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Letter

First structure information on the exotic ^{149}La from the β^--decay of ^{149}Ba

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Abstract. The β^--decay of ^{149}Ba to ^{149}La has been investigated by means of γ- and X-ray spectroscopy, and a partial level scheme of ^{149}La has been constructed for the first time. It includes thirteen γ-rays and ten excited states. The exotic ^{149}La is the heaviest lanthanum for which spectroscopic information is now available. We have applied the shell correction approach with the axially deformed Woods-Saxon potential in order to calculate the deformation energy for the ^{149}La ground state. The deformed ground state was found at $\beta_2 \simeq 0.23$, $\beta_3 \simeq 0$ and $\beta_4 \simeq 0.12$.

PACS. 27.60.+j $90 \leq A \leq 149$ – 29.30.Kv X- and γ-ray spectroscopy

1 Introduction

Nuclei in the exotic neutron-rich Ba region command a considerable interest as they represent the second region, after heavy Ra-Th nuclei, where there is an interplay of the octupole and quadrupole collectivities giving rise to interesting phenomena like the quenching of the $E1$ dipole moment in ^{146}Ba [1,2]. As part of the Warsaw-Uppsala Collaboration studies, we have investigated the odd-A nuclei in this region, especially those in the vicinity of ^{146}Ba in order to map the effect of this quenching on the neighboring nuclei. A strong weakening of $B(E1)$ rates was reported [3] for ^{147}La, for the heaviest odd-A lanthanum, whose nuclear structure has been studied so far [4]. Our recent investigation has been focussed on ^{149}Ce [5–7]. This work is now extended to ^{149}La, on which no detailed experimental studies were performed so far. The β^- activity of ^{149}Ba, which decays to ^{149}La, was identified fifteen years ago by Mach *et al.* [8] who reported three γ-rays from that decay with half-life $T_{1/2} = 0.4$ s. The properties of the ground-state β^--decay of ^{149}Ba: a half-life of 0.344(7) s, a small β-delayed neutron branch of 0.43(12)% and the $Q_\beta = 7.53(5)$ MeV, are listed in the compilations [9,10]. Our present work seems to represent the first study which yields information on the excited states in ^{149}La.

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2 Experimental procedure

The measurement was performed at the OSIRIS on-line fission-product mass separator at Studsvik in Sweden [11]. It was part of a study on the decay of ^{149}La to ^{149}Ce. Since the experimental procedures were already described in [6], only a brief summary is given below. The radioactive beam of mass $A = 149$ was produced by thermal-neutron–induced fission of a ^{235}U target, which consisted of about 1 g of uranium dispersed in graphite. The temperature of the ion source was kept at $\sim 2300°$. The beam intensity of ^{149}Ba was of the order of a few hundred ions per second. The mass-separated activity was deposited onto an aluminized Mylar tape in a moving-tape collection system. The singles γ-ray spectra, collected over 2 days, were measured with two Compton-suppressed Ge spectrometers with energy resolutions of 2.1 keV at 1.33 MeV and with relative efficiencies of about 25%. Low-energy photons were measured with a high-purity X-ray detector (LEP) for which the energy resolution was 0.7 keV at 122 keV. This three-detector system was positioned around the beam deposition point in close geometry in order to provide a good detection efficiency. The radioactive sample was dominated by the activity of ^{149}Nd ($T_{1/2} = 1.73$ h [9]), which obscured the short-lived activities. On the other hand, the presence of the ^{149}Nd decay allowed to perform an internal energy calibration and

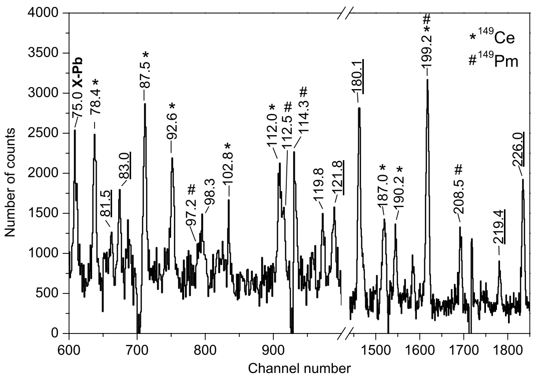

Fig. 1. γ-ray singles spectrum obtained in the MSS measurements. The beam-off background and impurities from the longer-lived $A = 149$ activities were subtracted. Transitions belonging to the ^{149}Ba $\rightarrow$ ^{149}La decay are underlined. Peaks are marked by γ energies in keV.

evaluate the level of corrections due to summing of γ-rays. We have "cleaned" the γ-ray singles spectra from the long-lived activity first by using the tape system which periodically, every 8 s, moved the old samples away. Moreover, in the multispectrum scaling (MSS) mode of measurement each cycle was divided into eight sequential periods lasting 1 s each. During the first period we have collected the background radiation, then the beam was switched on during the second and third periods of the cycle, and next the source was let decay out for 5 s. The γ-ray singles spectra were repeatedly cumulated during each period.

In the second step of spectrum purification, the γ-ray spectra collected in the second, third and fourth time periods, which included most of the short-lived activities of ^{149}Ba and ^{149}La, were added together. The spectra gathered during the first, seventh and eighth time periods were also added together and considered as beam-off γ-background plus daughter long-lived impurities. The latter spectrum was re-normalized and then subtracted from the former one. The resultant spectrum, which shows an enhanced presence of the ^{149}La γ transitions is illustrated in fig. 1.

In a second measurement, which lasted 2.5 days, we have collected γ-γ coincidence events. In order to increase the coincidence efficiency, both Ge detectors were used without BGO shields and were brought closer to the collection point. The low-energy photon (LEP) detector was kept in the same position as during the MSS measurement. The coincidence data were collected in eight sequential time periods, each 0.6 s long, starting after every movement of the tape. The beam-off spectrum was gathered during the first time period and the in-beam spectra were collected during the remaining consecutive seven periods. The recorded coincidence events were presorted off-line into blocks of data consisting separately of the LEP-Ge and Ge-Ge coincidences. Transitions belonging to the ^{149}Ba decay were identified on the basis of coincidences with the X-rays of La and γ-γ coincidences. In both cases the second, third and fourth time periods were taken into

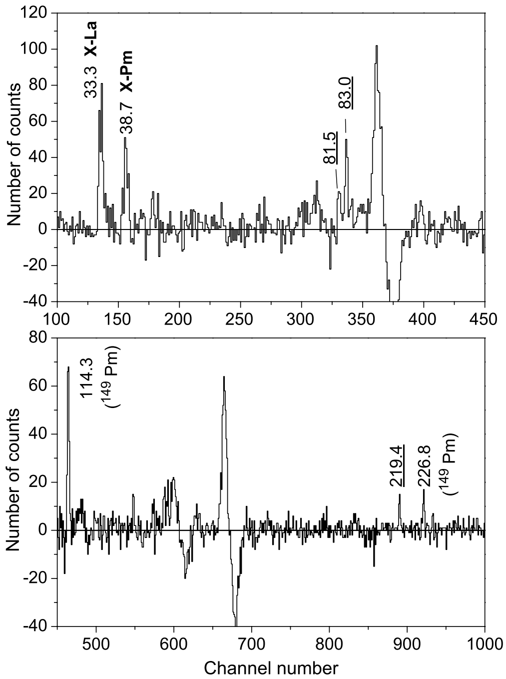

Fig. 2. γ-ray coincidence spectrum with gate set on the 121.8 keV transition feeding the 164.5 keV level. The appropriate spectrum coincident with the Compton distribution close to the gated peak has been subtracted. Due to mixing with the strong 122.4 keV γ transition in ^{149}Pm, a few γ-lines belonging to the ^{149}Pm are present in the resultant spectrum. Peaks are marked by γ energies in keV.

Table 1. Energies, intensities and placements in the level scheme of γ transitions belonging to the ^{149}Ba $\rightarrow$ ^{149}La decay.

Transition energy (keV)	$I^{\gamma}_{\mathrm{rel}}$	Initial level (keV)	Final level (keV)
46.0(1)(a)	16(2)(b)	46.0	0
81.5(2)(a)	7(2)(b)	164.5	83.0
83.0(1)(a)	14(2)(b)	83.0	0
121.8(2)(a)	16(4)(b)	286.3	164.5
131.3(2)(c)	12(2)(d)	357.3	226.1
180.1(1)(a)	79(4)(b)	226.1	46.0
219.4(2)(a)	25(4)(b)	505.7	286.3
226.0(1)(a)	69(5)(b)	226.1	0
286.3(2)(a)	100(24)(f)	286.3	0
290.5(2)(a)	12(4)(b)	516.6	226.1
357.3(2)(a)	45(7)(b)	357.3	0
607.6(2)(e)	10(2)(f)	893.9	286.3
617.6(5)(e)	8(2)(f)	843.7	226.1

(a) Energy deduced from γ-ray singles spectra.
(b) γ intensity taken from γ-ray singles spectra.
(c) Average value of energies taken from singles and γ-γ coincidence spectra.
(d) Average value of γ intensities taken from singles and γ-γdata.
(e) Energy deduced from γ-γ coincidence spectra.
(f) γ intensity deduced from γ-γ data.

account in the data analysis where the short-lived activity of ^{149}Ba was present with the best peak-to-background ratio. An example of a coincidence spectrum is shown in fig. 2. The energies and relative intensities of γ transitions, corrected for detector efficiencies and normalized to the γ intensity of 100 for the strongest 286.3 keV transition, are listed in table 1 together with their placements in the level scheme. The magnitude of summing effects, which could be important for crossover transition intensities, is negligible as has been shown in the case of ^{149}Ce [6].

3 Experimental results

In total thirteen transitions were identified as due to the decay of ^{149}Ba. Two separated bands were constructed on the basis of coincidence results and formed the level scheme of ^{149}La presented in fig. 3. Due to the lack of any evidence of the contrary, we assume that both sequences feed directly the ground state. Moreover, since there are no observed γ transitions which interconnect these structures, we suggest they have opposite parities. Then the "missing" transitions are interpreted as (rather weak) $E1$, which cannot compete against (much stronger: mainly intraband) $M1$ transitions. With this hint in mind, we examine two sequences of γ transitions of the energy 180.1-46.0 keV and 121.8-81.5-83.0 keV. Since their order in the cascades is not determined, we use secondary considerations to suggest the most likely scenarios. For the first sequence, we exclude as less likely the possibility that the 46.0 keV transition is placed above the 180.1 keV one. Consequently, the 46.0 keV transition is $M1$ as discussed below. For the second sequence, the coincidence relations point towards the 81.5 keV transition as having larger conversion coefficient by a factor of about 2 than the 83.0 keV one. Thus, if one of the three transitions in this cascade is $E1$, as would be required if the excited states on the right hand side of fig. 3 were of opposite parity to the structure on the left hand side, then it must be the 83.0 keV one. This is further discussed below. Therefore we take the 83.0 keV γ-ray as directly feeding the ground state.

The coincidence spectra, like fig. 2, show that the 81.5 keV transition has a much stronger electron conversion branch than the 83.0 keV one. The latter is thus assumed to follow the 81.5 keV transition and de-excite the 83.0 keV level to the ground state. Using the total-intensity relation

$$I_\gamma^{81}(1+\alpha_{\mathrm{tot}}^{81}) = I_\gamma^{83}(1+\alpha_{\mathrm{tot}}^{83}), \qquad (1)$$

the total internal conversion coefficients (ICCs) for the 81.5 and 83.0 keV transitions were estimated based on the γ-γ coincidence spectrum corresponding to the 121.8 keV gate. Assuming an $E1$ character for the 83.0 keV transition, the total ICC for the 81.5 keV line is $\alpha_{\mathrm{tot}}^{81} = 1.7(5)$ indicating multipolarity $M1$ (see table 2). Alternatively, if the 83.0 keV transition is $M1$, then one obtains for the 81.5 keV transition $\alpha_{\mathrm{tot}}^{81} = 4.6(1.5)$ and an $E2$ multipolarity. As for the second sequence, the total-intensity balance for the 180.1-46.0 keV cascade suggests the same parity for

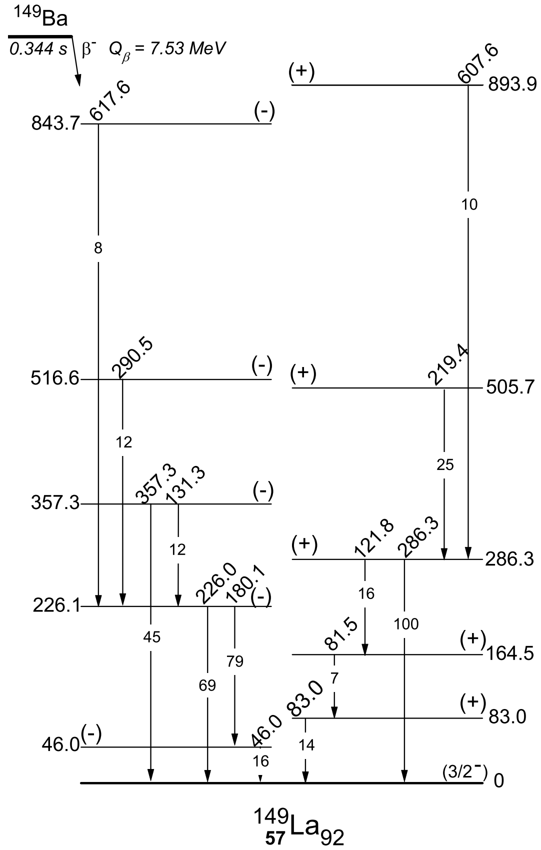

Fig. 3. The level scheme of ^{149}La as observed in the β^--decay of ^{149}Ba in the present work.

Table 2. Total internal conversion coefficients for the ^{149}La transitions.

Energy	Theoretical ICC(a)		
(keV)	$E1$	$M1$	$E2$
46.0	1.95	10.44	37.01
81.5	0.42	1.97	4.22
83.0	0.39	1.87	3.95
180.1	0.05	0.21	0.26

(a) From ref. [12].

the 46.0 level and the ground state. The total intensity of the 46.0 keV transition has to be greater than or equal to the total intensity of the 180.1 keV transition. In the case of $E1$ multipolarity of the latter transition the total internal conversion coefficient α_{tot} for the 46.0 keV transition is greater than 3.6 implying, within one standard deviation, an $M1$ or $M1+E2$ character (see table 2). Alternatively, by assuming an $M1$ or $E2$ multipolarity for the 180.1 keV transition, one obtains lower limits for $\alpha_{\mathrm{tot}}(46.0)$ as 4.3 and 4.5, respectively. Thus, all these scenarios exclude the $E1$ multipolarity for the 46.0 keV transition, provided it is the first line in the γ sequence. Unfortunately, the conversion coefficients deduced above did not allow a parity determination of the excited levels in an unambiguous way.

(We should note that weak beam intensity and strongly present lines from the daughter products, did not allow a dedicated conversion electron or level lifetime measurements.) The only conclusion is that the level sequence 0, 46.0, 226.1, 357.3, 516.6 and 843.7 keV has likely the same parity, while the level set 83.0, 164.5, 286.3, 505.7 and 893.9 keV has likely an opposite parity to the former one.

4 Discussion

Up to now spin and parity of the ground state of ^{149}La ($Z = 57$) have not been determined. Recent studies of the β^--decay of ^{149}La to ^{149}Ce [6] show that the $5/2^-$ spin/parity assignment for the ground state of ^{149}La was favored due to the strong β-feeding to the selected levels in ^{149}Ce, namely to the $3/2^-$, $5/2^-$ and also $7/2^-$ states. Since a large indirect gamma-feeding may have been unobserved even in the case of strongly populated states, a positive parity was not ruled out for the ground state of ^{149}La.

We have attempted to calculate the properties of the ground state of ^{149}La, using the shell correction approach with axially deformed Woods-Saxon potential [13,14]. We have found that the lowest two band heads, which are almost degenerate in energy, are built on the $1/2^+[420]$ and $3/2^+[422]$ proton configurations and are predicted with the deformation parameters of $\beta_2 \simeq 0.23$, $\beta_3 \simeq 0.03$, $\beta_4 \simeq 0.12$ and $\beta_2 \simeq 0.23$, $\beta_3 \simeq 0.0$, $\beta_4 \simeq 0.12$, respectively. For the case of $K = 3/2$, the plot of the deformation energy as a function of β_2 and β_3 is shown in the upper part of fig. 4. Additional calculations of rotational states in ^{149}La were performed in the framework of the Self-Consistent Total Routhian Surface (SC-TRS) model [15] without octupole deformation. They predict the positive-parity band to be yrast up to $\hbar\omega \simeq 0.075$ MeV, where it is crossed by a negative-parity band built on the $3/2^-[541]$ configuration. We note, however, that the $1/2^+[420]$ configuration, which is predicted to be the ground state of ^{149}La in the Woods-Saxon model calculations, is not consistent with the pattern of β-decay of ^{149}La to ^{149}Ce [6]. The alternative $3/2^+[422]$ assignment is also not favored as the $7/2^-$ levels in ^{149}Ce are populated in the β-decay of ^{149}La with a substantial intensity. We now turn our attention to the option of negative parity for the ground state of ^{149}La. The lowest negative-parity state, $3/2^-[541]$, is predicted at 65 keV above the ground state and is characterized by the deformation parameters: $\beta_2 \simeq 0.23$, $\beta_3 \simeq 0.01$ and $\beta_4 \simeq 0.12$. Unfortunately, no $I^\pi = 5/2^-$ state, which is favored by the data on the ^{149}La to ^{149}Ce decay [6], can be easily obtained within the theoretical approach used by us. The lowest $5/2^-$ state with the dominant configuration [532] and the deformation parameters comparable to the $I = 3/2$ states is lying about 2 MeV above them. As a consequence, we tentatively assign spin $I^\pi = 3/2^-$ for the ground state of ^{149}La.

To summarize, this work provides the first experimental information on the excited states in the exotic neutron-rich ^{149}La nucleus. Two separate level sequences are observed, and are suggested to be of opposite parity. Thirteen γ transitions and ten energy levels were identified.

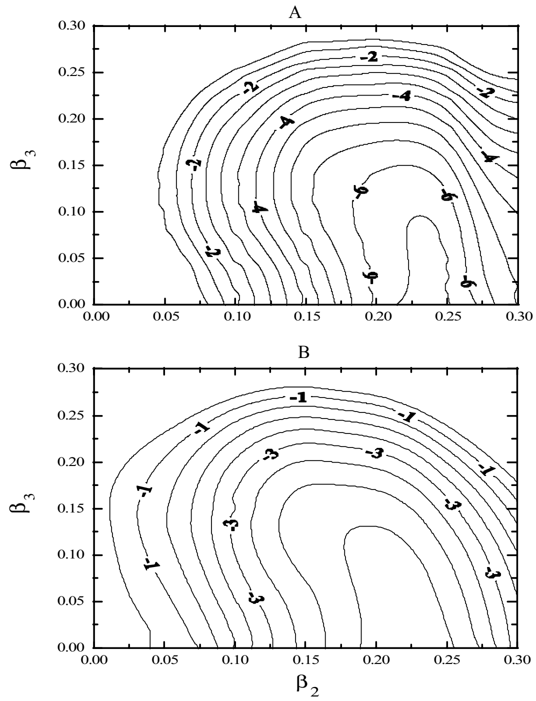

Fig. 4. The deformation energy in the (β_2, β_3)-plane for the a) $3/2^+[422]$ and b) $5/2^-[532]$ configuration. There is an apparent octupole softness in both cases. The distance between contour lines is equal to 0.5 MeV. Labels of the lines mean energies in MeV.

The data, although limited, seem to suggest that the $E1$ transitions are suppressed in this nucleus. The equilibrium shape in the ground state was found to be quadrupole deformed with a negligible octupole distortion.

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