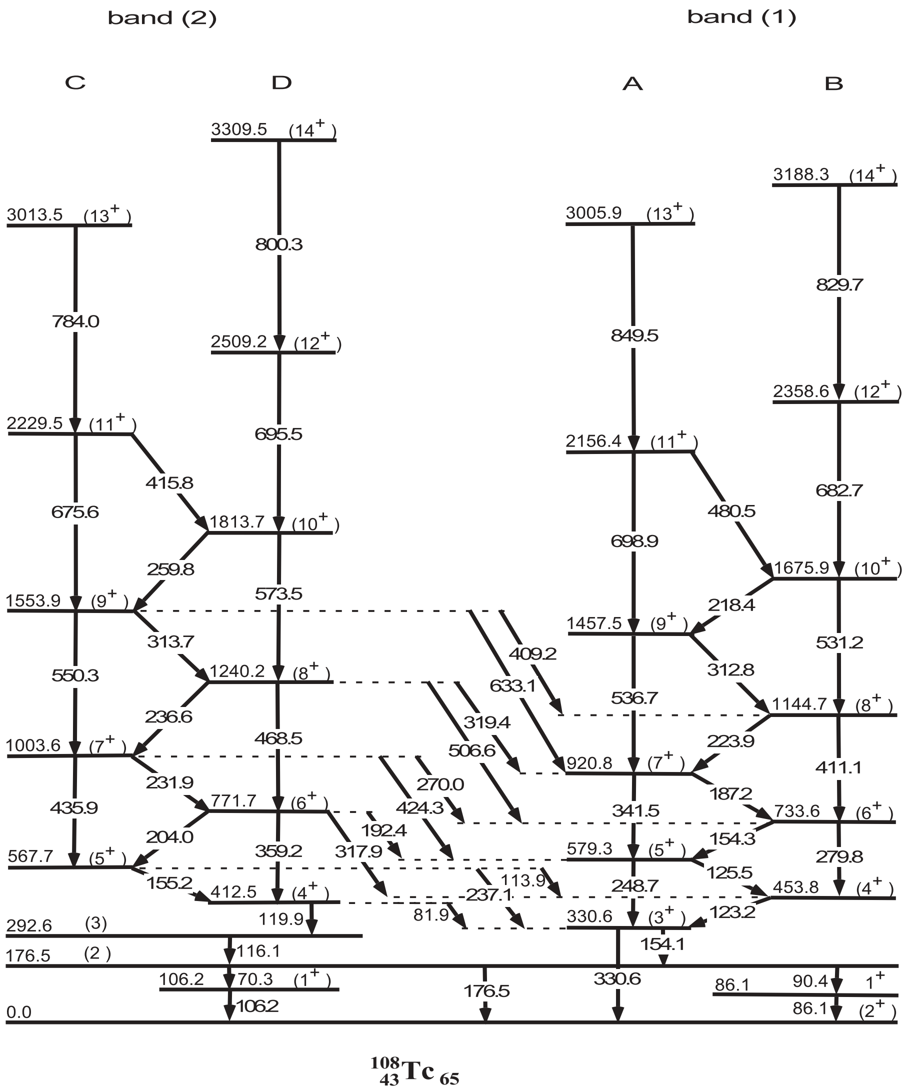

FIG. 1. Level scheme of ^{108}Tc.

in the present work. Only three levels at 412.5, 567.7, and 771.7 keV and three transitions 359.2, 155.2, and 204.0 keV in this band were observed in Ref. [10]. In addition, many new linking transitions between the bands (1) and (2) have been observed in the present work. A total of 11 new levels and 29 new transitions are identified compared to the previous work [10]. As an example, Fig. 2 shows a coincidence spectrum obtained by double gating on the 154.1 and 90.4 keV γ-transitions in ^{108}Tc. In this spectrum, one can see all the transitions above the 330.6 keV level and the lower transition of 86.1 keV known from beta decay work [11]. In addition to the γ-peaks observed in ^{108}Tc, the main γ-transitions in the partner nuclei $^{140-142}$Cs can also be seen.

III. DISCUSSION

In Ref. [11], the spins and parities (I^π) of the ground state and 106.2 keV level were tentatively assigned as 2^+ and 1^+, respectively, and the I^π of the 86.1 keV level has been assigned as 1^+. But in Ref. [10], I^π's for the observed levels in ^{108}Tc were not assigned. Based on the angular momentum alignment and the configuration analysis, we tentatively assign the I^π's of the band head levels in bands (1) and (2) as 3^+ and 4^+, respectively (see discussion below). According to the γ-transition selection rule, we also temporarily proposed the spin and parity of the 176.5 and 292.6 keV levels as 2^- and 3^+, respectively. The observed pair of doublet bands in ^{108}Tc could have chirality [16] as they have near degenerate energies as reported in some nuclei in the $A = 100$ region [17–19]. However, because the differences of $B(M1)/B(E2)$ values between bands (1) and (2) observed in the present work as seen in Fig. 5 later is so large, we can exclude the chiral doublet structure in ^{108}Tc. Here we suggest that they belong to pseudospin double bands, as reported in ^{128}Pr [6], ^{186}Ir [7], and ^{195}Pt [8].

The configurations of the bands in ^{108}Tc are expected to be composed of the proton the states $\pi g_{9/2}[413]7/2^+$, $\pi(g_{7/2}, d_{5/2})[431]1/2^+$, and $\pi f_{5/2}[303]5/2^-$ which have been observed as band in isotope ^{107}Tc [20,21], and of the neutron states $\nu(d_{5/2},\ g_{7/2})[413]5/2^+$, $\nu(d_{5/2},\ g_{7/2})[411]3/2^+$, and $\nu h_{11/2}[532]7/2^-$, which are observed in the isotone ^{107}Mo [22]. We denote the neutron states $[413]5/2^+$ and $[411]3/2^+$ by $(d_{5/2}, g_{7/2})$ in order to indicate their mixed composition.

The same holds for the proton states. This denoting method was used in Ref. [6]. We suggest possible configurations for the band head levels of bands (1) and (2) in ^{108}Tc in terms of the $\pi 1/2^+[431] \otimes \nu[\widetilde{312}\, 5/2^+, 3/2^+]$ structure, i.e., the coupling of an aligned proton and a neutron pseudospin doublet.

In order to give evidence for the above configuration assignments, we have carried out the analysis of the angular momentum alignments which has been used in Ref. [22]. The alignment i_{xpn} in an odd-odd nucleus equals the sum of the i_{xp} and i_{xn} which are the alignments of the collective bands in the neighboring odd-A isotope and isotone, respectively. Then the i_{xpn}, i_{xp}, and i_{xn} values for the collective bands can be obtained from the calculated I_x in the odd-odd and odd-A nuclei subtracted the I_x of the ground state (g.s.) band in the neighboring even-even nucleus, respectively. The I_x is calculated as a function of the rotational frequency ω from the usual formula $I_x = \sqrt{(I_\alpha + 1/2)^2 - K^2}$, where $I_\alpha = (I_i + I_f)/2, \hbar\omega = (E_i - E_f)/2$ and we propose $K = 3$ for bands (1) and (2) in ^{108}Tc. Figure 3 shows the spin alignment (I_x) vs. the rotational frequency $\hbar\omega$ in the observed bands in ^{107}Tc [20,21], ^{107}Mo [22], and ^{108}Tc in the present work along with that in the ground state (g.s.) band in ^{106}Mo. The average alignment values (i_x) in the range of $\hbar\omega$ from 100 to 300 keV calculated are 1.1$\hbar$ for the [413]7/2$^+$ band, 1.7$\hbar$ for [431]1/2$^+$ band, and 0.55$\hbar$ for the [303]5/2$^-$ band in ^{107}Tc; 1.0$\hbar$ for the [413]5/2$^+$ band, 0.9$\hbar$ for the [411]3/2$^+$ band, and 2.3$\hbar$ for the [523]7/2$^-$ band for ^{107}Mo. The average i_x values for ^{108}Tc are 2.4$\hbar$ for band (1) and 2.6$\hbar$ for band (2). So the average i_x values of bands (1) and (2) are near to sum of the i_x average values of the [431]1/2$^+$ band in ^{107}Tc and the [413]5/2$^+$/[411]3/2$^+$ band in ^{107}Mo. From the above analysis, the configurations of the two band heads in ^{108}Tc were shown to be consistent with a description in terms of the $\pi[431]1/2^+ \otimes \nu[\widetilde{312}\, 5/2^+, 3/2^+]$ structure. So the spin I values for the band head levels of bands (1) and (2) in ^{108}Tc can be assigned as 3 and 4$\hbar$, respectively. Based on the above configuration analysis, we assign both bands (1) and (2) with positive parity, and the spins and parities for all levels in bands (1) and (2) have been tentatively assigned, as shown in Fig. 1.

To obtain more information for the spin and parity assignments, we have measured a total internal conversion coefficient (α_T) of the low-energy crossing transition 113.9 keV from the 567.7 keV level in band (2) to the 453.8 keV level in band (1). This α_T value is obtained by double gating on the 468.5 and 123.2 keV transitions. In this gate the difference in relative intensities of the 204.0 and 113.9 keV transitions is equal to the internal conversion electron intensity of the 113.9 keV transition. The observed experimental α_T value is 0.24(6), and the theoretical value is 0.19 for an $M1$ transition. So the 113.9-keV transition in ^{108}Tc is an $M1$ transition (with a possible small $E2$ admixture allowed) and bands (1) and (2) should be of the same parity according to the transition selection rule, which supports our assignments of spin and parity (I^π) of the two bands.

The observation of two near-degenerate $\Delta I = 1$ bands should be considered as the fingerprint of the existence of the pseudospin doublet bands. The degree of degeneracy of the two bands in ^{108}Tc is indicated by the excitation energy of the band members as a function of spin as shown in Fig. 4. The two curves show near degeneracy within the observed spin interval. The reduced transition probability ratios $B(M1)/B(E2)$, which were deduced from the γ-intensities listed in Table I, are also shown in Fig. 5. It

TABLE I. Energy and intensity data for the transitions assigned to ^{108}Tc.

E_γ (keV)	E_i (keV)	E_f (keV)	I_γ(%)
70.3	176.5	106.2	72(5)
81.9	412.5	330.6	29(2)
86.1	86.1	0.0	140(5)
90.4	176.5	86.1	130(6)
106.2	106.2	0.0	80(4)
113.9	567.7	453.8	5.1(6)
116.1	292.6	176.5	20(2)
119.9	412.5	292.6	11(2)
123.2	453.8	330.6	52(4)
125.5	579.3	453.8	35(3)
154.1	330.6	176.5	106(7)
154.3	733.6	579.3	27(2)
155.2	567.7	412.5	16(1)
176.5	176.5	0.0	100(7)
187.2	920.8	733.6	17(1)
192.4	771.7	579.3	4.4(5)
204.0	771.7	567.7	7.8(8)
218.4	1675.9	1457.5	4.6(5)
223.9	1144.7	920.8	15(2)
231.9	1003.6	771.7	2.5(4)
236.6	1240.2	1003.6	0.9(1)
237.1	567.7	330.6	11(1)
248.7	579.3	330.6	7.9(9)
259.8	1813.7	1553.9	0.5(2)
270.0	1003.6	733.6	3.2(3)
279.8	733.6	453.8	5.5(6)
312.8	1457.5	1144.7	5.4(9)
313.7	1553.9	1240.2	1.1(2)
317.9	771.7	453.8	1.0(3)
319.4	1240.2	920.8	1.3(4)
330.6	330.6	0.0	0.4(1)
341.5	920.8	579.3	7.0(8)
359.2	771.7	412.5	12(1)
409.2	1553.9	1144.7	<0.1
411.1	1144.7	733.6	7.0(8)
415.8	2229.5	1813.7	0.8(1)
424.3	1003.6	579.3	0.5(1)
435.9	1003.6	567.7	6.3(5)
468.5	1240.2	771.7	8.7(8)
480.5	2156.4	1657.9	3.5(3)
506.6	1240.2	733.6	0.2(1)
531.2	1675.9	1144.7	8.5(8)
536.7	1457.5	920.8	7.8(1)
550.3	1553.9	1003.6	4.9(5)
573.5	1813.7	1240.2	6.4(6)
633.1	1553.9	920.8	<0.1
675.6	2229.5	1553.9	1.9(2)
682.7	2358.6	1675.9	6.3(7)
695.5	2509.2	1813.7	5.7(6)
698.9	2156.4	1457.5	4.4(5)
784.0	3013.5	2229.5	0.7(1)
800.3	3309.5	2509.2	1.3(2)
829.7	3188.3	2358.6	1.8(2)
849.5	3005.9	2156.4	1.0(2)

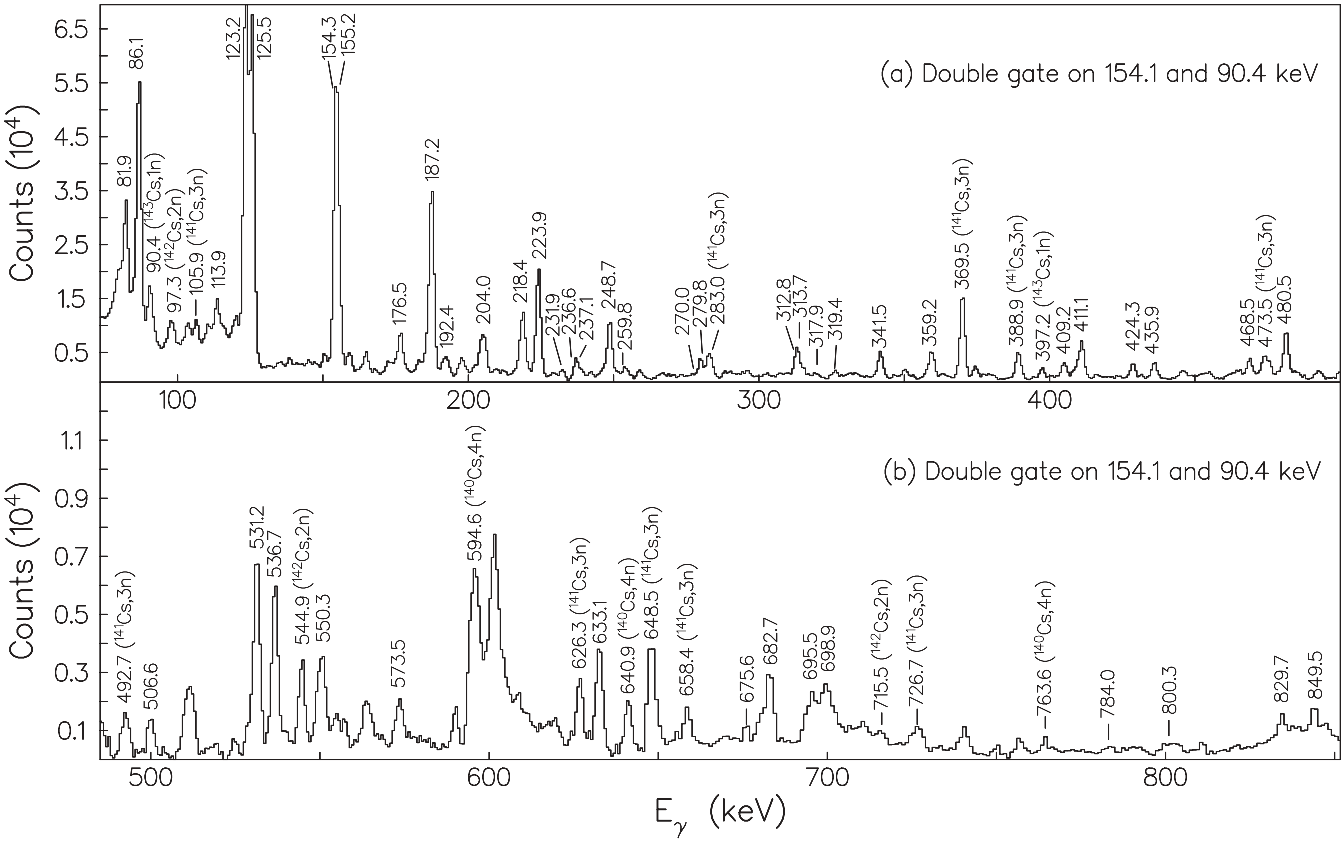

FIG. 2. Portion of coincidence spectra obtained by double gating on 154.1 and 90.4 keV γ-rays of ^{108}Tc.

is interesting to note that the staggering of $B(M1)/B(E2)$ ratios is evident for both the doublet bands. For band (1), even-spin states have higher values than odd-spin states and staggering of the $B(M1)/B(E2)$ of the partner band is opposite.

The theoretical calculations for ^{108}Tc have been carried out in this work to have a deeper understanding of the structural properties of ^{108}Tc. In order to obtain the deformation parameters of ^{108}Tc, we firstly carried out the total Routhian surfaces (TRS) calculations, which were based on the cranked shell model, employing the universal Woods-Saxon potential and Strutinsky shell-correction formalism [23]. The calculated results are presented in Fig. 6. The minima can be found to be $\beta_2 = 0.3$, $\beta_4 = 0.002$, $\gamma = -22^\circ$ for $\omega = 0.2$ MeV/$\hbar$ and $\beta_2 = 0.27$, $\beta_4 = 0.012$, $\gamma = -29^\circ$ for $\omega = 0.4$ MeV/$\hbar$. The calculations indicate the ^{108}Tc has triaxial deformation. The γ value increases when the rotational frequency increases, and when $\omega \geqslant 0.2$ MeV/$\hbar$, it presents a typical triaxiality with $\gamma = -29^\circ$. Then, we use the particle-rotor model (PRM) [24,25] to calculate the energies and branching ratios. The deformation parameters $\beta = 0.3$, $\gamma = -30^\circ$ are used. For the moment of inertia, a value of $J = 40\hbar^2$/MeV is obtained from the slope of the experimental E versus I curve. For the calculation of electromagnetic transitions, the intrinsic quadrupole moment Q_0 is taken to be $(3/\sqrt{5\pi})R^2 Z\beta = 3.2$ eb and gyromagnetic ratios for the collective rotor, protons and neutrons are given by $g_R = 0.75Z/A \approx 0.3$, $g_{g_{7/2}} = 0.74$ for proton, $g_{d_{5/2}} = -0.46$ and $g_{g_{7/2}} = 0.26$ for neutron, respectively. The similar calculation details for the PRM can be found in Refs. [24,25]. For the pseudospin doublet states $\nu[413]5/2^+$ and $\nu[413]5/2^+$, their main components are $\nu g_{7/2}$ and $\nu d_{5/2}$, respectively. Thus, bands (1) and (2) are investigated adopting the configurations $\pi g_{7/2} \otimes \nu d_{5/2}^{-1}$ and $\pi g_{7/2} \otimes \nu g_{7/2}^{-1}$, respectively. Figure 7 shows the calculated energy spectra as a function of spin. In the calculations, the energy difference between the band heads of band (1) ($I = 3\hbar$) and band (2) ($I = 4\hbar$) is set to 210 keV, which is the energy difference between the Nilsson states $\nu[413]5/2^+$ and $\nu[411]3/2^+$. The energy gap between the two bands in ^{108}Tc is approximately from 100 to 200 keV. The calculated energy spectra of the two bands are near-degenerate, similar as the experimental behaviors. Figure 8 shows the calculated transition probability $B(M1)/B(E2)$ for bands (1) and (2). For $I < 7\hbar$ of band (1) and $I < 8\hbar$ of band (2), the calculated $B(M1)/B(E2)$ values are much larger than the data due to the calculated $B(E2)$ values are very small in the present model, which are not plotted here. Comparing Fig. 5 with Fig. 8, we can see that experimental and the theoretical plots are not only very close in values but also show the same phase for the staggering, i.e., the values of odd spins are larger than those of the even spins for band (1), while in contrast with band (2). The good agreement between the experimental and calculated $B(M1)/B(E2)$ ratios further supported the configurations

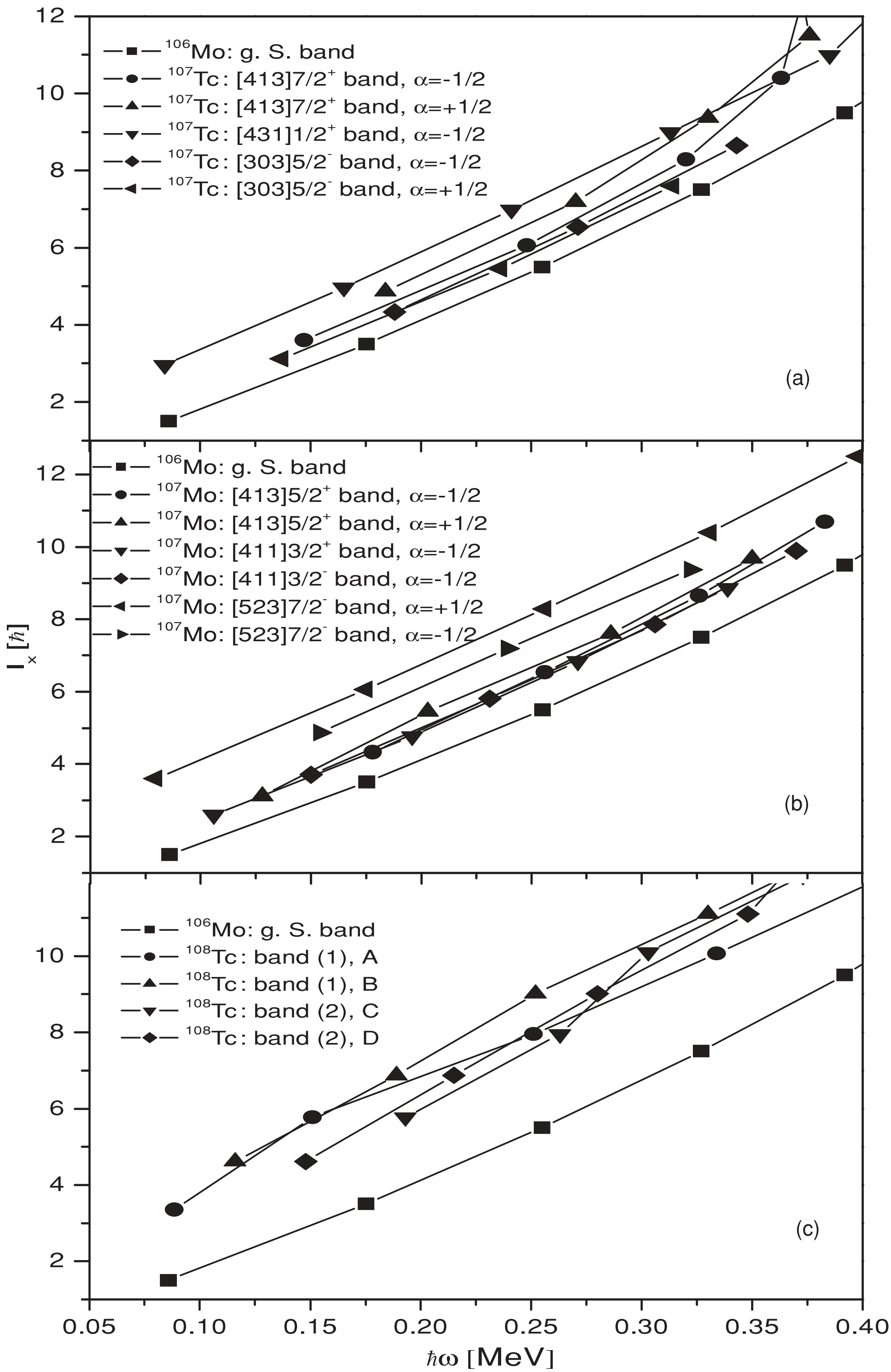

FIG. 3. Total angular momentum alignment I_x for observed bands: (a) in ^{107}Tc, (b) in ^{107}Mo, and (c) in ^{108}Tc, along with the ground-state (g.s.) band in ^{106}Mo in each figure.

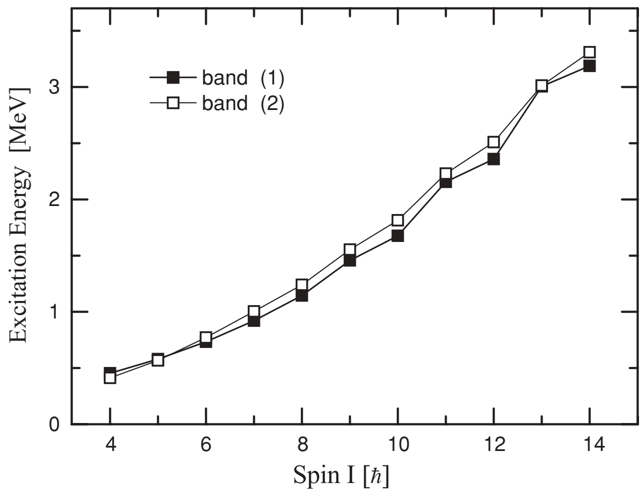

FIG. 4. Experimental energy vs. spin for bands (1) and (2) in ^{108}Tc.

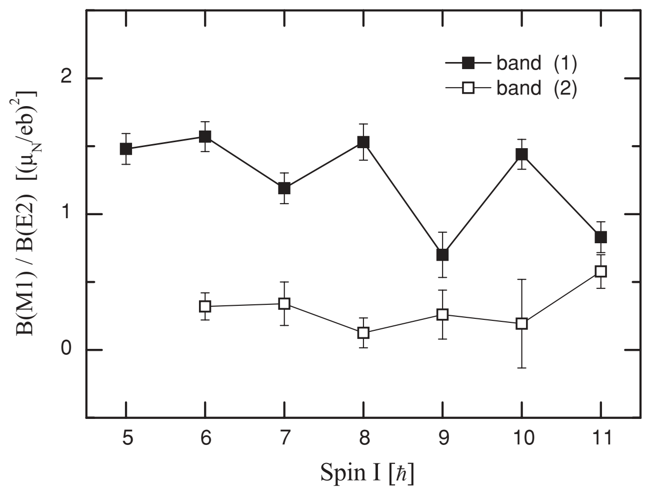

FIG. 5. Experimental $B(M1)/B(E2)$ vs. spin for bands (1) and (2) in ^{108}Tc.

proposed for bands (1) and (2). Therefore, the present results show that bands (1) and (2) indeed belong to pseudospin doublet bands.

IV. SUMMARY

The high spin states in ^{108}Tc have been restudied and the level scheme has been expanded. A pair of observed

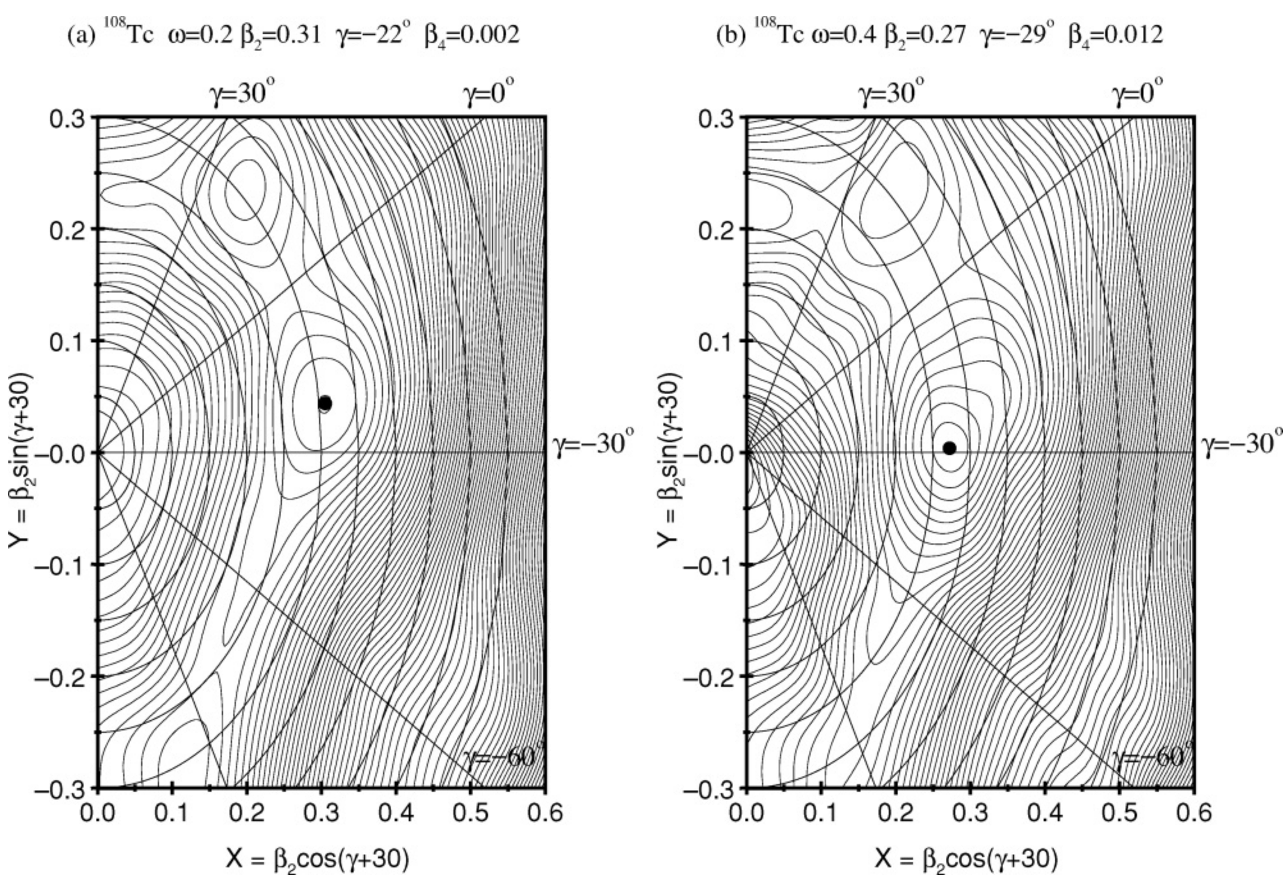

FIG. 6. Polar coordinate plots of total Routhian surface (TRS) calculated at (a) $\omega = 0.2$ MeV/$\hbar$, (b) $\omega = 0.4$ MeV/$\hbar$.

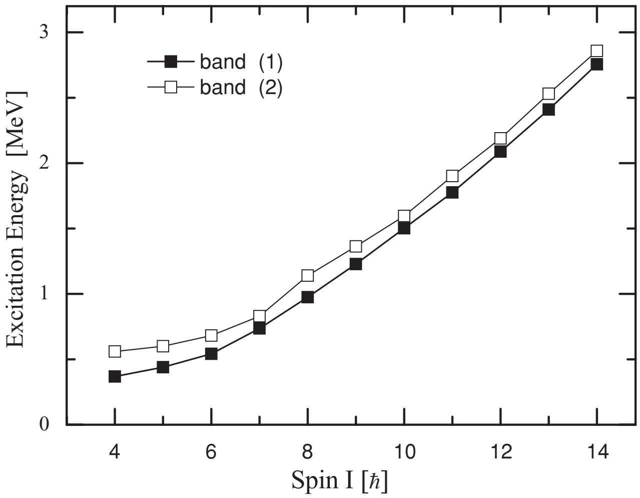

FIG. 7. Calculated energies vs. spin for bands (1) and (2) in ^{108}Tc.

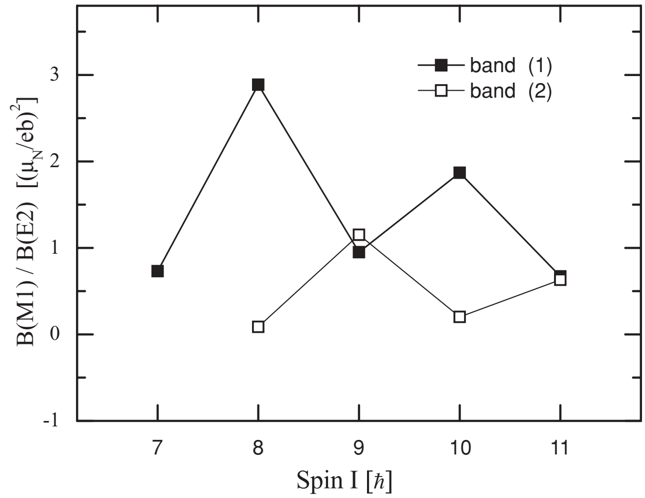

FIG. 8. Calculated $B(M1)/B(E2)$ vs. spin for bands (1) and (2) in ^{108}Tc.

collective bands is proposed as pseudospin doublet bands with $\pi[431]1/2^+ \otimes \nu[\widetilde{312}\,5/2^+, 3/2^+]$ configurations. Excitation energies of the pseudospin doublet bands in ^{108}Tc are nearly degenerate according to our experimental data. The PRM is applied to calculate the levels and $B(M1)/B(E2)$ of the pseudospin doublet bands, and good agreement of calculated results with the experimental ones further supports the pseudospin doublet band assignment in ^{108}Tc. This is a first observation of a such kind of structure in the $A \sim 100$ region.

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