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Short Note

Experimental evidence for signature inversion in ^{132}La from a revisited level scheme

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Abstract. The decay out of the $\pi h_{11/2}\nu h_{11/2}$ band to the known low-energy levels in ^{132}La was studied using the reaction $^{100}\mathrm{Mo} + {}^{36}\mathrm{S}$ at 160 MeV beam energy. The low-energy level scheme has been further developed and unambiguous spin and parity values have been assigned to the levels connecting the band to the 6^- isomeric state. According to the new level scheme the spins in the $\pi h_{11/2}\nu h_{11/2}$ band are shifted up by one unit compared to the earlier tentative experimental values. The obtained new spins prove the existence of signature inversion in ^{132}La and give further support to the spin assignments made for the $\pi h_{11/2}\nu h_{11/2}$ bands in the neighbouring odd-odd La isotopes from level energy systematics.

PACS. 21.10.Hw Spin, parity, and isobaric spin – 21.10.Re Collective levels – 27.60.+j $90 \le A \le 149$

The structure of the odd-odd ^{132}La has attracted a great interest recently, as the $\pi h_{11/2}\nu h_{11/2}$ band in this nucleus shows interesting phenomena, like expected signature inversion [1–3] or observed broken chiral symmetry [4–6]. Signature inversion has been systematically observed in the $\pi h_{11/2}\nu h_{11/2}$ bands of the $A \approx 130$ Cs and La nuclei in which the spins of the levels are experimentally known. In these bands at low spins the even-spin levels are favoured energetically rather than the odd-spin members that are expected to be favoured in the case of normal signature splitting. To decide whether signature inversion exists or not in a band it is important to know the exact spin values of the states in the band. However, among the odd-odd La isotopes in this region there is only one nucleus, ^{128}La, in which the spin assignment of the $\pi h_{11/2}\nu h_{11/2}$ band is based on strong experimental arguments [7]. In the cases of the other odd-odd La isotopes the experimental spin assignments for the states in the bands of this configuration are tentative or missing. For these bands Liu *et al.* [2] proposed spin values on the basis of their relative level energy systematics in the odd-odd La isotope chain. The spin values in the systematics are based on the experimental spins in ^{128}La. These spin values agree well with the expected systematical features of the signature inversion in this region [1], however, in many cases they contradict the tentatively proposed experimental values. This is the situation in the case of ^{132}La, too, as the tentative spins determined experimentally by Oliveira *et al.* [8] are one unit less than the spins obtained from the systematics. To solve this contradiction we have studied experimentally the decay of the $\pi h_{11/2}\nu h_{11/2}$ band to the known low-energy states in this nucleus. The determination of the exact spins in the band allows us to prove the existence or non-existence of signature inversion in ^{132}La. It can give also a further experimental support to the systematics of Liu *et al.* [2].

Excited states of ^{132}La have been populated using the $^{100}\mathrm{Mo}(^{36}\mathrm{S}, p3n)$ reaction at a bombarding energy of

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160 MeV. The beam was provided by the Vivitron accelerator at IReS, Strasbourg, with an intensity of approximately 30 *e*nA. The target was made of a single 500 μg/cm^2 self-supporting, enriched ^{100}Mo foil. γ-rays were detected by the EUROBALL IV spectrometer [9] which contained a multi-element inner ball of BGO detectors. Events were written on magnetic tape when at least four suppressed Ge detectors and at least 18 BGO elements detected γ-rays within the coincidence time window. Approximately 1.5×10^9 events were collected during the experiment. The energy and intensity calibration of the Ge detectors were made by using ^{133}Ba and ^{152}Eu radioactive sources.

The level scheme of ^{132}La has been deduced using $E_{\gamma1}$-$E_{\gamma2}$-$E_{\gamma3}$ triples events which were sorted into RADWARE cubes [10].

In order to obtain information on the γ-ray multipolarities, angular-correlation information has been extracted from the coincidence data. A γ-γ coincidence matrix was constructed using the method described in ref. [11] with one axis corresponding to γ-rays recorded by the seven-element cluster detectors at angles around $\theta = 130°$ and the other axis corresponding to the γ-rays recorded by the clover detectors positioned at angles around $\theta = 90°$. Angular intensity ratios defined as

$$R = \frac{I_\gamma[(\mathrm{cluster})_{\mathrm{measured}}(\mathrm{clover})_{\mathrm{gated}}]}{I_\gamma[(\mathrm{clover})_{\mathrm{measured}}(\mathrm{cluster})_{\mathrm{gated}}]} \qquad (1)$$

were extracted from this matrix and used to assist in the assignment of γ-ray multipolarities. The angular intensity ratios have been extracted by setting gates on known $M1$ transitions in the matrix. Intensity ratio values of ~ 1 and ~ 1.7 are expected for stretched dipole and stretched quadrupole transitions, respectively, for the present geometry. Values ~ 1.7 are, however, also expected for $\Delta I = 0$ dipole transitions.

The linear polarization of the strongest γ-rays were also measured using the 24 clover detectors as Compton polarimeters [12]. Two γ-γ coincidence matrices were constructed with one axis corresponding to single-hit γ-rays from any detector and the second axis corresponding to the double-hit scattering events in the clover detectors. One matrix contains the scattering events parallel to the reaction plane, while the other contains the perpendicular scattering events.

Experimental linear polarization, defined as

$$P = \frac{1}{Q}\frac{N_{\mathrm{perpendicular}} - N_{\mathrm{parallel}}}{N_{\mathrm{perpendicular}} + N_{\mathrm{parallel}}} \qquad (2)$$

was deduced for the strong γ-rays, where $N_{\mathrm{perpendicular}}$ and N_{parallel} are the number of scatters for a given γ-ray in the coincidence spectra obtained by setting the same gate on the single-hit axis in the two matrices, while Q is the polarisation sensitivity of the clover detectors. Positive linear polarization values correspond to stretched electric or $\Delta I = 0$ magnetic, while negative values correspond to stretched magnetic or $\Delta I = 0$ electric transitions.

Table 1. Characteristics of γ-rays in the low-energy level scheme of ^{132}La displayed in fig. 1. For the not observed 33.5 keV and 38.2 keV transitions the energy and intensity values are inferred (see text).

E_γ(keV)	I_γ	R	P	Multipolarity
33.5	1			
38.2	7			
66.8(2)	27(2)	1.1(3)		D
117.1(5)	1(0.4)			
150.6(3)	3(0.3)	1.1(2)		D
160.9(2)	93(5)	1.0(1)	$-0.2(3)$	$M1$
161.4(4)	17(3)			
169.0(2)	44(3)	1.0(1)	$-0.5(3)$	$M1$
202.4(2)	47(3)	0.9(1)	$-0.3(2)$	$M1$
226.8(3)	10(1)			
278.6(2)	51(3)	1.7(2)	$-0.3(2)$	$E1, \Delta I = 0$
288.2(3)	6(1)			
293.3(3)	100(6)	0.9(1)	$-0.2(1)$	$M1$
311.9(3)	16(2)	1.6(3)	$-0.5(4)$	$E1, \Delta I = 0$
319.6(2)	10(1)	1.5(2)	$-1.0(4)$	$E1, \Delta I = 0$
350.2(3)	11(1)	0.9(2)	0.8(6)	$E1$
454.2(4)	6(2)			
481.0(3)	22(2)	1.0(1)	0.3(2)	$E1$
668.4(4)	4(1)			

The γ-ray energies, relative intensities, angular intensity ratios and linear polarization values are given in table 1, together with the deduced multipolarities.

The low-energy part of the ^{132}La level scheme obtained from the present experiment is shown in fig. 1. The level scheme construction was based on the $E_{\gamma1}$-$E_{\gamma2}$-$E_{\gamma3}$ coincidence relations as well as on the γ-ray energy and intensity balances. We also accepted from Oliveira *et al.* [8] that the high-spin structure is built on the 6^-, 24.3 min isomeric state. They found two rotational bands in ^{132}La, one with probable positive and the other with probable negative parity. To the positive-parity band they assigned the $\pi h_{11/2}\nu h_{11/2}$ while to the negative-parity band the $\pi g_{7/2}\nu h_{11/2}$ configuration. Up to the first 7^+ state our results confirm the level scheme proposed by Oliveira *et al.* [8] and provide unambiguous spin-parity assignments for the observed levels. However, in our level scheme the 67 keV transition does not feed directly the 7^+ state as it was proposed by them, but instead it decays to a new 8^+ level. This new intermediate state shifts the spins of the $\pi h_{11/2}\nu h_{11/2}$ band members by one unit up in agreement with the suggestion by Liu *et al.* [2].

The new 8^+ level decays by a 350 keV transition to the 7^- member of the $\pi g_{7/2}\nu h_{11/2}$ band. The triples-coincidence spectra shown in fig. 2 prove the placement of the 350 keV transition in the low-energy level scheme. They show that this transition is in coincidence with the 67, 161, 169 and 293 keV transitions but it is not in coincidence with the other transitions in the low-energy level scheme, similarly to the case of the 312 keV transition. However, this 350 keV transition carries only about 10% of the total decay intensity of the 8^+ level. The analysis of the intensities feeding the 8^+ level and the intensities de-

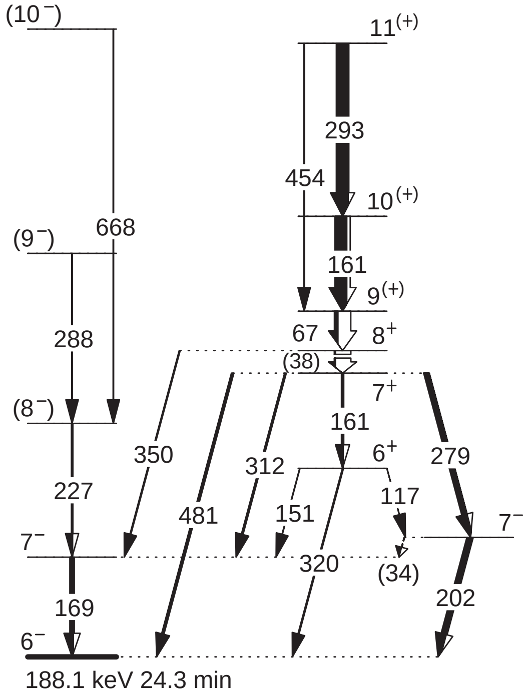

Fig. 1. Low-energy level scheme of ^{132}La obtained in the present work. γ-ray energies are given in keV. The width of the arrows is proportional to the transition intensities. Dashed arrows with energy labels in parentheses indicate tentative transitions.

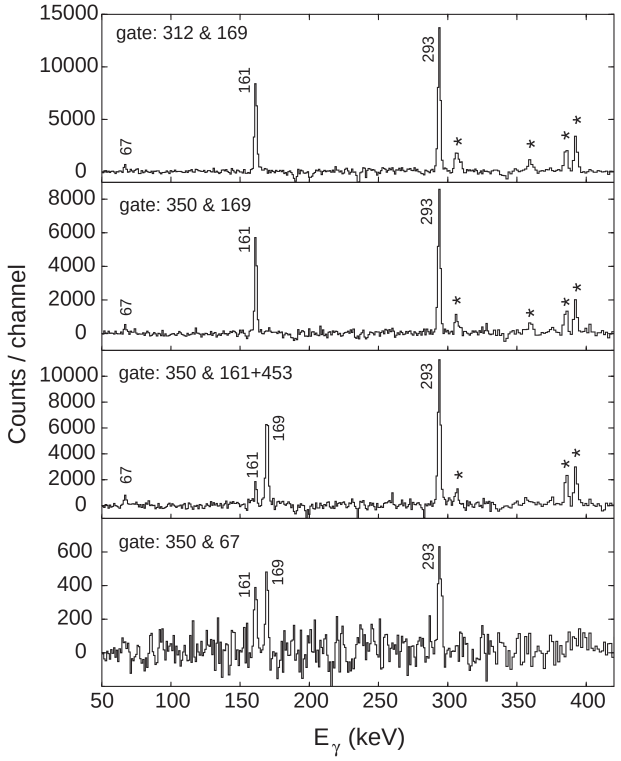

Fig. 2. Triple-coincidence spectra showing the coincidence relations between the 350 keV transition and the other transitions in the low-energy level scheme. The energies are given in keV. The $\star$ denotes ^{132}La γ-rays placed above the $11^{(+)}$ level in fig. 1. The 453 keV gate transition in the second panel from bottom is a strong and clean inband transition of the $\pi h_{11/2} \nu h_{11/2}$ band above the $11^{(+)}$ level in fig. 1.

populating the 7^+ level shows that the remaining $\sim 90\%$ is carried by a non-observed transition or by cascades of non-observed transitions to the 7^+ state. The simplest possible scenario is that the 8^+ level decays directly to the 7^+ level by a single $M1$ γ transition with energy of 38 keV. This is the case in the isobaric ^{132}Pr, too [13], which has a similar level scheme to the ^{132}La one in this spin region. Although more complicated decay paths between these two levels, containing cascades of two or more transitions are also possible, this tentatively accepted scenario is shown in fig. 1. In the case of this scenario the possible reasons of the non-observation of this transition can be that the transition is highly converted (the internal conversion coefficient is ~ 15), the detection efficiency of the spectrometer is very low at this energy, and this energy coincides with La X-ray energies. The intensity of the tentative 38 keV transition, given in table 1, was calculated from the total observed de-excitation intensity of the 7^+ state corrected for an internal conversion coefficient assuming pure $M1$ multipolarity.

Two other previously not observed transitions are also shown in fig. 1: the 117 keV transition connecting the 6^+ state to the 7^- one, and the tentative 34 keV trasition between the two 7^- states. The weak 117 keV γ-ray was seen in the spectra, while the 34 keV transition was inferred from the fact that the 169 keV transition is seen in the 279 keV gate spectrum. The intensity of the tentative 34 keV transition was calculated using the intensity of the 169 keV transition relative to the 202 keV transition in the 279 keV gate spectrum. It was corrected for internal conversion assuming $M1$ multipolarity for the 34 keV transition.

The spins and parities of the studied low-energy levels have been deduced from the measured angular intensity ratio and linear polarization values. The spin-parity assignment of the first and second 7^- states are based on the stretched $M1$ character of the 169 keV and 202 keV transitions, respectively. This character would allow also the 5^- spin-parity assignment, however, in that case we could expect strong transitions to the 136 keV 3^- state [14] (not shown in fig. 1), too, which are not observed. The spin-parity assignment of the 6^+ level is based on the stretched dipole character of the 151 keV transition and the $\Delta I = 0$ electric character of the 320 keV transition. The experimental angular intensity ratio and linear polarization values also allow $M2$ multipolarity for the 320 keV transition, however, in that case we could expect the 320 keV transition to be much weaker then the 151 keV one. Experimentally the 320 keV transition is stronger than the 151 keV one. For this reason, we accept $\Delta I = 0$ electric character for this transition. The spin-parity of the 7^+ state is based on the $E1$ multipolarity of the 481 keV transition and the $\Delta I = 0$ electric character of the 279 keV and 312 keV transitions. Here we accepted the $\Delta I = 0$ electric character for the same reason as in the case of the 320 keV transition. The $E1$ multipolarity of the 350 keV transition suggests 8^+ or 6^+ assignment for the new level. However, the 6^+ assignment is not probable because in that case we should expect a transition, stronger than the 350 keV one, to the 6^- level. The 67 keV transition has been found to have stretched dipole character, but its linear polarization value could not be determined because of its low energy. Its stretched dipole character suggests a spin value of 9 for the level which is fed by the strong 161 keV and the weaker 454 keV transitions and is considered as the base state of the $\pi h_{11/2} \nu h_{11/2}$ band. The parity of this state could not be determined firmly from the experimental data, however, from systematics and from the assumed configuration, we accept a probable positive parity for it and for the band built on this state. The spin assignments for the $10^{(+)}$ and $11^{(+)}$ levels are based on the $M1$ character of the depopulating transitions and on the assumption that within a rotational band the lower-energy level corresponds to lower spin value. The spin-parites of the (8^-), (9^-), and (10^-) states are proposed by Oliveira *et al.* [8]. No additional information on the spins and parities of these levels could be gained from the present experiment.

We note here that the obtained spin and parity values would allow transitions from the 8^+ and $9^{(+)}$ levels that were not observed. Indeed, a 317 keV transition from the 8^+ state to the second 7^- state should compete with the 350 keV transition. This 317 keV transition is not seen in the spectra and an upper limit of 0.4 can be given for its intensity from statistical analysis of the clean gate spectra at this energy. According to this value the ratio of the $B(E1)$ reduced transition probabilities between the 8^+ and the first 7^- and between the 8^+ and the second 7^- states is less then 0.05. This ratio for the 279 keV and 312 keV transitions from the 7^+ level is 4.5. The big difference between the two ratios probably indicates a considerable difference between the two states in the parts of their wave functions that are responsible for the $E1$ transitions to the 7^- states. On the other hand, the main parts of their wave functions are probably similar as the strongest transition from the 8^+ level goes to the 7^+ level. We can also expect a 190 keV transition from the $9^{(+)}$ state to the (8^-) state in analogy with the 350 keV transition. This transition is not seen, either, in the spectra and an upper limit of 0.5 was found for its possible intensity. The non-observation of this transition, however, can be due to the considerably smaller $E1$ energy and larger $M1$ energy from the $9^{(+)}$ state than they are from the 8^+ state. Indeed, assuming the same $B(E1)/B(M1)$ ratio for the missing 190 keV transition and the 67 keV transition as it is for the 350 keV transition and the tentative 38 keV transition, the expected intensity for the 190 keV transition is only ~ 0.3 which is below the experimental upper limit.

According to fig. 15 in ref. [2] there is an energy splitting between the even-spin and the odd-spin branches of the $\pi h_{11/2} \nu h_{11/2}$ band in ^{132}La. The branch which is built on the above discussed base state of this band, is energetically unfavoured. According to the new spin values this branch is the odd-spin one. In the case of normal signature splitting the odd-spin branch should be energetically favoured which means that the energy order of the two branches in ^{132}La are inverted. In this way our results prove experimentally the existence of the signature inversion in the $\pi h_{11/2} \nu h_{11/2}$ band of ^{132}La.

In summary, the intermediate structure connecting the $\pi h_{11/2} \nu h_{11/2}$ band to the 6^- isomeric state in ^{132}La has been further developed. A new level has been added to the top of this intermediate structure. Unambiguous spins and parities have been derived for these levels on the basis of experimental angular intensity ratios and linear polarization data. These experimental results enabled us to assign definite spins and tentative parity to the levels in the $\pi h_{11/2} \nu h_{11/2}$ band. Due to the addition of the new level the obtained spins in the band are higher by one unit than the former, tentative experimental values. These new spins agree well with those proposed for ^{132}La from the energy systematics of the levels in the $\pi h_{11/2} \nu h_{11/2}$ bands of the $A \approx 130$ odd-odd La isotopes. This agreement gives further support to the proposed spin assignment derived from level energy systematics for the $\pi h_{11/2} \nu h_{11/2}$ bands in the neighbouring odd-odd La isotopes. Using the new spin values we obtain inverted signature splitting for this band in ^{132}La at low spins, giving experimental evidence for the existence of signature inversion in this nucleus.

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