High spin states in ^{136}La

G. Deyanova[1], D. Balabanski[2], B. Akkus[3], L. Atanasova[1], P. Can[3], P. Detistov[1], K. Gladnishki[1], M. N. Erduran[3], E. A. Lawrie[4], J. J. Lawrie[4], A. Minkova[2], S. M. Mullins[4], J. Ncapayi[4], G. Rainovski[1], and J. F. Sharpey-Schafer[4]

[1] University of Sofia "St. Kl. Ohridski", Faculty of Physics, 1164 Sofia, Bulgaria
[2] Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Science, 1784 Sofia, Bulgaria
[3] Istanbul University, Department of Physics, Verneciler, 34459 Istanbul, Turkey
[4] iThemba LABS, P. O. Box 722, Somerset West 7129, South Africa

1 Introduction

Recently three different studies relating to excited states above the 115 ms isomer in ^{136}La [1–3] were published. These works together with the investigation of Ref. [4] provide contradicting information about the spin-parity assignments of the energy levels and their order, which results in different interpretations for the structure of this nucleus at high spin [2, 3]. The purpose of our study is to clarify the situation, fix this part of the level scheme of ^{136}La and thus, provide a basis to understand correctly its structure.

The doubly-odd nucleus ^{136}La ($N = 79$, $Z = 57$) has three neutron holes in the closed $N = 82$ shell and seven protons above the $Z = 50$ shell cloasure. In this mass region the proton Fermi surface lies at the bottom of the $h_{11/2}$ sub-shell, while for the neutrons it is near the top of the same sub-shell. Systematic studies of the doubly-odd nuclei in this mass region demonstrate the existence of positive parity yrast bands. These bands have the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration. For such excitations, these nuclei may develop triaxial shapes and, as a consequence, chiral twin bands might be observed when the asymmetry parameter γ takes values close to $\gamma \approx -30°$ [5]. Such doublet bands were recently established in ^{132}La [6, 7] and ^{134}La [8]. For the Lanthanum isotope at $N = 75$ a shape transition from prolate to oblate shape was predicted in the framework of Particle-plus-Rotor model (PRM) [9]. For the $\pi \mathrm{h}_{11/2} \otimes \nu \mathrm{h}_{11/2}$ band in ^{136}La Bhattacharjee *et al* [3], after comparison with the neighboring $N = 79$ isotones, ^{138}Pr and ^{140}Pm, and with PRM calculations, suggested that this band is built on an oblate shape. Thus, it is concluded that the predicted shape transition for the odd-odd La isotopes is observed [3].

The spin assignments of the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands were systematically compared for $^{124-136}$La [10]. It was shown that there are disturbances of the gradual change of the energies of the in-band transitions with the atomic number if the published values of the spins of the band-heads for the different nuclei are accepted and, as a result, new spin assignments were suggested for which the in-band transition energies vary smoothly [10]. As a result of this study it was shown that a signature inversion for the La isotopes in mass $A \approx 130$ region occurs. A level scheme of ^{136}La, which was suggested by Zhu *et al* [2], follows the systematics of Ref. [10], and the $\pi h_{11/2} \otimes \nu h_{11/2}$ band is interpreted as a rotational sequence, built on a prolate shape with triaxial deformation. However, a well defined minimum in the TRS plot is missing (see Fig.6 of Ref. [2]), the nucleus is γ soft and the absolute minimum is migrating from $\gamma \approx -30°$ for $\hbar\omega \approx 0.0$ MeV to $\gamma \approx -13°$ for $\hbar\omega \approx 0.2$ MeV.

The level scheme, proposed in Ref. [3], is closer to our results at low spins. The differences, observed in the published level schemes [1–3], are discussed here and we report a new level scheme, which results from the analysis of our experimental data.

2 Experimental Details

The experiment was performed at the iThemba LABS(Laboratory for Acceletator Based Sciences), South Africa. The data were collected using the multi-detector array AFRODITE [11], which consisted of eight CLOVER and seven LEPS detectors. They were placed in rings at $45°$, $90°$ and $135°$ with respect to the beam direction and covered 23% of 4π geometry.

Excited states in ^{136}La were populated in the ^{130}Te(^{11}B,5n) fusion-evaporation reaction. The ^{11}B beam was accelerated up to 60 MeV by the Separated Sector Cyclotron [12]. A 1 mg/cm^2 ^{130}Te target on a 10 mg/cm^2 Au backing was used. According to the PACE calculations [13], 74% of the reaction products are ^{136}La nuclei. In addition, ^{137}La (10% of total yield) was populated. Some ^{204}Po, were produced in reactions with the Au backing: ^{197}Au(^{11}B,4n)^{204}Po. About 2.4×10^8 double $\gamma\gamma$ coincidences (47%) and 1.9×10^8 triple $\gamma\gamma\gamma$ coincidences (36%), or in total 5.2×10^8 of events with multiplicity $M \geq 2$ were observed in this experiment.

It should be noted that in the experiment of Zhu *et al* [2] the same ^{130}Te(^{11}B,5n) reaction at 60 MeV was used. The beam energy was chosen after an excitation functions measurement and a 1.6 mg/cm^2 self-supporting ^{130}Te target was used. The collected data is one order of magnitude less than in our case. In the experiment of Bhattacharjee *et al* [3] the same reaction ^{130}Te(^{11}B,5n) was used but at 52 MeV. The target was 2.2 mg/cm^2 ^{130}Te on a 20 mg/cm^2 Au backing. The statistics is about two times less, which is due to the extra γ efficiency of the LEPS detectors in our experiment. In Ref. [1] the ^{128}Te(^{11}B,3n) reaction at 48 MeV was used, while in Ref. [4] excited states in ^{136}La were populated in a (p, 3n) reaction.

For the construction of the level scheme and the determination of the relative intensities of the transitions, the data were sorted in a cube, using the $\gamma\gamma\gamma$ coincidence data, and in $4K \times 4K$ matrices, which were sorted under the following conditions: CLOVER×CLOVER, CLOVER×LEPS and LEPS×LEPS. The data were analyzed using RADWARE software package [14].

In order to determine the multipolarity of the transitions the DCO (Directional Correlations of Oriented states) ratios [15] were calculated as

$$R_{DCO} = \frac{I^{\gamma_2}_{\Theta_1}(Gate^{\gamma 1}_{\Theta_2})}{I^{\gamma_2}_{\Theta_2}(Gate^{\gamma 1}_{\Theta_2})}. \quad (1)$$

Three $4K \times 4K$ matrices were constructed from the list-mode data with the γ rays detected at 90° on the x-axis and these at $45°$ and $135°$ on the y-axis respectively, *i.e.* $\Theta_1 = 90°$ *vs* $\Theta_2 = 45°, 135°$.

The level scheme was constructed based on the $\gamma\gamma$ and $\gamma\gamma\gamma$ coincidence relationships, the relative intensities of the γ rays and the deduced DCO ratios. Due to overlapping γ ray peaks in some cases the determination of the DCO ratios was not possible.

2.1 Construction of the Level Scheme

The proposed level scheme above the 115 ms isomer is shown in the Fig. 1. Four different structures were established, in correspondence with the previously reported results [1–3].

Sequence (1) is built on the 115 ms isomeric state itself, to which $I^\pi = (7^-)$ was assigned (see next section) and this structure was established up to $I^\pi = (20^+)$. Compared to previous studies we have established two new transitions in this sequence and have changed the placements of transitions and levels. We also suggest different spin-parity assignments in some cases. We suggest a cascade of two transitions of 28-keV and 835-keV above the isomeric state, which is parallel to the 584-280 keV cascade. The 28-keV transition was not reported previously. The 835-keV was reported to de-excite the same level in Ref. [1] and was suggested as quadrupole E2 transition.

The level schemes, which were previously proposed, place in a different way the 406-keV and 148.5-keV transitions. In Ref. [1,2] a single 406-keV transition is suggested as an in-band $\Delta I = 1$ transition, while in Ref. [3] two transitions with close energies are suggested, an in-band M1 transition and a crossover E2 transition. Our analysis confirms that the 406-407-keV transition is a doublet belonging to sequence (1). We place these two transitions as a 405.9-keV $(11^+) \rightarrow (10^+)$ in-band M1 transition and as a 406.8-keV $(14^+) \rightarrow (12^+)$ crossover E2 transition, in agreement with Bhattacharjee *et al* [3].

A 148.5-keV transition was not reported by Cybulska *et al* [1] and was suggested not to belong to this sequence by Zhu *et al* [2], who placed it as side-feeding transition to the (14^+) level of sequence (1). According to Bhattacharjee *et al* [3] it is an in-band M1 transition($14^+ \rightarrow 13^+$), which is in agreement with our results. In Fig. 2 are shown spectra, gated on known transitions from sequence (1), which clearly demonstrate that it is an in-band transition.

In the upper part of this sequence a 1030-keV crossover transition was reported [2], which is not observed in other studies [1,3]. We also observe a 1029.8-keV transition and place it as a $(17^+) \rightarrow (15^+)$ crossover transition. In this way the order of the 412.1 and 483.2 keV transitions is fixed in agreement with Ref. [2]. On the top of this band we observe a new 397.3-keV transition. The 597-keV transition, which was suggested in Ref. [2] in this band is not seen in our data. Instead, we observe a 559-keV transition which feeds the (16^+) state.

In the level scheme of Ref. [1] the 846-, 848-, 597- and 439-keV transitions were suggested to belong to this sequence. We observe 848- and 438.6-keV transitions, which are side-feeding transitions, the first one feeds the (12^+) state, while the second one is a linking transition between sequence (4) and sequence (1), in agreement with Ref. [2], but in our case it feeds the (13^+) level.

In the level scheme of Zhu *et al* [2] three crossover transitions of 666- and 896-keV are suggested, which were not reported in other studies [1, 3]. We also do not observe such transitions in our data.

The 324-, 458- and 480-keV transitions decay out of sequence (1) to the suggested second (8^-) level at 81 keV above the 115 ms isomer. Our analysis is consistent with the order, proposed in Ref. [2]. In addition we observe evidence for a 480-keV transition, which allows to fix the order of the 324- and 458-keV transitions. In the level scheme of Ref. [3] the 324- and 458-keV transitions are given in a reverse order.

There are differences in the reported multipolarities of the transitions and spin-parity assignments of the levels of sequence (1). Morek *et al* [4] have performed an angular correlation measurement and have determined the coefficients A_2 and A_4. The 280-, 584-, 155- and 406-keV γ rays are suggested to be of mixed M1+E2 character. However, within the error bars, the values for these coefficients could be interpreted as stretched dipole transitions $\Delta I = 1$. The authors of Ref. [2, 3] determined the multipolarity of the transitions using the DCO method. Zhu *et al* [2] suggest a mixed M1+E2 multipolarity for the 155-keV transition, while the 280- and 584-keV transitions are assumed as E1 transitions. Bhattacharjee *et al* [3] performed also an IPDCO (Integrated Polarization-Directional Correlation from Oriented nuclei) analysis, which unambiguously fixes the E1 character of the 584-keV transition (see Fig. 7 on Ref. [3]), while for the 280- and 155-keV transitions M1 multipolarity was suggested. Our DCO analysis is in line with the latter result and suggests that all three are $\Delta I = 1$ transitions. This, combined with the IPDCO result [3], fixes the multipolarities of these transitions and allows to define the spin and parity of the 115 ms isomer (see next section), in agreement with Ref. [3].

Sequence (2) is built on the 2577-keV level. It decays to sequence (1) via the 676.9-, 891.7- and 1003.5-keV transitions, and to sequence (3) via the 1057.4-keV transition. The 891.7- and 1003.5-keV transitions are weak and it was not possible to determine their DCO ratios and thus deduce their multipolarities. It is most likely that 1003.5 is E2 transitions. The DCO ratio of the 676.9-keV line corresponds to a mixed M1/E2 transition. Taking into consideration the decay of the the 2577-keV level to sequences (1) and (3), we suggest $I = (12)\ \hbar$ for this state. In this way, sequence (2) is observed up to $I = (17)\ \hbar$. Such a sequence of transitions was also reported in Ref. [1–3]. There are differences in the order of the lowest-lying 279.1- and 335.5-keV transitions. According to Ref. [3] they are reversed, with the 335.5-keV transition lying lower, compared to Ref. [1,2]. This is a weakly populated structure and a conclusion, based on the the intensity of the 279.1-keV transition is difficult, since its energy is close to the most intense 280.1-keV γ ray in ^{136}La, as well as to the 279.1-keV transition in ^{197}Au. However, the establishment of the 1003.5-keV decay-out transition, unambiguously fixes the order of the transitions in this band and places the 279.1-keV transition below the 335.5-keV γ rays. On top of this sequence a 681-keV [1, 2] and 835-keV [2] were suggested. They were not reported in Ref. [3], and in our data we do not observe such transitions.

Sequence (3) has negative parity and is built on the second $I^\pi = (8^-)$ state, which decays to the (7^-) isomer via the 81.0-keV transition. It was established up to $I^\pi = (14^-)$ state. Our analysis confirms the sequence of transitions as proposed by Bhattacharjee *et al* [3].

Sequence (4) is built on the 2806 keV level with $I = (14)\,\hbar$ and is extended up to $I = (19)\,\hbar$. It decays to sequence (1) via the 942.6-keV and 438.6-keV transitions. We confirm the transitions reported by Zhu *et al* [2], although we assign different spins to the levels in this sequence. In addition, a new crossover transition of 909.5-keV was added to this band.

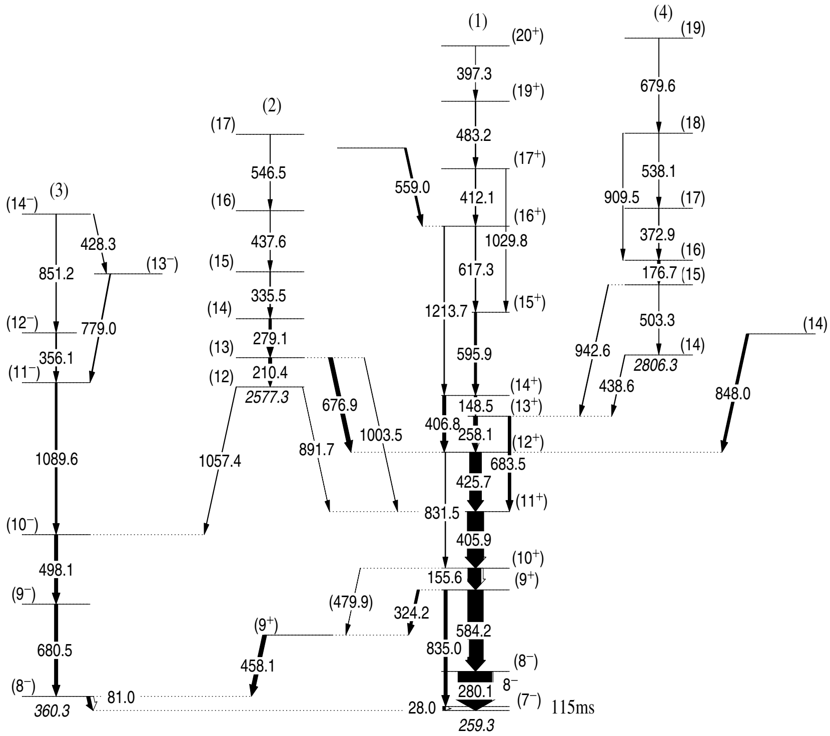

Figure 1. Partial Level scheme of ^{136}La built on 115 ms isomeric state ($E_x = 259.3$ keV [3]).

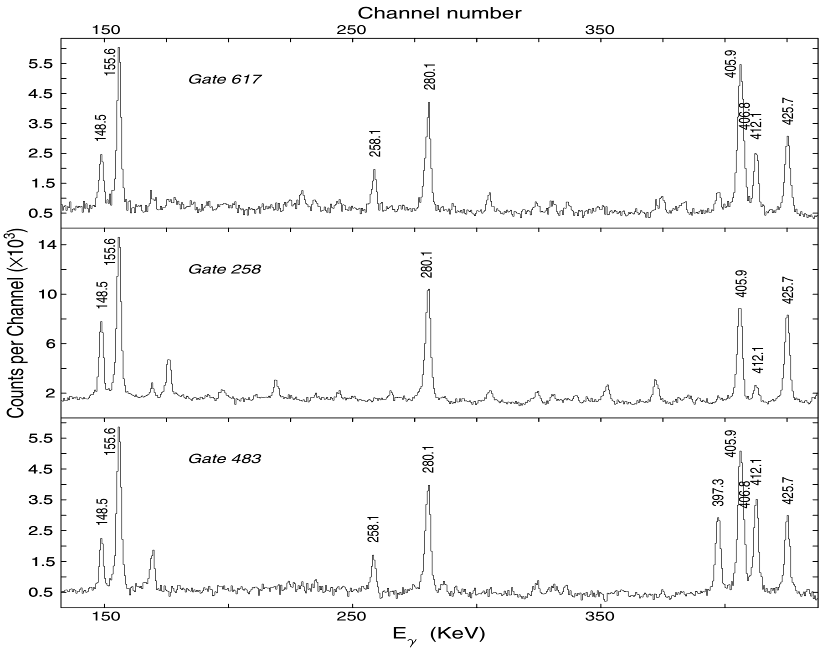

Figure 2. Coincidence spectra, revealing the position in the level scheme of the 148-keV transition.

3 Discussion

It is well known that the yrast bands in the doubly-odd nuclei in the $A \approx 130$ mass region are built on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration. A systematic comparison of the lowest-lying transitions in the yrast bands of the $N = 79$ isotones is presented in Fig. 3. The band-head spin for ^{138}Pr, ^{140}Pm and ^{142}Eu is considered to be $I^{\pi} = 10^{+}$ [16, 19, 20] and the 8^{+} and 9^{+} states which are established in these nuclei are part of the $\pi h_{11/2} \otimes \nu h_{11/2}$ multiplet. The spacing between the members of the multiplet increases as they approach the Z=50 shell. When accepting $I^{\pi} = (10)^{+}$ for the band-head of the yrast band in ^{136}La, the lowest-lying transitions in this band fit the systematics of the $N = 79$ isotones.

The 10^{+} state $\pi h_{11/2} \otimes \nu h_{11/2}$ band-head decays either to the 8^{-} isomer in ^{140}Pm and ^{142}Eu [19,20], or to the 7^{-} isomer in ^{138}Pr [16–18] (see Fig. 3). Previous studies assign $I^{\pi} = 8^{+}$ [1, 2] or $I^{\pi} = 7^{-}$ [3, 4] to the 115 ms isomer in ^{136}La. The $(10)^{+}$ band-head decays to the isomer via the 155-584-280 keV and the 155-836-28 keV cascades. The former one consists of stretched $\Delta I = 1$ transitions [3, 4], and the 584-keV γ rays has E1 multipolarity [3]. Thus, the spin of the isomer is most likely $I^{\pi} = 7^{-}$, as suggested in Ref. [3, 4]. The parallel cascade goes through a 28-keV excited state above the isomer. This cascade is very similar to the 695-18 keV cascade in ^{138}Pr [16–18], which goes through the first excited 8^- state, see Fig. 3.

This isomer has most probably the $\pi d_{5/2} \otimes \nu h_{11/2}$ configuration, in accordance with the similar isomer in ^{138}Pr [17]. Such a configuration for this state was suggested already by Morek *et al* [1]. Bhattacharjee *at al* [3] observed a 87-keV transition and suggested it as the isomeric transition. They assumed multipolarity M4 for it as it is considered to deexcite the isomer to the known 3^+ state, thus fixing the energy of the isomer. We also observe such a transition in our spectra, but cannot connect it to the known levels in ^{136}La.

In Fig. 4 we have compared the E2 crossover transitions in the chain of the Lanthanum nuclei, relative to the 13^+ level for the unfavored sequence and to the 14^+ level for the favored sequence. While the lowest-lying 831.5-keV $(12)^+ \rightarrow (10)^+$ transition follows the systematics of the lighter La isotopes, the higher-lying states in this band differ. This is related to the existence of the 148.5-keV γ-ray which was found to belong to this band. This behavior is in contradiction with the conclusion of Zhu *et al* [2] and we can not claim that the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band in ^{136}La is built on a prolate shape. Most probably, the observed changes in the $\pi h_{11/2} \otimes \nu h_{11/2}$ structure are due to a shape change.

Spin $I = (12)$ was suggested for the lowest level of sequence (2). This is a sequence of regularly spaced transitions. It was weakly populated and DCO analysis was difficult. However, the spectra which are shown in Fig. 5, demonstrate the existence of a large asymmetry of these gamma-rays, which is consistent with M1 multipolarity. Crossover E2 transitions were not observed for this sequence. Therefore, we suggest that this is a magnetic rotational band.

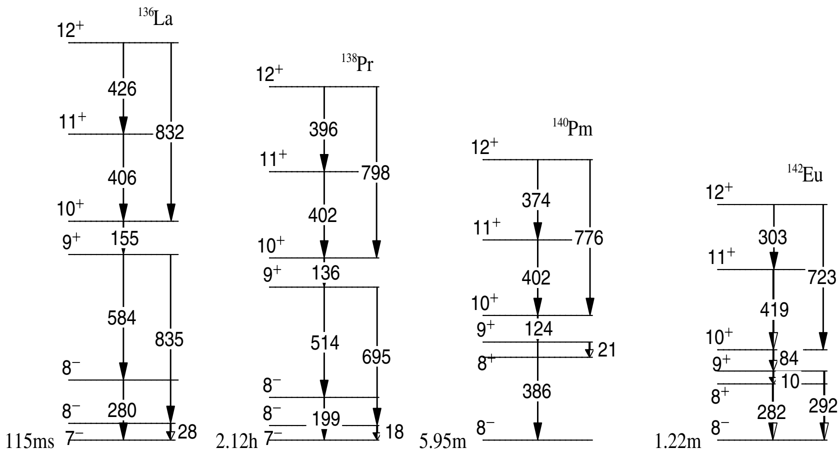

Figure 3. Comparison of the lowest-lying levels in the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast bands and the connecting transitions to the isomers in the N=79 isotones: ^{136}La, ^{138}Pr, ^{140}Pm, ^{142}Eu.

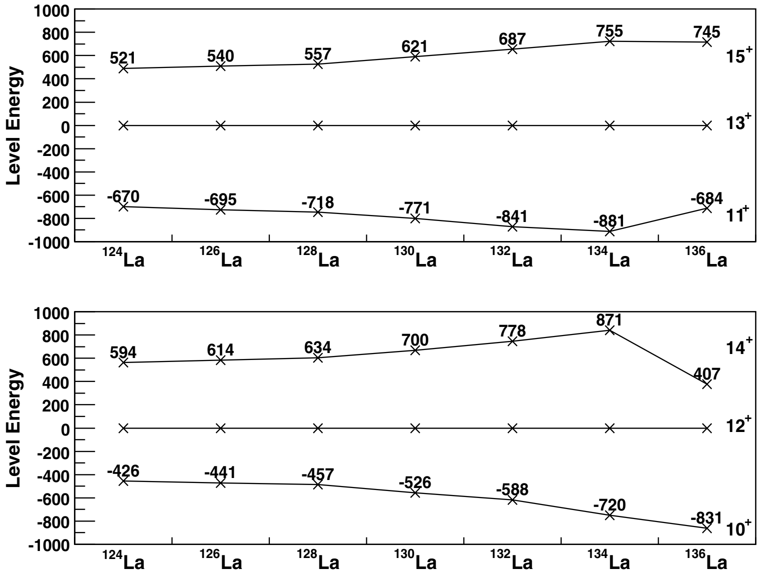

Figure 4. Spin-energy systematics of crossover E2 transitions, belonging to the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in the Lanthanum isotopes.

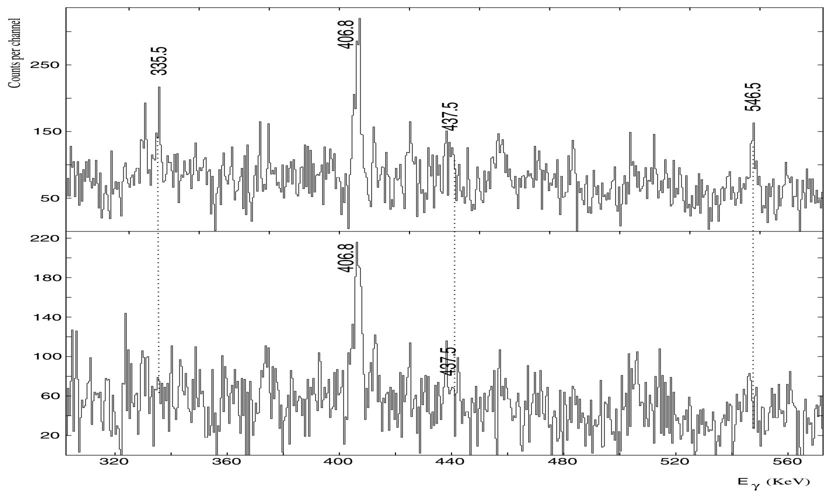

Figure 5. Coincidence spectra from DCO matrices gated on the 831-keV transition: (up) gate at the 90° detectors and (down) the 45° detectors.

4 Conclusions

A new partial level scheme of ^{136}La, revealing excited states above the 115 ms isomer, is presented. Some mistakes which appear in the previously published level schemes [1–4] for this nucleus were corrected in this work, which provides a basis for the proper understanding of the structure of ^{136}La. The spin of the 115 ms isomer is suggested to be $I^{\pi} = (7^{-})$, having a $\pi h_{5/2} \otimes \nu h_{11/2}$ configuration. The yrast $\pi h_{11/2} \otimes \nu h_{11/2}$ band differs from similar bands in the lighter La nuclei which is most probably related to a shape change. An excited magnetic rotational band was observed in this nucleus.

Acknowledgments

This work was partially supported by the Bulgarian Science Fund, contract VUF06/05 and by Research Fund of the Istanbul University, project number 1582/19032001.

References

1. E.W. Cybulska *et al.*, *Acta Phys. Pol.B* **32**, 929(2001)
2. S.J. Zhu *et. al.*, *Eur.Phys. J.A* **24**, 199-204 (2005)
3. T. Bhattacharjee *et al.*, *Nucl. Phys.A* **750**, 199-217 (2005)
4. T. Morek *et al.*, *Nucl.Phys. A* **433**, 159-180 (1985)
5. S. Frauendorf, J.Meng, *Nucl. Phys. A* **607**, 131 (1997)
6. K. Starosta *et al.*, *Phys. Rev. Lett.* **86**, 971 (2001)
7. E. Grodner *et al.*, *Phys. Rev. Lett.* **97**, 172501 (2006)
8. R. A.Bark *et al.*, *Nucl. Phys. A* **691**, 577 (2001)
9. D. Pramanik *et al.*, *Phys. Rev. C* **52**, 117 (1995)
10. Y. Liu *et al.*, *Phys. Rev. C* **54**, 719-730 (1996)
11. R.T. Newman *et al.*, *Balkan Phys. Lett.*,**Special Issue**, 182 (1998), http://www.tlabs.ac.za/public/nucafrodite.htm
12. A.H. Botha and H.N. Jungwirth, *"Proceedings of Tenth International Conference on Cyclotrons and their Applications, Michigan, 1984"* (Eds.: F.Marti), IEEE, N.Y., 1984, p.263, http://www.nac.ac.za/public/default.htm
13. A.Gavron, *Phys.Rev. C* **21**, 230 (1980)
14. D.C. Radford, *Nucl. Instrum. Meth. A* **361**, 297 (1995), http://radware.phy.ornl.gov/
15. K.S. Krane, R.M. Steffen and R.M. Wheeler, *Nuclear Data Tables* **11**, (1973) p 351
16. M.L. Li,S.J.Zhu *et al.*, *Phys. Rev. C* **75**, 034304 (2007)
17. M.A. Rizzutto *et al.*, *Z.Phys. A* **344**, 221-222 (1992)
18. G. Gangopadhyay *et al.*, *Eur. Phys. J. A* **24**, 173-178 (2005)
19. G. de Angelis *et al.*, *Z.Phys. A* **347**, 93-98 (1993)
20. M. Piiparinen *et. al.*, *Nucl. Phys. A* **605**, 191-268 (1996)