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128Cs as the Best Example Revealing Chiral Symmetry Breaking


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The results of the Doppler-shift attenuation method lifetime measurements in partner bands of 128Cs and 132La are presented. Experimental reduced transition probabilities in 128Cs are compared with theoretical calculations done in the frame of the core-quasiparticle coupling model. The electromagnetic properties, energy and spin of levels belonging to the partner bands show that 128Cs is the best known example revealing the chiral symmetry breaking phenomenon.


The manifestation of chirality in atomic nuclei, originally suggested in Ref. [1] and vigorously investigated over the past few years from both the experimental and theoretical standpoint, continues to be the subject of intense discussion. The results of theoretical calculations of Tilted Axis Cranking [2], Core-Particle-Hole-Coupling [3], and Tilted Skyrme Hartree-Fock [4] pointed out the possibility of spontaneous breaking of chiral symmetry in the intrinsic reference frame of the nucleus. This phenomenon manifests itself experimentally by the appearance of two rotational bands (chiral partner bands) with the same spins and parities, almost equal excitation energy and characteristic γ-decay properties [5,6]. Such partner bands were found in more than ten nuclei in the A = 130 and A = 100 mass regions. Their observation was considered to be a proof of chiral symmetry breaking in atomic nuclei [3,7].

Among these nuclei a detailed study of partner bands based on the $\pi h_{11/2} \otimes (\nu h_{11/2})^{-1}$ configuration was done in 132La [3], 128Cs [6], and 134Pr [8]. The latter was often considered as the best example of a chiral nucleus, however, the results presented in Ref. [8] show that the breaking of chiral symmetry in 134Pr cannot be strong. It was indicated in Ref. [9] that the energy levels as well as the electromagnetic properties of 134Pr can be interpreted without using the concept of chirality. Under these circumstances it is crucial to present new data that would settle whether the chirality phenomenon exists in nuclear systems. Lifetime measurements of excited levels belonging to the partner bands in 132La and 128Cs were the main aim of the experiments described in the present Letter. The preliminary results were published in [10,11]. The presented data show that the doublet bands observed in 128Cs, for the first time including the electromagnetic properties, exhibit characteristic features resulting from spontaneous formation of chirality.

The high spin states of the 128Cs and 132La nuclei were populated in the $^{122}$Sn($^{16}$B, 4n)$^{128}$Cs and $^{122}$Sn($^{14}$N, 4n)$^{132}$La reactions at a beam energy of 55 and 70 MeV, respectively. The beam was provided by the Warsaw U-200P cyclotron. The target thickness was 40 and 10 mg/cm² for the 128Cs and 132La reactions, respectively. The thick targets played both roles: that of the target and that of the stopper. About 10⁸ γ-γ coincidences were collected by the OSIRIS II multidetector array consisting of 10 Compton-suppressed HPGe detectors. The lifetimes of the excited levels were determined by the Doppler shift attenuation method with the use of the procedure and computer code developed by A. A. Pasternak [12–14]. Lifetime analysis was performed starting from the highest energy levels. The lifetimes of levels which decay to the studied level via the observed transitions (cascade feeding—see Sect. 3.3 in Ref. [12]) were considered in the DSA analysis. The unobserved feeding (side feeding—see Sect. 3.4 of Ref. [12]) was described by the model presented in detail in Refs. [12,13]. The parameters of the model are the same for all studied levels. The model includes statistical E1, M1, and E2 transitions. The presence of stretched E2 cascades and stretched M1 magnetic bands is also taken into consideration. The electromagnetic properties of E2 cascades are characterized by $Q_{\text{low}}$ and $Q_{\text{high}}$ parameters, i.e., the effective quadrupole moments of stretched E2 cascades in continuum for the low and high spin regions. The M1 magnetic bands are described by the $S_{MR}$ parameter, i.e., the relative density of stretched mag-
netic bands in continuum. The values of $Q_{\text{low}}$, $Q_{\text{high}}$, $S_{\text{MR}}$ were experimentally found for $^{131}\text{La}$ [12] from side-feeding intensities and line shape analysis of transitions for the two highest levels. For $^{132}\text{La}$ and $^{128}\text{Cs}$ the values of $Q_{\text{high}}$, $Q_{\text{low}}$, and $S_{\text{MR}}$ were assumed equal to those in $^{131}\text{La}$. Under this assumption the total intensities of $\gamma$-transitions in $^{128}\text{Cs}$ and $^{132}\text{La}$ yrast bands were well reproduced (see Fig. 1). The dashed and dotted lines for $^{128}\text{Cs}$ show the lower and upper limits of the calculated intensity distribution along the yrast band where we use the parameters describing the intensity depopulating the odd and even spin levels, respectively. The influence of two limiting sets of the side-feeding parameters on the lifetime values in $^{128}\text{Cs}$ is accounted for the lifetime uncertainties. For $^{132}\text{La}$ it was estimated that the uncertainty of the side-feeding pattern affects by $\pm 15\%$ the extracted lifetimes. The correctness of our method of the side-feeding evaluation is supported by the observation that the lifetime of the $31/2^-$ level in $^{131}\text{La}$ obtained by using the method described above agrees with the lifetimes determined by using the gating above and narrow gate methods [12,15,16] which are independent of the side-feeding distribution.

The spin and parity assignment of excited states, shown in Fig. 2, follows for $^{128}\text{Cs}$ and $^{132}\text{La}$ Ref. [6] and Refs. [3,17], respectively. The branching ratios were determined from our experiment by using intensities of $\gamma$-lines corrected for the Doppler broadening. In Fig. 3 the examples of analyzed shapes of $\gamma$-lines in $^{128}\text{Cs}$ and $^{132}\text{La}$ are shown. To obtain reliable DSAM results stopping power measurements of the recoil nuclei in the Sn matter were made. The semithick target method [14] was applied. The electronic stopping power parameter was experimentally found to be $f_{\text{e}} = 1.0 \pm 0.1$ for $^{128}\text{Cs}$ and $^{132}\text{La}$. In both cases the nuclear stopping power parameter $f_{\text{n}} = 0.87$ was used according to Ziegler et al. [18].

The resulting lifetimes, presented in Fig. 2 and experimental branching ratios were used to calculate the $B(E2)$ and $B(M1)$ reduced transition probabilities. The $B(M1; I \rightarrow I-1)$ values were obtained by assuming pure $M1$ multipolarity, since the contribution of the $E2$ admixture to the $I \rightarrow I-1$ transitions is less than 10%. This is supported by the experimental data given in [3,6] for $^{132}\text{La}$ and $^{128}\text{Cs}$, respectively. The reduced $B(E2)$ and $B(M1)$ transition probabilities resulting from our experiment are presented in Fig. 4. One can see a large difference between the electromagnetic properties of $^{132}\text{La}$ and of $^{128}\text{Cs}$. The $B(E2)$ values in the side band of $^{132}\text{La}$ are about 20 times lower than the corresponding ones in the yrast band, and

\begin{align*}
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\end{align*}
there is smooth spin dependence on these values. In the case of $M1$ transitions the $B(M1)$ values in the side band are 2–5 times lower than those in the yrast band. In contrast to $^{132}\text{La}$ data, the $B(E2)$ and also $B(M1)$ values are similar in the side and the yrast bands of $^{128}\text{Cs}$. The spin dependence of reduced $M1$ transition probabilities inside bands show characteristic staggering. The staggering of the $B(M1)$ values is observed also for the side → yrast transitions in $^{128}\text{Cs}$, while in case of $^{132}\text{La}$ no clear pattern of this quantity is observed.

The level scheme presenting the doublet band structure in $^{128}\text{Cs}$ is shown in Fig. 2. The energy splitting of these bands, connected with the extent of violation of chiral symmetry [5] is about 200 keV. This value is 2 times smaller than that in the case of $^{132}\text{La}$. This is the first indication that the partner bands in $^{128}\text{Cs}$ have properties closer to the expected features of chiral bands than those in $^{132}\text{La}$. The particle alignment in the side and the yrast bands in $^{128}\text{Cs}$ is similar (see Fig. 5). The same behavior is seen in $^{132}\text{La}$. In distinction a different particle alignment is observed in partner bands of $^{134}\text{Pr}$ and is claimed in Ref. [9] to contradict the chiral interpretation. A theoretical study of the transition probabilities and selection rules for the idealized case of chiral partner bands are presented in Ref. [19], where the Hamiltonian of the rigid triaxial rotor coupled to the proton (particle) and neutron (hole) in the chiral configuration is investigated. The results given in above quoted paper show that for the ideal case of chiral symmetry breaking (when energy splitting between bands equals zero) the transition probabilities in both bands should be the same for the corresponding spins. Also the $B(M1)$ staggering in inband transitions is predicted.

Similar staggering but with opposite phase is expected for the $B(M1)$ interband transitions. These characteristic properties of the partner bands are observed in our experimental data for $^{128}\text{Cs}$. A detailed calculation of the $^{128}\text{Cs}$ structure was done in the frame of the core-quasi particle coupling model [6]. Comparison of the calculated and the experimental $B(M1)$ and $B(E2)$ transition probabilities for this nucleus is presented in Fig. 6. One can see that the model reproduces the main features of experimental data.

![FIG. 3. Doppler broadened line shapes of $\gamma$-transitions registered by groups of detectors placed forward (25° and 38°) and backward (135° and 142°) with respect to the beam direction. Left part: 930 keV $18^+ \rightarrow 16^+$ transition in the yrast band of $^{128}\text{Cs}$. Right part: 959 keV $17^+ \rightarrow 15^+$ transition in the yrast band of $^{132}\text{La}$. Bold solid line: Doppler broadened lineshape of the analyzed transition. Dotted line: the contamination peaks. Thin solid line: the result of fit to the experimental data.](image1)

![FIG. 4 (color online). $B(E2)$ and $B(M1)$ reduced transition probabilities of $^{128}\text{Cs}$ (left part) and $^{132}\text{La}$ (right part). Top and middle: $B(E2)$ and $B(M1)$ values for inband transitions of $^{128}\text{Cs}$ and $^{132}\text{La}$. Bottom: $B(M1)$ values for interband side → yrast transitions.](image2)

![FIG. 5 (color online). Particle alignment for partner bands of $^{128}\text{Cs}$ and $^{132}\text{La}$. The used Harris parameters are $J_0 = 16\hbar^2 \text{MeV}^{-1}$, $J_1 = 33\hbar^4 \text{MeV}^{-3}$ for $^{128}\text{Cs}$ and $J_0 = 11\hbar^2 \text{MeV}^{-1}$, $J_1 = 37\hbar^4 \text{MeV}^{-3}$ for $^{132}\text{La}$. In distinction from the case of $^{134}\text{Pr}$ (Fig. 2, Ref. [9]) the particle alignment in both bands of $^{128}\text{Cs}$ and $^{132}\text{La}$ is very similar.](image3)
although the predicted staggering pattern in $B(M1)$ values is much more pronounced.

The results of the lifetime measurements of the excited states in $^{132}$La and $^{128}$Cs show that these nuclei, in spite of the similar level schemes, have essentially different electromagnetic properties. The reduced transition probabilities for $^{132}$La are not consistent with the symmetry requirements imposed by chirality attained in the intrinsic system. The properties of the $\frac{\pi h_{11/2} \otimes (\nu h_{11/2})}{2}$ bands in $^{128}$Cs exhibit the main features expected for chiral partner bands from nuclear models. It is the first case of such a good agreement of comprehensive experimental data with the chiral interpretation. The present study shows clearly that investigation of chirality would be impossible without lifetime measurements.

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*Deceased.