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Signature Inversion in the $\pi h_{9/2} \otimes \nu i_{13/2}$ Oblate Band of ^{190}Tl *

ZHOU Xiao-Hong[1;1)] XIE Cheng-Ying[1] ZHANG Yu-Hu[1] GUO Ying-Xiang[1]
LEI Xiang-Guo[1] ZHENG Yong[1] LIU Min-Liang[1] SONG Li-Tao[1] WANG Hua-Lei[1]
YU Hai-Ping[1] LUO Peng[1] GUO Wen-Tao[1] ZHU Li-Hua[2] WU Xiao-Guang[2]
1(Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China)
2(China Institute of Atomic Energy, Beijing 102413, China)

Abstract High-spin states in ^{190}Tl have been studied experimentally using the ^{160}Gd(^{35}Cl, 5n) fusion-evaporation reaction at beam energies of 167—175 MeV. A rotational band built on the $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration with oblate deformation has been established. Spin values have been firmly assigned to the $\pi h_{9/2} \otimes \nu i_{13/2}$ oblate band by combining the present in-beam experimental results with the complementary α-γ correlation measurements of ^{194}Bi α decay. With the configuration and spin-parity assignments, the low-spin signature inversion has been revealed for the $\pi h_{9/2} \otimes \nu i_{13/2}$ oblate band. It is the first experimental observation of low-spin signature inversion for a band associated with the oblate $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration. The low-spin signature inversion could be interpreted in the framework of the quasiparticles plus rotor model including a J dependent proton-neutron residual interaction.

Key words rotational band, signature inversion, oblate deformation

It is generally suitable to classify nuclear rotational band by the quantum number of signature α, which is related to the invariance of the intrinsic Hamiltonian of an axially deformed nucleus with respect to 180° rotation around a principle axis[1,2]. Two regular rotational sequences of nuclear states, which differ by only one unit in angular momentum, form a pair of signature partner bands. For nuclear systems with odd particle number, the signature defined by $\alpha^{f} = 1/2(-1)^{j-1/2}$ (favored signature) is usually lowered in energy with respect to the $\alpha^{uf} = 1/2(-1)^{j+1/2}$ (unfavored) signature[1], where the angular momentum of the odd particle is expressed by j. Signature α is an additive quantum quantity, therefore in odd-odd deformed nuclei, the expected favored signature ($\alpha^{f}_{p\text{-}n}$) of a two-quasiparticle band should result from the coupling between the favored signatures of both proton (α^{f}_{p}) and neutron (α^{f}_{n}) orbitals, while the unfavored signature ($\alpha^{uf}_{p\text{-}n}$) corresponds to either $\alpha^{f}_{p} + \alpha^{uf}_{n}$ or $\alpha^{uf}_{p} + \alpha^{f}_{n}$[2]. The signature inversion occurs if the expected favored signature branch of a rotational band lies higher in energy than the unfavored signature branch. The low-spin signature inversion has been systematically observed in deformed odd-odd nuclei throughout the chart of nuclides[2,3] (and references therein), concerning the high-j $\pi g_{9/2} \otimes \nu g_{9/2}$, $\pi h_{11/2} \otimes \nu h_{11/2}$, $\pi h_{11/2} \otimes \nu i_{13/2}$, $\pi h_{9/2} \otimes \nu i_{13/2}$, and $\pi i_{13/2} \otimes \nu i_{13/2}$ configurations. Greatly theoretical efforts have been devoted to the understanding of low-spin signature inversion in deformed odd-odd nuclei, and the nuclear triaxiality, proton-neutron residual interaction, et al. have been proposed to be the possible reasons for the inversion phenomenon[2—4]. Furthermore, the theoretical studies have suggested that the occurrence of signature inversion is associated closely with the positions of the Fermi surfaces of nucleons[2] and the configurations of states[4]. Therefore, the observation of signature inversion bands in new mass region and with new configurations is very important for a deeper understanding of the low-spin signature inversion phenomenon and to examine the theoretical models with different physical pictures.

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1) E-mail: zxh@impcas.ac.cn

The signature inversion associated with the oblate $\pi h_{9/2}\otimes\nu i_{13/2}$ configuration has not been definitely established so far. The neutron-deficient doubly odd Tl nuclei, in which the rotational band associated with the oblate $\pi h_{9/2}\otimes\nu i_{13/2}$ configuration dominates the yrast states[5—9], should provide best candidate to search for the signature inversion. Although bands based on $\pi h_{9/2}\otimes\nu i_{13/2}$ oblate configuration were observed in $^{192-200}$Tl[5—9], their spins could not be assigned unambiguously due to experimental difficulties. As a consequence of this, the interpretation of the distinctive energy staggering between the odd and even spin members in these bands has remained uncertain, and two completely different models were proposed to interpret the staggering[9,10]. Fortunately, the α-γ correlation measurements in the α decay studies of odd-odd Bi isotopes provided detailed information on the low-lying normal and intruder excited states in the daughter $^{184-192}$Tl nuclei[11,12]. This could help us to determine unambiguously spin values of the oblate $\pi h_{9/2}\otimes\nu i_{13/2}$ bands in certain odd-odd Tl nuclei. In this paper, we report on the first observation of low-spin signature inversion in the oblate $\pi h_{9/2}\otimes\nu i_{13/2}$ band in ^{190}Tl, for which the spins are firmly established by combining the in-beam experimental results with the complementary α-γ correlation measurements[11,12].

Prior to this work, information on the low-lying excited levels in ^{190}Tl was obtained in ^{190}Pb(EC) [13] and ^{194}Bi(α) decay studies[11,12]. It should be noted that the α-γ coincidence measurement in ^{194}Bi α decay studies established a few low-lying states in ^{190}Tl, for which the configurations were assigned definitely[11,12]. An early in-beam work[14] identified a long-lived isomer with an oblate configuration of $\pi h_{9/2}\otimes\nu i_{13/2}$ in ^{190}Tl, and three γ lines were suggested to be above the isomer.

The excited states in ^{190}Tl were populated via the ^{160}Gd(^{35}Si, 5n)^{190}Tl reaction. The ^{35}Cl beam was provided by the HI-13 tandem accelerator of China Institute of Atomic Energy, Beijing. The target was an isotopically enriched ^{160}Gd metallic foil of 1.3 mg/cm^2 thicknesses with a 7.0 mg/cm^2 Pb backing. In order to determine the optimum beam energy to produce ^{190}Tl and to identify the in-beam γ rays belonging to ^{190}Tl, relative γ-ray yields were measured at beam energies of 167—175MeV. Inspecting the relative yields of the known γ lines previously assigned to ^{190}Tl [14] at different bean energies, the optimum beam energy for producing ^{190}Tl was estimated to be 175MeV, at which the γ-γ-t coincidence measurements were performed. Here, t refers to the relative time difference between any two coincident γ rays detected within ±200ns. A γ-ray detector array including 12 HPGe with BGO anti-Compton shields was used. The detectors were divided into three groups of which the angle positions (and detector number at that angle) were 90°(3), ±70° (6), and ±45°(3) with respect to the beam direction, so that the DCO and ADO ratios could be deduced from the coincidence data. All the detectors were calibrated with standard ^{133}Ba and ^{152}Eu sources; typical energy resolution was 2.0 — 3.0keV at full width at half maximum for the 1332.5keV line from ^{60}Co. A total of about 100×10^6 γ-γ coincidence events were accumulated. After gain matching, these data were sorted into a total symmetric coincidence matrix, a DCO matrix and two ADO matrices for off-line analysis.

Assignments of the observed γ rays to ^{190}Tl were based on the coincidences with the known γ rays with energies of 272.3, 280.5 and 382.4keV[14]. The assignments were further confirmed by the measured relative γ-ray yields at different beam energies and Tl K X-ray coincident information. Gated spectrum was produced for each of the γ rays assigned to ^{190}Tl. Selected gated spectra are shown in Fig. 1. Based on the analysis of the γ-γ coincidence relationships, a level scheme for ^{190}Tl is proposed and shown in Fig. 2. The order of transitions in the level scheme is fixed firmly with the help of inter-band transitions. In Fig. 2, the excitation energy of the β-decaying 7^+ isomer, for which the dominant configuration of $(\pi s_{1/2}\otimes\nu i_{13/2})\ 7^+$ was suggested from laser spectroscopy measurements[15], was set to be zero as a reference due to its unknown excitation energy. As stated by Duppen et al [11,12], unhindered α decay through the $Z=82$ shellclosure can identify intruder states in the daughter nuclei, and observation of unhindered α decay provided an ideal tool for identifying states with the same spin, parity and configuration as the α-decaying mother state. The α-γ correlation measurements in α decay of ^{194}Bi[11,12] established the spin and parity of $(\pi h_{9/2}\otimes\nu i_{13/2})10^-$ for the state located 300keV above the 7^+ isomer in ^{190}Tl. The measurements showed also that the $(\pi h_{9/2}\otimes\nu i_{13/2})10^-$ state in ^{190}Tl was depopulated directly by an M1 63.9keV transition[11,12], which corresponds well to the energy difference between the 336 and 272keV transitions as shown in Fig. 2. Furthermore, the 272keV transition, connecting the 572keV level and the $(\pi h_{9/2}\otimes\nu i_{13/2})10^-$ state as suggested in the previous work[11,12], was observed in the present work. Therefore, the excitation energies for the states observed in the present work were fixed with respect to the $(\pi s_{1/2} \otimes \nu i_{13/2})\,7^+$ isomer, and the configuration of $(\pi h_{9/2} \otimes \nu i_{13/2})\,10^-$ is assigned definitely to the 300keV state. In order to illustrate the spin and parity assignments, the partial level scheme of ^{194}Bi α decay is also displayed on the right side in Fig. 2. Spins for the levels above the 300keV $(\pi h_{9/2} \otimes \nu i_{13/2})\,10^-$ state were proposed from the measured DCO and γ-ray anisotropy results. However, it should be pointed out that the $(\pi h_{9/2}\otimes\nu i_{13/2})8^-$ isomer reported by Kreiner et al[14]. was not confirmed in the α-γ correlation measurements, and the 9^- state was suggested to be the lowest member of the $(\pi h_{9/2} \otimes \nu i_{13/2})$ multiplet in ^{190}Tl[11,12].

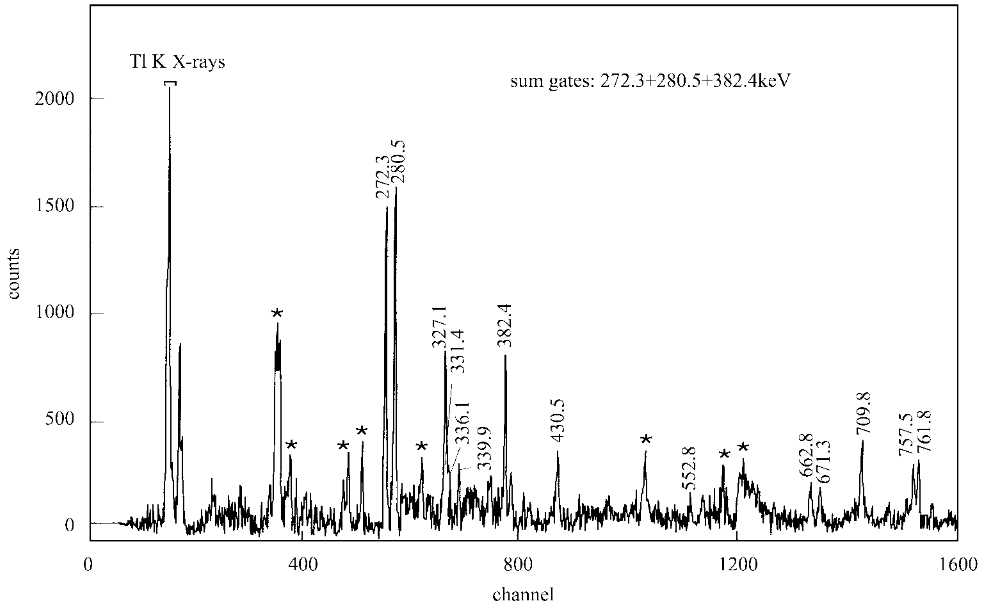

Fig.1.　Representative spectrum produced from a sum of gates as indicated on the panel. The * symbols indicate contaminations.

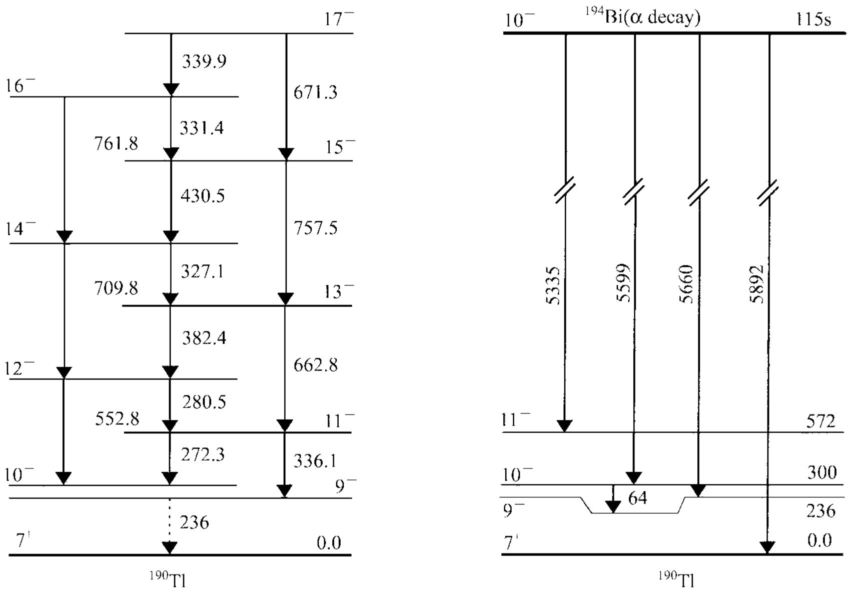

Fig.2.　Level scheme of ^{190}Tl deduced from the present work, and the partial level scheme obtained in ^{194}Bi α decay.

As discussed above, the $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration with oblate deformation can be likely assigned to the band observed in ^{190}Tl. This configuration assignment was also supported strongly by comparing with the level structure in the neighboring nuclei and the heavier odd-odd Tl isotopes [5—9,16—18]. For oblate deformation in Tl nuclei with $Z = 81$[17,18], the proton Nilsson orbitals originating from $\pi h_{9/2}$ spherical parentage are intruding from the above $Z = 82$ shellclosure, and the Nilsson state with the largest projection on the nuclear symmetry axis ($\Omega_p = 9/2$) lies nearest to the proton Feimi surface, giving rise to strongly coupled bands in the odd-A Tl nuclei. On the other hand, for the odd-A Hg isotopes ranging from $A = 189$ to 199[16], the neutron Fermi surface is near the top of the $\nu i_{13/2}$ subshell, and since the deformation is oblate the neutron angular momentum is approximately in a plane perpendicular to the symmetry axis, resulting in decoupled $\nu i_{13/2}$ bands in the odd-A Hg isotopes. In the mass region of present interest, the signature splittings in the oblate $\pi h_{9/2}$ bands in odd Tl nuclei are much smaller than those in the oblate $\nu i_{13/2}$ bands of neighboring odd-N Hg nuclei. Therefore, we propose the oblate configurations $\pi h_{9/2}(\alpha = \pm 1/2) \otimes \nu i_{13/2}(\alpha^f = 1/2)$ for the bands in ^{190}Tl.

As described in the experimental section, spin and parity values were firmly established for the $\pi h_{9/2} \otimes \nu i_{13/2}$ oblate band in ^{190}Tl thanking to the complementary α-γ correlation measurement[11,12]. It is the first time that spin values are assigned unambiguously to an oblate band in doubly odd Tl nuclei. An interesting phenomenon concerning the oblate band in ^{190}Tl nucleus is the distinctive energy staggering between the odd and even spin members, indicating an apparent energy signature splitting. With the configuration and spin-parity assignments discussed above, this staggering reveals that the signature splitting in the $\pi h_{9/2} \otimes \nu i_{13/2}$ band is inverted at low spins, i.e., that the expected $\alpha^f_{p\text{-}n} = \alpha^f_p + \alpha^f_n = 1/2 + 1/2 = 1$ favored signature branch (odd spin sequence) lies higher in energy than the $\alpha^{uf}_{p\text{-}n} = \alpha^{uf}_p + \alpha^f_n = 1/2 - 1/2 = 0$ unfavored signature branch (even-spin sequence). Fig. 3 presents plot of the signature splitting for the $\pi h_{9/2} \otimes \nu i_{13/2}$ oblate bands in ^{190}Tl, defined as

$$S(I) = [E(I) - E(I-1)] - 1/2[E(I+1) - E(I) + E(I-1) - E(I-2)]. \quad (1)$$

Here $E(I)$ is the level energy of state I; $S(I)$ is directly proportional to the signature splitting, but magnified by approximately a factor of two. As shown in Fig. 3, the signature inversion is distinct and kept upto the highest spin values observed experimentally.

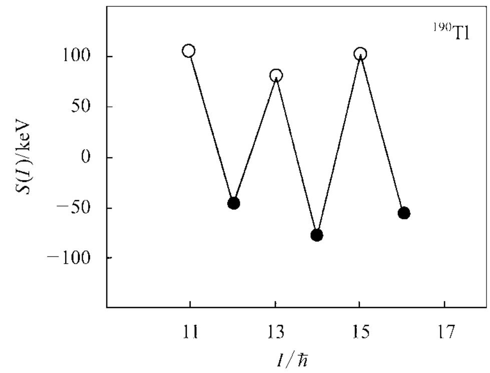

Fig.3. Signature splitting $S(I)$ as a function of spin I. The open circles for states with $\alpha = 1$, and filled ones for $\alpha = 0$.

Due to the uncertainties of level spin assignments to the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands in $^{192-200}$Tl[5—9], Kreiner[10] has proposed two different models to interpret the level energy staggering. The first approach, utilizing a two noninteracting quasiparticle plus rotor model, suggested that the level energy staggering is associated with the signature dependence of the Coriolis interaction [i.e., $a(-)^I$ effect, I being the total angular momentum]. The other one, which is almost identical to the first approach except for the inclusion of a residual proton-neutron (p-n) interaction, attributed the staggering to a J dependence of the p-n residual interaction (J being the total intrinsic angular momentum). These two models produced opposite phases of the staggering[10]. With the spin assignment in the present work, this long-standing problem is now solved. It is the p-n residual interaction that reproduces a correct phase of the staggering observed in the $\pi h_{9/2} \otimes \nu i_{13/2}$ band in ^{190}Tl. If a strong repulsive matrix element of the p-n residual interaction acts in the maximally aligned intrinsic state $J = 11$, above the 10^- state a further alignment of the proton and neutron intrinsic spins is energetically more costly and the system prefers to increase its total angular momentum at the expense of collective energy. As a consequence of this, the amplitude of $J = 11$ component in the wave functions for the 11^- and higher states is drastically reduced, and meanwhile the role of $J = 10$ component becomes dominant[10]. This leads to the energetically favored states with angular momenta of $I = R + J = R + 10 =$ even and the unfavored states being $I - 1 = R + 10 - 1 =$ odd ($R =$ even is the collective angular momentum). Therefore, signature inversion occurs at low spin.

As well known, low-spin signature inversion in doubly odd nuclei was mainly identified experimentally by observing the change of the staggering phase at medium angular momentum[2—4]. For the $\pi h_{9/2}\otimes\nu i_{13/2}$ oblate configuration, the interplay between the Coriolis and p-n residual interactions, which favor the odd and even spins, respectively, is expected to produce at a given spin (inversion point) a mutual cancellation of the opposite contributions to the staggering. Above this inversion point, odd spins are favored energetically by the stronger Coriolis interaction, and thus the signature splitting reverts to the normal ordering. Due to the small kinematical moment of inertia associated with an oblate deformation, the Coriolis interaction in the $\pi h_{9/2}\otimes\nu i_{13/2}$ oblate configuration should be much stronger than that in the prolate case. Therefore, we might expect to observe the inversion point in the $\pi h_{9/2}\otimes\nu i_{13/2}$ oblate band at low spin value. In order to prove this expectation, it is very desirable to extend the $\pi h_{9/2}\otimes\nu i_{13/2}$ oblate band in ^{190}Tl to higher angular momentum.

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^{190}Tl 的 $\pi h_{9/2}\otimes\nu i_{13/2}$扁椭球转动带的旋称反转研究 *

周小红[1;1)]　谢成营[1]　张玉虎[1]　郭应祥[1]　雷相国[1]　郑勇[1]　柳敏良[1]
宋立涛[1]　王华磊[1]　于海萍[1]　骆鹏[1]　郭文涛[1]　竺礼华[2]　吴晓光[2]
1(中国科学院近代物理研究所　兰州　730000)
2(中国原子能科学研究院　北京　102413)

摘要　利用能量为 167—175MeV 的^{35}Cl 束流，通过^{160}Gd(^{35}Cl, 5n)熔合蒸发反应研究了^{190}Tl 的高自旋态能级结构.实验建立了^{190}Tl 基于 $\pi h_{9/2}\otimes\nu i_{13/2}$组态的转动带.在束测量结果和^{194}Bi α 衰变的 α-γ 测量结果确定地指定了^{190}Tl 的 $\pi h_{9/2}\otimes\nu i_{13/2}$转动带的自旋值.基于自旋指定，发现了^{190}Tl 的 $\pi h_{9/2}\otimes\nu i_{13/2}$扁椭球转动带在低自旋时旋称反转.这是首次在基于 $\pi h_{9/2}\otimes\nu i_{13/2}$组态的扁椭球转动带中观测到旋称反转.考虑了质子－中子剩余相互作用的粒子－转子模型能够解释 $\pi h_{9/2}\otimes\nu i_{13/2}$扁椭球转动带的低自旋旋称反转.

关键词　转动带　旋称反转　扁椭球形变

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1) E-mail: zxh@impcas.ac.cn