CF10919 is being considered for publication in Physical Review C as a regular article.

Chirality of ^{115}Sb: further evidence for a new chiral island in neutron-rich A$\approx$120 mass region
by G. Y. Li, S. Y. Wang, Y. Zheng, et al.

Dear NNDC data scientists,

We would appreciate your review of this manuscript, which is being considered by Physical Review C. The abstract is below.

Please let us know within 3 weekdays whether you can review it. We generally hope for reports within 3 weeks, but if you need more time than that, please let us know. If you cannot review, advice on suitable referees would be welcome.

To download the manuscript, obtain more information, or send a report, please log into our referee server at:
https://referees.aps.org/reviews/CF10919-8b29350-942931

To accept to review, visit:
https://referees.aps.org/reviews/CF10919-8b29350-942931/promise

To decline to review, visit:
https://referees.aps.org/reviews/CF10919-8b29350-942931/decline

We would appreciate your help with a data consistency check for this manuscript against the NNDC databases. – Thank you for offering this data quality assurance service!

For your information, we are also consulting a regular referee in parallel, so there is no rush to review this as the referee will likely need at least two weeks to send a report.

The editorial process remains as follows:

- PRC is using its "referee" process to communicate with the NNDC.

- Please treat the manuscript with the same level of confidentiality that PRC expects referees to apply to such correspondence.

- Please return your findings by submitting your report via the referee server, but please indicate that this is a data consistency check.

- If you wish to address any remarks solely to the editors, then please separate them clearly from the remarks that we can transmit to the authors.

- PRC will inform the authors about the outcome and send along your/the NNDC's remaining findings (if any).

Thank you for your help.

Yours sincerely,

Andrea Jungclaus (she/her/hers)
Associate Editor
Physical Review C
Email: prc@aps.org

ADDITIONAL MATERIAL AVAILABLE (SEE FULL REFERRAL LETTER):

- Memo: Guidelines to referees for Physical Review

Chirality of ^{115}Sb: further evidence for a new chiral island in neutron-rich $A \approx 120$ mass region

G. Y. Li (李广有),[1] S. Y. Wang (王守宇),[1,2,*] Y. Zheng (郑云),[3] W. Z. Xu (许文政),[1] E. H. Wang (王恩宏),[1,2] H. F. Bai (白洪斐),[1] G. S. Li (李广顺),[4] B. Qi (亓斌),[1,2] C. Liu (刘晨),[1,2] X. C. Han (韩星池),[1,2] S. Wang (王硕),[1,2] D. P. Sun (孙大鹏),[1,2] Z. Q. Li (李志泉),[1,2] H. Jia (贾慧),[5] X. L. Luo (罗晓丽),[1] Y. J. Li (李英健),[1] X. Liu (刘鑫),[1] S. W. Wei (魏苏伟),[1] X. Xiao (肖骁),[1] S. Q. Zuo (左思琪),[1] L. Zhu (祝霖),[1] H. Y. Zhang (张弘燚),[1] X. G. Wu (吴晓光),[3] C. B. Li (李聪博),[3] H. Y. Wu (吴鸿毅),[6,7] T. X. Li (李天晓),[3] M. Zheng (郑敏),[3] Z. H. Zhao (赵子豪),[3,8] C. Y. He (贺创业),[3] and M. L. Liu (柳敏良)[4]

[1]*Shandong Provincial Key Laboratory of Nuclear Science, Nuclear Energy Technology and Comprehensive Utilization, Weihai Frontier Innovation Institute of Nuclear Technology, School of Nuclear Science, Energy and Power Engineering, Shandong University, Shandong 250061, People's Republic of China*

[2]*WeiHai Research Institute of Industrial Technology of Shandong University, Weihai 264209, People's Republic of China*

[3]*China Institute of Atomic Energy, Beijing 102413, China*

[4]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

[5]*School of Science, Harbin institute of technology, Weihai, 264209, China*

[6]*Key Laboratory of Nuclear Data, China Institute of Atomic Energy, Beijing 102413, China*

[7]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

[8]*College of Physics, Jilin University, Changchun 130012, China*

(Dated: May 26, 2025)

Abstract

High-spin states in ^{115}Sb were populated using the reaction ^{109}Ag(^{12}C,α2n) at a beam energy of 54 MeV. A new $\Delta I = 1$ negative parity rotational band with several transitions linking the existing negative band has been identified. Based on the experimental results and their comparison with the relativistic mean-field and multiparticle plus rotor model calculations, a chiral character of the two bands based on the $\pi g_{9/2}^{-1} \otimes \upsilon h_{11/2} d_{3/2}$ configuration is proposed. This observation provides further evidence for a new chiral island in the neutron-rich $A \approx 120$ mass region.

PACS numbers: 27.50.+e, 21.60.-n, 23.20.Lv, 21.10.Re

INTRODUCTION

Chirality is an important concept in nature across various scientific fields such as chemistry, biology, and particle physics, in which the mirror image of the system does not coincide with the original. In nuclear physics, chirality was first predicted by Frauendorf and Meng [1], which is expected to manifest in rotating triaxial nuclei. They pointed out an initial consideration of chirality: the angular momentum vectors of a high-j valence particle, a high-j valance hole and the core are mutually perpendicular and align with the short, long and intermediate axes, respectively. Under the above conditions, a pair of nearly degenerate $\Delta I = 1$ bands with the same parity is expected, i.e., chiral doublet bands. This type of chiral configuration was found in a number of odd-odd nuclei (see recent reviews [2–11] and references therein). Besides, chiral doublet bands have also been observed in the odd-A systems [12–26]. In odd-A nuclei, chiral doublet bands are based on three- or more quasiparticle configurations with a more complex angular momentum coupling, which is generated after the proton or neutron pairs break. Studies on chiral doublet bands in odd-A nuclei deepen the understanding of how multi-quasiparticles form chirality.

Searching for new chiral nuclear regions has been a research hotspot in the recent years. Presently, chiral nuclei have been observed in the $A \approx 80$, 100, 130 and 190 mass regions [2–11]. Very recently, chiral doublet bands based on $\pi g_{9/2}^{-1} \otimes \nu(g_{7/2}/d_{5/2})h_{11/2}^{2}$ configuration were identified in ^{116}In (Z=49) [27], which indicates that a possible new region of chirality in the neutron-rich $A \approx 120$ mass region. In this mass region, an obvious triaxial deformation for forming chirality based on more quasiparticle configurations would occur when the nuclei approach the $Z = 50$ magic number and the number of neutrons crosses the $N = 64$ subshell. Further experimental work is needed in order to find more evidence supporting the existence of chirality in this mass region. The odd-A nucleus ^{115}Sb (Z=51), is located near the ^{116}In in the nuclide chart, in which a $\Delta I = 1$ negative parity rotational band involving high-j $g_{9/2}^{-1}$ and $h_{11/2}$ intruder orbitals has been observed [28]. Therefore, the experiment research for chirality in the ^{115}Sb is expected. In the present work, we report a pair of candidate chiral doublet bands in the odd-A nucleus ^{115}Sb, which provides further evidence for a new chiral island in the neutron-rich $A \approx 120$ mass region.

1996Ch36 Band 4

EXPERIMENTAL DETAILS

High spin states in ^{115}Sb were populated by the reaction ^{109}Ag(^{12}C,α2n) at a beam energy of 54 MeV. The beam was provided by the HI-13 Tandem Accelerator of the China Institute of Atomic Energy (CIAE). The target consisted of 1.03 mg/cm^2 ^{109}Ag evaporated on a 10.6 mg/cm^2 Pb backing. The deexciting γ rays were detected by twenty-three Compton-suppressed HPGe detectors, four Compton-suppressed clover detectors and one clover detector without Compton-suppression. The detectors were placed at 60° (seven HPGe), 90° (three HPGe and four clover), 120° (seven HPGe and one clover) and 150° (six HPGe). A total of approximately 2.3×10^9 two-fold coincidence events and 2.2×10^7 three-fold coincidence events were recorded with a general-purpose digital data acquisition system (GDDAQ) [29] based on Pixie-16 modules from XIA LLC [30]. The coincidence events were sorted into several symmetric and asymmetric matrices. The symmetric matrices were used to construct the level scheme and extract the relative intensities of the γ transitions. The asymmetric matrices were used to obtain angular distributions from the oriented states (ADO) ratios [31], which are determined by the ratio of $I_\gamma(150°)$ to $I_\gamma(90°)$. In this experiment, an ADO ratio of $\approx$ 1.6 is expected for the stretched quadrupole or unstretched dipole transitions and $\approx$ 0.8 for the pure stretched dipoles.

E2, ΔI = 2

M1 or E1, ΔI=0

M1 or E1, ΔI = 1

Report: ratios between them

EXPERIMENTAL RESULTS

Prior to this work, high-spin states of ^{115}Sb have been studied in Refs. [28, 32–35]. In Ref. [32], a positive-parity rotational band built on 9/2$^+$ proton-hole states was observed for the first time. In Ref. [33], three isomeric states having $I^\pi = 11/2^-$, $19/2^-$ and $25/2^+$ with half-lives of 6.7 ns, 156 ns and 4.0 ns respectively were identified. A $\Delta I = 2$ negative-parity rotational band based on the $\pi h_{11/2}$ orbital has been identified for the first time in Ref. [35]. Additionally, a more comprehensive level structure of ^{115}Sb was reported in Ref. [28], in which a $\Delta I = 1$ negative parity coupled rotational band based on $\pi g_{9/2}^{-1} \otimes \upsilon h_{11/2} d_{3/2}$ configuration was established for the first time. 1996Ch36 Band 4

Based on the present $\gamma - \gamma$ coincidence relationships and intensity balances, the level structures of ^{115}Sb was constructed. The partial level scheme of ^{115}Sb resulting from the present work is illustrated in Fig. 1. As shown in Fig. 1, a new $\Delta I = 1$ band (labelled as 2) and several linking transitions were found. Fig. 2 shows spectrums gated by the 247.1 and 540.4 keV transitions, in which the newly identified transitions can be clearly seen.

The spin-parity assignments are deduced from the measured ADO ratios. In the present work, a difference exists in the spin assignment for the band-head of band 1 compared to the Ref. [28], where $(21/2)^-$ was assigned to this level. However, in this work, the same level is assigned $(19/2)^-$. This contradiction is caused by the different multi-polarity for the 540.4 keV transition. Based on the present ADO measurement, the ADO ratio of 540.4 keV transition is 0.98(8), which indicates a $\Delta I = -1$ or 1 $M1/E2$ character. We adopted the $\Delta I = -1$ $M1/E2$ character for the 540.4 keV transition due to the new 905.3 keV transition linking the band-head of band 1 to the $(15/2)^-$ state at 2637.6 keV, which is an $E2$ character. Therefore, we assigned $(19/2)^-$ for the band-head of band 1. Band 2 feeds into the level state of band 1 through several linking transitions. The measured ADO ratios of the 159.6 keV and 428.2 keV transitions indicate a $\Delta I = 0$ $M1/E2$ character and a $\Delta I = 1$ $M1/E2$ character, respectively. We therefore assigned $(19/2)^-$ for the lowest observed state of band 2. The spins and parities of the other levels were assigned based on the same method. The excitation energies, spin-parity assignments for the initial and final states, the transition energies, relative intensities, and ADO ratios of the γ rays in ^{115}Sb are listed in Table. I.

DISCUSSION

Band 1 has been assigned the $\pi g_{9/2}^{-1} \otimes \upsilon h_{11/2} d_{3/2}$ configuration in Ref. [28]. The newly established band 2 feeds into band 1 by several $M1/E2$ linking transitions, which should be strongly hindered unless the side-band is built on the same configuration, as discussed in Refs. [36–38]. To investigate the characteristics of bands 1 and 2, The excitation energies relative to a rigid-rotor reference $E(I) = J \cdot I(I+1)$, energy staggering parameters $S(I) = [E(I) - E(I-1)]/2I$ and the $B(M1)/B(E2)$ values of bands 1 and 2 were extracted and presented in Fig. 3 as functions of spin. As shown in Fig. 3, bands 1 and 2 are nearly degenerate, and the average energy difference is small ($\approx$ 110 keV). The two bands have similar $S(I)$ values with smooth variations versus spin. In addition, the reduced transition probability ratios are also an important criterion for the properties of rotational bands. The experimental $B(M1)/B(E2)$ ratios of these two bands are close to each other and show the same odd-even staggering. Thus, we suggest that bands 1 and 2 are a pair of candidate chiral doublet bands.

In order to further understand the chirality in ^{115}Sb, calculations based on the relativistic mean-field theory (RMF) [39] and the multiparticle plus rotor model (MPRM) [40, 41] have been performed. The RMF calculations with the PC-PK1 [42] parameter sets show that the triaxial deformation parameters are $(\beta, \gamma) = (0.21,\ 15.6°)$ for the $\pi g_{9/2}^{-1} \otimes \upsilon h_{11/2} d_{3/2}$ configuration. The deformation parameter $\beta = 0.21$ was used as input to the MPRM calculations. While the triaxial deformation parameter γ was adjusted because the values of γ usually vary as rational frequently increasing [43–46]. The value of $\gamma = 22°$ was found to be the best agreement with the experiment data. Moreover, a Coriolis attenuation factor of ξ =0.85 was used because of the effect of the mixing between low-j neutrons. The other parameters in the MPRM were fixed following those in Refs. [40, 41, 47, 48].

The calculated $E(I) - J \cdot I(I+1)$, $S(I)$ and $B(M1)/B(E2)$ ratios as functions of spin are compared with the corresponding experimental data, as presented in Fig. 3. As illustrated in Fig. 3, the small energy differences between bands 1 and 2 are well reproduced. The calculated $S(I)$ values are in good agreement with the experimental values. Though, the calculated staggering phase of the $B(M1)/B(E2)$ ratios of bands 1 and 2 is not perceptible, it has similar amplitudes with the experimental values. The agreement between the experimental data and the calculations supports the present configuration assignment and chiral interpretations of the observed bands.

To study the chiral geometry of bands 1 and 2 in ^{115}Sb， the root-mean-square values of the squared angular momenta components for the core R_k, the valence proton J_{pk} and the valence neutron J_{nk} were calculated. The calculated results are presented in Fig. 4, in which $k = i, l, s$ represent the intermediate, long, and short axes, respectively. As shown in Fig. 4, the angular momenta of the core lies along the intermediate axis, the $g_{9/2}^{-1}$ valence proton lies along the long axis, the $h_{11/2}$ valence neutron lies along the short axis, and the $d_{3/2}$ valence neutron acts as a spectator. The present coupling pattern of angular momenta in ^{115}Sb forms the obvious chiral geometry of aplanar rotation, which supports the chiral interpretation for bands 1 and 2.

The energy difference of the doublet bands in ^{115}Sb decreases with I, which indicates a transition from chiral vibration to stable chirality along the bands. In order to understand the development of chirality with increasing angular momentum for the candidate chiral doublet bands in ^{115}Sb, we calculated the probability distributions for the projection of the total angular momentum along the l, i, and s axes [40]. The calculated results are presented in Fig. 5. With $\gamma = 22.0°$, the l axis is used for quantization. The distributions with respect to the s and the i axes are obtained by replacing γ with 142° ($\gamma + 120°$) and -98° ($\gamma - 120°$) respectively. As shown in Fig. 5, for $19/2\hbar \leqslant I \leqslant 23/2\hbar$, the K_i of the two bands is different. For band 1, the maximum probability for the i axis appears at K_i =0. However, the probability for band 2 is zero at K_i =0. It indicates an oscillation through the $s - l$ plane and reveals the structure of the chiral vibration. For $I \geqslant 25/2\hbar$, the probability distributions for bands 1 and 2 become similar, and the maximum K probabilities for the two bands along the three axes are comparable. These features imply the appearance of static chirality in ^{115}Sb. Based on the present calculations, there might be a change from a chiral vibration to a static chirality.

From the above discussion, the negative parity doublet bands in ^{115}Sb are proposed to be chiral bands. This work presents the first observation of chiral doublet bands in an odd-A nucleus in neutron-rich $A \approx 120$ mass region, indicating that a triaxial deformation capable of forming chirality can also occur when the number of protons crosses the $Z = 50$ closed shell in this mass region.

CONCLUSION

In summary, high-spin states of ^{115}Sb were investigated by fusion-evaporation reaction. A new $\Delta I = 1$ negative parity rotational band with several transitions linking the existing negative band has been identified. The experimental properties and the theoretical calculations suggest that the doublet bands in ^{115}Sb are chiral doublet bands with the $\pi g_{9/2}^{-1} \otimes \upsilon h_{11/2} d_{3/2}$ configuration. Further probability distribution calculations show that a change from a chiral vibration to a static chirality in ^{115}Sb. The present work provides further evidence for the existence of chirality in the neutron-rich $A \approx 120$ mass region. Further experimental research is needed to explore the chirality of other Sb isotopes in this mass region.

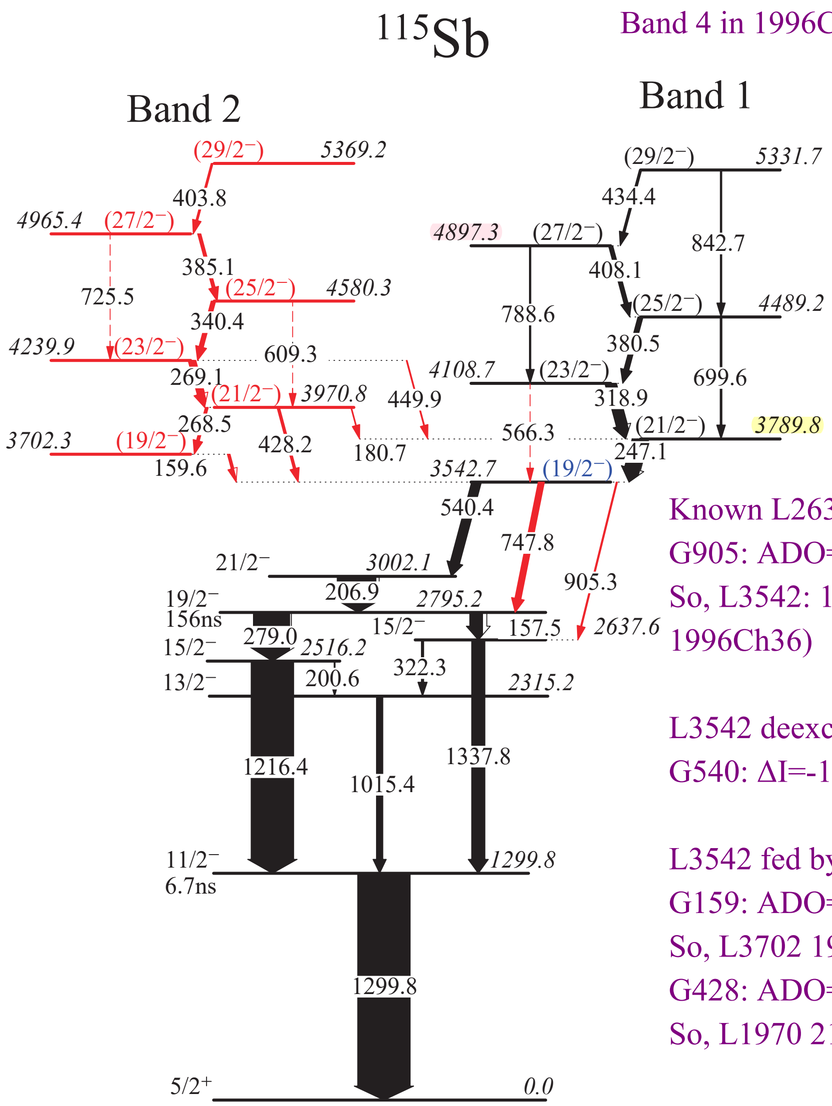
ACKNOWLEDGEMENTS

We thank the staff of the China Institute of Atomic Energy (CIAE), for their technical support during this experiment. This work was partly supported by the National Natural

Science Foundation of China (No. 12225504, No. U2167202, No. 12321005).

Checked color Elevel, Eγ, Jπ w/wo (). dashed γ (RI upper limit)

Band 4 in 1996Ch36



Known L2637: 15/2-
G905: ADO=1.54, so, ΔI=2
So, L3542: 19/2- (was 21/2- in 1996Ch36)

L3542 deexcites by
G540: ΔI=-1, ADO=0.98, so M1+E2

L3542 fed by
G159: ADO=1.49, so ΔI=0 M1+E2
So, L3702 19/2-
G428: ADO=1.20, so ΔI=1 M1+E2
So, L1970 21/2-

FIG. 1: Partial level scheme of ^{115}Sb established in the present work. The energies of the γ transitions and levels are given in keV. The measured relative intensities of transitions are proportional to the widths of the arrows. New transitions and levels are marked in red, while adjustments to previous work in Ref. [28] were marked in blue.

The γ-ray intensity deexciting the 1299.8 level is 100(5), while the γ-ray intensity feeding the 1299.8 level is 81.1(41)+13.2(9)+26.2(13)=121(5), so we have a negative net feeding of -21(7).

Checked: all γ should indeed be in coincidence with 540 and 247

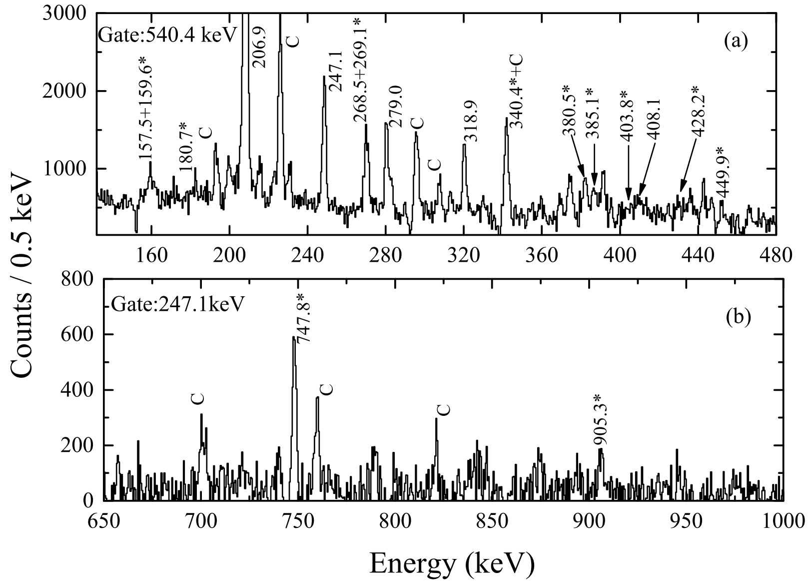


FIG. 2: Two spectrums of γ-rays gated on the 247.1 and 540.4 keV transitions. Peaks marked with asterisks are new in the present work. Contaminations are denoted with C.

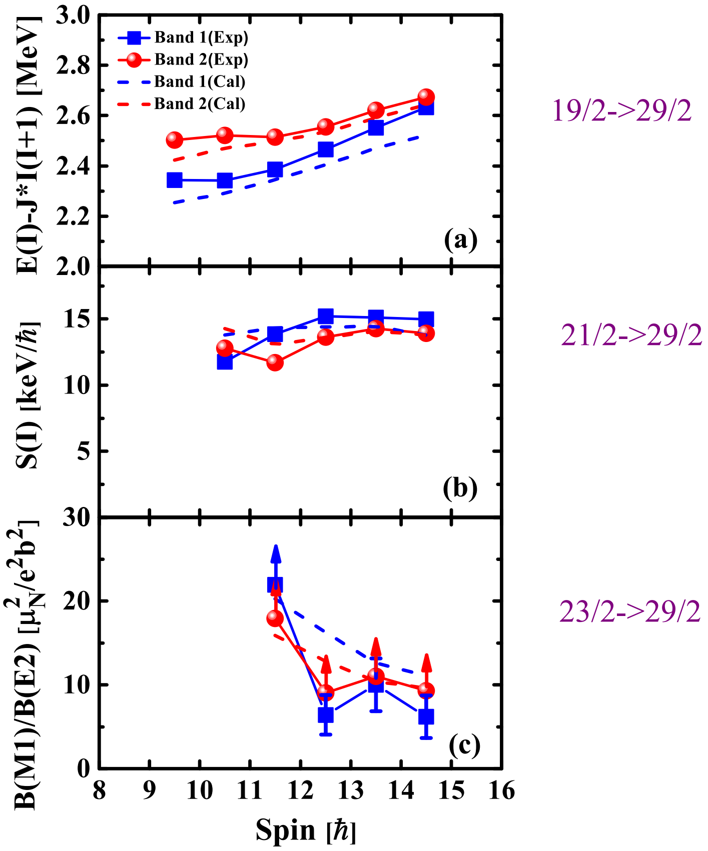


FIG. 3: Excitation energies relative to a rigid-rotor reference $E(I) - J \cdot I(I+1)$ (a) (The $J \approx 0.012$ parameters are evaluated from the relation $J = 0.007 \times (\frac{158}{A})^{5/3}$MeV), energy staggering parameters $S(I) = [E(I) - E(I-1)]/2I$ (b) and the reduced transition probability ratios $B(M1)/B(E2)$ (c)for bands 1 and 2 in ^{115}Sb as functions of spin in comparison with the MPRM calculations.

Report

νh11/2 νd3/2

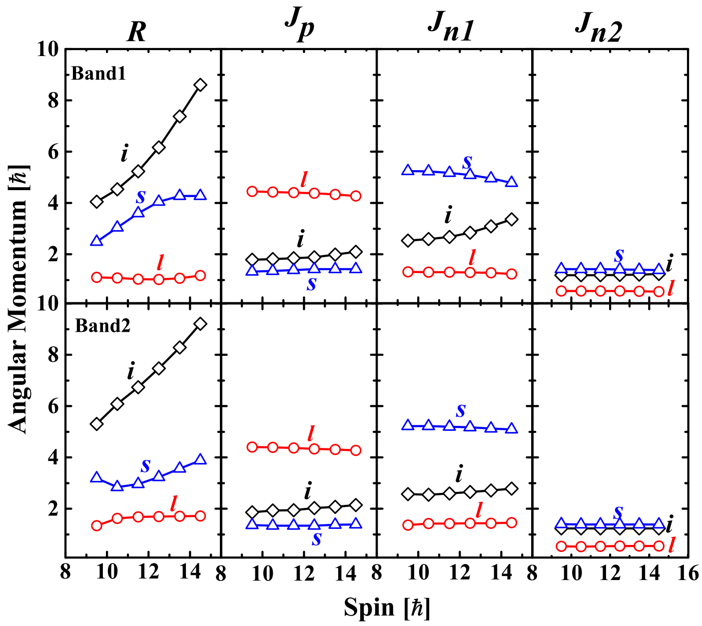


FIG. 4: The root-mean-square components along the intermediate (i-, squares), short (s-, triangles) and long (l-, circles) axes of the core, valence neutron, and valence proton angular momenta calculated as functions of spin I by means of the MPRM for bands 1 and 2 in ^{115}Sb.

From low-spin to high-spin: a change from a chiral vibration to a static chirality.

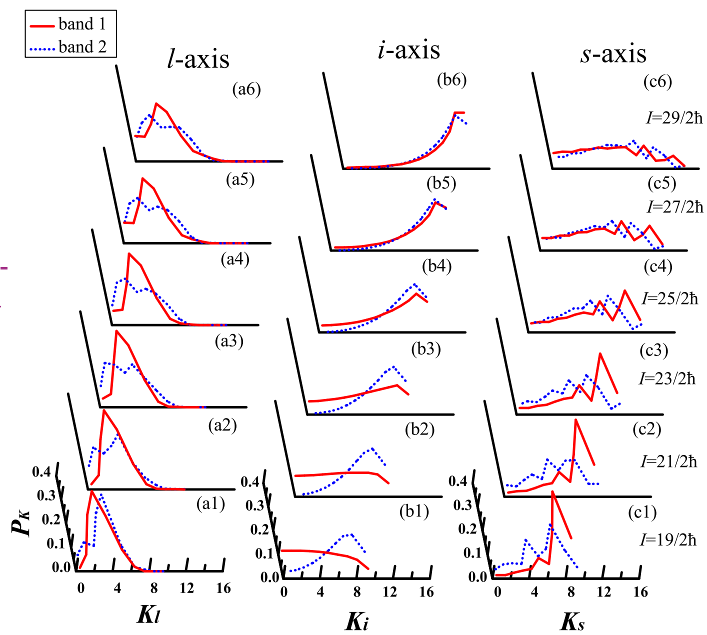


FIG. 5: The probability distributions for projection of total angular momentum on the long (l-), intermediate (i-) and short (s-) axes in MPRM for bands 1 and 2 in ^{115}Sb.

TABLE I: The γ-ray energies, spin-parity assignments and excitation energies for the initial and final states, relative intensities and ADO ratios of the transitions in ^{115}Sb. The γ-ray energies are accurate to $\pm$ 0.5 keV.

E_γ (keV)	$I_i^\pi \to I_f^\pi$	E_i (keV) $\to$ E_f (keV)	I_γ	R_{ADO}
157.5	$19/2^- \to 15/2^-$	2795.2 $\to$ 2637.6	24.8(1.2)	2.06(0.11)
159.6	$(19/2^-) \to (19/2^-)$	3702.3 $\to$ 3542.7	4.5(0.9)	1.49(0.20)
180.7	$(21/2^-) \to (21/2^-)$	3970.8 $\to$ 3789.8	1.3(0.6)	
200.6	$15/2^- \to 13/2^-$	2516.2 $\to$ 2315.2	2.0(0.2)	1.20(0.30)
206.9	$21/2^- \to 19/2^-$	3002.1 $\to$ 2795.2	75.0(2.6)	0.80(0.06)
247.1	$(21/2^-) \to (19/2^-)$	3789.8 $\to$ 3542.7	31.1(3.9)	1.24(0.06)
268.5	$(21/2^-) \to (19/2^-)$	3970.8 $\to$ 3702.3	5.4(2.1)	
269.1	$(23/2^-) \to (21/2^-)$	4239.9$\to$ 3970.8	14.5(3.5)	1.19(0.16)
279.0	$19/2^- \to 15/2^-$	2795.2$\to$ 2516.2	70.3(3.6)	1.66(0.07)
318.9	$(23/2^-) \to (21/2^-)$	4108.7 $\to$ 3789.8	22.8(3.0)	1.23(0.11)
322.3	$15/2^- \to 13/2^-$	2637.6 $\to$ 2315.2	4.2(0.3)	0.95(0.17)
340.4	$(25/2^-) \to (23/2^-)$	4580.3 $\to$ 4239.9	7.9(1.5)	1.16(0.19)
380.5	$(25/2^-) \to (23/2^-)$	4489.2 $\to$ 4108.7	10.4(1.4)	1.12(0.13)
385.1	$(27/2^-) \to (25/2^-)$	4965.4 $\to$ 4580.3	5.8(1.7)	1.12(0.23)
403.8	$(29/2^-) \to (27/2^-)$	5369.2 $\to$ 4965.4	3.8(1.1)	1.19(0.28)
408.1	$(27/2^-) \to (25/2^-)$	4897.3 $\to$ 4489.2	8.7(1.2)	1.24(0.19)
428.2	$(21/2^-) \to (19/2^-)$	3970.8 $\to$ 3542.7	4.9(1.8)	1.20(0.23)
434.4	$(29/2^-) \to (27/2^-)$	5331.7 $\to$ 4897.3	5.1(1.0)	1.23(0.26)
449.9	$(23/2^-) \to (21/2^-)$	4239.9$\to$ 3789.9	1.8(0.8)	
540.4	$(19/2^-) \to 21/2^-$	3542.7 $\to$ 3002.1	18.2(1.0)	0.98(0.08)
566.3	$(23/2^-) \to (19/2^-)$	4108.7 $\to$ 3542.7	<1.3	
609.3	$(25/2^-) \to (21/2^-)$	4580.3 $\to$ 3970.8	<1.3	
699.6	$(25/2^-) \to (21/2^-)$	4489.2 $\to$ 3789.8	3.5(1.2)	1.51(0.30)
725.5	$(27/2^-) \to (23/2^-)$	4965.4$\to$ 4239.9	<1.3	

Report:
4897.2->4897.3
3789.9->3789.8

TABLE I. (Continued)

747.8	$(19/2^-) \to 19/2^-$	$3542.7 \to 2795.2$	11.9(1.4)	1.53(0.17)
788.6	$(27/2^-) \to (23/2^-)$	$4897.2 \to 4108.7$	2.7(1.0)	1.42(0.33)
842.7	$(29/2^-) \to (25/2^-)$	$5331.7 \to 4489.2$	3.0(1.2)	1.47(0.34)
905.3	$(19/2^-) \to 15/2^-$	$3542.7 \to 2637.6$	2.3(0.3)	1.54(0.29)
1015.4	$13/2^- \to 11/2^-$	$2315.2 \to 1299.8$	13.2(0.9)	0.51(0.05)
1216.4	$15/2^- \to 11/2^-$	$2516.2 \to 1299.8$	81.1(4.1)	1.51(0.07)
1299.8	$11/2^- \to 5/2^+$	$1299.8 \to 0$	100(5.0)	1.57(0.07)
1337.8	$15/2^- \to 11/2^-$	$2637.6 \to 1299.8$	26.2(1.3)	1.45(0.08)

* sywang@sdu.edu.cn

[1] S. Frauendorf and J. Meng, Nucl. Phys. A **617**, 131 (1997).

[2] S. Frauendorf, Rev. Mod. Phys **73**, 463 (2001).

[3] J. Meng, B. Qi, S. Q. Zhang, and S. Y. Wang, Mod. Phys. Lett. A **23**, 2560 (2008).

[4] J. Meng and S. Q. Zhang, J. Phys. G **37**, 064025 (2010).

[5] R. A. Bark, E. O. Lieder, R. M. Lieder, E. A. Lawrie, J. J. Lawrie, S. P. Bvumbi, N. Y. Kheswa, S. S. Ntshangase, T. E. Madiba, P. L. Masiteng, S. M. Mullins, S. Murray, P. Papka, O. Shirinda, Q. B. Chen, S. Q. Zhang, Z. H. Zhang, P. W. Zhao, C. Xu, J. Meng, D. G. Roux, Z. P. Li, J. Peng, B. Qi, S. Y. Wang and Z. G. Xiao, Int. J. Mod. Phys. E **23**, 1461001 (2014).

[6] J. Meng and P. W. Zhao, Phys. Scr **91**, 053008 (2016).

[7] A. A. Raduta, Prog. Part. Nucl. Phys **90**, 241 (2016).

[8] K. Starosta and T. Koike, Phys. Scr **92**, 093002 (2017).

[9] B. W. Xiong and Y. Y. Wang, At. Data Nucl. Data Tables **125**, 193 (2019).

[10] S. Y. Wang, Chin. Phys. C **44**, 112001 (2020).

[11] S. Y. Wang, C. Liu, B. Qi, W. Z. Xu, H. Zhang, Front. Phys **18**, 64601 (2023).

[12] L. Mu, S. Y. Wang, C. Liu, B. Qi, R. A. Bark, J. Meng, S. Q. Zhang, P. Jones, S. M. Wyngaardt, H. Jia, Q. B. Chen, Z. Q. Li, S. Wang, D. P. Sun, R. J. Guo, X. C. Han, W.

Z. Xu, X. Xiao, P. Y. Zhu, H. W. Li, H. Hua, X. Q. Li, C. G. Li, R. Han, B. H. Sun, L. H. Zhu, T. D. Bucher, B. V. Kheswa, N. Khumalo, E. A. Lawrie, J. J. Lawrie, K. L. Malatji, L. Msebi, h, J. Ndayishimye, J. F. Sharpey-Schafer, O. Shirinda, M. Wiedeking, T. Dinoko and S. S. Ntshangase, Phys. Lett. B **827**, 137006 (2022).

[13] I. Kuti, Q. B. Chen, J. Tim´ár, D. Sohler, S. Q. Zhang, Z. H. Zhang, P. W. Zhao, J. Meng, K. Starosta, T. Koike, E. S. Paul, D. B. Fossan and C. Vaman, Phys. Rev. Lett **113**, 032501 (2014).

[14] J. Timár, P. Joshi, K. Starosta, V.I. Dimitrov, D. B. Fossan, J. Molnár, D. Sohler, R. Wadsworth, A. Algora, P. Bednarczyk, D. Curien, Zs. Dombrádi, G. Duchene, A. Gizon, J. Gizon, D. G. Jenkins, T. Koike, A. Krasznahorkay, E. S. Paul, P. M. Raddon, G. Rainovski, J. N. Scheurer, A. J. Simons, C. Vaman, A. R. Wilkinson, L. Zolnai and S. Frauendorf, Phys. Lett. B **598**, 178(2004).

[15] J. A. Alcántara-Núũez, V. I. Dimitrov, J. R. B. Oliveira, E. W. Cybulska, N. H. Medina, M. N. Rao, R. V. Ribas, M. A. Rizzutto, W. A. Seale, F. Falla-Sotelo, K. T. Wiedemann and S. Frauendorf, Phys. Rev. C **69**, 024317 (2004).

[16] B. Zhang, L. H. Zhu, H. B. Sun, C. Y. He, X. G. Wu, J. B. Lu, Y. J. Ma, X. Hao, Y. Zheng, B. B. Yu, G. S. Li, S. H. Yao, L. L. Wang, C. Xu, J. G. Wang and L. Gu, Chin. Phys. C **35**, 11 (2011).

[17] Y. X. Zhao, T. Komatsubara, Y. J. Ma, Y. H. Zhang, S. Y. Wang, Y. Z. Liu and K. Furuno, Chin. Phys. Lett **26**, 082301 (2009).

[18] S. Chakraborty, H. P. Sharma, S. S. Tiwary, C. Majumder, P. Banerjee, S. Ganguly, S. Kumar, A. Kumar, A. Kumar, R. P. Singh and S. Muralithar, J. Phys. G: Nucl. Part. Phys **47** 095104 (2020).

[19] K. K. Zheng, C. M. Petrache, Z. H. Zhang, A. Astier, B. F. Lv, P. T. Greenlees, T. Grahn, R. Julin, S. Juutinen, M. Luoma, J. Ojala, J. Pakarinen, J. Partanen, P. Rahkila, P. Ruotsalainen, M. Sandzelius, J. Sarén, H. Tann, J. Uusitalo, G. Zimba, B. Cederwall, Ö. Aktas, A. Ertoprak, W. Zhang, S. Guo, M. L. Liu, X. H. Zhou, I. Kuti, B. M. Nyakó, D. Sohler, J. Timár, C. Andreoiu, M. Doncel, D. T. Joss, R. D. Page, Eur. Phys. J. A **58** 50 (2022). Report

[20] K. Singh, S. Sihotra, S. S. Malik, J. Goswamy, D. Mehta1, N. Singh1, R. Kumar, R. P. Singh, S. Muralithar, E. S. Paul, J. A. Sheikh and C. R. Praharaj, Eur. Phys. J. A **27** 321 (2006).

[21] C. M. Petrache, Q. B. Chen, S. Guo, A. D. Ayangeakaa, U. Garg, J. T. Matta, B. K. Nayak, D.

Patel, J. Meng, M. P. Carpenter, C. J. Chiara, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, D. Seweryniak, S. Zhu, S. S. Ghugre and R. Palit, Phys. Rev. C **94**, 064309 (2016).

[22] A. D. Ayangeakaa, U. Garg, M. D. Anthony, S. Frauendorf, J. T. Matta, B. K. Nayak, D. Patel, Q. B. Chen, S. Q. Zhang, P. W. Zhao, B. Qi, J. Meng, R. V. F. Janssens, M. P. Carpenter, C. J. Chiara, F. G. Kondev, T. Lauritsen, D. Seweryniak, S. Zhu, S. S. Ghugre and R. Palit, Phys. Rev. Lett **110**, 172504 (2013).

[23] S. Zhu, U. Garg, B. K. Nayak, S. S. Ghugre, N. S. Pattabiraman, D. B. Fossan, T. Koike, K. Starosta, C. Vaman, R. V. F. Janssens, R. S. Chakrawarthy, M. Whitehead, A. O. Macchiavelli and S. Frauendorf, Phys. Rev. Lett **91**, 132501 (2003).

[24] C. M. Petrache,B. F. Lv, Q. B. Chen, J. Meng, A. Astier, E. Dupont, K. K. Zheng, P. T. Greenlees,H. Badran, T. Calverley, D. M. Cox, T. Grahn, J. Hilton, R. Julin, S. Juutinen, J. Konki, J. Pakarinen, P. Papadakis, J. Partanen, P. Rahkila, P. Ruotsalainen, M. Sandzelius, J. Saren, C. Scholey, J. Sorri, S. Stolze, J. Uusitalo, B. Cederwall, A. Ertoprak, H. Liu, S. Guo, J. G. Wang, X. H. Zhou, I. Kuti1, J. Tim´ár, A. Tucholski, J. Srebrny and C. Andreoiu, Eur. Phys. J. A **56** 208 (2020).

[25] J. Ndayishimye, E. A. Lawrie, O. Shirinda, J. L. Easton, S. M. Wyngaardt, R.A. Bark, S. P. Bvumbi, T. R. S. Dinoko, P. Jones, N. Y. Kheswa, J. J. Lawrie, S. N. T. Majola, P. L. Masiteng, D. Negi, J. N. Orce, P. Papka, J. F. Sharpey-Schafer, M. Stankiewicz and M. Wiedeking, Acta. Phys. Pol. B **48**, 343 (2017).

[26] T. Roy, G. Mukherjee, Md. A. Asgar, S. Bhattacharyya, Soumik Bhattacharya, C. Bhattacharya, S. Bhattacharya, T. K. Ghosh, K. Banerjee, Samir Kundu, T. K. Rana, P. Roy, R. Pandey, J. Meena, A. Dhal, R. Palit, S. Saha, J. Sethi, Shital Thakur, B. S. Naidu, S. V. Jadav, R. Dhonti, H. Pai, and A. Goswami, Phys. Lett. B **782**, 768 (2018).

[27] W. Z. Xu, S. Y. Wang, X. G. Wu, H. Jia, C. Liu, H. F. Bai, Y. J. Li, B. Qi, H. Y. Zhang, G. S. Li, Y. Zheng, C. B. Li, L. Mu, A. Rohilla, S. Wang, D. P. Sun, Z. Q. Li, N. B. Zhang, R. J. Guo, X. C. Han and X. Xiao, Phys. Lett. B **839**, 137789 (2023).

[28] R. S. Chakrawarthy and R. G. Pillay, Phys. Rev. C **54**, 2319 (1996).

[29] H. Y. Wu, Z. H. Li, H. Tan, H. Hua, J. Li, W. Henning, W. K. Warburton, D. W. Luo, X. Wang, X. Q. Li, S. Q. Zhang, C. Xu, Z. Q. Chen, C. G. Wu, Y. Jin, J. Lin, D. X. Jiang, and Y. L. Ye, Nucl. Instrum. Methods Phys. Res. A 975, 164200 (2020).

[30] D. W. Luo, H. Y. Wu, Z. H. Li, C. Xu, H. Hua, X. Q. Li, X. Wang, S. Q. Zhang, Z. Q. Chen,

C. G. Wu, Y. Jin and J. Lin, Nucl. Sci. Tech 32:79 (2021).

[31] M. Piiparinen, A. Ataç, J. Blomqvist, G. B. Hagemann, B. Herskind, R. Julin, S. Juutinen, A. Lampinen, J. Nyberg, G. Sletten, P. Tikkanen, S. Törmänen, A. Virtanen, and R. Wyss, Nucl. Phys **A605**, 191 (1996).

[32] A. K. Gaigalas, R. E. Shroy, G. Schatz, and D. B. Fossan, Phys. Rev. Lett **35**, 555 (1975).

[33] J. Bron, W. H. A. Hesselink, H. Bedet and H. Verheul, Nucl. Phys **A279**, 365 (1977).

[34] R. E. Shroy, A. K. Gaigalas, G. Schatz, and D. B. Fossan, Phys. Rev. C **19**, 1324 (1979).

[35] C. B. Moon, S. J. Chae, J. H. Ha, T. Komatsubara, J. Lu, T. Hayakawa and K. Furuno, Z. Phys. A **352**, 245 (1995).

[36] K. Starosta, T. Koike, C. J. Chiara, D. B. Fossan, D. R. LaFosse, A. A. Hecht, C. W. Beausang, M. A. Caprio, J. R. Cooper, R. Krücken, J. R. Novak, N. V. Zamfir, K. E. Zyromski, D. J. Hartley, D. L. Balabanski, Jing-ye Zhang, S. Frauendorf, and V. I. Dimitrov, Phys. Rev. Lett **86**, 971 (2001).

[37] T. Koike, K. Starosta, C. J. Chiara, D. B. Fossan, and D. R. LaFosse, Phys. Rev. C **63**, 061304(R) (2001).

[38] G. Rainovski, E. S. Paul, H. J. Chantler, P. J. Nolan, D. G. Jenkins, R. Wadsworth, P. Raddon, A. Simons, D. B. Fossan, T. Koike, K. Starosta, C. Vaman, E. Farnea, A. Gadea, Th. Kröll, R. Isocrate, G. de Angelis, D. Curien, and V. I. Dimitrov, Phys. Rev. C **68**, 024318 (2003).

[39] J. Meng, J. Peng, S.Q. Zhang, S. -G. Zhou, Phys. Rev. C **73**, 037303 (2006).

[40] B. Qi, S. Q. Zhang, J. Meng and S. Frauendorf, Phys. Lett. B **675**, 175 (2009).

[41] B. Qi, S. Q. Zhang, S.Y. Wang, J. Meng and T. Koike, Phys. Rev. C **83**, 034303 (2011).

[42] P. W. Zhao, Z. P. Li, J. M. Yao, J. Meng, Phys. Rev. C **82**, 054319 (2010).

[43] H. Jia, B. Qi, C. Liu and S. Y. Wang, J. Phys. G **46**, 035102 (2019).

[44] P. W. Zhao, S.Q. Zhang, J. Peng, H. Z. Liang, P. Ring and J. Meng, Phys. Lett. B **699**, 181 (2011).

[45] P. W. Zhao, J. Peng, H. Z. Liang, P. Ring and J. Meng, Phys. Rev. Lett **107**, 122501 (2011).

[46] J. Meng, J. Peng, S. Q. Zhang and P. W. Zhao, Front. Phys **8**, 55 (2013).

[47] R. J. Guo, S. Y. Wang, C. Liu, R. A. Bark, J. Meng, S. Q. Zhang, B. Qi, A. Rohilla, Z. H. Li, H. Hua, Q. B. Chen, H. Jia, X. Lu, S. Wang, D. P. Sun, X. C. Han, W. Z. Xu, E. H. Wang, H. F. Bai, M. Li, P. Jones, J. F. Sharpey-Schafer, M. Wiedeking, O. Shirinda, C. P. Brits, K.

L. Malatji, T. Dinoko, J. Ndayishimye, S. Mthembu, S. Jongile, K. Sowazi, S. Kutlwano, T. D. Bucher, D. G. Roux, A. A. Netshiya, L. Mdletshe, S. Noncolela, and W. Mtshali, Phys. Rev. Lett **132**, 092501 (2024).

[48] S. Y. Wang, B. Qi and S. Q. Zhang, Chin. Phys. Lett **26** 052102 (2009).