FRONTIERS OF PHYSICS

TOPICAL REVIEW
Volume 19 / Issue 3 / 34202 / 2024

The *g*-factor measurement as an ultimate test for nuclear chirality

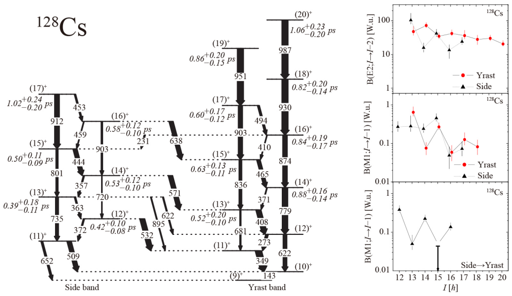
Ernest Grodner[1,†], Michał Kowalczyk[2,‡], Julian Srebrny[2,§], Leszek Próchniak[2,¶], Chrystian Droste[3,**], Jan Kownacki[2], Maciej Kisieliński[2,††], Krzysztof Starosta[4,‡‡], Takeshi Koike[5]

1 National Centre for Nuclear Research, 05-540 Świerk, Poland
2 Heavy Ion Laboratory, University of Warsaw, Pasteura 5a, 02-093 Warsaw, Poland
3 Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland
4 Simon Fraser University, 8888 University Drive Burnaby, B.C. Canada V5A 1S6
5 Department of Physics, Tohoku University, Sendai, Miyagi 980-8577, Japan
Corresponding authors. E-mail: †grodner.ernest@gmail.com, ‡mkk@fuw.edu.pl, §js@slcj.uw.edu.pl, ¶prochniak@slcj.uw.edu.pl, **cdroste@fuw.edu.pl, ††kisiel@slcj.uw.edu.pl, ‡‡starosta@sfu.ca

Received May 8, 2023; accepted August 28, 2023

ABSTRACT

We present results of a series of experiments aimed at finding the most direct fingerprints of a phenomenon of nuclear chirality. These experiments brought a detailed knowledge of the so called partner bands in ^{132}La, ^{128}Cs and ^{126}Cs including absolute values of E2 and M1 transition probabilities obtained through the DSA (Doppler Shift Attenuation) method. Considering the indirect character of observables such as energies and transition rates we proposed measurement of the *g*-factor of a chosen state as a direct, ultimate test of chirality. Our experiment on the bandhead of partner bands in ^{128}Cs showed feasibility of this approach. Measured value of the *g*-factor which suggests non-chiral character of this state leads to another puzzle in the chirality studies — how the chirality emerges with increasing spin of levels along a partner band.



Keywords nuclear chirality, electromagnetic transitions, electromagnetic moments, level lifetimes

Contents

---

*Dedicated to the memory of S.G. Rohoziński, our teacher and friend.
Special Topic: Nuclear Chirality over the Past 25 Years
(Eds. Qibo Chen & Pengwei Zhao).

Higher Education Press

https://doi.org/10.1007/s11467-023-1359-2

1 Introduction

Analysis of data on low energy nuclear excitations and their decay via electromagnetic (EM) transitions obtained by nuclear gamma spectroscopy can bring insight into various properties of nuclei. However, not all interesting phenomena can easily or directly be observed. In the case of nuclear chirality, excited states studied via gamma spectroscopy are superpositions of opposite handedness for which expectation values of operators sensitive to handedness always vanish (chiral symmetry is broken spontaneously while nuclear Hamiltonian is invariant with respect to this symmetry) thus preventing direct chiral geometry measurements. In this context, the experimental study of nuclear chirality resembles the well known Schrödinger's cat problem, where superimposed states (the cat simultaneously dead and alive) are accessible in quantum description for an observer outside the closed box. At the initial stage of research of spontaneous chiral symmetry breaking our gamma spectroscopy group looked for the best indirect indications of nuclear chirality. Later on we focused on a direct determination of the chiral geometry through g-factor measurements and the first results of our attempts were published in 2018.

2 Indirect signatures of nuclear chirality — Hints for experimenters

There are various indirect signatures of nuclear chirality that are widely studied by nuclear spectroscopists. Some of the signatures relate to nuclear chirality regardless of mechanisms generating it, while others relate to specific structures underneath the chirality phenomenon. Here we briefly discuss features of nuclear spectra which can indicate impact of chirality on nuclear structure in a given isotope.

F1. Existence of nearly degenerate chiral doublets (all chiral nuclei, i.e., odd–odd as well as odd nuclei)

The chiral symmetry operator $R_Y T$, where T is the time-reversal operator and R_Y is a rotation around the y axis by 180°, commutes with Hamiltonian and with spin and its projection operators (see Eqs. (1)–(39) of Refs. [1, 2]). Therefore the basic feature of spontaneous chiral symmetry breaking is the existence of chiral doublets — two nearly degenerate states with the same spin and parity quantum numbers. In the case of a rotating nucleus this leads to existence of the chiral partner bands – two nearly degenerate rotational bands called yrast and side-band with the same spins and parities of corresponding levels. This feature is expected in all chiral nuclei regardless of mechanisms on which the handedness is formed. Until now such partner bands were found in more than 60 nuclei [3]. The extent of spontaneous chiral symmetry breaking may vary from chiral vibrations to chiral rotations depending on tunneling probability between the opposite handedness configurations. Chiral vibrations relates to weak chiral symmetry breaking with large tunneling probability, while chiral rotation corresponds to strong chiral symmetry breaking and low tunneling probability. The energy splitting between chiral doublets is expected to be smaller for chiral rotations [4, 5]. In the absence of other expected chiral signatures, the chiral nature of such bands may be questioned, for instance, the existence of such rotational bands in two quasi-particle configurations may be the result of signature splitting [6]. Using degeneracy of states as a fingerprint of chirality requires proper identification of rotational bands without which a misinterpretation may occur [7].

F2. Similar values of corresponding EM transition probabilities in partner bands (all chiral nuclei)

The chiral symmetry operator $R_Y T$ commutes with Hamiltonian as well as with EM transition operators of M1, E2, M3, E4,... multipolarities [Eqs. (1A-73) and (3C-10) [1]]. As a consequence, for the near degenerate chiral doublets in rotational partner bands values of the M1 and E2 transition probabilities between corresponding levels in both bands should be similar. The absence of this feature may effectively be used to reject the stable chiral rotation in a nucleus in favor of weak chiral vibrations scenario.

F3. Absence of signature energy staggering S(I) in chiral configuration (odd–odd nuclei, 2qp configuration only)

It was suggested [8] that nearly ideal chiral geometry results in small Coriolis force which is proportional to the scalar product of the angular momenta of a single particle and the collective core. In such a case a smooth dependence of $S(I)$ on spin value I is expected. This feature was used in search for minimum rotational frequency necessary for chirality to emerge in ^{124}Cs nucleus [6].

F4. B(M1) staggering along the chiral bands (2qp configuration, single j-shell, "maximal" triaxial deformation)

A staggering of the B(M1) values was initially predicted in Ref. [9] for maximal triaxiality (i.e., with $\gamma = 30°$) in rigid, odd–odd nuclei with an odd proton and odd neutron occupying single j-shell levels. These conditions also favor nuclear chirality with respect to energy minimization [10]. The rigidity requirement was later lifted in the CPHC model [11–13] where, in addition, the condition of maximal triaxiality was replaced by an invariance with respect to a new symmetry S, see Section 4. Observation of this feature indicates nuclear chirality in its cleanest form of coupling of three perpendicular angular momentum vectors (spin of only two quasiparticles and even–even core). Finding the B(M1) staggering in a nucleus fulfilling (at least with a good accuracy) stringent conditions listed above would be a convincing proof of existence of nuclear chirality.

3 Experimental search for nuclear chirality signatures conducted in warsaw

Experimental research into nuclear chirality was carried out by physicists from the National Centre For Nuclear Research (NCNR) and the University of Warsaw (Heavy Ion Laboratory (HIL) and Faculty of Physics). Experiments were done at HIL using the U200P cyclotron and various detectors available there. Our research was focused on odd–odd nuclei in the $A \approx 130$ region for which the chiral character of rotational bands was suggested in Ref. [14]. The most promising candidate seemed to be the ^{132}La isotope which level scheme and other properties were studied in detail [15]. Our intent was to measure lifetimes of levels and EM transitions probabilities within tentative chiral bands to check if the feature ***F2*** could be verified experimentally. Ion beams available at HIL and their characteristics provided easy access to production of odd–odd nuclei around mass $A \approx 130$ with relatively low excitation energies and high production rates. This in turn created favorable conditions for lifetime measurements in the picoseconds range using the Doppler Shift Attenuation (DSA) method.

3.1 Lifetime measurements of excited states in ^{132}La

Existence of rotational partner bands in ^{132}La based on $\pi h_{11/2} \otimes \nu^{-1} h_{11/2}$ configuration was suggested in Refs. [14–20] where a phenomenon of signature inversion was reported in addition to the chirality hypothesis. Experimental data available at the time on partner bands in ^{132}La lacked the EM transition probabilities. First results regarding the EM transitions were obtained in 2003 using the Doppler Shift Attenuation Method. A literature survey shows that the ^{132}La was the first nucleus for which lifetimes were published for proposed chiral band candidates.

Excited states of ^{132}La were populated via the ^{122}Sn(^{14}N,4n)^{132}La fusion-evaporation reaction at ^{14}N beam energy of 70 MeV. About 10^8 γ–γ coincidences were registered by the OSIRIS II array built of 10 Anti-Compton-Shielded HPGe detectors (a predecessor of our recent EAGLE array). A new type of Doppler-Shift-Attenuation method at that time was used [21] which was suitable for thick 10 mg/cm^2 Sn target measurement. In total lifetimes of 13 excited states in partner bands of ^{132}La were measured and the results were reported in Refs. [21–24].

In ^{132}La the energy splitting between doublet band members of around 400 keV is constant as a function of spin indicating the same moment of inertia in both rotational bands. This is consistent with the chiral interpretation; however, as the DSA measurement results showed this is the only one signature that matches the expectations of chirality in the ^{132}La isotope. The observed EM reduced transition probabilities differ significantly in both bands, see Fig. 1. The B(M1) transition probabilities in the side-band are systematically few times smaller than the corresponding B(M1) transition probabilities in the yrast band. Even higher difference was detected for B(E2) transitions that are systematically around 50 times lower in the side-band than in the yrast-band. Considering the ***F2*** signature this observation indicates that if chirality is present in ^{132}La isotope then it has the chiral vibrational character rather than chiral rotational one. The chiral vibration scenario in ^{132}La is also supported by a parametric analysis of mutual overlap of the wave function with opposite handedness and the probability of EM transition to reverse handedness [Eqs. (15), (16), (17) and Fig. 3 in Ref. [5]] both of which are large in chiral vibrational mode.

Partner bands in ^{132}La are built on $\pi h_{11/2} \otimes \nu^{-1} h_{11/2}$ configuration, and hence, according to some nuclear models [9], one could expect the existence of chiral EM selection rules, in particular the B(M1) staggering as a function of spin (signature ***F4***). These selection rules are not observed which can be explained by triaxial deformation of ^{132}La deviating from 30° [11]. The final interpretation of ^{132}La partner bands in the context of nuclear chirality is still being sought [2, 4].

3.2 Lifetime measurements of excited states in ^{128}Cs

In parallel to data analysis of EM transition probabilities in ^{132}La, another DSAM measurement was performed at HIL aiming at a lifetime measurement of excited states in partner bands of ^{128}Cs. Rotational partner bands in ^{128}Cs isotope were identified in Ref. [26], and assignment of positive parity rotational states lead to chiral interpretation based on the signature ***F1***. Moreover, the energy splitting of these bands is constant as a function of spin and, approximately, by a factor of two smaller than in ^{132}La. Thus a chiral-rotation scenario in ^{128}Cs seems to be more likely than in ^{132}La (see signature ***F1***). An in-depth study of ^{128}Cs partner bands structures for chirality was published in Ref. [27] where level energies, DCO ratios and transition intensities in partner bands were discussed. The absolute reduced B(E2) and B(M1) transition probabilities were still missing and were the aim of ^{128}Cs DSA measurement at HIL in 2003. Excited states of ^{128}Cs were populated by the ^{122}Sn(^{10}B, 4n)^{128}Cs reaction with a 40 mg/cm^2 thick target while the same experimental instrumentation as in the case of ^{132}La was

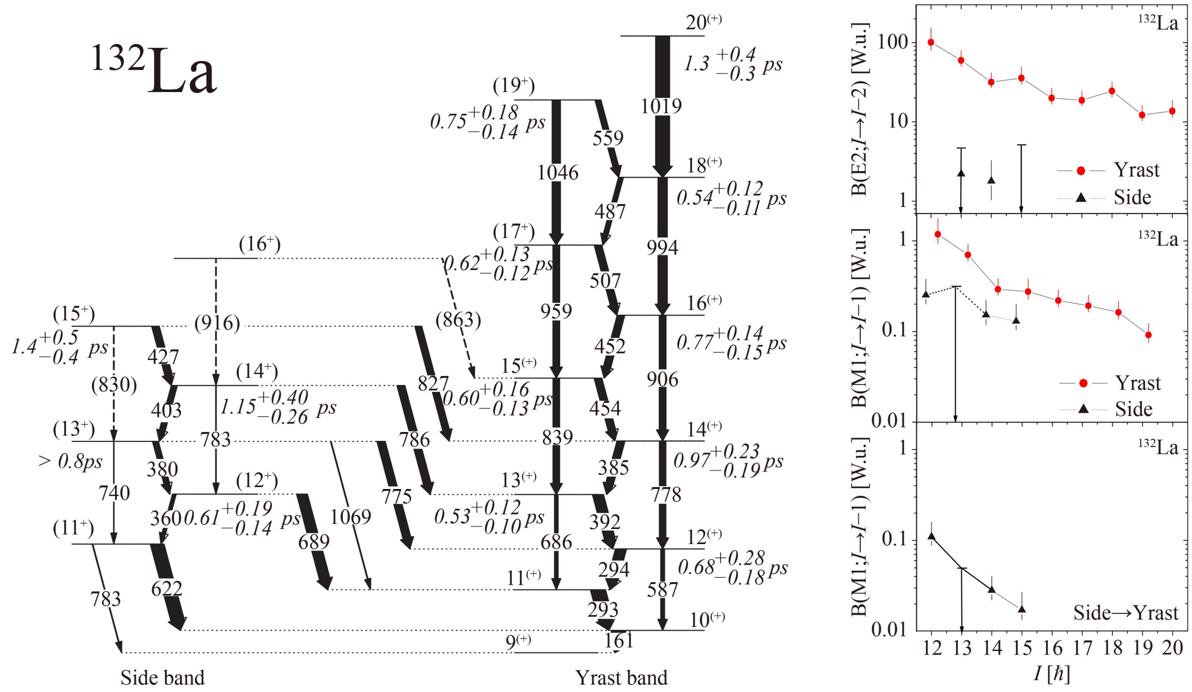


Fig. 1 Partner bands (left panel) and E2 and M1 transitions probabilities (right panel) for ^{132}La. Reproduced from Ref. [25].

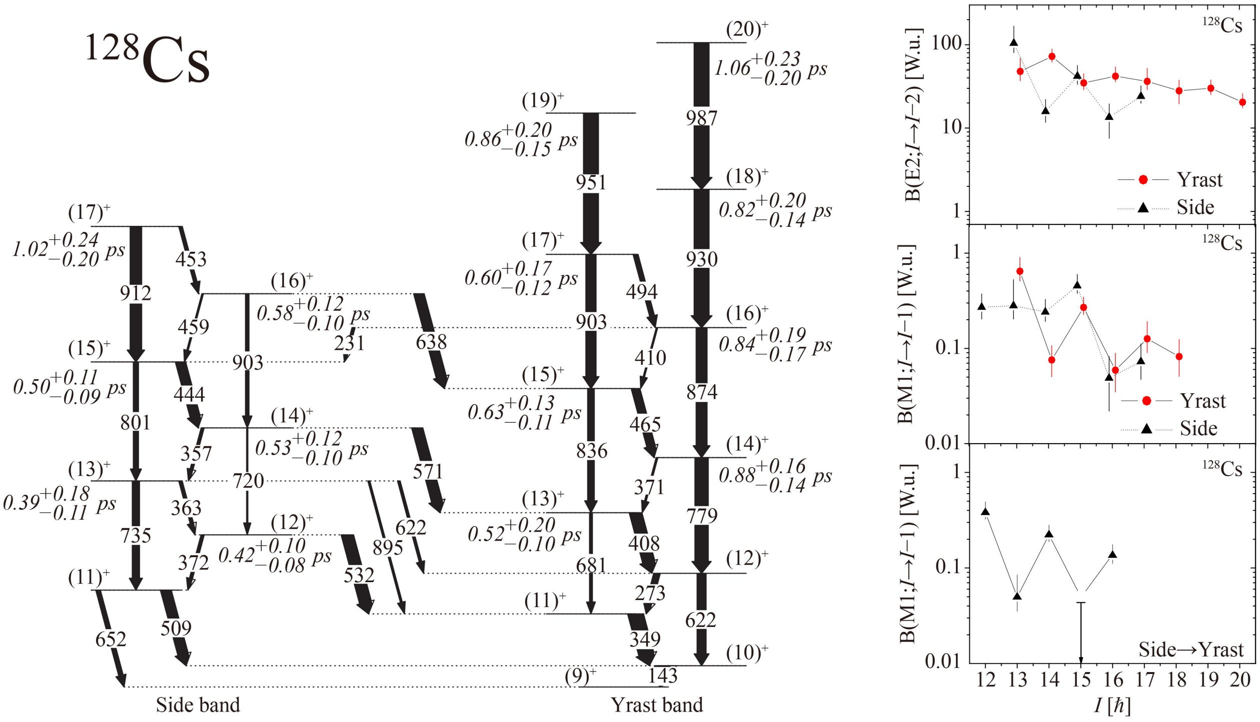


Fig. 2 Partner bands (left panel) and E2 and M1 transitions probabilities (right panel) for ^{128}Cs. Reproduced from Ref. [25].

used. Lifetime of 14 states belonging to partner bands were determined and the corresponding reduced transition probabilities were reported in Refs. [23–25, 28].

The measurement of B(M1) and B(E2) in ^{128}Cs was the first case which indicated similar values of these observables in a set of partner bands, thus confirming the prediction of signature ***F2***, see Fig. 2. Moreover, the parametric analysis of the obtained results [Eqs. (15)–

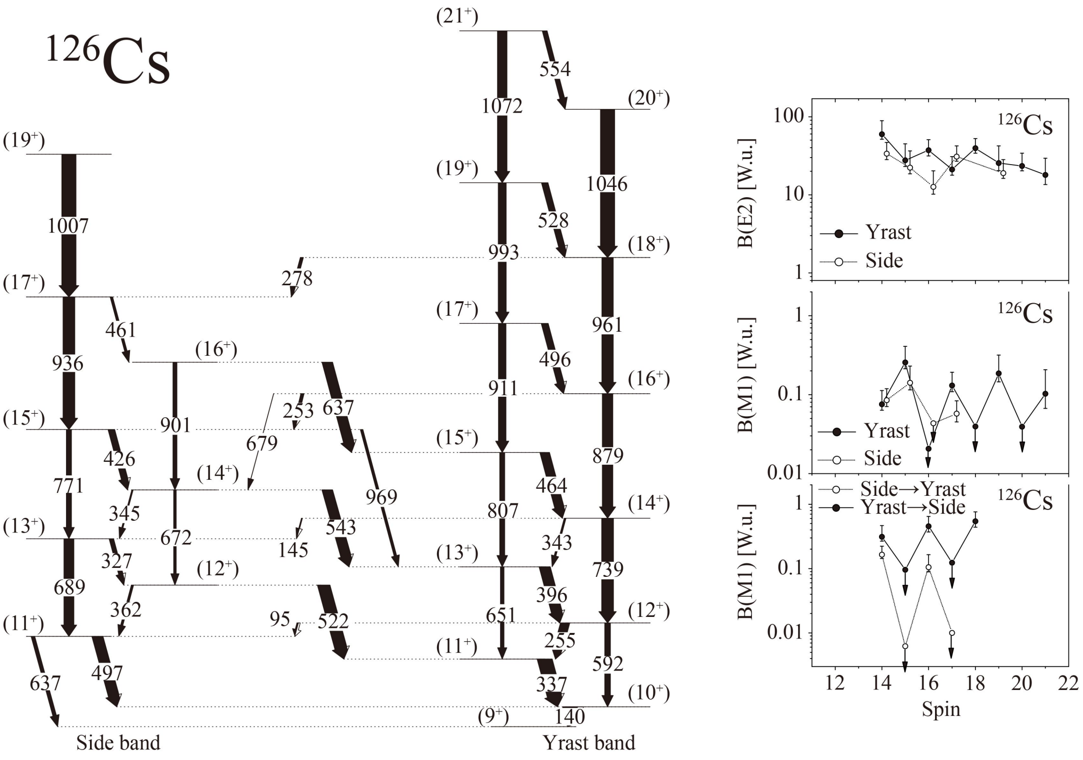


Fig. 3 Partner bands (left panel) and E2 and M1 transitions probabilities (right panel) for ^{126}Cs. Reproduced from Ref. [31].

(17) and Fig. 3 in Ref. [5]] suggests little overlap of opposite-handedness wave functions and no handedness change due to EM transitions which provides further support for the stable chiral-rotation scenario in ^{128}Cs. Alternate high and low B(M1) transition probabilities as a function of spin (the B(M1) staggering) were observed which was explained in the theoretical article [9] that appeared simultaneously with the first experimental results. All model predictions (all signatures ***F1–F4***) applicable to stable chiral rotational mode of ^{128}Cs partner bands were confirmed making ^{128}Cs the best example revealing the chiral symmetry breaking at the time.

3.3 Lifetime measurements of excited states in ^{126}Cs

Although the ^{128}Cs isotope turned out to reproduce all known signatures of stable chiral rotation quite successfully, some additional chiral features predicted theoretically were not yet fully observed. Specifically, not all electromagnetic selection rules predicted in Ref. [9] were detected. Therefore the ^{126}Cs isotope was chosen for the next DSA measurement in Warsaw with the aim to verify all chiral selection rules for EM transitions in partner bands. Again the OSIRIS II array located at HIL was utilized, but this time equipped with 12 ACS HPGe spectrometers. Positive parity rotational partner bands in ^{126}Cs were identified previously in refs [29, 30]. Excited states belonging to these bands were populated via the ^{120}Sn(^{10}B, 4n)^{126}Cs fusion-evaporation reaction. The ^{10}B beam of 55 MeV energy was provided by U200P cyclotron. Again a thick 40 mg/cm^2 target was used. Lifetimes of 13 states in partner bands were determined and reported in the letter paper [31].

In the case of ^{126}Cs, the in-band reduced B(E2) and B(M1) transition probabilities for corresponding levels in the yrast and in side band are similar thus reproducing the signature ***F2*** expected from chiral-rotation model scenario, see Fig. 3. B(M1) staggering for the in-band transitions is also observed in the spin range wider than in ^{128}Cs case. For the first time the B(M1) inter-band transition probabilities in both directions; from yrast to side-band and from side- to yrast band were measured. The B(M1) staggering of the intra-band transitions has opposite phase to that of the in-band one thus confirming the complete set of EM selection rules expected for stable chiral rotation in this isotope (signature ***F4***). These selection rules were interpreted through a new symmetry S in the CPHC model [12, 13] (see also Section 4), which generalized the previous theoretical predictions to γ-soft nuclei. The results obtained for ^{126}Cs confirmed stable chiral rotation and triaxial deformation of this isotope. This suggests that among all isotopes studied by the Warsaw group, just in ^{126}Cs, there exist the most favorable energy conditions for the nuclear chirality to appear.

4 Theoretical interlude

Most papers aimed at theoretical description of the phenomenon of nuclear chirality apply the particle-rotor model (PRM) in its various implementations. In depth analysis of the model can be found in [32], where a basis specially adapted to discussion of chirality is also proposed. One of the assumptions of the PRM model is a rigid deformation of the core. When applied to tentative chiral nuclei the deformation is assumed to be nonaxial (triaxial). On the other hand, nuclei in the $A = 130$ region are known to be rather weakly deformed and susceptible to nonaxial (γ) deformation. To take this fact into account a different model, in some aspects complementary to PRM, was proposed in Ref. [15]. The model is formulated in the laboratory frame and describes a coupling of a particle and a hole to an even–even core through quadrupole interaction (CPHC — Core–Particle–Hole–Coupling). The Hamiltonian contains also terms responsible for core excitations and a particle–hole interaction. It can be viewed as an extension of the Core–Particle–Coupling model [33, 34]. An important feature of the model is that various models of the core can be used, including rigid cores (a la Davydov–Filippov model) as well as cores soft against (β,γ) deformation (a la General Bohr Hamiltonian approach).

Ref. [15] contains a detailed discussion of a theoretical background of the model as well as an application of the model to partner bands in ^{132}La with a rigid triaxial rotor chosen as a core. Existence of the doublet-band structure and its dependence on the parameter of triaxiality (γ) of the core was extensively studied, showing that decisive factor is the value of γ close to 30°. The geometry of the system of three angular momentum vectors were analyzed through calculating average values of respective scalar products. It turned out again that for γ around 30° these products are close to zero indicating chiral geometry. Moreover, it was proposed to use as an indication of the handedness an average value of an orientation operator built in the form of a mixed product

$$\sigma = (\boldsymbol{j}_p \times \boldsymbol{j}_n)\cdot\boldsymbol{j}_R, \tag{1}$$

where $\boldsymbol{j}_p$, $\boldsymbol{j}_n$ and $\boldsymbol{j}_R$ are operators of angular momentum for a proton, a neutron and a core, respectively.

Quite a different core, namely completely γ-soft described by the Wilets-Jean type potential, was used in calculations presented in Ref. [11]. Now, not only energy spectra but also EM transitions were extensively studied. The results, compared with the ones for a rigid core of maximal triaxiality ($\gamma = 30°$), appeared to be very similar; hence, the condition of rigidity of the core as a background of chirality is not essential. Moreover, there was observed a very distinct staggering of the E2 and M1 transitions with $\Delta I = 1$, both for in- and inter-band transitions (cf. Section 2, ***F4***). Similar characteristics were predicted within the PRM model in Ref. [9].

Further analysis in Refs. [12, 13] showed that these distinctive properties of EM transitions as well as near degeneracy of partner bands appear also for more general cores, namely when their Hamiltonian is invariant with respect to the so called P_α symmetry. In the laboratory frame the P_α operator changes the sign of quadrupole variables, $\alpha_\mu \to -\alpha_\mu$. In the intrinsic frame it means, among others, that the potential should be such that $V(\beta,\gamma) = V(\beta, 60° - \gamma)$. Of course, γ-independent potential fulfills that condition. Moreover, if the P_α is appropriately modified for rigid cores, the P_α invariance requires that the value of the triaxiality parameter is 30°. The P_α invariance of the core is, however, not sufficient. In addition, a nucleon and a hole should occupy the same j-level. This condition is quite reasonable, e.g., for nuclei from the $A \sim 130$ region. A new symmetry S proposed in Refs.[12, 13] is a combination

$$S = P_\alpha C_{\text{pn}}, \tag{2}$$

where C_{pn} corresponds to exchanging of a nucleon and a hole. EM selection rules and other consequences of invariance of the Hamiltonian with respect to the S symmetry were then extensively analyzed. The paper [12] also treats various possible ways of breaking the S symmetry, both in the core as well as in the particle–hole sector. The latter case occurs where a particle and a hole occupy different orbitals.

It is worth noting that the CPHC model opens an interesting possibility of extending the microscopic mean-field theory to odd–odd nuclei. A Hamiltonian of an even–even core can be calculated using methods presented e.g. in Ref. [35]. Similarly, one-particle properties can be obtained also from the same HFB theory. With these choices, the only remaining free parameters of the theory are the core-particle coupling parameters.

5 Search for unique signatures of chirality

Large set of experimental facts — from identification of partner bands in level schemes by spectroscopic techniques up to the results of DSA lifetime measurements — show an agreement with chiral interpretation of many isotopes among which the ^{128}Cs and ^{126}Cs seem to be the most thoroughly studied experimentally. Despite rich experimental information, which exists for example for Cs isotopes, questions about the chiral interpretation still arise due to the fact that only indirect signatures of nuclear chirality were observed so far. This is an inevitable situation since there is still a risk that the indirect signatures may result from phenomena other than the nuclear chirality. Let us briefly mention some examples. A possibility of misinterpretation of partner bands as chiral ones was discussed already in Ref. [7] based on rotational moment of inertia analysis in both bands. An interpretation of partner bands as the result of signature splitting was illustrated in Ref. [6] and closely related energy signature staggering $S(I)$ was discussed in Ref. [36]. Part of the EM selection rules predicted for nuclear chirality (the in-band B(M1) staggering) was obtained in Ref. [37] as a result of chopstick-like motion of two angular momenta of unpaired neutron and unpaired proton. Only direct access to nuclear chirality, e.g., by the determination of the geometry of angular momentum coupling for vectors forming the system with handedness can dispel doubts and answer questions regarding the chiral interpretation of some nuclear properties. Such a direct determination is possible, and it was performed for the first time as a *g*-factor measurement of an excited state belonging to partner bands in ^{128}Cs.

6 The *g*-factor measurement as a direct test for nuclear chirality

As we mentioned in the Introduction, nuclear chirality results form a spontaneous (not fundamental) chiral symmetry breaking meaning that there is exactly the same amount of possible configurations with opposite handedness mutually canceling in expectation values of operators which are sensitive to handedness. Hence, the parameter of handedness itself belongs to the quantities unavailable to the experimental detection. A possibility of a direct nuclear chirality measurement can be based on a determination of mutual configuration of angular momentum vectors regardless of the handedness they are forming. The configuration can be expressed through expectation values of scalar products of respective angular momentum vectors. An observable which depends on these products is the magnetic dipole moment and the resulting *g*-factor value of states belonging to partner bands. We explain the main concept of the proposed method using as an example of the ^{128}Cs isotope for which we performed an experiment described at length in Refs. [38, 39].

The partner bands in the ^{128}Cs isotope are built on two quasi-particle $\pi h_{11/2} \otimes \nu^{-1} h_{11/2}$ configuration. In such a case the total level spin $\boldsymbol{J}$ is the result of coupling of angular momentum vectors of three components: the angular momentum of the unpaired proton $\boldsymbol{j}_p$, the angular momentum of the unpaired neutron (hole) $\boldsymbol{j}_n$ and the angular momentum of the even–even core $\boldsymbol{j}_R$. Assuming a definite values of j_p, j_n and j_R (the single-particle coupling scheme) various mutual orientations of these vectors form the same total spin J of the excited state. The unpaired proton, unpaired neutron and the even–even core all have different electric charges; therefore their relative values of the dipole magnetic moment vectors differ from relative values of their angular momentum vectors. While the total level spin $\boldsymbol{J}$ remains the same for various possible mutual orientations of $\boldsymbol{j}_p$, $\boldsymbol{j}_n$, $\boldsymbol{j}_R$, the total dipole magnetic moment and the corresponding *g*-factor of the excited state changes with the orientation of $\boldsymbol{j}_p$, $\boldsymbol{j}_n$, $\boldsymbol{j}_R$ vectors due to the different magnetic moments of these three components. The *g*-factor measurement provides an information on the mutual orientation of the three angular momentum vectors $\boldsymbol{j}_p$, $\boldsymbol{j}_n$, $\boldsymbol{j}_R$ which is the basic principle of the direct nuclear chirality measurement. In such a three component system the *g*-factor of an excited state with spin J is described by the following formula [38]:

$$g = g_{\text{chiral}} - \frac{1}{\boldsymbol{J}^2}\left(g_p\langle \boldsymbol{j}_n \cdot \boldsymbol{j}_R\rangle + g_n\langle \boldsymbol{j}_p \cdot \boldsymbol{j}_R\rangle + g_R\langle \boldsymbol{j}_p \cdot \boldsymbol{j}_n\rangle\right), \tag{3}$$

where g_{chiral} is a *g*-factor expected for the ideal chiral configuration where all three angular momentum vectors are mutually perpendicular. The *g*-factor given by the above formula depends on the mutual orientation of $\boldsymbol{j}_p$, $\boldsymbol{j}_n$, $\boldsymbol{j}_R$ vectors through their scalar products having the same value for opposite handedness configurations, thus in contrast to the expectation value of handedness itself the expected *g*-factor does not cancel out in the states observed experimentally. The information on mutual configuration of the three spins $\boldsymbol{j}_p$, $\boldsymbol{j}_n$, $\boldsymbol{j}_R$ in an excited state can be obtained regardless of the handedness that these three spins are forming.

7 The *g*-factor experiment in ^{128}Cs isotope as the first direct nuclear chirality measurement

The *g*-factor experiment as the proof of concept for a method of direct determination of nuclear chirality was performed for the $I = 9^+$ state in ^{128}Cs. This state is the bandhead of the doublet-band structure [38, 39]. The half-life of this state is 56 ns making it suitable for the Time Dependent Perturbed Angular Distribution method which is very precise for dipole magnetic moment and the corresponding *g*-factor measurements. In this method an external magnetic field is applied causing the excited state magnetic moment vector to precess around the external field axis. The precession frequency depends on the amplitude of the external magnetic field as well as on the value of the dipole magnetic moment. While the amplitude of the external field is known the value of the magnetic moment of the excited state can be determined provided that enough precession angle is registered between subsequent beam pulses.

The ^{128}Cs isotope was produced in the ^{122}Sn(^{10}B,4n) ^{128}Cs reaction at 55 MeV beam energy. The pulsed beam with 400 ns repetition period was provided by the TANDEM accelerator of the ALTO facility at IPN Orsay. The self supporting ^{122}Sn target 22 mg/cm^2 thick

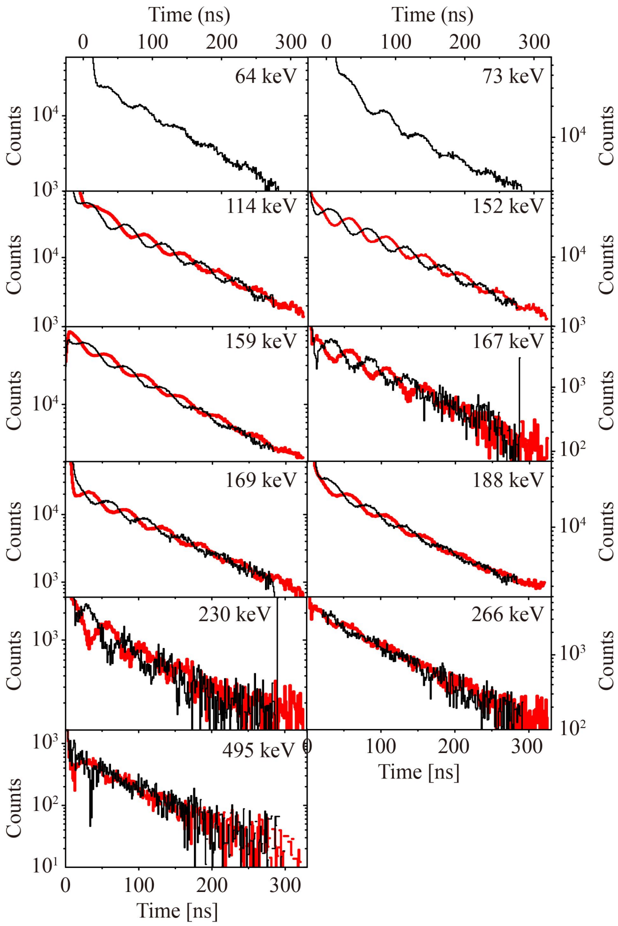


Fig. 4 Intensity oscillation spectra registered by LEPS detectors of several transitions following a decay of the $I = 9$ state in ^{128}Cs. Black lines shows the intensity registered at +45° with respect to beam axis while red lines show the intensity seen at −45°, see also Ref. [39] from which the figure is taken.

played simultaneously the role of the stopper for the recoils. External magnetic field of nearly 0.8 T was generated by the Orsay electromagnet and was amplified/focused with help of GAMIPE setup reaching 2.146 T at the beam spot position. The precession of $I = 9^+$ state magnetic moment was observed by two LEPS detectors placed at +45° and −45° angles with respect to beam direction as an oscillating gamma radiation intensity coming from initial spin alignment after the fusion-evaporation reaction and the resulting precession of anisotropic distribution of the gamma radiation. Almost seven full gamma intensity oscillation periods were detected between beam pulses making very precise g-factor determination possible. Figure 4 shows oscillations of the intensity of EM radiation for several transitions following a decay of the $I = 9$ state.

The g-factor expected in the chiral configuration of $\boldsymbol{j}_p$, $\boldsymbol{j}_n$, $\boldsymbol{j}_R$ vectors forming the $I = 9$ total spin was $g = 0.5$ [12]. Moreover the same $g = 0.5$ value was expected in a non-chiral scenario where $j_R = 0$ and the total $I = 9$ spin is formed chiefly by angular momentum vectors $\boldsymbol{j}_p$, $\boldsymbol{j}_n$ of two unpaired nucleons. The result obtained experimentally $g = 0.59(1)$ did not fit to the above expectations and proved both:

i) The spin of the $I = 9$ bandhead cannot be built by coupling only two $\boldsymbol{j}_p$, $\boldsymbol{j}_n$ angular momentum vectors. There must be significant contribution of the core rotation $\boldsymbol{j}_R$ similar to that of the unpaired nucleons which implies that the chiral angular momentum coupling in the $I = 9$ bandhead is possible.

ii) The three angular momentum vectors $\boldsymbol{j}_p$, $\boldsymbol{j}_n$, $\boldsymbol{j}_R$ must be oriented close to one 2D plane giving non-chiral geometry of the $I = 9$ bandhead in order to reproduce the $g = 0.59(1)$ experimental value.

Non-chiral character of the $I = 9$ bandhead together with the complete set of chiral features of the partner bands in ^{128}Cs above spin $I = 13$ suggest an evolution from non-chiral to chiral configuration of three $\boldsymbol{j}_p$, $\boldsymbol{j}_n$, $\boldsymbol{j}_R$ angular momentum vectors with increasing rotational frequency. Whether it is a gradual evolution or a sharp, phase-transition like, jump is an interesting topic related to the predicted (and not observed so far) chiral critical frequency [40]. The results of this experiment therefore successfully proved the concept of the direct chiral geometry verification via measuring the g-factor value. The mutual orientation of the three angular momentum vectors obtained in this method gives the unique and hardly questionable chirality verification data that is a big advantage of this method. However, experimental determination of the g-factor values in states other than the rotational bandheads is very difficult due to shorter lifetimes of these states (in the picoseconds rather than nanoseconds range).

8 Future perspectives for chirality experiments in warsaw

In the case of ^{128}Cs there are abundant data obtained for the chiral states in partner bands with spins a few units above the head of rotational partner bands. Similar situation occurs for the ^{126}Cs and ^{124}Cs [41] isotopes. In contrast, as can be seen also from the results of the g-factor experiment in ^{128}Cs, very little is known about EM properties of the excited states in partner bands close to the bandhead. Lifetime measurements of these states in ^{128,126,124}Cs isotopes with the plunger technique are the lowest hanging fruit for the most recent experimental study of chirality in Warsaw.

Another, more remote, perspective of chirality studies is measurement of g-factors in the ^{124,126}Cs isotopes. The g-factor measurement of $I = 9$ bandhead in ^{128}Cs was possible since the bandhead's lifetime is 56 ns, a value suitable for application of the TDPAD method. It is worth noting that this experimental value appeared to be very close to the one estimated before the experiment. The first step to pave the way for similar measurements in ^{126}Cs and ^{124}Cs is identification of the heads of partner bands in these isotopes. Again the estimated lifetimes are in the nanosecond range. This first step can be done at HIL and to perform such measurements the new EAGLE-EYE array [42] consisting of 16 HPGe and 21 LaBr3 detectors was recently constructed.

Declarations The authors declare that they have no competing interests and there are no conflicts.

Acknowledgements We want to express our deep gratitude to our late colleagues, Alexandr A. Pasternak and Tomasz Morek, for a long-standing collaboration and a significant contribution to our studies of nuclear chirality. In particular, to Alexandr A. Pasternak for playing a leading role in DSAM analysis and creating excellent software and to Tomasz Morek for a very important role in all stages of experiments and data analysis.

References

1. A. Bohr and B. R. Mottelson, Nuclear Structure, Vol. I, Benjamin Inc., 1969
2. E. Grodner, Staggering of the B(M1) value as a fingerprint of specific chiral bands structure, *Int. J. Mod. Phys. E* 20, 380 (2011)
3. B. W. Xiong and Y. Y. Wang, Nuclear chiral doublet bands data tables, *At. Data Nucl. Data Tables* 125, 193 (2019)
4. E. Grodner, S. G. Rohoziński, and J. Srebrny, Simple picture of the nuclear system diverging from the strong chiral symmetry breaking limit, *Acta Phys. Pol. B* 38, 1411 (2007)
5. E. Grodner, Quest for the chiral symmetry breaking in atomic nuclei, *Acta Phys. Pol. B* 39, 531 (2008)
6. E. Grodner, J. Srebrny, A. A. Pasternak, Ch. Droste, M. Kowalczyk, M. Kisieliński, J. Mierzejewski, M. Gołębiowski, T. Marchlewski, T. Krajewski, D. Karpinski, P. Olszewski, P. Jones, T. Abraham, J. Perkowski, L. Janiak, J. Samorajczyk, J. Andrzejewski, J. Kownacki, K. Hadyńska-Klęk, P. Napiorkowski, M. Komorowska, and S. F. Ozmen, Spontaneous time reversal symmetry breaking in ^{124}Cs, *AIP Conf. Proc.* 1491, 140 (2012)
7. C. M. Petrache, G. B. Hagemann, I. Hamamoto, and K. Starosta, Risk of misinterpretation of nearly degenerate pair bands as chiral partners in nuclei, *Phys. Rev. Lett.* 96, 112502 (2006)
8. T. Koike, K. Starosta, P. Joshi, G. Rainovski, J. Timar, C. Vaman, and R. Wadsworth, Recent progress on the investigation of spontaneous formation of chirality in rotating nuclei, *J. Phys. G (London)* 31, S1741 (2005)
9. T. Koike, K. Starosta, and I. Hamamoto, Chiral bands, dynamical spontaneous symmetry breaking, and the selection rule for electromagnetic transitions in the chiral geometry, *Phys. Rev. Lett.* 93, 172502 (2004)
10. S. Frauendorf and J. Meng, Tilted rotation of triaxial nuclei, *Nucl. Phys. A* 617, 131 (1997)
11. Ch. Droste, S. G. Rohoziński, K. Starosta, L. Próchniak, and E. Grodner, Chiral bands in odd–odd nuclei with rigid or soft cores, *Eur. Phys. J. A* 42, 79 (2009)
12. S. G. Rohoziński, L. Próchniak, K. Starosta, and Ch. Droste, Odd–odd nuclei as the core particle–hole systems and chirality, *Eur. Phys. J. A* 47, 90 (2011)
13. L. Próchniak, S. G. Rohoziński, Ch. Droste, and K. Starosta, A symmetry of the CPHC model of odd–odd nuclei and its consequences for properties of M1 and E2 transitions, *Acta Phys. Pol. B* 42, 465 (2011)
14. K. Starosta, T. Koike, C. J. Chiara, D. B. Fossan, D. R. LaFosse, A. A. Hecht, C. W. Beausang, M. A. Caprio, J. R. Cooper, R. Krucken, J. R. Novak, N. V. Zamfir, K. E. Zyromski, D. J. Hartley, D. L. Balabanski, J.-Y. Zhang, S. Frauendorf, and V. I. Dimitrov, Chiral doublet structure in odd–odd N=75 isotones: Chiral vibrations, *Phys. Rev. Lett.* 86, 971 (2001)
15. K. Starosta, C. J. Chiara, D. B. Fossan, T. Koike, T. T. S. Kuo, D. R. LaFosse, S. G. Rohoziński, Ch. Droste, T. Morek, and J. Srebrny, Role of chirality in angular momentum coupling for A~130 odd–odd triaxial nuclei: ^{132}La, *Phys. Rev. C* 65, 044328 (2002)
16. Y. Liu, J. Lu, Y. Ma, S. Zhou, and H. Zheng, Systematic study of spin assignments and signature inversion of $\pi h_{11/2}\otimes\nu h_{11/2}$ bands in doubly odd nuclei around A~130, *Phys. Rev. C* 54, 719 (1996)
17. J. Timar, D. Sohler, B. M. Nyako, L. Zolnai, Z. Dombradi, E. S. Paul, A. J. Boston, C. Fox, P. J. Nolan, J. A. Sampson, H. C. Scraggs, A. Walker, J. Gizon, A. Gizon, D. Bazzacco, S. Lunardi, C. M. Petrache, A. Astier, N. Buforn, P. Bednarczyk, and N. Kintz, Experimental evidence for signature inversion in ^{132}La from a revisited level scheme, *Eur. Phys. J. A* 16, 1 (2003)
18. R. A. Bark, A. M. Baxter, A. P. Byrne, G. D. Dracoulis, T. Kibedi, T. R. McGoram, and S. M. Mullins, Candidate chiral band in ^{134}La, *Nucl. Phys. A* 691, 577 (2001)
19. K. Starosta, T. Koike, C. J. Chiara, D. B. Fossan, and D. R. LaFosse, Chirality in odd–odd triaxial nuclei, *Nucl. Phys. A* 682, 375c (2001)
20. L. L. Riedinger, D. J. Hartley, A. Galindo-Uribarri, B. H. Smith, C. Baktash, M. P. Carpenter, M. Danchev, M. Devlin, C. J. Gross, R. V. F. Janssens, M. Lipoglavsek, S. D. Paul, D. C. Radford, W. Reviol, D. G. Sarantites, D. Seweryniak, C.-H. Yu, and O. Zeidan, Signature inversion in odd–odd nuclei, *Acta Phys. Pol. B* 32, 2613 (2001)
21. E. Grodner, A. A. Pasternak, Ch. Droste, T. Morek, J. Srebrny, J. Kownacki, W. Płóciennik, A. A. Wasilewski, M. Kowalczyk, M. Kisieliński, R. Kaczarowski, E. Ruchowska, A. Kordyasz, and M. Wolinska, Lifetimes and side-feeding population of the yrast band levels in ^{131}La, *Eur. Phys. J. A* 27, 325 (2006)
22. E. Grodner, J. Srebrny, Ch. Droste, T. Morek, A. Pasternak, and J. Kownacki, DSAM lifetime measurements in the yrast band of ^{131}La and the chiral bands in ^{132}La, *Int. J. Mod. Phys. E* 13, 243 (2004)
23. E. Grodner, I. Zalewska, T. Morek, J. Srebrny, Ch. Droste, M. Kowalczyk, J. Mierzejewski, M. Salata, A. A. Pasternak, J. Kownacki, M. Kisieli«ski, A. Kordyasz, P.

Napiorkowski, M. Wolińska, S. G. Rohoziński, R. Kaczarowski, W. Płóciennik, E. Ruchowska, A. Wasilewski, and J. Perkowski, Lifetime measurements in ^{128}Cs and ^{132}La as a test of chirality, *Int. J. Mod. Phys. E* 14, 347 (2005)

24. J. Srebrny, E. Grodner, T. Morek, I. Zalewska, Ch. Droste, J. Mierzejewski, A. A. Pasternak, J. Kownacki, and J. Perkowski, Search for chirality in ^{128}Cs and ^{132}La, *Acta Phys. Pol. B* 36, 1063 (2005)
25. E. Grodner, J. Srebrny, A. A. Pasternak, I. Zalewska, T. Morek, Ch. Droste, J. Mierzejewski, M. Kowalczyk, J. Kownacki, M. Kisieliński, S. G. Rohoziński, T. Koike, K. Starosta, A. Kordyasz, P. J. Napiorkowski, M. Wolińska-Cichocka, E. Ruchowska, W. Płóciennik, and J. Perkowski, ^{128}Cs as the best example revealing chiral symmetry breaking, *Phys. Rev. Lett.* 97, 172501 (2006)
26. T. Koike, K. Starosta, C. J. Chiara, D. B. Fossan, and D. R. LaFosse, Observation of chiral doublet bands in odd–odd N=73 isotones, *Phys. Rev. C* 63, 061304 (2001)
27. T. Koike, K. Starosta, C. J. Chiara, D. B. Fossan, and D. R. LaFosse, Systematic search of $\pi h_{11/2}\otimes\nu h_{11/2}$ chiral doublet bands and role of triaxiality in odd–odd Z=55 isotopes: $^{128,\ 130,\ 132,\ 134}$Cs, *Phys. Rev. C* 67, 044319 (2003)
28. E. Grodner, J. Srebrny, I. Zalewska, T. Morek, Ch. Droste, M. Kowalczyk, J. Mierzejewski, A. A. Pasternak, J. Kownacki, and M. Kisieliński, Support for the chiral interpretation of partner bands in ^{128}Cs – the electromagnetic properties, *Int. J. Mod. Phys. E* 15, 548 (2006)
29. G.-S. Li, R. Meng, L.-H. Zhu, Z.-L. Zhang, Y. Wang, Z.-M. Wang, S.-X. Wen, J.-B. Lu, G.-Y. Zhao, X.-F. Li, L.-J. Wen, Y.-N. Zheng, Y. Zheng, Y.-Z. Liu, G.-J. Yuan, and C.-X. Yang, Lifetimes of high spin yrast states in odd–proton nucleus ^{131}Pr, *Chin. Phys. Lett.* 20, 475 (2003)
30. S. Wang, Y. Liu, T. Komatsubara, Y. Ma, and Y. Zhang, Candidate chiral doublet bands in the odd–odd nucleus ^{126}Cs, *Phys. Rev. C* 74, 017302 (2006)
31. E. Grodner, I. Sankowska, T. Morek, S. G. Rohoziński, Ch. Droste, J. Srebrny, A. A. Pasternak, M. Kisieliński, M. Kowalczyk, J. Kownacki, J. Mierzejewski, A. Krol, and K. Wrzosek, Partner bands of ^{126}Cs – first observation of chiral electromagnetic selection rules, *Phys. Lett. B* 703, 46 (2011)
32. K. Starosta and T. Koike, Nuclear chirality, a model and the data, *Phys. Scr.* 92, 093002 (2017)
33. F. Dönau and S. Frauendorf, Description of odd transitional nuclei in terms of core quasiparticle models, *Phys. Lett. B* 71, 263 (1977)
34. Ch. Droste, D. Chlebowska, J. Dobaczewski, F. Dönau, A. Kerek, G. Leander, J. Srebrny, and W. Walus, Collective quadrupole dynamics and the band structure of the nucleus ^{127}Cs, *Nucl. Phys. A* 341, 98 (1980)
35. L. Próchniak and S. G. Rohoziński, Quadrupole collective states within the Bohr collective hamiltonian, *J. Phys. G (London)* 36, 123101 (2009)
36. T. Marchlewski, J. Srebrny, and E. Grodner, Study of chirality in odd–odd Cs isotopes: Search for critical frequency, *Acta Phys. Pol. B Proc. Suppl.* 11, 89 (2018)
37. N. Yoshinaga and K. Higashiyama, A simple model for doublet bands in doubly odd nuclei, *Eur. Phys. J. A* 30, 343 (2006)
38. E. Grodner, J. Srebrny, Ch. Droste, L. Próchniak, S. G. Rohozinski, M. Kowalczyk, M. Ionescu-Bujor, C. A. Ur, K. Starosta, T. Ahn, M. Kisielinski, T. Marchlewski, S. Aydin, F. Recchia, G. Georgiev, R. Lozeva, E. Fiori, M. Zielińska, Q. B. Chen, S. Q. Zhang, L. F. Yu, P. W. Zhao, and J. Meng, First measurement of the g factor in the chiral band: The case of the ^{128}Cs isomeric state, *Phys. Rev. Lett.* 120, 022502 (2018)
39. E. Grodner, M. Kowalczyk, M. Kisieliński, J. Srebrny, L. Próchniak, Ch. Droste, S. G. Rohozinski, Q. B. Chen, M. Ionescu-Bujor, C. A. Ur, F. Recchia, J. Meng, S. Q. Zhang, P. W. Zhao, G. Georgiev, R. Lozeva, E. Fiori, S. Aydin, and A. Nałęcz-Jawecki, Examination of nuclear chirality with a magnetic moment measurement of the I= 9 isomeric state in ^{128}Cs, *Phys. Rev. C* 106, 014318 (2022)
40. P. Olbratowski, J. Dobaczewski, J. Dudek, and W. Płóciennik, Critical frequency in nuclear chiral rotation, *Phys. Rev. Lett.* 93, 052501 (2004)
41. T. Marchlewski, R. Szenborn, J. Samorajczyk, E. Grodner, J. Srebrny, Ch. Droste, L. Próchniak, A. A. Pasternak, M. Kowalczyk, M. Kisieliński, T. Abraham, J. Andrzejewski, P. Decowski, K. Hadyńska-Klęk, L. Janiak, M. Komorowska, J. Mierzejewski, P. Napiorkowski, J. Perkowski, and A. Stolarz, Electromagnetic properties of chiral bands in ^{124}Cs, *Acta Phys. Pol. B* 46, 689 (2015)
42. E. Grodner, M. Kowalczyk, T. Cap, V. Charviakova, S. Mianowski, J. Srebrny, T. Abraham, M. Kisieliński, T. Marchlewski, C. Mihai, R. Mihai, A. Turturica, S. Pascu, and A. Korgul, First fast-timing measurement with triple coincidence techniques at HIL. Construction of the EAGLE-EYE setup, in: HIL Annual Report, Heavy Ion Laboratory UW, Warsaw, Poland, 2017, p. 48