First Measurement of the g Factor in the Chiral Band: The Case of the ^{128}Cs Isomeric State

E. Grodner,[1,2] J. Srebrny,[3] Ch. Droste,[2] L. Próchniak,[3] S. G. Rohoziński,[2] M. Kowalczyk,[3] M. Ionescu-Bujor,[4] C. A. Ur,[5] K. Starosta,[6] T. Ahn,[7] M. Kisieliński,[3] T. Marchlewski,[3] S. Aydin,[8,10] F. Recchia,[9] G. Georgiev,[11] R. Lozeva,[11] E. Fiori,[11] M. Zielińska,[3] Q. B. Chen,[12] S. Q. Zhang,[12] L. F. Yu,[12] P. W. Zhao,[12] and J. Meng[12,13]

[1]National Centre for Nuclear Research, 05-540 Świerk, Poland
[2]Faculty of Physics, University of Warsaw, 02-093 Warsaw, Poland
[3]Heavy Ion Laboratory, University of Warsaw, 02-093 Warsaw, Poland
[4]Horia Hulubei National Institute for Physics and Nuclear Engineering, 077125 Bucharest, Romania
[5]Extreme Light Infrastructure, IFIN-HH, 077125 Bucharest, Romania
[6]Simon Fraser University, V5A 1S6 Vancouver, British Columbia, Canada
[7]Department of Physics, University of Notre Dame, 46556 Notre Dame, Indiana, USA
[8]Instituto Nazionale di Fisica Nucleare, 2 35020 Legnaro, Italy
[9]Dipartimento di Fisica dell'Università di Padova and INFN sez. Padova, I-35131 Padova, Italy
[10]Department of Physics, Aksaray University, 68100 Aksaray, Turkey
[11]CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 91405 Orsay, France
[12]State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China
[13]Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

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The g factor of the 56 ns half-life isomeric state in ^{128}Cs has been measured using the time-differential perturbed angular distribution method. This state is the bandhead of the positive-parity chiral rotational band, which emerges when an unpaired proton, an unpaired neutron hole, and an even-even core are coupled such that their angular momentum vectors are aplanar (chiral configuration). g-factor measurements can give important information on the relative orientation of the three angular momentum vectors. The measured g factor $g = +0.59(1)$ shows that there is an important contribution of the core rotation in the total angular momentum of the isomeric state. Moreover, a quantitative theoretical analysis supports the conclusion that the three angular momentum vectors lie almost in one plane, which suggests that the chiral configuration in ^{128}Cs demonstrated in previous works by characteristic patterns of electromagnetic transitions appears only above some value of the total nuclear spin.

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The concept of nuclear chirality was first proposed in 1997 [1] with the signature of doublets of states with the same spin and parity. In the chiral scenario of an odd-odd nucleus, the three angular momentum vectors of the proton, the neutron, and the even-even core span a three-dimensional space giving the possibility of two distinct orientations. Since 1997, many theoretical as well as experimental works related to nuclear chirality have been published where indirect signs of the spontaneous chiral symmetry breaking have been found; for a brief review, see Refs. [2–5]. Such signs are mainly the existence of doublets of nearly degenerate states with the same spin, parity, and characteristic patterns of the E2 and M1 electromagnetic transition probabilities. In this Letter, the first g-factor measurement corresponding to the magnetic dipole moment of a chiral nucleus is reported. The g factor is directly related to the geometry of three angular momentum vectors that define the chiral configuration. The chiral configuration in the positive parity band built on the 56 ns isomeric state in ^{128}Cs is expected based on the properties of the transition probabilities linking the chiral doublet states [6]. However, the g-factor value obtained in this work indicates the nonchiral geometry of the positive parity bandhead in ^{128}Cs—namely, the three angular momentum vectors are located nearly in one plane. This observation suggests that the chiral configuration in the ^{128}Cs nucleus appears only for a nuclear spin exceeding some minimal value, which may be relevant also for the chiral interpretation of other odd-odd nuclei where the chiral doublets at low spin are absent. This phenomenon is closely related to a notion of the critical rotational frequency, predicted theoretically in Ref. [7] using a cranking Skyrme-Hartree-Fock approach. Results of this work suggest that the chiral configuration cannot exist below a certain frequency of nuclear rotation.

For the g-factor measurement of the positive parity bandhead in ^{128}Cs, the time-differential perturbed angular distribution method (TDPAD) has been used where interaction between the nuclear magnetic moment and applied external magnetic field results in a precession of the angular distribution of the γ radiation around the applied magnetic field axis. Thus, an oscillating intensity from the decay of the isomeric state is observed. The sign and magnitude of

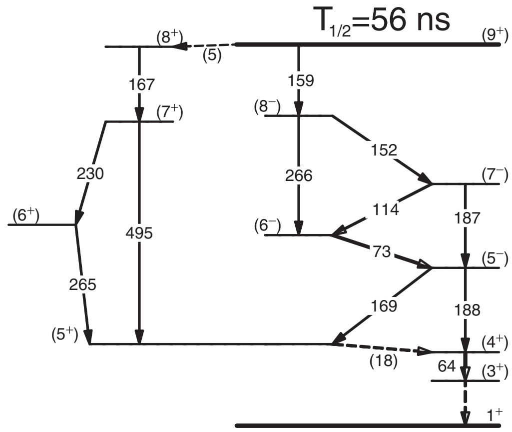

FIG. 1. Relevant part of the level scheme of ^{128}Cs obtained in Ref. [9]. The assigned value of spin $I^{\pi} = 9^{+}$ of the $T_{1/2} = 56$ ns isomeric state is compatible with the systematics of levels in the neighboring nuclei. Dashed arrows correspond to unobserved, highly converted transitions. The arrows with energy labels in parentheses indicate unobserved transitions included in the level scheme based on experimental arguments.

the g factor can be extracted from the intensity ratio of two measurements at angles $\theta = \pm 45°$:

$$R(t) = \frac{I(-45°, t) - I(+45°, t)}{I(-45°, t) + I(+45°, t)} = D \sin(\phi - 2\omega_L t), \qquad (1)$$

with D being an oscillation amplitude and ϕ being a phase depending on the detector position angle and the beam bending in the magnetic field. $\omega_L = -gB\mu_N/\hbar$ stands for the Larmor frequency of precession of the angular distribution around the magnetic field axis, where μ_N denotes the nuclear magneton and g is the nuclear g factor of the isomeric state that has to be determined. ^{128}Cs nuclei were produced in the $^{122}\mathrm{Sn}(^{10}\mathrm{B}, 4n)^{128}\mathrm{Cs}$ reaction with a beam energy of 55 MeV. The pulsed beam with 1 ns pulses and a 400 ns repetition period was provided by the Tandem accelerator of the ALTO facility at IPN Orsay. The self-supporting ^{122}Sn target, 22 mg/cm^2 thick, played simultaneously the role of the stopper for the recoils. The target was placed between the pole tips of an electromagnet (in the GAMIPE setup from LNL Legnaro). A magnetic field of 21450 ± 10 G was applied perpendicular to the beam-detection plane. Two low-energy photon spectrometer (LEPS) detectors were placed at angles $\pm 45°$ with respect to the beam axis. In total, around 10^{10} gamma quanta have been registered during 5 days of the beam time.

In the Warsaw-Orsay-Legnaro Collaboration experiment, a modulated intensity was observed for gamma transitions in accordance with the level scheme of the isomeric state decay given in Ref. [8] and extended significantly in Ref. [9]; see Fig. 1. The uncertainty in spin assignment for levels in Fig. 1 is due to unobserved highly converted transitions below the 64 keV gamma decay. In the following discussion, an $I^{\pi} = 9^{+}$ spin value of the isomeric state is taken according to the excitation energy systematics [10]. The background subtracted time spectra collected at angles $+45°$ and $-45°$ were used to construct the intensity ratios for transitions from the decay of the isomeric state (Fig. 2). An attenuation of the $R(t)$ oscillations has been taken into account by the time dependence of the $D(t) = D\exp(-\lambda_2 t)$ oscillation amplitude reflecting the spin-deorientation process. An average value of $1/\lambda_2 \approx 300$ ns has been determined. The parameters of formula (1) resulting from the corresponding fits are listed in Table I. According to Ref. [9], the transitions below the isomeric state are fast enough to preserve the original gamma

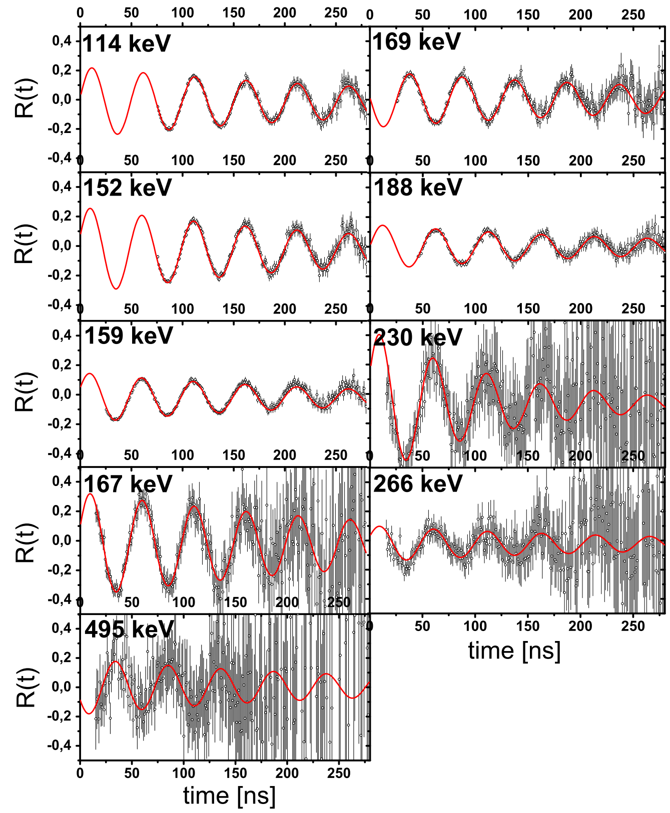

FIG. 2. Experimental modulation ratios for the transitions involved in the isomeric decay and least-squares fits (red lines).

TABLE I. Fit parameters of the oscillation function. ω_L is the Larmor frequency of precession, and λ_2 enters the attenuation factor; see Eq. (1) and the text.

E_γ [keV]	ω_L [10^9 s^{-1}]	$1/\lambda_2$ [ns]
114	0.0625(1)	334 ± 34
152	0.0622(1)	279 ± 12
159	0.0620(1)	255 ± 15
167	0.0618(4)	360 ± 101
169	0.0631(2)	373 ± 53
188	0.0625(2)	277 ± 36
230	0.062(1)	123 ± 31
266	0.061(2)	300[a]
495	0.062(2)	300[a]

[a]Fixed during fitting.

angular distribution of the preceding states. Therefore, in all transitions the same oscillation frequency is observed that can be attributed to the g factor of the $\pi h_{11/2} \otimes \nu h_{11/2}^{-1}$ isomeric bandhead, leading to the value $g = +0.59(1)$.

An independent measurement using the TDPAD technique was also performed at the Nuclear Structure Laboratory at the State University of New York at Stony Brook using the same ^{122}Sn(^{10}B, $4n$)^{128}Cs reaction. The FN Tandem Van de Graaff and superconducting linear post accelerator was used to produce a beam of 47 MeV ^{10}B ions that impinged on a 3.0 mg/cm^2 ^{122}Sn foil with a 34 mg/cm^2 Pb backing. A beam sweeper was used to extend the period of beam pulses to 212 ns. The γ rays were detected with two LEPS detectors positioned at $\pm 135°$ with respect to the beam axis. A glass target chamber was used to limit the attenuation of low-energy γ rays. A 1.5 T water-cooled electromagnet was used to produce a magnetic field of $14,000^{+200}_{-500}$ G, which was measured at the target position with a Hall probe. The g factor measured at Stony Brook is $g = 0.59^{+0.01}_{-0.02}$ based on a Larmor frequency of $41.3(2) \times 10^6$ s^{-1}.

In nuclear physics, the g-factor measurement provides essential data for the two-odd-nucleon configuration assignment. For the two-component system where only two angular momentum vectors are coupled, there is a direct relation, known as the additivity relation [11], between the magnetic moments of the two components and the magnetic moment of the resultant state. Assuming that the core rotation does not contribute to the total spin of the $\pi h_{11/2} \otimes \nu h_{11/2}^{-1}$ bandhead, the additivity formula gives the expected g-factor value provided that the gyromagnetic factors of the proton g_p and neutron g_n are known. To find the values of g_p and g_n, one can use either theoretical estimates, e.g. from the covariant density functional theory (CDFT) [12], or adopt it from experimental data of magnetic moments measured in neighboring single-odd nuclei. Table II contains three sets of g_p and g_n estimates, namely one theoretical estimate for ^{128}Cs and two experimental values found from $h_{11/2}$ and $s_{1/2}$ orbitals (here experiment gives spin gyromagnetic factors) [13] in neighboring ^{129}Cs and ^{129}Xe nuclei. Inspection of Table II shows that within the simple two-component model, the value $g \approx 0.5$ of the g factor is expected independently of the chosen sets of g_p and g_n. This result does not match the experimental $g = 0.59(1)$ value.

TABLE II. The g-factor values estimated for the $\pi h_{11/2} \otimes \nu h_{11/2}^{-1}$ configuration within the $j_R = 0$ assumption compared with the experimental g factor of the isomeric state.

g_p	g_n	g	g_{exp}
$+1.21^{a}$	-0.21^{a}	$+0.50^{a}$	$+0.59(1)$
$+1.191(18)^{b}$	$-0.1619(2)^{b}$	$+0.515(9)^{b}$	
$+1.1802(15)^{c}$	$-0.1414502(15)^{c}$	$+0.519(2)^{c}$	

[a] g_p, g_n from theoretical estimates (see text).
[b] g_p, g_n estimated from $h_{11/2}$ orbitals in single-odd neighboring nuclei.
[c] g_p, g_n estimated from $s_{1/2}$ orbitals in single-odd neighboring nuclei.

In reality, the wave function of the isomeric bandhead may have admixtures of the nonzero j_R core rotation ($j_R = 2$, 4, and even 6). The $j_R \neq 0$ admixtures may be responsible in driving the g factor from the value $g \approx 0.5$ expected in the two-component model to the value 0.59 obtained in the experiment. Thus, a generalization of the additivity formula to three coupled angular momentum vectors j_p, j_n, and j_R is required to account for these admixtures. The additivity formula generalized to the three-component system takes the form

$$g = \frac{1}{2}\bigg((g_p + g_n + g_R) + \frac{\langle j_p^2 \rangle}{\langle J^2 \rangle}(g_p - g_n - g_R) + \frac{\langle j_n^2 \rangle}{\langle J^2 \rangle}(g_n - g_p - g_R) + \frac{\langle j_R^2 \rangle}{\langle J^2 \rangle}(g_R - g_p - g_n)\bigg) - \frac{1}{\langle J^2 \rangle}(g_p \langle \boldsymbol{j}_n \cdot \boldsymbol{j}_R \rangle + g_n \langle \boldsymbol{j}_p \cdot \boldsymbol{j}_R \rangle + g_R \langle \boldsymbol{j}_p \cdot \boldsymbol{j}_n \rangle), \quad (2)$$

where g_R is the gyromagnetic factor of the core. The last $1/\langle J^2 \rangle$ term contains the expectation values of the scalar products of the angular momentum vectors and thus is sensitive to their mutual orientation. This term is zero for the ideal chiral configuration and can take on positive or negative values for other cases (see Fig. 3). Therefore, a g-factor measurement may be used to recognize whether the three angular momentum vectors of the constituents of a system are located in one plane (planar configuration) or span the three-dimensional space (aplanar configuration).

A qualitative picture of the dependence of the g-factor value on the mutual orientation of the three angular

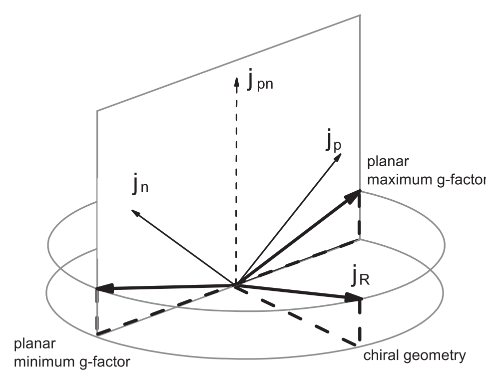

FIG. 3. Core angular momentum $\boldsymbol{j}_R$ may be coupled at different precession angles about the resultant $\boldsymbol{j}_{pn}$ of proton and neutron angular momenta to form the specified spin of the isomeric state. The planar geometry where $\boldsymbol{j}_R$ tends toward $\boldsymbol{j}_p$ gives the highest possible value of the g factor (0.6 for $j_p = j_n = 11/2, j_R = 2$). A second planar geometry where $\boldsymbol{j}_R$ tends toward $\boldsymbol{j}_n$ gives the lowest possible value of the g factor (0.4 for $j_p = j_n = 11/2, j_R = 2$). Aplanar geometry corresponding to chiral configuration gives the g-factor value in between.

momentum vectors can be shown by semiclassical coupling where the three spatial components of an angular momentum vector $\boldsymbol{j}$ are well defined with the squared value $\boldsymbol{j}^2 = j(j+1)$. By coupling first j_p and j_n at a given angle θ_{pn}, one obtains the classical resultant j_{pn} to which j_R can be coupled at various precession angles, as shown in Fig. 3. The planar geometry where the three angular momenta lie in one plane with j_R tending toward j_p gives the upper limit of the g factor. The opposite planar geometry where j_R tends toward j_n gives the lower limit of the g factor. The g-factor value is in between for the chiral geometry where the angular momentum vectors in question span the three-dimensional space.

In the quantum-mechanical case, one should calculate the expectation values which enter Eq. (2) for the considered state. In general, such calculations need detailed knowledge of the quantum state. However, in a special case of the single-coupling scheme, they can be performed utilizing only quantum angular momentum theory. The single-coupling scheme $|(j_p j_n) j_{pn} j_R; JM\rangle$ is defined as the coupling of j_p and j_n to a fixed value j_{pn}, which in turn is coupled to a fixed angular momentum j_R, with the condition that the angular momentum numbers are sufficient to determine the state. A useful quantity describing the relative orientation of $\boldsymbol{j_n}$, $\boldsymbol{j_p}$, $\boldsymbol{j_R}$ is the normalized orientation parameter $\langle\hat{o}\rangle$ [14]:

$$\langle\hat{o}\rangle = \frac{\langle(\boldsymbol{j_p}\times\boldsymbol{j_n})\cdot\boldsymbol{j_R}\rangle}{\sqrt{\langle j_p^2\rangle\langle j_n^2\rangle\langle j_R^2\rangle}}. \tag{3}$$

For the two lowest core excitations $j_R = 2$, 4, we have found the single coupling schemes $|(j_p j_n) j_{pn} = 9, j_R = 2; J = 9\rangle$ and $|(j_p j_n) j_{pn} = 8, j_R = 4; J = 9\rangle$, which have the maximum value of $\langle\hat{o}\rangle$, i.e., close to 1, and therefore the maximum chirality. For these coupling schemes, the obtained value of the g factor is $g \approx 0.50$. For even higher values of the core angular momentum j_R, the expected g factor becomes less than 0.50. Therefore, it is not possible to reproduce the experimental $g = 0.59(1)$ result by adding the admixtures of $j_R = 2, 4, \ldots$ core excitations with chiral geometry ($g = 0.50$) to the $j_R = 0$ ingredient of the wave function, for which $g = 0.51$. In general, however, a quantum three-component system is a superposition of several coupling schemes of the form (with additional quantum numbers denoted as ξ):

$$|JM\rangle = \sum_{\substack{j_p, j_n, j_{pn},\\ j_R, \xi}} c_J(j_p, j_n, j_{pn}, j_R, \xi)|(j_p j_n) j_{pn} j_R, \xi; JM\rangle.$$

Thus, to study the orientation of the three constituent angular momentum vectors and its relation to the value of the g factor, one needs a model enabling the calculation of the coefficients $c_J(j_p, j_n, j_{pn}, j_R, \xi)$ of the wave function.

Below, we present results obtained within the particle rotor model (PRM) [1,15–19], which is the most widely used model in the context of nuclear chirality. Before performing the PRM calculations, the adiabatic and configuration-fixed constrained CDFT [20–23] with the effective interaction PC-PK1 [24] is first used to search for the possible configurations and deformations. We have considered three positive-parity configurations for the studied isomeric state, denoted by A, B, and C. After transforming the spinors corresponding to these configurations to the spherical basis, it was found that the main components can be expressed as $\pi(1h_{11/2})^1 \otimes \nu(1h_{11/2})^{-5}$, $\pi(1h_{11/2})^1 \otimes \nu(1h_{11/2})^{-3}$, and $\pi(1h_{11/2})^1 \otimes \nu(1h_{11/2})^{-1}$, for the A, B, and C configurations, respectively (for details of the method applied and notation, see Ref. [20]). For the configuration A, which gives the lowest energy value, the corresponding quadrupole deformation parameters are $\beta = 0.23$ and $\gamma = 23.8°$. Subsequently, the PRM calculations are performed to calculate the g factor using Eq. (2). In the calculations, we fixed the quadrupole deformation parameter $\beta = 0.23$, the value of the core g factor ($g_R = 0.41$, taken from ^{128}Xe 2^+ experimental data [25]), and the moment of inertia ($\mathcal{J} = 12\hbar^2/\mathrm{MeV}$), but varied the triaxial deformation parameter γ from 0° to 60° to investigate the dependence of the g factor on the mutual orientation of the vectors. The nucleon spin g factor g_s was taken as $0.6 g_s^{\mathrm{free}}$ (g_s^{free} is 5.586 for the proton and −3.826 for the neutron). Analogous calculations were done for configurations B and C, and the obtained results in comparison with the experimental value are shown in Fig. 4. The calculated rms values of j_R ($\sqrt{\langle j_R^2\rangle}$) lie in the range 3.8–4.3 for the whole range of nonaxiality parameter γ for the three configurations A, B, and C. It is shown that the calculated g factor becomes close to the experimental value $g = 0.59$ for the orientation parameter approaching zero, which corresponds to the nonchiral (planar) configuration. If the triaxial deformation parameter is equal to that obtained

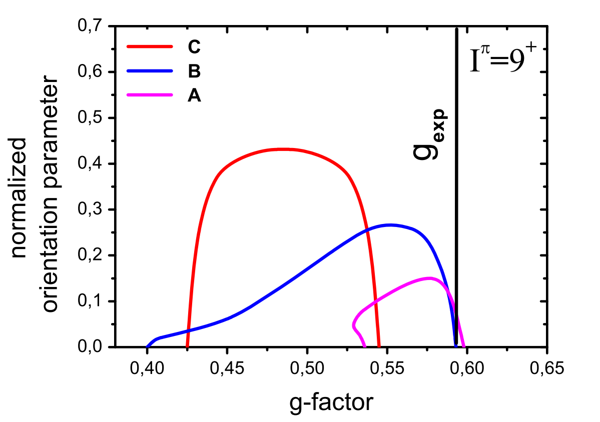

FIG. 4. The normalized orientation parameter, Eq. (3), versus g-factor values for the three configurations A (purple line), B (blue line), and C (red line) at $I = 9\hbar$ calculated by PRM with varying triaxial deformation parameters from 0° to 60°. The experimental value is also shown for comparison (black solid line). See text for details.

from the constrained CDFT calculations, the calculated g factor of the configuration A, $g = 0.58$, is closest to the experimental value. It is worth noting that in this case, the orientation parameter is still rather small ($\langle \hat{o} \rangle \sim 0.15$), which suggests that the bandhead of ^{128}Cs is far from the ideal chiral geometry, which requires $\langle \hat{o} \rangle \sim 1.0$.

Thus, the nonzero core rotation components of the wave function are indispensable to drive the total g-factor value from $g = 0.51$, derived when the core rotation is neglected, to the value $g = 0.59$ measured experimentally. Moreover, the theoretical calculations (see Fig. 4) show that the value $g = 0.59$ can be obtained only for the almost planar (i.e. nonchiral) geometry of the bandhead. This result gives the first indication for the existence of the critical frequency $\omega_{\rm crit}$ for nuclear rotation [7] below which the planar geometry is energetically favored. The qualitative conclusions drawn above are not altered by choosing other sets of g_p, g_n, and g_R values according to Table II.

The results of this Letter show that the g-factor measurement can be an effective method to study the geometry formed by three coupled angular momentum vectors. Further investigations of the spin geometry through g-factor measurements of chiral doublet bands are especially interesting in the ^{124,126,128}Cs isotopes where observed gamma-selection rules [6,16,26,27] indicate significant aplanarity of the angular momentum vectors. g-factor measurements could help answer the questions of how chirality develops, e.g., if a change from a planar to a chiral configuration occurs suddenly, similar to a phase transition, or in a more smooth manner. Let us mention here the paper [28], where the aplanarity was suggested for the whole chiral bands in ^{126}Cs. However, an analysis there was based on the classical notion of angles between the angular momenta vectors without calculating the orientation parameter (3). Moreover, a value of the g factor, which could be useful in comparing with the results of the present paper, was not calculated.

However, new experimental techniques would be required for g-factor measurements of the higher positive-parity levels in ^{128}Cs, since the lifetimes of these states are much shorter (in the picosecond range) than the 56 ns lifetime of the bandhead where the TDPAD method was quite successful.

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[1] S. Frauendorf and J. Meng, Nucl. Phys. **A617**, 131 (1997).
[2] J. Meng and S. Q. Zhang, J. Phys. G **37**, 064025 (2010).
[3] J. Meng and P. Zhao, Phys. Scr. **91**, 053008 (2016).
[4] J. Meng, Q. B. Chen, and S. Q. Zhang, Int. J. Mod. Phys. E **23**, 1430016 (2014).
[5] A. A. Raduta, Prog. Part. Nucl. Phys. **90**, 241 (2016).
[6] E. Grodner, J. Srebrny, A. A. Pasternak, I. Zalewska, T. Morek, C. Droste, J. Mierzejewski, M. Kowalczyk, J. Kownacki, M. Kisieliński *et al.*, Phys. Rev. Lett. **97**, 172501 (2006).
[7] P. Olbratowski, J. Dobaczewski, J. Dudek, and W. Płóciennik, Phys. Rev. Lett. **93**, 052501 (2004).
[8] T. Koike, K. Starosta, C. J. Chiara, D. B. Fossan, and D. R. LaFosse, Phys. Rev. C **67**, 044319 (2003).
[9] E. Grodner *et al.* (to be published).
[10] Y. Liu, J. Lu, Y. Ma, S. Zhou, and H. Zheng, Phys. Rev. C **54**, 719 (1996).
[11] P. J. Brussaard and P. M. Glaudemans, *Shell-Model Applications in Nuclear Spectroscopy* (North-Holland, Amsterdam, 1977).
[12] *Relativistic Density Functional for Nuclear Structure*, edited by J. Meng (World Scientific, Singapore, 2016).
[13] N. J. Stone, At. Data Nucl. Data Tables **90**, 75 (2005).
[14] K. Starosta, T. Koike, C. J. Chiara, D. B. Fossan, and D. R. LaFosse, Nucl. Phys. **A682**, 375 (2001).
[15] J. Peng, J. Meng, and S. Q. Zhang, Phys. Rev. C **68**, 044324 (2003).
[16] T. Koike, K. Starosta, and I. Hamamoto, Phys. Rev. Lett. **93**, 172502 (2004).
[17] S. Q. Zhang, B. Qi, S. Y. Wang, and J. Meng, Phys. Rev. C **75**, 044307 (2007).
[18] B. Qi, S. Q. Zhang, J. Meng, S. Y. Wang, and S. Frauendorf, Phys. Lett. B **675**, 175 (2009).
[19] E. Lawrie and O. Shirinda, Phys. Lett. B **689**, 66 (2010).
[20] J. Meng, J. Peng, S. Q. Zhang, and S.-G. Zhou, Phys. Rev. C **73**, 037303 (2006).
[21] J. Peng, H. Sagawa, S. Q. Zhang, J. M. Yao, Y. Zhang, and J. Meng, Phys. Rev. C **77**, 024309 (2008).
[22] J. M. Yao, B. Qi, S. Q. Zhang, J. Peng, S. Y. Wang, and J. Meng, Phys. Rev. C **79**, 067302 (2009).
[23] J. Li, S. Q. Zhang, and J. Meng, Phys. Rev. C **83**, 037301 (2011).
[24] P. W. Zhao, Z. P. Li, J. M. Yao, and J. Meng, Phys. Rev. C **82**, 054319 (2010).
[25] A. Arnesen, K. Johansson, E. Karlsson, T. Noreland, L.-O. Norlin, and S. Ogaza, Hyperfine Interact. **5**, 81 (1977).
[26] E. Grodner, I. Sankowska, T. Morek, S. G. Rohoziński, C. Droste, J. Srebrny, A. A. Pasternak, M. Kisieliński, M. Kowalczyk, J. Kownacki *et al.*, Phys. Lett. B **703**, 46 (2011).
[27] T. Marchlewski, R. Szenborn, J. Samorajczyk, E. Grodner, J. Srebrny, C. Droste, L. Próchniak, A. A. Pasternak, M. Kowalczyk, M. Kisieliński *et al.*, Acta Phys. Pol. B **46**, 689 (2015).
[28] S. Y. Wang, S. Q. Zhang, B. Qi, and J. Meng, Phys. Rev. C **75**, 024309 (2007).