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High-Spin States in ^{162}Lu and Signature Inversion of Yrast Bands in Doubly Odd Nuclei Around the A = 160 Mass Region

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High-spin states of ^{162}Lu have been produced and studied via the ^{147}Sm (^{19}F, 4nγ) ^{162}Lu reaction. In-beam γ-rays were measured by using 1 planar detector and 7 high-purity Ge detectors with BGO anti-Compton shield. The level scheme of the yrast band in ^{162}Lu was established for the first time and the signature inversion in energy was discovered at the low rotational frequencies. The yrast bands of doubly odd nuclei in the A = 160 mass region have been reinvestigated and the systematics of signature inversion is briefly discussed.

Key words: in-beam γ-rays spectroscopy, yrast bands of doubly odd nuclei, signature inversion, triaxial deformation.

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1. INTRODUCTION

The rotational bands of deformed nuclei are normally classified by the parity (π) and signature (α). Here the signature is a quantum number related to the invariance of the Hamiltonian of a deformed nucleus with respect to the rotation of 180° about an axis perpendicular to the symmetry axis. For the doubly odd nuclei, the band based on the $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ quasiparticle configuration is separated into the two $\Delta I = 2\hbar$ transition sequences with different α. The series of levels with even spin is called the favored band and is indicated by $\alpha = \alpha_f = 0$; the series with odd spin is called the unfavored band with $\alpha = \alpha_u = 1$. It is considered normal when the excitation energy of the favored band is lower than that of the unfavored band. However, for many doubly odd nuclei in the $A = 160$ mass region, the rotational bands based on the $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ quasiparticle configurations exhibit an anomalous signature splitting [1] at frequencies lower than the first backbending, i.e., the excitation energy of the favored band is higher than that of the unfavored band. This anomalous signature splitting is conventionally called the signature inversion in energy (SI). There are presently some theoretical arguments in understanding the mechanism of SI; the main point of these arguments is focused on if the experimentally observed SI is evidence of triaxial deformation of a nucleus [2-5].

In order to understand the mechanism of SI, it is certainly important to study the dependence of SI on the proton and neutron numbers and to search for the possible border (limit) of SI. Ref. [6] investigated the systematics of SI for ten doubly odd nuclei in the $A = 160$ mass region and pointed out that the amplitude of anomalous signature splitting decreases with the increasing proton number. K. Hara and Y. Sun studied the SI using the angular momentum projection method (or the projected shell model (PSM)); it is predicted that the amplitudes of signature splitting in Lu isotopes should be larger than that of neighboring Tm isotopes [4]. So the high-spin states in ^{162}Lu have been experimentally observed in our laboratory. Furthermore the existing data of yrast bands have been inspected and analyzed for 17 doubly odd nuclei in $A = 160$ mass region. From this reinvestigation, it is noted that some parameters characterizing the SI have certain regularity. The difficulties of the present theoretical models in explaining the SI will be briefly discussed. While a preliminary report of this work has been published elsewhere [7], the more detailed result is presented in this paper.

2. EXPERIMENT AND DATA ANALYSIS

The experiment was carried out at the in-beam γ terminal of HI-13 tandem accelerator of CIAE, Beijing. A 7.3 mg/cm^2 self-supporting Sm target enriched to 98% of ^{147}Sm was bombarded by the ^{19}F beam. The standard γ-ray in-beam spectroscopic measurements have been performed by using 7 BGO(AC)HPGe detectors and one planar detector which were calibrated by the standard ^{152}Eu and ^{60}Co sources. The typical energy resolution was about 2.0 — 2.3 keV at FWHM for the 1332 keV peak from ^{60}Co. Prior to this work, there is no information on high-spin states about ^{162}Lu. Therefore, the measurements of excitation functions obtained at 85, 90, 95, and 100 MeV beam energies and K X-γ coincidence were carried out in order to assign the γ-rays related to ^{162}Lu. The γ-γ coincidence measurement was performed at the 95 MeV beam energy at which the cross section for producing ^{161}Lu was negligible and the main contamination was from ^{162}Yb and ^{163}Lu nuclei. 50 million events with the γ_1-γ_2-t_{12} mode were recorded one by one on magnetic tapes through the VAX-780 computer.

Off-line data analysis was performed in the VAX-8350 of the Institute of Modern Physics. Every γ-γ coincident event was energetically normalized in order to avoid the spectrum deviation caused by the electronics variations. Two 4k × 4k γ-γ coincident matrices were established by selecting different time windows from which the gated γ-ray spectra can be obtained. Figure 1 shows some γ-γ coincident spectra gated by several typical γ-rays. In these gated spectra the 511 keV γ-ray is relatively strong since there are certain contaminations from positron annihilation besides the in-beam γ-rays of ^{162}Lu.

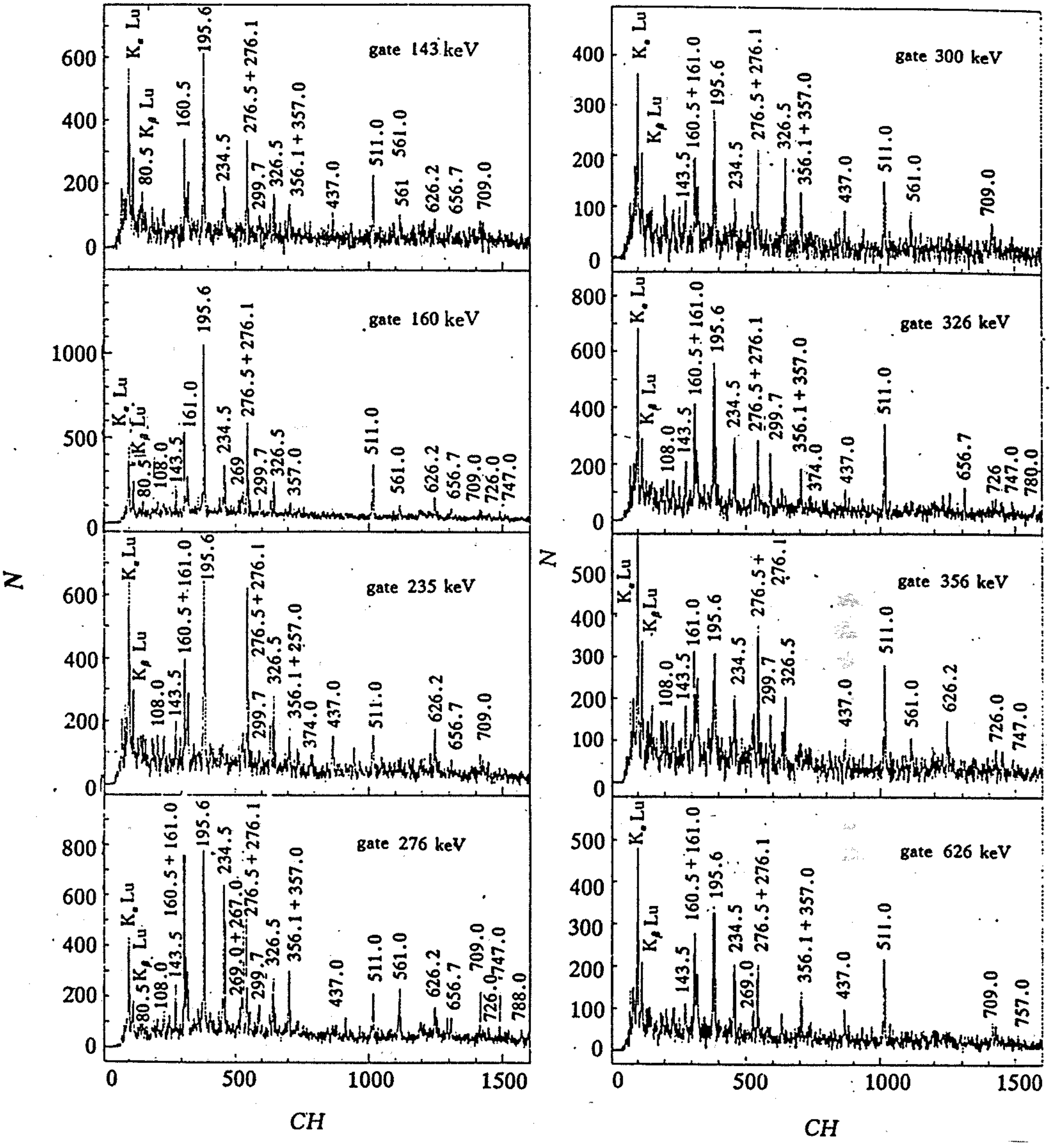

Fig. 1
Gated γ-γ coincidence spectra.

3. RESULTS AND DISCUSSIONS

3.1. Energy level scheme

For the rotational bands of deformed doubly odd nuclei, the typical level scheme is composed of two *E*2 cascades and a series of *M*1 / *E*2 competing transitions where the *E*2 transition energies increase regularly with the increasing excitation energy. For the residual nucleus from the heavy ion-induced fusion-evaporation reactions (such as ^{162}Lu), the higher the excitation energy of the levels, the smaller the population rates, then the γ-rays deexcited from these levels will be weaker.

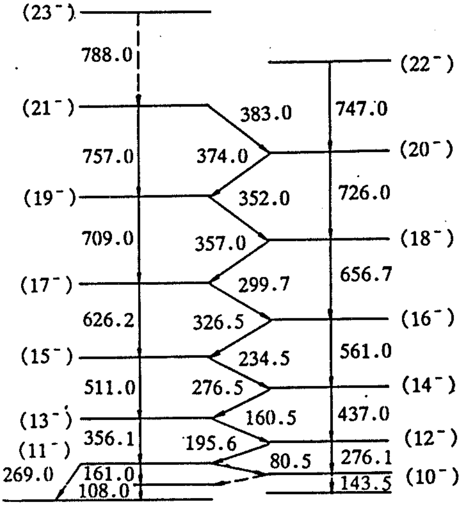

Fig. 2

The level scheme proposed in this work.

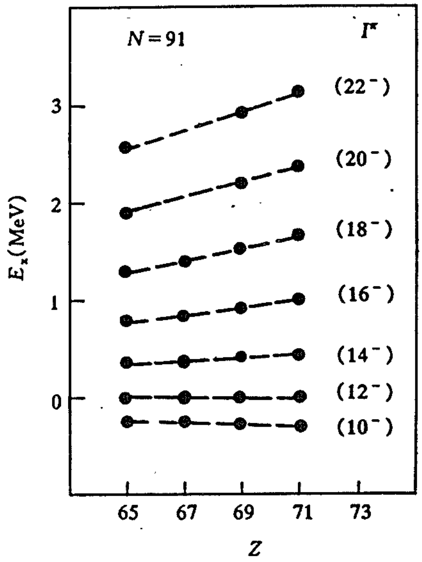

Fig. 3

Systematic variation of excited levels in the $\alpha = 0$, $\Delta I = 2$ cascade of $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ bands in the $N = 91$ isotones. Take $I = (12^-)$ state as a reference.

Considering all these factors and analyzing carefully the gated spectra, the level scheme of rotational bands in ^{162}Lu has been constructed as shown in Fig. 2 for the first time in this work where the dashed lines are tentative and need further confirmation.

The spin of the ground state is assigned to be (1), and its parity is not ascertained. Two low-lying isomeric states deexcite mainly through the β^+ decay. The study of the ^{162}Hf β^+ / EC decay identified only a few lower spin states in ^{162}Lu. The γ-rays decaying from these states could not be detected in this experiment because of low population rates of these states in the reaction selected. Moreover, the level density is high in doubly odd nucleus ^{162}Lu, and the γ transitions from the band head to the ground state or low-lying states are very complex, thus the accompanying low-energy γ-rays are normally difficult to be detected. As a consequence the connection from the band head to ground state cannot be established in this work. This imperfection makes it quite difficult to assign experimentally the spin for the band hand.

The parity of rotational band can be proposed by referring to yrast bands in the other nuclei around the $A = 160$ mass region. In this region, the yrast bands of odd neutron nuclei are based on the $\nu i_{13/2}$ configuration, while the yrast bands of odd-proton nuclei are based on the $\pi h_{11/2}$ configuration. The yrast bands of the doubly odd nuclei should be the two quasiparticles excited band based on $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ configuration. In fact, for all the doubly odd nuclei from Eu to Ta, the yrast bands already known are identified to be based on the $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ quasiparticle configuration. Therefore the rotation band of ^{162}Lu observed in this work is considered to be the yrast band based on the same configuration, and its parity is negative. Furthermore, the alignment in ^{162}Lu rotational band backbends at the frequency of 0.36 MeV, which is the result of the blocking effect of quasiproton and quasineutron. It also testifies that the rotational band is a two quasiparticle band based on the $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ configuration.

The spin values of the energy levels in ^{162}Lu have been determined through some theoretical calculations [1,7] according to the fundamental property of the additivity rule for alignments in the framework of the cranked shell model (CSM). Using the spin values in Fig. 2 and comparing the aligned angular momentum of the two $E2$ transition sequences, it is found that the even spin sequence ($\alpha = \alpha_f$) has larger alignment than that of odd spin sequence ($\alpha = \alpha_u$) [7]. Moreover, in the neighboring isotopes and isotones, the $E2$ transition energies corresponding to the same initial-to-final levels show a smooth trend with the proton and neutron numbers (see Fig. 3). These two arguments support our spin assignment to the yrast levels in ^{162}Lu. It must be pointed out that the spin values are proposed according to the theoretical calculations and thus need further experimental confirmation.

3.2. Signature inversion of yrast levels

The SI of yrast levels can be shown in different ways; here the method used in Ref. [5] was adopted. Figure 4 shows the dependence of the quantity $S(I) = E(I) - E(I-1) - 1/2[E(I+1) - E(I) + E(I-1) - E(I-2)]$ on the spin I (see ^{162}Lu in Fig. 4), where $S(I)$ denotes the amplitude of signature splitting. It is clearly seen in Fig. 4 that the signature splitting of ^{162}Lu is inverted in the low-spin region (low rotational frequencies), and the two rotational sequences cross in a certain frequency, i.e., the signature splitting changes from anomalous to normal.

In the traditional CSM, the SI is considered to be evidence of triaxial deformation [2]. In the framework of the particle-rotor model (PRM) without introducing the triaxial deformation, I. Hamamoto made some calculations and explained the SI [3] qualitatively by considering that the neutron (or the proton) aligns its angular momentum along the total angular momentum while the other nucleon rotates around the effective rotor. In Ref. [9], it is thought that the competition between the proton-neutron interaction and the Coriolis force is the source of SI [9]. Based on the PSM, K. Hara and Y. Sun proposed that there are two mechanisms which can result in the phenomenon of SI: one is called the self-inversion of a band based on the $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ configuration, the other is due to the crossing of two bands based on $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ and $\{\nu i_{13/2} \otimes \pi h_{9/2}\}$ configurations [10]. The triaxial deformation is not introduced in Refs. [3,9,10]. It is worthwhile to note that the different theories mentioned above cannot fit the amplitude of SI at low spins although the calculations can explain the phenomenon qualitatively. So it becomes meaningful to systematically study the SI both in theory and experiment in order to further understand its mechanism.

4. SYSTEMATICS OF SI IN YRAST BANDS OF NUCLEI AROUND $A = 160$ MASS REGION

The SI is found in many yrast bands of doubly odd nuclei around the $A = 160$ mass region; however, there is no model explaining this phenomenon satisfactorily. Furthermore, the uncertainty of spin values leads to difficulties for theoretical analysis. Therefore, we have systematically investigated and analyzed the yrast bands in the doubly odd nuclei already known at present by using the additivity rule for alignments in the CSM and assuming that the alignment of the favored band is larger than that of unfavored band under the same rotational frequencies. This method has been applied to 17 doubly odd nuclei from Eu to Ta, and the spin values of the yrast band have been determined by changing the spin values of the levels and comparing the alignment of the yrast band in a doubly odd nucleus with the sum of alignments in the odd-A neighboring nuclei. It is found that the spins of band head in ^{156}Tb, ^{158}Ho, ^{166}Lu, and ^{168}Ta ($6\hbar$[11], $5\hbar$[12], $7\hbar$[13], and $10\hbar$[14]) are probably wrong. Our studies suggest that the spins of band head in the four nuclei should be $8\hbar$, $8\hbar$, $8\hbar$, and $9\hbar$, respectively. These assignments are in agreement with the results of Ref. [15]. Adopting the new spin values, Fig. 4 shows $S(I)$ of the yrast bands in 17 doubly odd nuclei as a function of I. From this figure, it can be seen that: (1) The SI occurs at low rotational frequencies (before the first backbending) in all the yrast bands based on the $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ configuration; at certain spins,

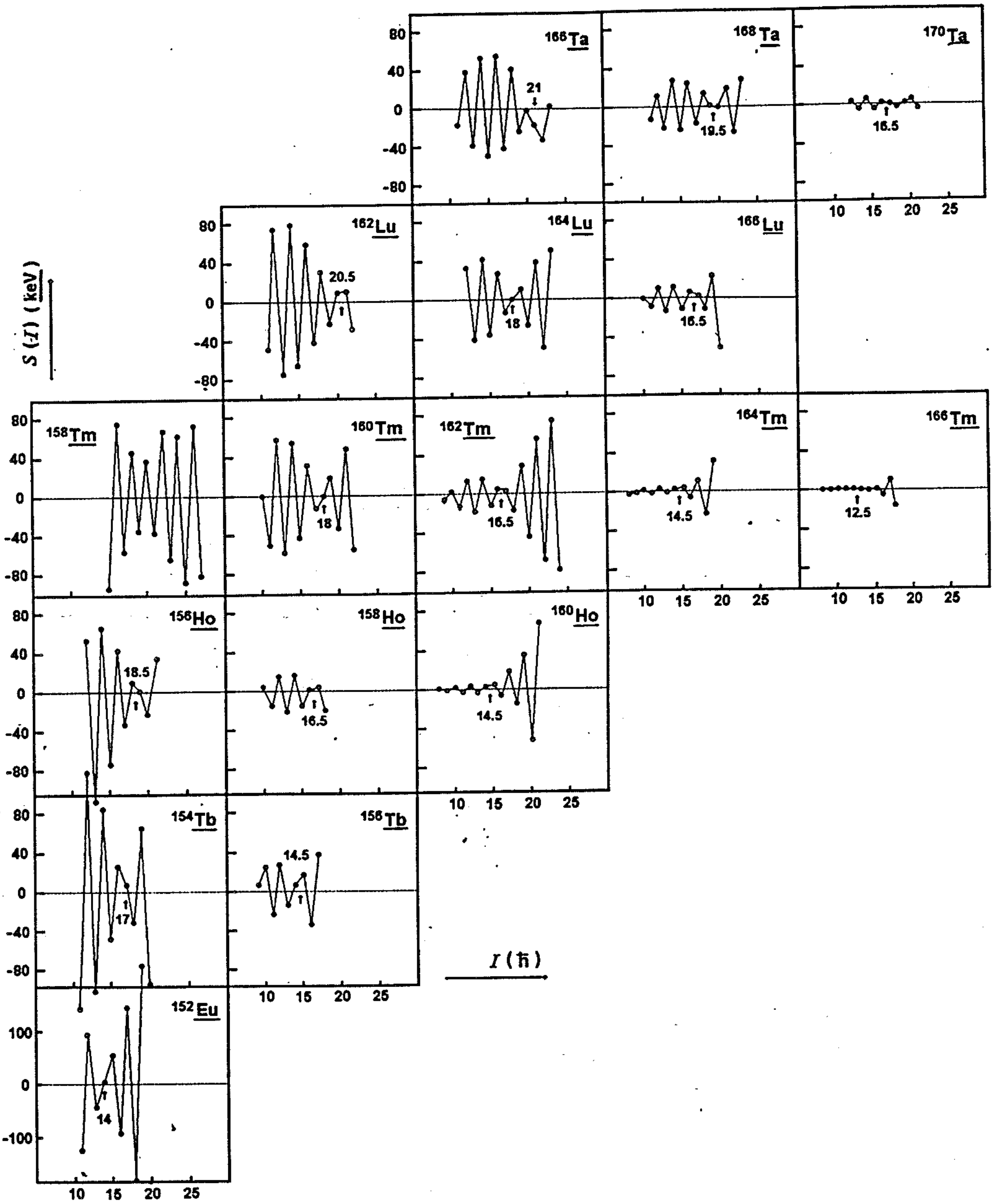

Fig. 4

Systematics of SI for the yrast bands in the A = 160 mass region.

$S(I)$ is a quantity describing the signature splitting amplitude, the arrows and nearby values represent the signature crossing and the corresponding crossing spins ($\hbar$); ● are favored bands and ○ are the unfavored ones.

two rotation sequences cross each other (except for ^{158}Tm, the reason will be discussed below). (2) For a chain of isotopes, the anomalous splitting amplitude decreases with the increasing neutron number. (3) For a chain of isotones (such as $N = 91$), with the increases of proton number, the splitting amplitude varies first from larger (^{156}Tb) to smaller (^{158}Ho) and then to the larger amplitude again (^{160}Tm and ^{162}Lu); the spin value corresponding to the signature crossing increases regularly by a step of about $2\hbar$; this behavior is not consistent with the conclusion indicated in Ref. [5]. (4) Corresponding to the crossing point, the so-called crossing frequency can be extracted [1], and it varies regularly with Z and N (see Fig. 5).

As motioned above, although the mechanisms considered are quite different in the different theories, they can all explain the phenomenon of SI qualitatively. Evidently, it becomes quite necessary to investigate the trend of splitting amplitude in order to clarify the physical nature of SI. In the theory of PRM, the splitting amplitude is determined by the distance of the proton Fermi surface to the $\pi h_{11/2}[550]1/2$ Nilsson level — the farther the distance, the smaller the splitting amplitude [3]. For the rotational levels in ^{156}Tb and ^{158}Ho, the variation of the splitting amplitude consists with this rule. But for ^{158}Ho, ^{160}Tm, and ^{162}Lu, the splitting amplitude increases with the proton number, which is opposite to the prediction of PRM.

Concerning to the trend of splitting amplitude with the increase of proton number, K. Hara and Y. Sun, using the PSM, gave the following theoretical explanations: the SI of the yrast band in ^{156}Tb comes from the self-inversion of the bands based on the $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ configuration [10]. The larger splitting amplitude is due to the shorter distance of the proton Fermi surface to the $\pi h_{11/2}[550]1/2$ Nilsson level, where the strong decoupling effect makes the splitting amplitude of the yrast band in ^{156}Tb much larger. Whereas for ^{158}Ho and ^{160}Tm the SI comes from the crossing of the two bands based on the $\{\nu i_{13/2} \otimes \pi h_{11/2}\}$ and $\{\nu i_{13/2} \otimes \pi h_{9/2}\}$ configurations, in this case, the splitting amplitude is determined by the competition of the decoupling effects between the $\pi h_{11/2}[550]1/2$ and $\pi h_{9/2}[541]1/2$ Nilsson orbitals. With the increase of proton number, the proton Fermi surface becomes farther from the $\pi h_{11/2}[550]1/2$ Nilsson level but closer to the $\pi h_{9/2}[541]1/2$ orbital. As a consequence, the effect of the $\pi h_{11/2}$ [550]1/2 orbital becomes weaker while the effect of $\pi h_{9/2}[541]1/2$ level becomes stronger; therefore, the behavior of splitting amplitude is presented as experimentally observed. However, Hara predicted that the SI in ^{162}Lu is due to the self-inversion of a band based on the $\{\nu i_{13/2} \otimes \pi h_{9/2}\}$ configuration. The systematics shown in Fig. 4 indicates that not only in Lu isotopes but also in Ta isotopes the SI still shows the band crossing characters which is opposite to the prediction of the PSM.

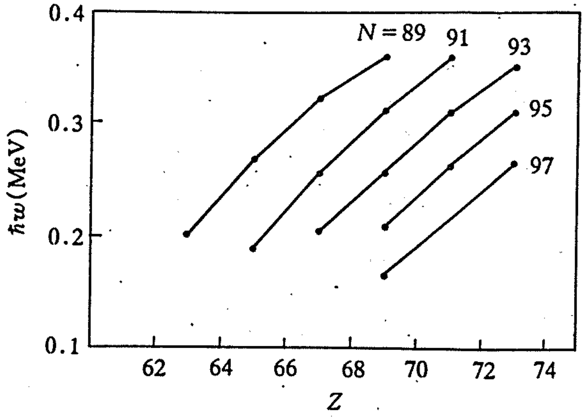

Fig. 5
Systematics of signature crossing frequencies for the yrast bands in the $A = 160$ mass region.

Finally, it should be pointed out that the phenomenon of SI and the regular variation pattern of splitting amplitude with the number of protons and neutrons can be explained qualitatively [2] if the positive triaxial deformation is considered in the framework of CSM. However, the $\beta/(\gamma)$ deformation must be decreased/(increased) with the increasing proton number in order to fit with the systematics of splitting amplitude and signature crossing frequencies determined from the experimental data. For example, it demands the deformation variables β and γ be 0.19 and 25° [1]; this γ value seems too large and the quadruple deformation (2.95 eb) extracted from this $\beta/(\gamma)$ value is not consistent with the experimental value (4.41 ± 0.47 eb) [16]. Furthermore, even if the doubly odd nuclei have positive triaxial deformation, it should be the result of the total effect from the γ deformation driving forces of the quasiproton and the quasineutron. As the proton number increases, the Fermi surface of proton becomes closer to the high Ω Nilsson level in the $\pi h_{11/2}$ subshell, and the quasiproton in this high Ω orbital has a stronger negative γ deformation driving force. The positive γ deformation driving force of the quasineutron in a certain Nilsson orbital would not have remarkable variation with the proton number; the fact that the amplitude of normal signature splitting in the neighboring odd-Z nuclei increases as the proton number increases, might be evidence of larger negative γ deformation in the corresponding nuclei. Adding a neutron to the odd-Z nucleus, its positive γ deformation driving force does not seem large enough to counteract the increasing negative γ deformation. Therefore, if based on the CSM and by fitting with the experimental data, the trend that the positive γ deformation increases greatly with the increasing proton number [2] seems too difficult to be understood.

From the qualitative discussions above, it is seen that the systematics shown in Figs. 4 and 5 cannot be satisfactorily explained based on the present model-dependent theories. Detailed inspection on Fig. 4 shows that the signature splitting of the yrast bands in ^{158}Tm and ^{170}Ta deviates from the systematics at the high-spin region. It is therefore considered that something might be wrong in the level schemes given in Refs. [17,18]. Indeed, the reinvestigation of ^{158}Tm in Ref. [19] demonstrated that the level scheme above $22\hbar$ proposed in Ref. [17] was wrong; this conclusion is consistent with our result from the systematic analysis of SI.

5. CONCLUSION

The high spin states in the doubly odd nucleus ^{162}Lu have been observed for the first time in the present work, and the level scheme of the rotational band is established. The spin values of the rotational band are proposed according to the additivity rule for alignments in the CSM. It is found that the SI of the yrast band occurs at low rotational frequencies and the crossing of two signature series appears at $\hbar\omega = 0.36$ MeV. At the low rotational frequencies, the splitting amplitude of the yrast band in ^{162}Lu is larger than that in its lower Z neighboring isotones.

The systematic analysis demonstrates that the phenomenon of SI exists with generality in the nuclei around $A = 160$ mass region and some quantities present a certain regularity indicating the effects of some kinds of physical reasons. The difficulties in describing SI based on the present theories are discussed, and it is especially pointed out that systematics shown in Figs. 4 and 5 cannot be well described. To understand the physical nature of SI, it is considered primarily that the positive γ deformation might not be the necessary requirement of SI, while the splitting amplitude and its variation pattern with (Z, N) should be associated with triaxial deformation. Therefore, better fitting results to the experimental data may be obtained in the framework of PSM by considering the γ triaxiality and adjusting the single-particle energy levels. In summary, it is still important to understand the physical nature of SI by investigating systematically the splitting amplitude, especially the dependence of the splitting amplitude on proton and neutron numbers both in theory and experiment.

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