Parity-doublet structure in the $_{57}^{147}La_{90}$ nucleus

J. Wiśniewski, W. Urban, T. Rząca-Urban, A. G. Smith, J. F. Smith, G. S. Simpson, I. Ahmad, and J. P. Greene

Phys. Rev. C **96**, 064301 — Published 1 December 2017

DOI: 10.1103/PhysRevC.96.064301

Parity-doublet structure in the $^{147}_{57}La_{90}$ nucleus.

J. Wiśniewski, W. Urban, and T. Rząca-Urban
Faculty of Physics, University of Warsaw, ulica Pasteura 5, PL-02-093 Warsaw, Poland

A.G. Smith and J. F. Smith
Department of Physics and Astronomy, The University of Manchester, M13 9PL Manchester, UK

G. S. Simpson
Laboratoire de Physique Subatomique et de Cosmologie,
IN2P3-CNRS/Université Grenoble Alpes, F-38026 Grenoble Cedex, France

I. Ahmad and J. P. Greene
Argonne National Laboratory, Argonne, IL 60439, USA

Excited states in ^{147}La, populated in spontaneous fission of ^{252}Cf have been reinvestigated by means of γ-ray spectroscopy, using high-fold γ-ray coincidences measured with Gammasphere array of Ge detectors. The 229.5-keV level, which has been assigned spin-parity $9/2^-$ in a recent evaluation, is shown to have spin-parity $11/2^-$. Consequently, the ground state has spin-parity $5/2^+$. Excited levels in ^{147}La have been arranged into a parity-doublet structure, showing that at medium excitation energy the ^{147}La nucleus may have octupole deformation. The B(E1) rates in ^{147}La, which are factor four lower than in ^{145}La, suggest that the electric dipole moment in ^{147}La is depressed by an extra mechanism, probably connected with the population of particular neutron orbitals.

PACS numbers: 21.10.Tg, 23.20.Lv, 25.85.Ca, 27.70.+q

I. INTRODUCTION

Over the past decades a lot of effort has been devoted to determine the role of octupole correlations in neutron-rich nuclei of the mass A≈150 region. Strong octupole correlations were predicted here [1], pointing to a stable octupole deformation in the ^{146}Ba nucleus. This was later supported experimentally [2] leaving, however, some open questions. In a nucleus with octupole deformation one expects enhanced E1 decays, but in ^{146}Ba the E1 decays are week. Further development in the theory allowed the explanation as due to a particular canceling of the E1 strength at the neutron number N=90 [3], while reproducing strong E1 decays, observed in the ^{144}Ba neighbor at N=88 [4]. The present status, supported by further studies of ^{144,146}Ba [4–6] is, that an octupole deformation is present in even-even, Ba isotopes.

It is expected that odd-A neighbors of even-even nuclei with stable octupole deformation should also possess octupole deformation. Such a deformation should alter positions of single-particle orbitals in an odd-A nucleus (see Ref. [1] and the recent energy-density-functional calculations [7]). For example, the theory predicted, that due to an octupole deformation the ground state of the ^{147}Ba nucleus should have spin and parity $3/2^-$ [1]. However, the experiment has shown that the spin and parity of the ground state in ^{147}Ba is $5/2^-$ and the low-spin structure corresponds to a reflection-symmetric shape [8]. A similar situation is encountered in ^{145}Ba [9]. This raises questions about the presence of octupole deformation in odd-A, Ba isotopes.

It is possible that the odd neutron "blocks" octupole correlations in these odd-N nuclei. Therefore, it is of interest to probe the strength of octupole effects in the in odd-Z nuclei of the region. At the neutron number N=90 parity-doublet bands [10] have been proposed in ^{151}Pm [11, 12] and ^{153}Eu [13]. Also in the N=90 isotone, ^{147}La excited states were reported, which could be arranged into a parity-doublet structure, though only at medium excitation energies [14, 15].

The proposed parity-doublet arrangement in ^{147}La depends on the properties of the 229.5-keV level in this nucleus. Both works [14, 15] reported spin-parity $11/2^-$ for this level. Therefore it came as a surprise that the following compilation [16] reported a $9/2^-$ spin-parity for the 229.5-keV level in ^{147}La. Such an assignment is in conflict with the parity-doublet structure in ^{147}La and with the observation of $11/2^-$ bands in other N=90 isotones, ^{145}Cs [17, 18] and ^{149}Pr [19].

In the present work we reinvestigated the excitation scheme of ^{147}La using improved data, with enhanced statistics as compared to previous studies [14, 15]. The aim was to verify spin-parity assignments and the presence of the parity-doublet band in ^{147}La.

II. EXPERIMENT AND THE RESULTS.

The present data has been obtained from a measurement of high-fold γ-ray cascades following spontaneous fission of ^{252}Cf, performed using the Gammasphere array of Anti-Compton Spectrometers (ACS) [20]. We have analyzed prompt-γ, triple coincidences using analysis techniques described in Refs. [21–23].

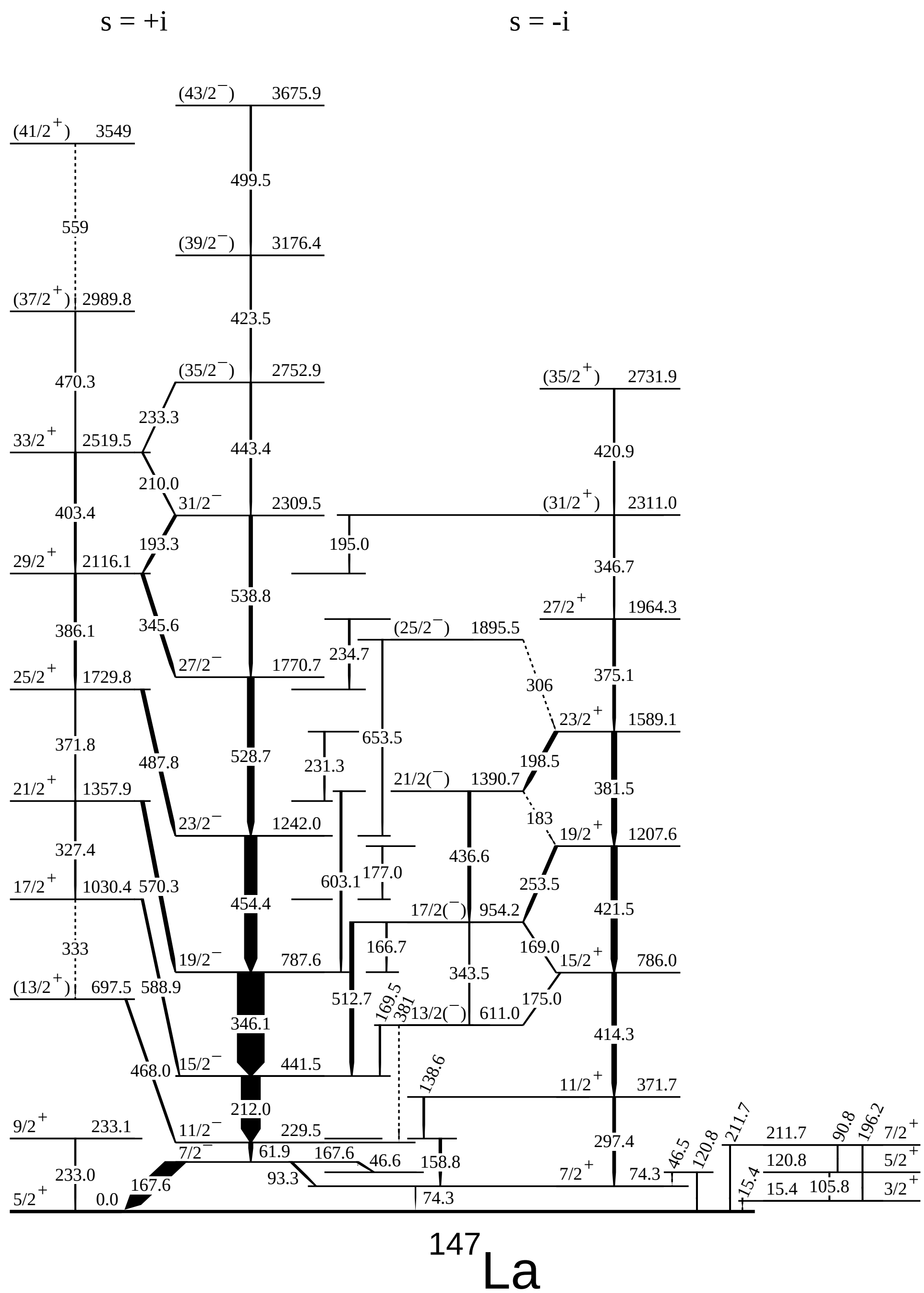

FIG. 1: Scheme of excited levels in ^{147}La, populated in spontaneous fission of ^{252}Cf, as observed in the present work. Thickness of arrows representing transitions is proportional to their relative γ-ray intensities. The 15.4-, 120.8- and 211.7-keV levels and their decays are drawn after Refs. [24, 25], to assist the discussion.

A. Near-yrast, excitation scheme of ^{147}La.

The present work confirms the excitation scheme of ^{147}La reported previously [14, 15]. In addition we observe several new transitions in the low-spin part, which allow the arrangement of excited levels in ^{147}La into a parity-doublet structure, analogous to the structure observed in ^{151}Pm [11]. The excitation scheme of ^{147}La, obtained this work is shown in Fig. 1. The properties of γ-ray transitions in ^{147}La, populated in spontaneous fission of ^{252}Cf, as measured in this work, are listed in Table I. The γ-ray intensities shown in Table I were derived from coincidence spectra. They are not corrected for internal conversion.

In Fig. 2 we show a sum of γ-ray spectra, gated on

TABLE I: Properties of γ-ray transitions and excited levels in ^{147}La, as observed in this work following spontaneous fission of ^{252}Cf.

E_γ (keV)	I_γ (rel.)	E^{ini}_{lev} (keV)	J^{ini}_{lev}	Multi-polarity
46.6 (2)	4 (1)	167.6 (1)	$7/2^-$	M1+E2, ΔJ=1
74.3 (1)	6 (1)	74.3 (2)	$7/2^+$	E1, ΔJ=1
61.9 (1)	13 (2)	229.5 (2)	$11/2^-$	E2, ΔJ=2
93.3 (1)	5 (1)	167.6 (1)	$7/2^-$	M1+E2, ΔJ=1
138.6 (2)	4 (1)	371.7 (1)	$11/2^+$	M1+E2, ΔJ=1
158.8 (2)	7 (1)	233.1 (2)	$9/2^+$	M1+E2, ΔJ=1
166.7 (2)	3 (1)	954.2 (3)	$17/2^-$	M1+E2, ΔJ=1
167.6 (1)	54 (2)	167.6 (1)	$7/2^-$	E1, ΔJ=1
169.0 (3)	2 (1)	954.2 (3)	$17/2^-$	M1+E2, ΔJ=1
169.5 (2)	3 (1)	611.0 (3)	$13/2^-$	E2, ΔJ=2
175.0 (2)	2 (1)	786.0 (2)	$15/2^+$	E2, ΔJ=2
177.0 (2)	2 (1)	1207.6 (4)	$19/2^+$	M1+E2, ΔJ=1
183 (1)	1 (1)	1390.7 (4)	$21/2^-$	(E1)
193.3 (1)	8 (1)	2309.5 (5)	$31/2^-$	E1, ΔJ=1
195.0 (3)	2 (1)	2311.0 (6)	$31/2^+$	M1+E2, ΔJ=1
198.5 (1)	12 (1)	1589.1 (5)	$23/2^+$	E1, ΔJ=1
210.0 (1)	3.2 (5)	2519.5 (6)	$33/2^+$	E1, ΔJ=1
212.0 (1)	70 (3)	441.5 (2)	$15/2^-$	E2, ΔJ=2
231.3 (1)	3.0 (3)	1589.1 (5)	$23/2^+$	M1+E2, ΔJ=1
233.0 (2)	2.0 (5)	233.1 (2)	$9/2^+$	E2, ΔJ=2
233.3 (2)	2.1 (4)	2752.9 (6)	$35/2^-$	M1+E2, ΔJ=1
234.7 (2)	4.0 (4)	1964.3 (5)	$27/2^+$	E2, ΔJ=2
253.5 (1)	9 (1)	1207.6 (4)	$19/2^+$	E1, ΔJ=1
297.4 (1)	8 (2)	371.7 (2)	$11/2^+$	E2, ΔJ=2
306.0 (4)	1 (1)	1895.5 (6)	$25/2^-$	(E1)
327.4 (3)	2 (1)	1357.9 (3)	$21/2^+$	E2, ΔJ=2
333 (1)	1 (1)	1030.4 (3)	$17/2^+$	(E2)
343.5 (3)	2 (1)	954.2 (3)	$17/2^-$	E2, ΔJ=2
345.6 (1)	10 (1)	2116.2 (5)	$29/2^+$	E1, ΔJ=1
346.1 (1)	100 (3)	787.6 (2)	$19/2^-$	E2, ΔJ=2
346.7 (2)	3.1 (6)	2311.0 (6)	$31/2^+$	E2, ΔJ=2
371.8 (1)	1.9 (2)	1729.8 (3)	$25/2^+$	E2, ΔJ=2
375.1 (1)	8.3 (7)	1964.3 (5)	$27/2^+$	E2, ΔJ=2
381 (1)	1 (1)	611.0 (3)	$23/2^+$	E2, ΔJ=2
381.5 (1)	17 (1)	1589.1 (5)	$23/2^+$	E2, ΔJ=2
386.1 (1)	5.5 (7)	2116.1 (5)	$29/2^+$	E2, ΔJ=2
403.4 (1)	5 (1)	2519.5 (5)	$33/2^+$	E2, ΔJ=2
414.3 (1)	15 (3)	786.0 (2)	$15/2^+$	E2, ΔJ=2
420.9 (2)	3 (1)	2731.9 (7)	$35/2^+$	E2, ΔJ=2
421.5 (1)	21 (2)	1207.6 (4)	$19/2^+$	E2, ΔJ=2
423.5 (1)	3 (1)	3176.4 (6)	$39/2^-$	(E2)
436.6 (1)	9 (1)	1390.7 (4)	$21/2^-$	E2, ΔJ=2
443.4 (2)	3.7 (5)	2752.9 (6)	$35/2^-$	E2, ΔJ=2
454.4 (1)	45 (2)	1242.0 (3)	$23/2^-$	E2, ΔJ=2
468.0 (3)	5 (2)	697.5	$(13/2^+)$	(E1)
470.3 (2)	0.9 (3)	2989.8 (7)	$(37/2^+)$	(E2)
487.8 (1)	11 (1)	1729.8 (4)	$25/2^+$	E1, ΔJ=1
499.5 (2)	3 (1)	3675.9 (7)	$43/2^-$	(E2)
512.7 (2)	13 (1)	954.2 (3)	$17/2^-$	M1+E2, ΔJ=1
528.7 (1)	23 (1)	1770.7 (3)	$27/2^-$	E2, ΔJ=2
538.8 (1)	10 (1)	2309.5 (5)	$31/2^-$	E2, ΔJ=2
559 (1)	1 (1)	3549 (1)	$(41/2^+)$	(E2)
570.3 (1)	11 (1)	1357.9 (3)	$21/2^+$	E1, ΔJ=1
588.9 (1)	6 (1)	1030.4 (3)	$17/2^+$	E1, ΔJ=1
603.1 (2)	5 (1)	1390.7 (4)	$21/2^-$	M1+E2, ΔJ=1
653.5 (2)	2 (1)	1895.5 (6)	$25/2^-$	M1+E2, ΔJ=1

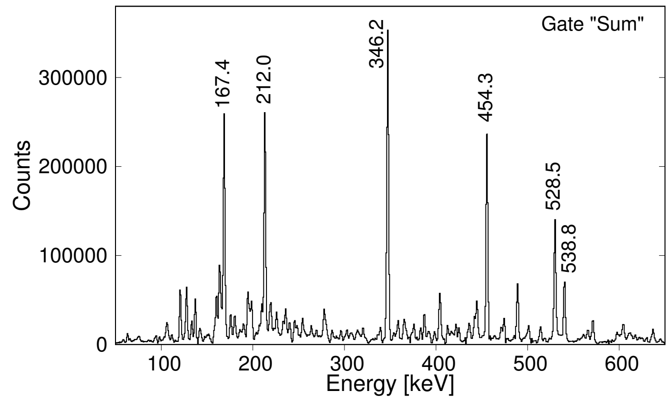

FIG. 2: Sum of γ-ray spectra doubly gated in a triple-γ histogram on pairs of lines from the 167.6-212.0-346.1-454.4-528.7-keV, yrast cascade in ^{147}La, as observed in this work.

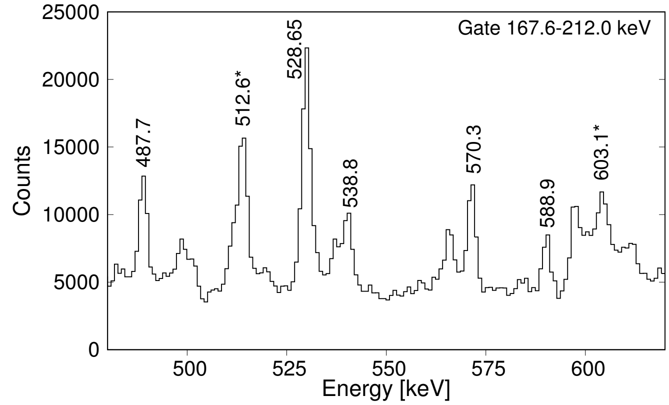

FIG. 3: A γ-ray spectrum doubly gated on the 167.6- and 212.0-keV lines in the ^{252}Cf fission data. Energies are given in keV. Newly observed lines are marked with an asterisk.

the yrast cascade in ^{147}La. The spectra were cut from a 3D histogram containing triple-γ coincidences, sorted within a time window of 900 ns. The summed spectrum is analogous to the spectrum shown in Fig.4 of Ref.[15], but with about 20 times higher statistics. It is dominated by lines corresponding to stretched E2 transitions in the simplex, $s = +i$ band.

Figure 3 shows fragment of a γ-ray spectrum obtained by double gating on the known, 167.6-212.0-keV cascade. In the spectrum one can see known γ-ray lines at 487.8, 528.7, 538.8, 570.3 and 588.9 keV, present in the simplex, $s = +i$ band. In addition, there are two newly observed lines at 512.7 and 603.1 keV, marked with an asterisk.

Figures 4 and 5 show spectra obtained by gating on the known, 212.0-keV line and the newly observed 512.7- and 603.1-keV lines, respectively. Next to the 167.6-, 346.7- and 375.1-keV lines, reported earlier [14, 15], there are newly observed lines at 198.5, 253.5, 381.5 and 436.6 keV. These and other gated spectra allowed the assignment of the newly observed lines as members of the $s = -i$ branch of the parity-doublet, as shown in Fig. 1.

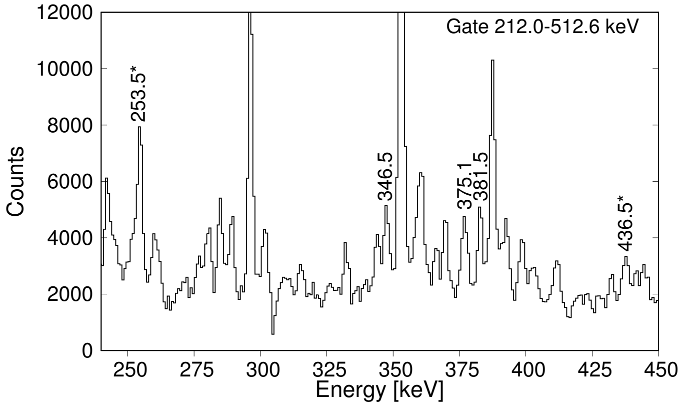

FIG. 4: A γ-ray spectrum doubly gated on 212.0- and 512.7-keV lines in the ^{252}Cf fission data. Energies are given in keV. Newly observed lines are marked with an asterisk.

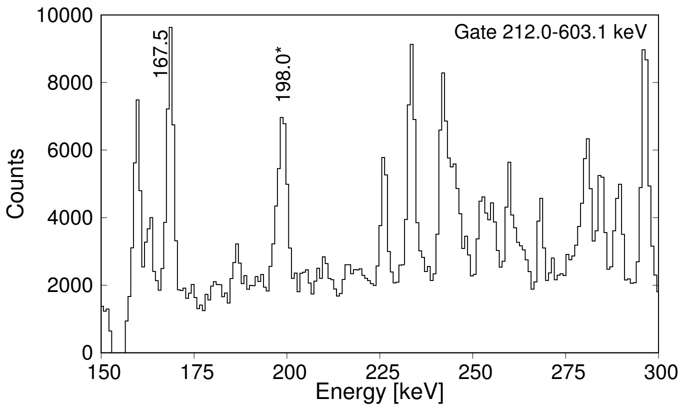

FIG. 5: A γ-ray spectrum doubly gated on the 212.0- and 603.1-keV lines in the ^{252}Cf fission data. Energies are given in keV. Newly observed lines are marked with an asterisk.

A γ-ray spectrum displayed in Fig. 6, which is doubly gated on the 297.4- and 381.5-keV, newly observed lines of ^{147}La, shows the 346.7- and 375.1-keV lines reported previously [14, 15] and newly observed lines at 414.3 and 421.5 keV. This and other double gated spectra indicate that the newly observed two transitions connect the 1207.6- and 371.7-keV levels via a newly observed level at 786.0 keV.

B. Spin-parity assignments in ^{147}La.

Spins and parities of levels shown in Fig. 1 are, generally, adopted from Refs. [14, 15], but some values have been altered and some are new.

New multipolarities of transitions in ^{147}La have been deduced from angular-correlation measurement for cascades of γ-rays in ^{147}La, populated in spontaneous fission of ^{252}Cf. The technique is described in Ref. [26] and more details of the present analysis can be found in Ref. [27]. To the experimental intensities of $\gamma\gamma$ coincidences

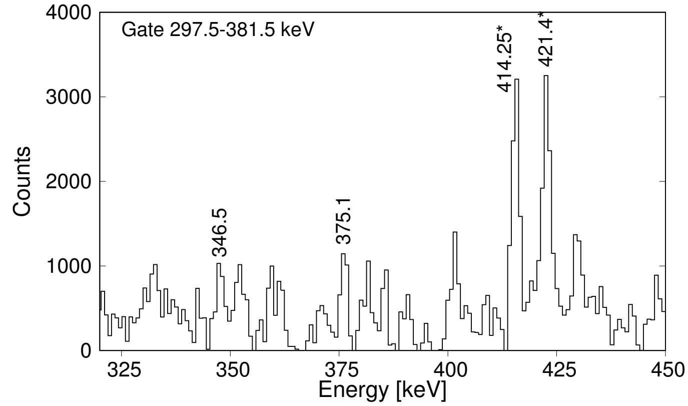

FIG. 6: A γ-ray spectrum doubly gated on the 297.4- and 381.5-keV newly observed lines of ^{147}La in the ^{252}Cf fission data. Energies are given in keV. Newly observed lines are marked with an asterisk.

in a cascade, observed at various angles, θ, we fitted the angular correlation function

$$W(\theta) = \sum_k A_k P_k(\cos\theta) \qquad (1)$$

where θ is an angle between the directions of the two γ-rays in a cascade and P_k are the Legendre polynomials of rank k (k=0, 2, 4).

In Fig. 7 examples of angular correlations for a characteristic, quadrupole-quadrupole (Q-Q) and dipole-quadrupole (D-Q) cascades are shown. Theoretical values for a pure Q-Q cascade are $A_2/A_0 = 0.102$, $A_4/A_0 = 0.009$ and for a pure D-Q cascade $A_2/A_0 = -0.071$ and $A_4/A_0 = 0.00$. The corresponding, experimental values measured for the 346.1-212.0-keV cascade are 0.102(9) and 0.025(16) (Q-Q case) and for the 512.7-212.0-keV cascades are $-0.085(15)$ and $-0.009(22)$ (D-Q case).

The results of the analysis for $\gamma\gamma$ cascades in ^{147}La are presented in Table II, showing the experimental A_k/A_0 coefficients and mixing ratios, δ. The 167.6-212.0-keV cascade is not analyzed because of multiplet nature of the 167-keV line in ^{147}La and high conversion coefficient of the 61.9-keV, intermediate transition.

To help determining spin and parity of the 229.5-keV level we estimated the conversion coefficient for the 61.9-keV transition. By setting a double gate on the 346.1- and 167.6-keV lines we produced a spectrum, in which the 212.0- and 61.9-keV transitions have the same total intensities. Taking the theoretical value of $\alpha_{tot}(212.0)$ =0.146 for a pure E2 transition of 212.0 keV [28], we calculated its total intensity in this gate (in relative units), which was then used to calculate the total conversion coefficient of the 61.9-keV transition. The obtained value of $\alpha_{tot}(62.1) = 11.8(15)$ is consistent with pure E2 multipolarity of the 61.9-keV transition, considering the theoretical value, $\alpha_{tot} = 11.3$ [28] for a pure E2 transition of 61.9 keV.

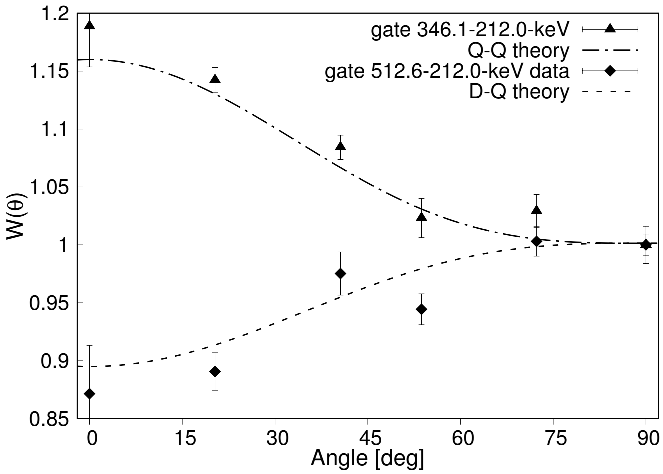

FIG. 7: An example of angular correlations in ^{147}La for quadrupole-quadrupole (Q-Q) and dipole-quadrupole (D-Q) cascades, as measured in this work. See text for further information.

TABLE II: Experimental angular-correlation coefficients, $(A_2/A_0)_{exp}$ and $(A_4/A_0)_{exp}$ for cascades of γ-ray transitions in ^{147}La populated in fission of ^{252}Cf, as determined in the present work. "sum" denotes summed effect with all stretched, quadrupole transition below the studied one.

$E_{\gamma\gamma}$ (keV)	$(A_2/A_0)_{exp}$	$(A_4/A_0)_{exp}$	δ
297.4 - 414.3	0.110(24)	0.032(36)	0
212.0 - 346.1	0.102(9)	0.025(16)	0
346.1 - 454.4	0.095(11)	0.00(1)	0
371.8 - 570.3	-0.075(42)	-0.064(61)	-0.10(7)
512.7 - 212.0	-0.085(15)	-0.009(22)	-0.02(3)
528.7 - sum	0.098(9)	0.008(14)	0
538.8 - sum	0.111(18)	0.076(26)	0
570.3 - 346.1	-0.105(42)	-0.043(60)	-0.06(7)
588.9 - 212.0	-0.68(23)	-0.082(35)	0.005(38)

The $3/2^+$ spin-parity proposed for the ground state of ^{147}La in the compilation [16] was based on the systematics from Ref. [29], reporting spin-parity $3/2^+$ for the ground state of ^{147}La. This assignment was based on the properties of the β^- decay of ^{147}La to ^{147}Ce [29], the similarities to the β^- decay of the isotone ^{145}Cs to ^{145}Ba [29, 30] and a systematics from an unpublished work. However, the key spin-parity assignments to levels in ^{147}Ce, populated in β^- decay of ^{147}La have been changed recently, disabling the comparison with the ^{145}Cs→^{145}Ba β decay and pointing to $5/2^+$ spin-parity of the ground state of ^{147}La. For example, in ^{147}Ce the 117.7-keV level has spin $(7/2^-)$ [31, 32] instead of $(3/2, 5/2)^-$ reported previously [29], the 273.8-keV level has spin $(9/2^-)$ and the 401.1-keV level has spin $(9/2^+)$ [31, 32]. Such assignments to levels observed in β^- decay of ^{147}La to ^{147}Ce require spin-parity $5/2^+$ for the ground state of ^{147}La rather than $3/2^+$. We also note that in Ref. [33] spin-parity $5/2^+$ was assigned to the g.s. of ^{147}La, even though the spin-parity of the g.s. ^{147}Ba was proposed to be $(3/2^-)$. Considering, that the spin-parity of the g.s. of ^{147}Ba was recently shown to be $5/2^-$ [8], the $5/2^+$ spin-parity of the g.s. ^{147}La is further confirmed. Finally, the detailed study of β^- decay of ^{147}Ba to ^{147}La [24, 25] reported spin-parity $5/2^+$ for the ground state of ^{147}La. Considering all the new evidence we adopt spin-parity $5/2^+$ for the ground state of ^{147}La, in accord with our previous work [14] and Refs. [15, 24, 25, 33].

For the 167.6-keV level spin-parity $7/2^-$ is proposed, based on the stretched E1 character of the 167.6-keV transition [14]. Considering the E2 character of the 61.9-keV transition, being the only decay branch of the 229.5-keV level, and the near-yrast character of the population in fission [34], we propose spin-parity $11/2^-$ for the 229.5-keV level in ^{147}La. This is in agreement with previous findings [14, 15] and changes the $9/2^-$ value reported in the recent evaluation [16].

The $\gamma\gamma$ angular correlations for the 212.0-346.1-keV, 346.1-454.4-keV, 528.7-sum and 538.8-sum cascades are consistent with a stretched quadrupole nature of transitions in these cascades and provide spin-parity assignments to the 441.5-, 787.6-, 1242.0-, 1770.7- and 2309.5-keV levels as shown in Fig. 1. Spin-parity assignments to higher-energy levels in the $s = +i$ band are based on the observed branchings and the well established fact that spins are growing with excitation energy in nuclei populated in spontaneous fission [34].

Angular correlations are consistent with the dipole character of the 570.3- and 588.9-keV transitions. Angular correlations for the 371.8-570.3-keV $\gamma\gamma$ cascade are consistent with the stretched quadrupole character of the 371.7-keV transition. Therefore, we propose that the band above 1357.9-keV level consist of stretched E2 transitions. Positive parity, assigned tentatively, as in Ref. [15], is consistent with small δ values of the 570.3- and 588.9-keV transitions (see Table II).

Angular correlations for the 297.4- 414.3-keV cascade are consistent with the stretched, quadrupole character of both transitions. This allows to assign positive parity to the band based on the $7/2^+$ level at 74.3 keV. These data, the observed branchings and the assumption that spins are increasing with an increasing excitation energy, indicate spins in this band, as shown in Fig. 1. Here we differ with Ref. [15], where negative parity was proposed for levels in the upper part of this band.

Angular correlations for the 512.6-keV transition are consistent with a ΔJ=1 character of this transition. This observation, together with spin assignments to the band on top of the $7/2^+$, 74.3-keV level, provides spin assignments to the 611.0-, 954.2- and 1390.7-keV levels as shown in Fig.1. Negative parity is tentatively proposed for these levels, because of their proximity to the 697.5-, 1030.4- and 1357.9-keV levels, where we proposed positive parity.

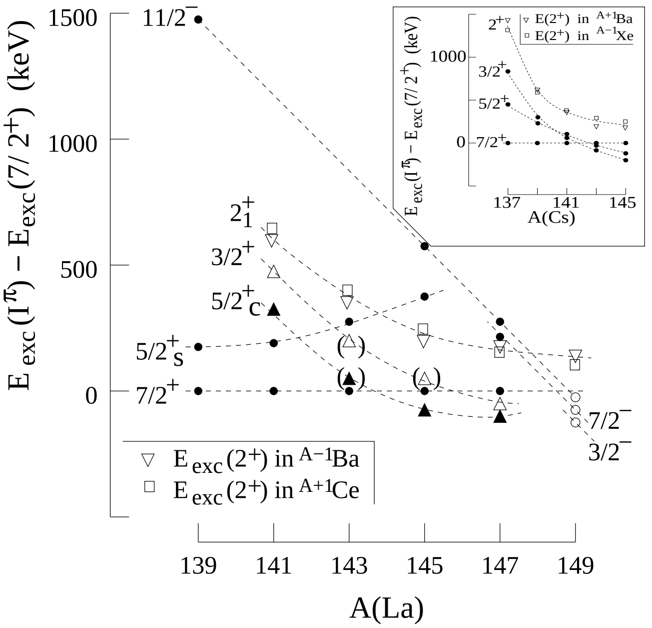

FIG. 8: Systematics of excitations in odd-A La isotopes. The data are taken from the present work and from Refs. [14, 15, 24, 25, 33, 35–39]. Dashed lines are drawn to guide the eye. Parentheses indicate tentative spin-parity assignments. See text for more comments.

III. DISCUSSION

A. Configurations in ^{147}La.

The key spin-parity assignment of $11/2^-$ to the 229.5-keV level is further supported by other observations, including systematics of excitation energies in the region, the identification of the underlying single-particle structure based on alignment plots and arguments from other studies.

The systematics of excitations energies in the La isotopes with N $\geq$ 82 is shown in Fig. 8. We note the regular trend of the $11/2^-$ excitation energy relative to the $7/2^+_1$ level in the La isotopes (because the exact position of the $7/2^+$ level is not yet known in ^{149}La [35, 36], the $3/2^-$, $7/2^-$ and $11/2^-$ levels are shown as open circles). The 229.5-keV level in ^{147}La fits well this trend (another version of this figure, comprising $11/2^-$ levels in Cs - to - Eu, odd-A isotopes can be found in Ref. [18]). In ^{147}La one observes a $7/2^-$ level at 167.6 keV. Analogous $7/2^-$ levels are observed 81.5, 91.2, and 102.6 keV below the $11/2^-$ in ^{149}La [36], ^{145}Cs [18] and ^{149}Pr [19], respectively. These levels have been interpreted as members of the $1/2^-[550]$ or $3/2^-[541]$ band, originating from the $h_{11/2}$ proton orbital [18, 19, 24, 25]. In ^{149}La the $3/2^-[541]$ band-head most likely forms the ground state [35, 36], as shown in Fig.8. In the next section we discuss the alignment in the band on top of the 229.5-keV level, which confirm spin-parity $11/2^-$ assignment for this level.

In Fig. 8 we also show positions of $3/2^+$ and $5/2^+$ levels. Although their systematics still needs to be verified and completed, the available data suggest that in ^{147}La the $5/2^+$ level is located below the $3/2^+$ level. It is interesting to note that there is many low-energy, $3/2^+$ and $5/2^+$ levels in odd-A La isotopes in this region. For example, in ^{143}La there are four $5/2^+$ levels below 0.65 MeV and a $3/2^+$ level at 29.9 keV [37, 38], the latter being difficult to explain [37]. Two possible origins of such excitations are the single-particle, $d_{5/2}$ proton excitation and the, so called, anomalous $j-1$ coupling of the $g_{7/2}$ proton [40–42] with the core quadrupole phonon, as also mentioned in Ref. [37]. The $d_{5/2}$ proton levels are probably those shown as $5/2^+_s$ (s for single-particle) in Fig. 8, while the $5/2^+_c$ (c for collective) levels in the figure may result from the $j-1$ coupling. Such coupling has been recently observed and discussed above the N=50 closed shell [43, 44]. That this effect may also occur above the Z=50 closed shell, in La isotopes, is supported by Fig. 8, where the trend for the $5/2^+_c$ level is compared against excitation energies of the 2^+_1 levels in the corresponding Ba and Ce core nuclei. As can be seen, the collectivity in the core correlates with positions of the $5/2^+_c$ levels. Furthermore, the same correlation is observed for $3/2^+$ levels, which may result from the $j-2$ coupling of the $g_{7/2}$ proton with the core, quadrupole phonon, as observed in nuclei above N=50 closed shell [45, 46] and in Cs isotopes, shown in the inset of Fig. 8.

B. Octupole correlations in ^{147}La.

As can be seen in Fig. 1 the newly observed transitions and levels allow the arrangement of excited levels in ^{147}La into a parity-doublet structure, suggesting the presence of octupole correlations in this nucleus. It is therefore, of interest to estimate the rate of electric dipole transitions in this nucleus.

In Table III we show $B(E1)/B(E2)$ branching ratios for ^{147}La obtained in this work. The average value of $0.34\times10^{-6}\mathrm{fm}^{-2}$, calculated for the 1207.6-, 1589,10 and 1729.8-keV levels, is about factor four lower than the average branching observed in ^{145}La [14, 15] (the high value for the 2309.5-keV level is probably due to a low E2 rate at the backbending, as pointed out in Ref. [15]). These branching ratios can be used to estimate the intrinsic electric dipole moment using the "rotational" formula $D_0 = \sqrt{5B(E1)/16B(E2)} \times Q_0$ [47]. The electric quadrupole moment of $Q_0 = 411$ efm^2 is obtained for ^{147}La from an interpolation, using values for the neighboring even-even nuclei [48]. The average electric dipole moment obtained for ^{147}La is $D_0 = 0.13(2)$ efm.

The B(E1)/B(E2) branchings observed in ^{147}La in the newly proposed $s=-i$ band are slightly higher than reported previously for the $s=+i$ band [14, 15], supporting the presence of octupole correlations in this nucleus. Still, the electric dipole moment in ^{147}La is lower than in ^{145}La, showing the same variation (see Fig. 8 in Ref.

TABLE III: The $B(E1)/B(E2)$ branching ratios in ^{147}La, as obtained in this work.

E_{exc} (keV)	$E_\gamma(E1)$ (keV)	$E_\gamma(E2)$ (keV)	B(E1)/B(E2) 10^{-6}fm^{-2}
1207.6	253.5	421.5	0.20(1)
1589.1	198.5	381.5	0.57(3)
1729.8	487.8	371.8	0.27(2)
2309.5	193.3	538.8	3.96(36)
2752.9	233.3	443.4	1.04(15)

[15]) as observed in the ^{144}Ba and ^{146}Ba cores (see Fig. 11 in [4]). So in both Ba and La nuclei there is a decrease of the D_0 between N=88 and N=90 (to date, the data for ^{149}La [35, 36] is still insufficient to check if the D_0 moment in ^{149}La increases again, as observed in its core nucleus ^{148}Ba [4]).

A similar decrease with the neutron number has been also observed in odd-A barium isotopes. The D_0 of 0.14 efm seen in ^{143}Ba at the neutron number N=87 drops to 0.05 efm value in ^{145}Ba (see Fig. 8 in [49]). Further studies confirmed that octupole correlations in ^{145}Ba and ^{147}Ba are low and that, probably, ground states of both nuclei have reflection-symmetric shapes [8, 50].

The variation of D_0 in even-even Ba isotopes have been explained by the theory [3] as due to two competing contributions, which vary differently with the neutron number. It is worth noting that, according to this calculation, at the same time the octupole deformation does not change. This latter suggestion may be consistent with the recent measurements of B(E3) rates in even-even nuclei, ^{144}Ba and ^{146}Ba [5, 6], where the authors suggest that octupole effect are similar in both nuclei. The calculations reported in Ref. [6] support the picture proposed in Ref. [3] and relate the change in D_0 to the varying occupation of specific neutron orbitals at the Fermi level.

It should be mentioned, however, that large uncertainties on the reported B(E3) rates [5, 6] do not allow definite statements at present. Moreover, there are other observations, as different alignments in g.s. bands of ^{144}Ba and ^{146}Ba and extra-low 2_1^+ and 3_1^- excitation energies in ^{144}Ba [4], which suggest that octupole effects in ^{144}Ba are stronger than in ^{146}Ba. Whether this difference has the same origin as the difference between ^{143}Ba and ^{145}Ba, mentioned above, or whether the effect in odd-N isotopes in due to the, so called, blocking effects, is not yet clear.

The D_0 may also strongly depend on protons, as suggested by the observation that, unlike in Ba nuclei, in even-even Ce isotopes this moment does not decrease between N=88 and N=90 (see Fig. 9 in Ref. [18]). Another example is the change of octupole correlations in the odd-Z, N=90 isotones, from a very weak effect in ^{145}Cs to a clear parity-doublet structure in ^{151}Pm [11] and ^{153}Eu [13]. Studies of odd-Z nuclei in the region, such as observation of the blocking effect, which may influence the octupole coupling between protons, should provide further information on the subject.

To learn more about the underlying quasi-particle structure of ^{147}La, we have produced plots of total aligned angular momentum, J_x, for bands in ^{147}La, as shown on Fig. 9. The J_x values have been calculated using energies of the in-band, $\Delta J = 2$ transitions. For a transition with energy $E_\gamma = E_i - E_f$ between levels with energies E_i and E_f and spins J_i and J_f, the J_x value has been calculated using the procedure described in Ref. [51],

$$J_x = \sqrt{(J_a + 1/2)^2 - K^2} \tag{2}$$

where $J_a = (J_i + J_f)/2$ and K is a projection on the symmetry axis of the spin of the band head. The rotational frequency was calculated as [51]

$$\hbar\omega = (E_i - E_f)/(J_x^i - J_x^f), \tag{3}$$

where

$$J_x^{i,f} = \sqrt{(J_{i,f} + 1/2)^2 - K^2} \tag{4}$$

For the band on top of the 229.65-keV level we assumed a value of $K = 5/2$.

In Fig. 9 one observes clear gains in total alignments, J_x, which signal changes in quasi-particle structures (for brevity those gains in J_x will be called alignments and denoted by symbol i).

The alignment, $i_1 \approx 5\hbar$, for the band on top of the $11/2^-$, 167.6-keV level ($7/2^-$ band, filled circles in Fig. 9a), calculated relative to the ground-state band of ^{146}Ba (triangles in Fig. 9a), is consistent with this band being the favored branch of the decoupled band based on the $h_{11/2}$ neutron orbital. This band undergoes a crossing (backbend) at a frequency, $\hbar\omega_1 \approx 0.27$ MeV, which coincides with the crossing in the ground-state bands of the ^{146}Ba core. In the crossing the $7/2^-$ band gains an alignment of $i_2 \approx 9\hbar$, which is consistent with the alignment of a pair of 3/2[541] neutrons. The same alignment gain is observed in the g.s. band of ^{146}Ba, where we added a new level at 4139 keV with spin (18^+), observed in the present work.

The $13/2^-$ band (open circles in Fig. 9b), has an alignment $i_3 \approx 4\hbar$, which is consistent with this band being the unfavored branch of the decoupled band based on the $h_{11/2}$ neutron orbital.

The two bands drawn as filled and empty squares in Fig. 9b start with a small alignment of $i_4 \approx 2\hbar$, each. These bands gain a large alignment of $i_5 \approx 9\hbar$ each, which happens at low rotational frequency $\hbar\omega_2 \approx 0.18$ MeV. Such a low crossing frequency is observed in octupole bands and is interpreted as due to aligning an octupole phonon along the axis of rotation. However, the maximum alignment gain in such a process should not

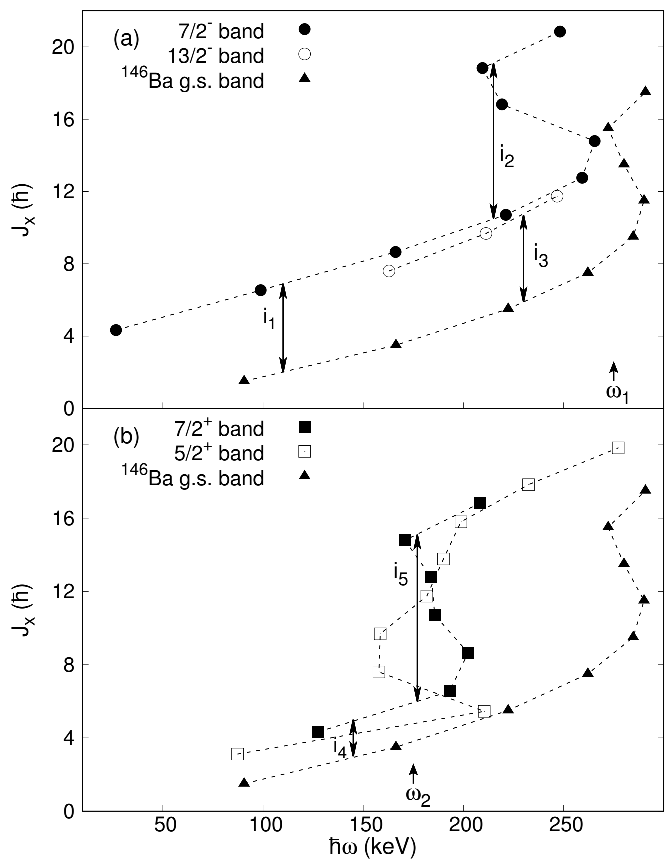

FIG. 9: Total aligned angular momenta in bands of ^{147}La and in the g.s. band of ^{146}Ba. Fig. a) shows positive parity bands while Fig. b) negative parity bands. See text for the description of $\hbar\omega_1$ and $\hbar\omega_2$.

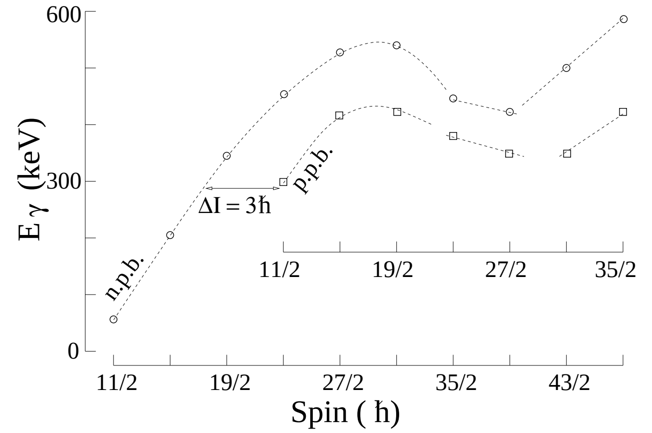

FIG. 10: Energies of γ-ray transitions in bands of ^{147}La vs. spin of the initial level. Lower abscissa corresponds to the n.p.b. and higher to the p.p.b. Dashed lines are drawn to guide the eye. See text for more comments.

exceed 6 $\hbar$. Thus, there must be also another contribution, probably corresponding to an alignment of orbitals forming the octupole band.

That the positive-parity band (p.p.b.) on top of the $7/2^+$, 74.3-keV level may be an octupole band is seen in Fig. 10, where we have drawn energies of in-band γ-ray transitions. A clear similarity between the p.p.b. and the negative-parity band (n.p.b) on top of the $7/2^-$, 167.6-keV level is seen, when the p.p.b. curve is shifted approximately 3 $\hbar$ to the right, relative to the n.p.b. curve. This is a picture characteristic of an octupole band in even-even nuclei, where γ-ray energies in the n.p.b branch have similar values to γ-ray energies in the g.s. band, but at spins higher by 3 $\hbar$ (see octupole g.s. bands in ^{144}Ba and ^{146}Ba). The observed similarity suggests that the extra alignment in the p.p.b. (filled squares) mentioned above may be due to an alignment in the n.p.b.

In the level scheme of ^{145}La reported in Ref. [15] there is five cascades, one more than needed for a parity-doublet structure. Their bands (2) and (3), the positive-parity ground-state band and the positive-parity band based on the 2186.0-keV level, respectively, do not communicate and are most likely different structures. Band (3), which is probably the favored branch of a coupled band, based on top of the $5/2^+$, $j-1$ anomalous level, (see Fig. 8 [15]) has as its octupole counterpart the low-energy part of band (1). The B(E1)/B(E2) ratios for bands (1) and (3), seen in Fig.7 of Ref. [15], are very low. One can conclude that bands (1) and (3) do not form a parity doublet.

At higher spin band (1) acquires a "true" parity-doublet partner, band (2). The B(E1)/B(E2) ratios for bands (1) and (2), are significantly higher. Similarly high are B(E1)/B(E2) ratios for bands (4) and (5) in ^{145}La.

In ^{147}La bands (1) and (2), reported in Ref. [15], form the $s=+i$ band, (see Fig. 1) and show weak B(E1)/B(E2) ratios [14, 15]. In the new, $s=-i$ band of ^{147}La, found in this work, these ratios are slightly higher, but still factor four lower than in the $s=-i$ band of ^{145}La (bands (4) and (5) in Ref. [15]). This tells, that although the parity-doublet structure is formed in ^{147}La, the B(E1) rates are low. These two observations support the idea that while the octupole correlation (octupole deformation) may be comparable at N=88 and N=90, the D_0 moment decreases at N=90 as compared to N=88, due to some extra dependence on the neutron number.

The dependence of octupole effects on neutrons may be higher than on protons. This is suggested by the observation that while in odd-Z, even-N nuclei one observes parity doublets, in the odd-N, even-Z nuclei of the discussed region such structures are not present. It has been argued that the shapes of ^{145}Ba and ^{147}Ba are reflection-symmetric because the octupole correlations are diminished by "blocking" neutron orbitals in these odd-N nuclei [8, 50]. Similarly, in ^{147}Ce, ^{149}Ce and ^{151}Ce no parity-doublet structures are reported to date [31, 32, 52, 53].

The observation of pronounced parity-doublet structures in ^{151}Pm and ^{153}Eu, which are much better developed than in lower-Z, N=90 isotones, raises again the question, whether octupole correlations at Z$\geq$60 are stronger or weaker than at Z$\approx$56. A popular view is that, because the proton number, Z=56 is an “octupole magic number”, there is an octupole deformation around Z=56, while strong E1 transitions at Z≥60 are more of a “single-particle” type. This is a difficult problem, because even the “enhanced” B(E1) rates are quite low, being less than 0.01 W.u. in both, Z≥60 and Z≈56, regions. However, in ^{151}Pm one observes both, single-particle and “enhanced” E1 transitions [11], for which B(E1)rates differ by 6 orders of magnitude. This indicates that in ^{151}Pm and ^{153}Eu there is an effect causing an enhancement of E1 rates, which also produces parity doublet. This, most likely is due to octupole correlations, which are at Z≥60 at least as strong as at Z≈56, as indicated in our previous works [54, 55].

IV. SUMMARY

We have reinvestigated the excited states in ^{147}La using high-fold γ-ray coincidences from spontaneous fission of ^{252}Cf, identifying several newly observed transitions. The present study shows that the ground state of ^{147}La has spin-parity $5/2^+$, which differs from the recent compilation. On one hand, the newly observed transitions found in ^{147}La allowed the arrangement of the excitations in this nucleus into a parity doublet. On the other hand the B(E1)/B(E2) rates in both, $s = +i$ and $s = -i$ branches of the parity doublet are factor four lower than those observed in the ^{145}La nucleus. These two observations support the idea proposed in earlier works, that while the the degree of octupole correlations is similar at N=88 and N=90, because in both, ^{145}La and ^{147}La parity doublet is formed, the D_0 moment decreases at N=90 as compared to N=88. The decrease is likely due to competing contributions to D_0, depending on the population of various *neutron* orbitals.

The new data obtained in this work and other recent works on odd-A nuclei in the region provide a useful test for further, much needed theoretical studies, which might help understanding the properties of octupole correlations here. For example, the inspection of odd-A nuclei in the region suggest that octupole effects are better developed in odd-Z nuclei than in odd-N nuclei. In the odd-N nuclei the effect seems to be blocked by the odd neutron. As the blocking by the odd proton does not have such a strong effect, one may conclude that the contribution of neutron orbitals to octupole correlations is more important than the contribution of protons. A dedicated calculation could help verifying this suggestion.

This material is based upon work supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract number DE-AC02-06CH11357.

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