Study of parity-doublet structure in the $^{147}$La nucleus

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Abstract.
The work reports several new excited states in the neutron-rich $^{147}$La nucleus, populated in spontaneous fission of $^{252}$Cf. The excitation scheme has been reinvestigated by means of $\gamma$-ray spectroscopy, using high-fold $\gamma$ coincidences measured with the Gammasphere array of Ge detectors. It is shown that the 229.65-keV level has spin and parity $11/2^-$, which changes the $9/2^-$ spin-parity reported in a recent evaluation and sets up the spin-parity of the ground state as $5/2^+$. New levels allow to arrange the excitation scheme of $^{147}$La into a parity-doublet-like structure showing that the $^{147}$La nucleus may have an octupole deformation.

1 Introduction

The region of neutron-rich nuclei with masses $A \approx 150$ is a place where octupole correlations can be studied in detail. The presence of strong octupole correlations in this region has been predicted [1]. Results suggested the presence of stable octupole deformation in the $^{146}$Ba nucleus which was supported experimentally later [2], leaving, however, some open questions. In octupole deformed nuclei one would expect enhanced E1 transitions but in $^{146}$Ba those transitions are weak. This kind of behavior has been explained by further developments in theory as particular canceling of the E1 strength at the neutron number $N = 90$ [3], while reproducing strong E1 decays observed in the $^{144}$Ba neighbor [4] at $N = 88$. The present status based on studies of of $^{144}$Ba [4, 5] is that there is an octupole deformation in Ba isotopes.

It is interesting to ask about the presence of octupole correlations in odd-A neighbors of even-even nuclei possessing stable octupole deformation. Such correlations should alter positions of single-particle orbital as seen e.g. in the $^{147}$Ba nucleus. Theoretical calculations predicted spin and parity $3/2^-$ for its ground state [1] but experimental results are pointing to $5/2^-$ value and the low-spin structure is assigned to a reflection-symmetric shape [6]. Similar behavior is observed in $^{145}$Ba [7]. This raises questions about the presence of octupole deformation in odd-A, Ba isotopes and the mechanism of weakening of octupole correlations in these nuclei.

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One may search for parity doublets in odd-Z nuclei to probe the strength of octupole effects in the region. Parity-doublet bands have been proposed in $^{151}$Pm [8, 9] and $^{153}$Eu [10], N=90 isotones. In the N=90 isotope $^{147}$La, excited states could be arranged into a parity-doublet structure, though only at higher excitation energy [11, 12]. In both works spin and parity $11/2^-$ were assigned to the 229.65-keV level, therefore it was a surprise that the recent compilation [13] has reported $9/2^-$ spin-parity for this level. Such an assignment does not agree with the proposed parity doublet structure in $^{147}$La. Moreover, recent works report the presence of $11/2^-$ bands in other N=90 isotones, $^{145}$Cs [14] and $^{149}$Pr [15]. In the present work the excitation scheme of $^{147}$La was reinvestigated, using higher-statistics data, as compared to previous studies. The aim was to confirm the presence of parity doublet bands by verifying spins and parities of excited states.

2 Reinvestigation of $^{147}$La

The presented data results from a measurement of $\gamma$-rays emitted in spontaneous fission of $^{252}$Cf. $\gamma$-rays were registered with the Gammasphere array of Anti-Compton Spectrometers (ACS) [16]. Prompt $\gamma$-rays emitted in fission were analyzed using triple-$\gamma$ coincidence matrices. This technique was described in a number of previous papers (see e.g. Refs. [17–19]). The sum of $\gamma$ spectra, gated on the yrast cascade of $^{147}$La is presented in Fig. 1. This is similar to the spectrum shown in Ref. [12], but now the statistics is about 20 times higher.

![Image of Figure 1](image.png)

**Figure 1.** Sum of $\gamma$-ray spectra doubly gated in a triple-$\gamma$ histogram on pairs of lines from the 167.6-212.0-346.3-454.4-528.5-keV, yrast cascade in $^{147}$La, as obtained in this work.

In this work we confirm major coincidence relations and the arrangement of excited levels into bands in $^{147}$La, as reported in previous works [11, 12]. Moreover, in the low-spin part, we observe a number of important transitions, which allow to arrange excited levels and transitions in $^{147}$La into a parity-doublet structure similar to the structure observed in $^{151}$Pm. In Fig. 2 we present the new excitation scheme of $^{147}$La. New lines are marked with asterisks. Strong in-band E2, stretched transitions with simplex value $s = +i$ can be seen in Fig. 1. In the excitation scheme we omitted transitions and levels populated in $\beta$ decay of $^{147}$Ba [20] presented in a previous work [12].
Figure 2. Scheme of excited levels in $^{147}\text{La}$, populated in spontaneous fission of $^{252}\text{Cf}$, as observed in the present work. The thickness of the arrows is proportional to their relative $\gamma$ intensities. New lines are marked with asterisks. See text for further information.
Figure 3 shows a $\gamma$-ray spectrum cut from a 3D histogram containing prompt triple-$\gamma$ coincidences, sorted within a time window of 600 ns. The spectrum is obtained by gating on the known 167.55–211.98-keV lines. In the spectrum one can see prompt-$\gamma$ 487.7-, 528.65-, 538.8-, 570.3-, 588.9-keV lines in band corresponding to the simplex value $s = +i$. In addition one observes two new transitions of energies 512.6- and 603.1-keV, marked with asterisks.

![Figure 3. $\gamma$-ray spectrum doubly gated on the 167.55- and 212.0-keV lines in $^{252}$Cf fission data. Energies are given in keV. New lines are marked with asterisks.](image)

Spectra obtained by gating on the known 211.98-keV transition and new 512.6- and 603.1-keV transitions, respectively are shown on Figs. 4 and 5. Next to the 167.55-, 346.1- and 375.1-keV lines, reported earlier [11, 12], there are new lines at 198.0, 253.5, 381.5 and 436.5 keV. This and other gated spectra allow to assign these transitions to the $s = -i$ branch of the parity doublet.

![Figure 4. $\gamma$-ray spectrum doubly gated on 212.0- and 512.6-keV lines in the $^{252}$Cf fission data. Energies are given in keV. New lines are marked with asterisks.](image)
A γ-ray spectrum, doubly gated on the 297.45- and 381.5-keV new lines of $^{147}$La, is presented in Fig. 6. One can see the 346.5- and 375.1-keV lines reported previously as well as two new lines at 414.25 and 421.4 keV. Analysis of other doubly-gated spectra lead us to the conclusion that these two transitions connect the 1207.64- and 371.9-keV levels via new 786.15-keV level. We propose the ordering of the two new lines as presented in Fig. 2.

Spins and parities of levels shown in Fig. 2 have been, generally, adopted from Refs. [11, 12], but some values have been altered and some are new. In order to determine new spins and parities we analyzed angular correlations for cascades of γ rays in $^{147}$La populated in spontaneous fission of $^{252}$Cf. Characteristic, pure quadrupole-quadrupole (Q-Q) and pure dipole quadrupole (D-Q) angular correlations are shown in figure 7. The γγ angular correlations in the 346.1-211.98-keV and 454.3-346.1-keV cascades are consistent with a stretched quadrupole nature of these transitions.
Spin assignments to higher energy levels in this band are proposed based on the assumption of a stretched E2 character for the transitions between those levels and the fact that spins are growing with excitation energy, as commonly observed for excited states populated in spontaneous fission [21].

Angular correlation data are also consistent with the dipole character of the 570.3- and 588.9-keV transitions and therefore they are in-band transitions connecting states, which differ by one unit of angular momentum and have opposite parity. Angular correlations for the 371.7-570.3-keV γγ cascade shows that the 371.7-keV transition may be a quadrupole transition. Therefore we propose that the yrast band above the 1358.0-keV level consists of stretched E2 transitions connecting levels in a positive-parity band. The mixing ratios, $\delta = 0.030^{+38}_{-37}$ and $-0.021^{+24}_{-26}$ for the 603.1- and 512.6-keV transitions respectively indicate a pure M1 multipolarity for both transition. This provides negative parity assignments for the 954.23- and 1390.78-keV levels.

![Figure 7. Example of angular correlations in $^{147}$La for Quadrupole-Quadrupole and Dipole-Quadrupole cascades, as measured in this work. See text for further information.](image)

To establish spin and parity of the 229.65-keV level we have determined the conversion coefficient for the 62.1-keV transition. By setting a double gate on the 346.1- and 167.55-keV transitions we obtain a spectrum in which the 211.98- and 62.1-keV transitions have the same total intensity. We have established earlier by using angular correlations that the 211.98-keV transition is pure E2. Taking the theoretical $\alpha_{tot}(211.98) = 0.1463$ value we calculated the total intensity in this gate and then used it to calculate the total conversion coefficient for the 62.1-keV transition. The obtained value of $\alpha_{tot}(62.1) = 11.8(1.5)$ is consistent with a pure E2 transition, considering the theoretical value of $\alpha_{tot} = 11.29$ for a pure E2 transition. We adopt spin-parity $5/2^+$ and $7/2^-$ for the ground state and the 167.55-keV level, respectively. These assignments were made by confirming the stretched E1 character of the 167.55-keV transition and the $\beta$-decay properties of the ground state of $^{147}$Ba. Therefore we propose the 229.65-keV level to have spin and parity $11/2^-$. This is in agreement with
the previous findings [11, 12] and changes the value $9/2^-$, reported in the evaluation of the data for $^{147}$La [13].

References