Chinese Physics C Vol. 37, No. 4 (2013) 044001

# Doublet bands in $^{128}$La and systematic features of energy separation of doublet bands observed in the $A\sim130$ mass region*

MA Ke-Yan(马克岩)[1] LU Jing-Bin(陆景彬)[1;1)] YANG Dong(杨东)[1] WANG Hui-Dong(王辉东)[1]
LIU Yun-Zuo(刘运祚)[1] LI Jian(李剑)[1] LIU Gong-Ye(刘弓冶)[1] LI Li(李黎)[1] MA Ying-Jun(马英君)[1]
WU Xiao-Guang(吴晓光)[2] LI Guang-Sheng(李广生)[2] ZHENG Yun(郑云)[2] HE Chuang-Ye(贺创业)[2]

[1] College of Physics, Jilin University, Changchun 130023, China
[2] China Institute of Atomic Energy, Beijing 102413, China

**Abstract:** High spin states of $^{128}$La have been studied through the fusion-evaporation reaction $^{118}$Sn($^{14}$N, 4n)$^{128}$La at a beam energy of 69 MeV. A positive-parity side band with the same configuration as that of the yrast band has been identified. Moreover, it is noted that the energy separation $\Delta E(I)=E(I)_{\rm side}-E(I)_{\rm yrast}$ of all doublet bands reported in odd-odd nuclei in the $A\sim130$ mass region exhibit a staggering pattern systematically, and they stagger up at even-spin and stagger down at odd-spin.

**Key words:** high spin state, fusion-evaporation reaction, doublet band

**PACS:** 21.10.Re, 23.20.Lv, 27.60.+j **DOI:** 10.1088/1674-1137/37/4/044001

## 1 Introduction

In the $A\sim130$ mass region, the doublet bands with the $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration have attracted significant attention and intensive discussion in the past few years. The interpretations of some of the reported doublet bands have been controversial and the most noted example is the doublet bands in $^{134}$Pr. The doublet bands in $^{134}$Pr were argued to be the doublet bands with best chiral characteristics among the doublet bands observed in $N=75$ isotones ($^{130}$Cs, $^{132}$La, $^{134}$Pr, $^{136}$Pm and $^{138}$Eu) [1]. However, this claim was not supported by the later analysis of related data [2] and the experimental results of electromagnetic transition probabilities based on lifetime measurements [3].

The validity of a theory is often tested by how well the theory reproduces the systematic behavior of the phenomenon, and thus it is important to establish the systematic behavior of the doublet bands which systematically appeared in the $A\sim130$ mass region. To serve this purpose, the present work extends the observation of doublet bands in odd-odd nuclei to $^{128}$La and reviews the systematic behavior of the energy separation, $\Delta E(I)=E(I)_{\rm side}-E(I)_{\rm yrast}$, of all doublet bands reported in the $A\sim130$ mass region.

## 2 Experimental details

The experiment was performed through the $^{118}$Sn($^{14}$N, 4n)$^{128}$La reaction with the beam provided by the HI-13 tandem accelerator at CIAE in Beijing. The $^{118}$Sn target with an enrichment of 92.8% and a thickness of 2.4 mg/cm$^2$ was rolled onto a lead backing. The $\gamma$-ray detecting array consisting of 12 Compton-suppressed HPGe detectors and two planar HPGe detectors was used to collect $\gamma$-$\gamma$ coincidence data. The Ge detectors in the array were placed at 90°, ±37°, ±30°, and ±60° relative to the beam direction. Energy and efficiency calibrations of the detectors were performed by standard sources of $^{60}$Co and $^{152}$Eu. The bombarding energy of 69 MeV was selected to populate the nucleus $^{128}$La by the excitation function measurements. A total of $3.6\times10^6$ two fold coincidence events were collected. A symmetrized coincidence matrix and an asymmetric DCO (directional correlation ratios of oriented states) matrix were constructed for off-line analysis. In our array geometry, if one gates on a quadrupole transition, the expected $R_{\rm DCO}$ value is close to 1.0 for stretched quadrupole transitions and close to 0.6 for stretched dipole transitions. Similarly, with a dipole gating transition, the $R_{\rm DCO}$ value is close to 1.7 and 1.0 for quadrupole

---

Received 21 May 2012

* Supported by National Basic Research Programme of China (2007CB815005), National Natural Science Foundation of China (11075064) and Specialized Research Fund for the Doctoral Programme of Higher Education of China (20050183008)

1) E-mail: ljb@jlu.edu.cn

and dipole transitions, respectively. Based on the $\gamma$-$\gamma$ coincidence relationship, together with the intensity balance of transitions, the partial level scheme of $^{128}$La is constructed and presented in Fig. 1.

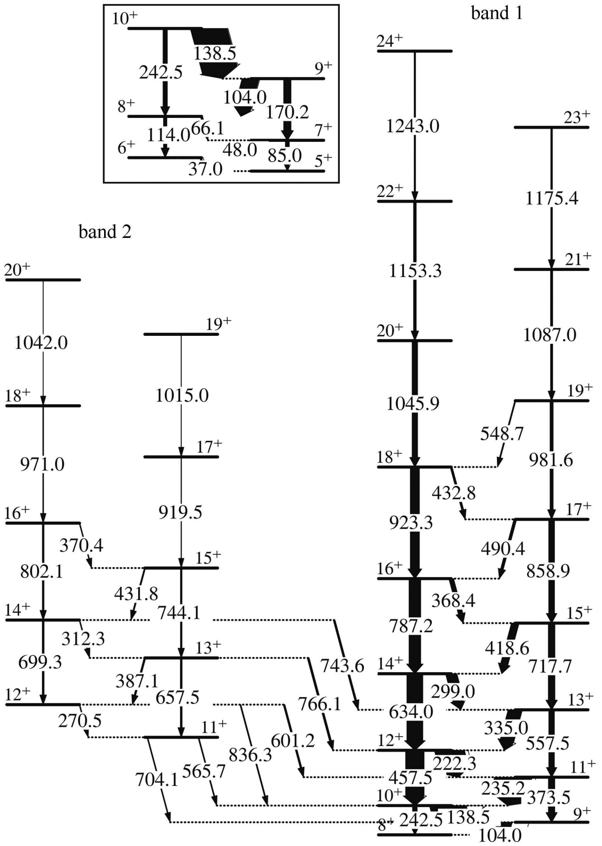

Fig. 1. Partial level scheme of $^{128}$La deduced from the present study. The insertion shows the bottom portion of band 1.

## 3 Result and discussion

Yrast band 1 is the most intensely populated in the present experiment, and its configuration has been assigned to $\pi h_{11/2}\otimes\nu h_{11/2}$ in previous work [4, 5]. After the work of [4, 5], $I^{\pi}=5^{+}$ was assigned to the bandhead of the $\pi h_{11/2}\otimes\nu h_{11/2}$ band by T. Hayakawa et al. [6] based on the studies of $\beta$-decays of $^{128}$La and $^{128}$Ce.

Band 2 (the side band) has been reported for the first time in the present study. The intraband transitions of this band have been extended up to $20\hbar$, and six new linking transitions of 743.6, 766.1, 601.2, 836.3, 565.7 and 704.1 keV between bands 1 and 2 are observed. A typical $\gamma$-$\gamma$ coincidence spectrum is shown in Fig. 2. Considering the dipole character of the linking transitions of 766.1 and 565.7 keV with DCO ratios of 0.93 and 1.12, and the quadrupole character of 704.1 and 836.3 keV transitions with DCO ratios of 1.78 and 1.82 (DCO ratios from gating on the dipole transition), the spin-parity assignments of band 2 are firmly confirmed.

The alignment plots of band 1, band 2 and the known $\pi h_{11/2}\otimes\nu(d_{5/2}/g_{7/2})$ band, reported in Ref. [4], of $^{128}$La are shown in Fig. 3 where the $\pi h_{11/2}\otimes\nu(d_{5/2}/g_{7/2})$ band exhibits a sharp backbend at $\hbar\omega$=0.45 MeV caused by the rotational alignment of the first pair of $h_{11/2}$ neutrons. The absence of a band crossing at this frequency for bands 1 and 2 in Fig. 3 indicates that the $\nu h_{11/2}$ orbital is Pauli blocked in both bands, which suggests that an $\pi h_{11/2}$ orbital is involved in the configurations of these two bands. Moreover, the large initial alignments ($\sim 6\hbar$) for both bands 1 and 2 strongly suggests that the $h_{11/2}$ proton is involved in the configuration of bands 1 and 2. All these experimental observations suggest that band 2 has the same $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration as that of band 1.

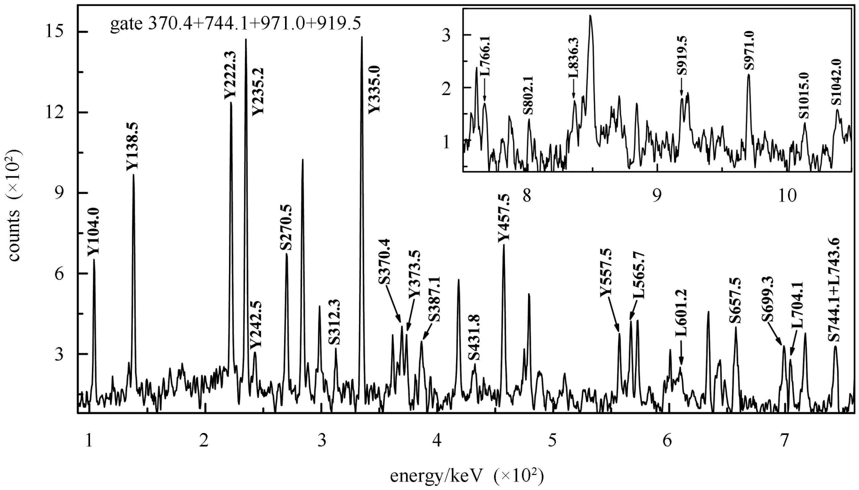

Fig. 2. Typical $\gamma$-$\gamma$ coincidence spectrum supporting the level scheme of doublet bands in $^{128}$La. Y, S and L stand for transitions in the yrast band, the side band, and the linking transitions.

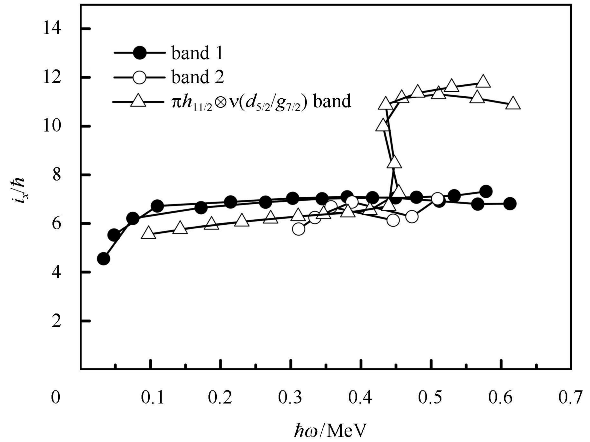

Fig. 3. Rotational alignments of bands in $^{128}$La. The Harris parameters are $J_0$=17.0 MeV$^{-1}\hbar^2$, $J_1$=25.8 MeV$^{-3}\hbar^4$.

Furthermore, it should be noted that the particle orbitals of the $\pi h_{11/2}\otimes\nu h_{11/2}$ band have been assigned as $h_{11/2}[550]1/2^-$ for the proton and $h_{11/2}[523]7/2^-$ for the neutron [5]. According to the Gallagher-Moszkowski rules [7], the deduced bandhead spin of the $\pi h_{11/2}\otimes\nu h_{11/2}$ band should be 1/2+7/2=4. This is in contradiction with the $I$=5 assignment of T. Hayakawa et al. [6]. It is well known that the signatures of the $\pi h_{11/2}\otimes\nu h_{11/2}$ band of odd-odd nuclei in the mass region of $A\sim130$ are inverted at low spins. A spin assignment of $I=4$ or of any even number to the bandhead of the $\pi h_{11/2}\otimes\nu h_{11/2}$ band in $^{128}$La will lead to the normal signature splitting without inversion at low spin, and thus the assignment of $I=4$ is not acceptable. One of the possible ways to remove this contradiction is to assign the neutron orbital as $h_{11/2}[514]9/2^-$ instead of $h_{11/2}[523]7/2^-$ or to assign the proton orbital as $h_{11/2}[541]3/2^-$ instead of $h_{11/2}[550]1/2^-$. This is a problem which needs to be studied further.

Finally, to inspect the systematic features, $\Delta E(I)=E(I)_{\rm side}-E(I)_{\rm yrast}$ of experimentally observed doublet bands in the $A\sim$ 130 mass region are presented in Fig. 4. To avoid overlap, the $\Delta E(I)$ of neighbouring isotopes are separated by 120 keV. Two systematic features are revealed in Fig. 4. Firstly, the $\Delta E(I)$ of all reported doublet bands exhibit a staggering pattern, and they stagger up at even-spin and stagger down at odd-spin (except at $I$=13 for $^{130}$Cs and $I\geqslant18$ for $^{136}$Pm and $^{134}$Pr). This phenomenon is most pronounced at $I$=11, 12 and 13. Usually, the experimental error of $\gamma$-ray energy is much less than 1 keV and by taking into account the cumulative effect of errors, the errors of the level energies are not more than 1–2 keV. The error bar of $\Delta E(I)$ is less than the diameter of the dots in Fig. 4, and thus the staggering pattern of $\Delta E(I)$ is believed to be a real effect. Secondly, the "slope" of the variation trend of the average magnitude of $\Delta E(I)$ decreases from positive (such as $^{122}$Cs, $^{128}$La and $^{132}$Pr) to negative (such as $^{132}$Cs, $^{134}$La and $^{134}$Pr) with increasing neutron number for isotopes Cs, La, and Pr.

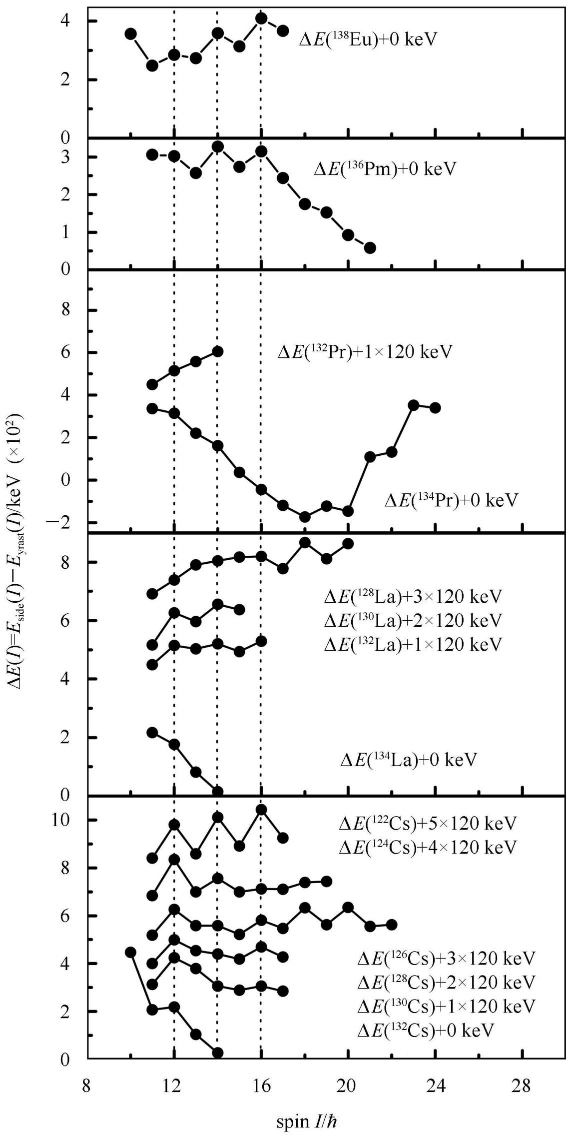

Fig. 4. $\Delta E(I)=E(I)_{\rm side}-E(I)_{\rm yrast}$ of all reported doublet bands in odd-odd nuclei in the $A\sim130$ mass region. Data sources: $^{122}$Cs [8], $^{124}$Cs [9], $^{126}$Cs [10], $^{128}$Cs [11], $^{130}$Cs [11], $^{132}$Cs [11], $^{128}$La (present work), $^{130}$La [12], $^{132}$La [1], $^{134}$La [13], $^{132}$Pr [12], $^{134}$Pr [14], $^{136}$Pm [1], and $^{138}$Eu [15].

The formation of chiral geometry in odd-odd nuclei requires that the valence proton sits on the orbital located in the lower part of the $\pi h_{11/2}$ subshell and the valence neutron sits on the orbital located in the upper part of the $\nu h_{11/2}$ subshell. It is difficult to imagine that the valence neutrons of all the Cs isotopes from $^{122}$Cs to $^{132}$Cs sit on the three orbitals located in the upper part of $\nu h_{11/2}$ subshell, and thus the reported doublet bands in $^{122-132}$Cs cannot all originate from chirality. On the other hand, the $\Delta E(I)$ staggering pattern clearly appears in all doublet bands of Cs isotopes from $^{122}$Cs to $^{132}$Cs. Therefore, it is possible that the $\Delta E(I)$ staggering phenomenon is not relevant to the chirality. Hopefully, the above discussions will stimulate more experimental studies based on life-time measurements and systematical theoretical studies on the systematically appeared doublet bands in odd-odd nuclei in the $A\sim130$ mass region.

## 4 Summary

The level scheme of $^{128}$La has been improved following the $^{118}$Sn ($^{14}$N, 4n) $^{128}$La reaction at a beam energy of 69 MeV. One new positive parity band based on the $\pi h_{11/2}\otimes\nu h_{11/2}$ configuration has been established. It is noted that energy separation of all reported doublet bands of odd-odd nuclei in the $A\sim130$ mass region systematically exhibit a staggering pattern and they stagger up at even-spin and stagger down at odd-spin.

### References

1 Starosta K et al. Phys. Rev. Lett., 2001, **86**: 971
2 Petrache C M, Hagemann G B, Hamamoto I, Starosta K. Phys. Rev. Lett., 2006, **96**: 112502
3 Tonev D et al. Phys. Rev. Lett., 2006, **96**: 052501
4 Godfrey M J, HE Y, Jenkins I, Kirwan A, Nolan P J, Thornley D J, Mullins S M, Wadsworth R. J. Phys. G, 1989, **15**: 487
5 Godfrey M J, HE Y, Jenkins I, Kirwan A, Nolan P J, Thornley D J, Mullins S M, Wadsworth R, Wyss R A. J. Phys. G, 1989, **15**: 671
6 Hayakawa T, LU J, Mukai J, Saitoh T, Hasimoto N, Komatsubara T, Furuno K. Z. Phys. A, 1995, **352**: 241
7 Gallagher C J, Jr, Moszkowski S A. Phys. Rev., 1958, **111**: 1282
8 U Yong-Nam et al. J. Phys. G, 2005, **31**: B1
9 Gizon A et al. Nucl. Phys. A, 2001, **694**: 63
10 WANG S Y, LIU Y Z, Komatsubara T, MA Y J, ZHANG Y H. Phys. Rev. C, 2006, **74**: 017302
11 Koike T, Starosta K, Chiara C J, Fossan D B, LaFosse D R. Phys. Rev. C, 2003, **67**: 044319
12 Koike T, Starosta K, Chiara C J, Fossan D B, LaFosse D R. Phys. Rev. C, 2001, **63**: 061304
13 Bark R A, Baxter A M, Byrne A P, Dracoulis G D, Kibédi T, McGoram T R, Mullins S M. Nucl. Phys. A, 2001, **691**: 577
14 Petrache C M et al. Nucl. Phys. A, 1996, **597**: 106
15 Hecht A A et al. Phys. Rev. C, 2001, **63**: 051302