DSA lifetime measurements in $^{132}$La in the context of spontaneous chiral symmetry breaking accompanied by the new S-symmetry.

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Abstract. The lifetimes of the excited states belonging to three rotational bands of $^{132}$La have been measured with help of the DSA technique. The obtained results are interpreted in frame of the chiral symmetry breaking and recently postulated S-symmetry. Explanation of the absence of the characteristic B(M1) staggering in the chiral partner bands of $^{132}$La is suggested.

1. Introduction
Symmetry considerations dominate modern quantum physics from theoretical as well as experimental standpoint. Time-reversal is one of the fundamental symmetry incorporated in the description of the atomic nucleus. The possibility of time reversal symmetry breaking appears in the Cabibbo-Kobayashi-Maskawa matrix of the standard model, however, it is not associated with low energy nuclear excitations where time-reversal invariance rules the quantum description of the strong interaction. Even if the time-reversal is fundamentally conserved, there is a possibility of its spontaneous breakdown. Observation of spontaneous time-reversal symmetry breaking via the eigenstate properties of the nucleus has a general difficulty since there are no eigenstates of the time-reversal operator. A solution of that problem came with the hypothesis of the chiral symmetry breaking [1] where the symmetry operator is a combination of the $\pi$-rotation and the time-reversal. Apparently, spontaneous chiral symmetry breaking has been observed in Cs isotopes [2, 3] as presence of characteristic gamma selection rules in the chiral rotational bands. Recently, those selection rules have been explained in frame of new S-symmetry related to the specific structure of the chiral nuclei [4]. In the present work the chirality phenomenon is investigated on the example of $^{132}$La DSA lifetime measurements.

2. Experimental method
The excited states of $^{132}$La were populated in the $^{122}$Sn($^{14}$N,4n)$^{132}$La reaction. The $^{14}$N beam of 70 MeV energy was provided by the U-200P cyclotron at the Heavy Ion Laboratory of the University of Warsaw. The $^{122}$Sn target, 10mg/cm$^2$ thick, acted also as a stopper. About $10^8 \gamma - \gamma$ coincidences were collected by the OSIRIS II multidetector array consisting of 10 ACS germanium detectors placed at angles 25°, ±38°, 63°, ±90°, 117°, ±142° and 155° with respect to the beam axis.
The analysis of the Doppler broadened lineshapes of the γ transitions was carried out by using the programs COMPA, GAMMA and SHAPE [5]. The software includes Monte-Carlo simulation of the recoils production (COMPA) as well as the slowing down process, γ emission and registration (GAMMA). The lifetime analysis was performed starting from highest observed excited levels that decay to the levels of interest. In this way the influence of all observed transitions on the lifetime value has been taken into account. The unobserved feeding – side feeding – was described by the model presented in detail in Ref.[5]. The parameters of the side-feeding model were the same for all studied states and were experimentally determined from the analysis of the feeding intensities and lineshapes of high-energy levels of $^{131}$La. The determined side-feeding parameters have been verified by comparing the lifetime of the $I^\pi=31/2^-\gamma$ yrast level in $^{131}$La obtained with the method described above and with the method less sensitive to the side-feeding distribution (gating from above and narrow gate techniques) [5]. The stopping power parameters being input data for the GAMMA code were measured in an additional experiment with the use of semi-thick target method [6]. The uncertainties of the stopping-power parameters were accounted for the final lifetime uncertainties.

The γ – γ coincidence events collected by the OSIRIS II detection setup were sorted into 10 coincidence matrices. Each matrix contained energies of gamma quanta registered by a selected detector being in coincidence with gammas registered by any of the remaining detectors. In this way a coincidence spectrum from a selected HPGe spectrometer was obtained whereas the others played the role of the trigger. The γ – γ angular correlation coefficients were the input parameters for the GAMMA code. This is particularly important when a sum of coincidence spectra is used for the DSA analysis.

3. Results of the DSA study

![Figure 1](image-url).

Relevant part of the level scheme of $^{132}$La. Band 1 and band 2 built on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration as observed in the present experiment. Band 3 - newly found rotational band. The arrow widths are proportional to the γ-intensities observed during the measurement.

Relevant part of the level scheme of $^{132}$La observed in our experiment is shown in Fig.1. Additionally to the previously known band 1 and band 2 [7, 8] a new rotational band (band 3
Figure 2. Comparison of $\gamma$ transition probabilities in the partner bands of $^{126}$Cs (left column), $^{128}$Cs (middle), and $^{132}$La (right column). Upper and middle rows – $B$(E2) and $B$(M1) values for in-band transitions, bottom row – $B$(M1) values for inter-band transitions.

in Fig.1) connected with the yrast one with six strong linking transitions has been found [9]. The spin and parity assignment of the levels belonging to band 1 and 2 follows Ref.[7, 8]. The assignment of band 3 has not been uniquely determined. For the band $3 \rightarrow$ band 2 linking transitions the $R_{DCO}$ and lifetime values allow $\Delta I = \pm 1, \pm 2$ without parity change and $\Delta I = 0$ where parity change is not excluded. The $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration has been assigned for band 1 and band 2 which were proposed as the candidates for the chiral partner bands [7]. The lifetimes of 13 levels belonging to those bands were extracted from our DSA experimental data. We also observed the Doppler broadening of the transitions coming from the newly found band 3 where lifetimes of 7 excited states have been determined. The results of the DSA analysis are listed in Table 1 and shown in Fig.2 together with similar data obtained for the $^{126,128}$Cs nuclei [2, 3].

4. Discussion
The obtained gamma transition probabilities show a striking difference in the electromagnetic behavior of $^{132}$La and $^{126,128}$Cs observed in the partner bands. The $B$(M1) and $B$(E2) values in the yrast band are systematically different then the corresponding side-band values in $^{132}$La while in $^{126,128}$Cs both bands present similar electromagnetic properties. According to Ref.[10] the $^{132}$La lifetime results show that the chiral symmetry cannot be broken strongly. The energy splitting between the partner bands in $^{132}$La supports the above conclusion. The average splitting is around 350 keV in $^{132}$La while in Cs isotopes it is twice smaller, around 150-200 keV. This unquestionably shows that in the chiral scenario of $^{132}$La the energy barrier between left- and right-handed configurations has to be smaller than in odd-odd Cs nuclei. A deviation from the full $\gamma = 30^\circ$ triaxial deformation can be one of the reasons for the lowering of the barrier. Another feature distinguishing $^{132}$La form $^{126,128}$Cs are gamma selections rules along the partner bands observed as specific B(M1) staggering.
As it has been discussed in Refs.[10, 3] a characteristic feature results from the breaking of the chiral symmetry, namely, if the inband transition is strong then the corresponding interband one should be weak and vice-versa. This is consistent with the observed selection rules. In Cs isotopes, strong inband E2 transitions are observed while the interband ones are not seen. Also, the inband B(M1) staggering has opposite phase to the interband one. The described feature tells us how the inband and interband B(M1) staggering should be related to each other but does not explain the origin of the staggering itself. In contrast to Cs nuclei, no B(M1) staggering is observed in $^{132}$La.

Recently, new explanation of the B(M1) staggering in the partner bands have been reported [4] as appearance of new additional symmetry called the S-symmetry. The new symmetry is a combination of the parity operation in the five dimensional space of deformation of the core and an exchange of states of the unpaired particles. The B(M1) staggering in the context of the S-symmetry should appear when the expectation value of the triaxial deformation is $\gamma = 30^\circ$ (independently on the gamma-softness) and the partner bands are built on two quasiparticle states where odd proton and odd neutron are in the same j-shell. It was shown in Ref.[11] that even little deviation from $\gamma = 30^\circ$ triaxial deformation causes vanishing of the B(M1) staggering.

5. summary
In the present paper lifetimes of the excited states belonging to rotational bands of $^{132}$La are analyzed in the context of the spontaneous chiral symmetry breaking. In contrast to Cs isotopes, the probabilities of the gamma transitions observed in the chiral partner bands (band 1 and band 2 in Fig. 1) of $^{132}$La do not show characteristic B(M1) staggering. Recently a new symmetry, has been introduced in order to explain the appearance of the chiral gamma selection rules. In frame of the new symmetry the $\gamma \neq 30^\circ$ nonaxial deformation is the possible mechanism responsible for absence of the electromagnetic selection rules in $^{132}$La.

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Table 1. $^{132}$La results of the lifetime study.

| band | $I^+$ | $\tau$ [ps] | $E_\gamma$ [keV] | $\sigma \lambda$ | $I_\gamma$ [a.u.] | $B(\sigma \lambda)$ [W.u.] |
|------|-------|--------------|-----------------|------------------|-------------------|--------------------------|
| 1    | 12+   | 0.61$^{+0.19}_{-0.14}$ | 360             | M1 4             | 0.25$^{+0.13}_{-0.05}$ | 689 M1 10               |
|      |       |              |                 |                  | 0.11$^{+0.05}_{-0.02}$ | 740 E2 0.3             |
|      |       |              |                 |                  | < 1.5             | 380 M1 4               |
|      |       |              |                 |                  | < 0.14            | 775 M1 5               |
|      | 15+   | 1.43$^{+0.52}_{-0.38}$ | 427             | M1 3             | 0.13$^{+0.07}_{-0.03}$ | 827 M1 13               |
|      |       |              |                 |                  | 0.02$^{+0.01}_{-0.01}$ | 12+ 0.38               |
|      | 15+   | 0.68$^{+0.28}_{-0.18}$ | 587             | E2 24            | 200$^{+50}_{-20}$    | 294 M1 66              |
|      |       |              |                 |                  | 1.2$^{+0.6}_{-0.2}$ | 686 E2 17              |
|      | 15+   | 0.53$^{+0.12}_{-0.10}$ | 392             | M1 50            | 0.70$^{+0.22}_{-0.11}$ | 778 E2 27              |
|      |       |              |                 |                  | 32$^{+5}_{-10}$     | 385 M1 33              |
|      | 15+   | 0.60$^{+0.16}_{-0.13}$ | 839             | E2 18            | 36$^{+6}_{-13}$      | 454 M1 21              |
|      |       |              |                 |                  | 0.28$^{+0.10}_{-0.05}$ | 906 E2 16              |
|      | 16+   | 0.77$^{+0.14}_{-0.15}$ | 452             | M1 17            | 0.22$^{+0.07}_{-0.02}$ | 959 E2 9               |
|      |       |              |                 |                  | 19$^{+6}_{-13}$     | 507 M1 10              |
|      | 17+   | 0.62$^{+0.13}_{-0.12}$ | 994             | E2 7             | 0.19$^{+0.06}_{-0.03}$ | 487 M1 4               |
|      |       |              |                 |                  | 25$^{+4}_{-5}$      | 1046 E2 7              |
|      | 18+   | 0.54$^{+0.12}_{-0.11}$ | 19+ 0.18        | E2 7             | 0.16$^{+0.05}_{-0.03}$ | 559 M1 5               |
|      |       |              |                 |                  | 12$^{+3}_{-4}$      | 1019 E2 3              |
|      | 20+   | 1.27$^{+0.40}_{-0.28}$ | 257             | M1 0.8           | 0.47$^{+0.28}_{-0.19}$ | 1142 M1 3              |
|      |       |              |                 |                  | 0.03$^{+0.08}_{-0.05}$ | 242 M1 1              |
|      | 3     | 13+   | 0.72$^{+0.25}_{-0.20}$ | 991             | M1 5              | 0.5$^{+0.3}_{-0.1}$    | 305 M1 6               |
|      |       |              |                 |                  | 0.03$^{+0.17}_{-0.06}$ | 501 E2 0.4             |
|      | 3     | 15+   | 1.06$^{+0.47}_{-0.31}$ | 259             | M1 4              | 0.63$^{+0.30}_{-0.12}$ | 865 M1 11              |
|      |       |              |                 |                  | 0.05$^{+0.02}_{-0.01}$ | 564 E2 0.6             |
|      |       |              |                 |                  | 15$^{+14}_{-5}$     | 305 M1 6               |
|      | 3     | 16+   | 1.15$^{+0.37}_{-0.25}$ | 718             | M1 4              | 0.03$^{+0.02}_{-0.01}$ | 358 M1 5               |
|      |       |              |                 |                  | 0.5$^{+0.2}_{-0.1}$ | 663 E2 0.6             |
|      | 3     | 17+   | 1.07$^{+0.29}_{-0.24}$ | 718             | M1 4              | 0.44$^{+0.07}_{-0.06}$ | 384 M1 4               |
|      |       |              |                 |                  | 8.1$^{+3.4}_{-3.5}$ | 742 E2 0.5             |
|      |       |              |                 |                  | 0.44$^{+0.16}_{-0.07}$ | 432 M1 4               |
|      | 3     | 18+   | 0.81$^{+0.18}_{-0.16}$ | 815             | E2 0.5            | 7.2$^{+3.3}_{-2.2}$    | 384 M1 4               |
|      |       |              |                 |                  | 0.41$^{+0.12}_{-0.06}$ | 815 E2 1               |
|      | 3     | 19+   | 0.83$\pm0.07$ | 431             | M1 4              | 0.41$^{+0.10}_{-0.05}$ | 1.1$^{+3.0}_{-2.6}$    |