Abstract.
A hypothesis of the chiral symmetry breaking opened a new opportunity for the study of spontaneous time-reversal symmetry breaking in an atomic nucleus. The occurrence of chirality has been found in $^{126,128}\text{Cs}$ nuclei for which specific electromagnetic selection rules have been found in Doppler Shift Attenuation experiments. Here, recent DSA measurements in the $^{124}\text{Cs}$ nucleus are presented. The $^{124}\text{Cs}$ nucleus was produced in the $^{114}\text{Cd}(^{14}\text{N},4\text{n})^{124}\text{Cs}$ reaction at Heavy Ion Laboratory of the University of Warsaw. The obtained results agree with basic expectations deduced from the chiral symmetry breaking. A connection between the chirality phenomenon and the time-reversal symmetry is discussed and a possibility of using chiral doublets for studies of fundamental time reversal symmetry is suggested.

1. Introduction
In the first half of the last century a quantum description of microscopic processes has been postulated by Schrödinger as wave mechanics following a non-relativistic wave equation [1, 2, 3, 4, 5]. Although first relativistic formula has been proposed by several authors [6, 7, 8, 9, 10] including Schrödinger [5] in the same year, the real understanding of it came with the paper of P. Dirac [11, 12] after two years. Such a long period arose due to the problems with interpretation of negative-energy solutions appearing in the quantum relativistic case. These solutions where assigned to particles propagating backward in time that are physically observed as antiparticles. Hence a question about fundamental time-reversal symmetry breaking arose that is not clearly answered until today. Numerous experiments have been performed in order to find the time-reversal symmetry breaking in atomic and nuclear physics (see for example [13, 14]). The results of those experiments show that the contribution of the T-symmetry
breaking terms into the total nuclear Hamiltonian is very small. Instead of looking for such a small effect one may look for a process that may present a conservation of the T-symmetry. An idea of such a process is considered in the next section. Regardless of fundamental conservation or non-conservation of the T-symmetry there is a possibility of its spontaneous breakdown and appearance of nuclear chirality effect. Spontaneous chiral symmetry breaking has been observed in $^{128,126}\text{Cs}$ nuclei as presence of specific gamma selection rules following from the picosecond lifetime measurements. In the present paper first results of DSA lifetime measurements of the states belonging to the chiral partner bands of $^{124}\text{Cs}$ are presented.

2. Fundamental T-symmetry considerations

The unification of space and time by the relativistic mechanics induced a unification of the conjugated values i.e., the momentum and the energy into the four-momentum in the quantum mechanics. In this elegant picture, a reflection of an object in time is described in the same way as a mechanical reflection of the momentum in a collision process.

---

**Figure 1.** Left: electron propagating forward in time collides with photon propagating backward in time. The four-momentum of each particle is reversed by the collision. Center: after the strong interaction of the proton with matter its four momentum is reversed by the photon. The proton propagating backward in time (anti-proton) interacts with antimatter. Right: strong interaction of the proton confined in a time loop. Arrows indicate the four-momentum directions.

An example of such a process involving only electromagnetic interaction is shown in Fig.1-left. An electron propagating forward in time collides with a photon propagating backward in time. After the collision, the electron is scattered back while the photon is scattered forward in time. This process is physically seen as an annihilation of electron and positron into two 511 keV photons. When the time-reversal symmetry of the strong interaction has to be examined one has to replace leptons with hadrons and observe if the interaction of the hadron-particle with matter is the same as hadron-antiparticle with antimatter Fig.1-center. Such an experiment needs to be repeated many times in order to see the small contributions of T-non-conservation effects. However, instead of increasing the statistics one can modify the experiment and use a time loop that tests the interaction an infinite number of times in both - forward and backward time direction Fig.1-right. If small effects of T-non-conservation would accumulate in each cycle then it would possibly lead to the abandonment of the loop by the hadron. In such a case the existence of the loop would not be possible. These are however only academic considerations and regardless of fundamental breaking or conservation of T-symmetry there is a possibility of its spontaneous breakdown due to collective properties of a nucleus. This phenomenon, known as nuclear chirality or spin-chirality, has been intensively studied in the recent decade.
3. Study of the spontaneous spin-chiral symmetry breaking

The phenomenon of nuclear chirality has been postulated in 1997 by S. Frauendorf and J. Meng in Ref.[15]. The most simple case of nuclear chirality relates to odd-odd triaxial nuclei, where the angular momenta of odd nucleons and the angular momentum of the even-even core can form either left or right handed system. Physics laws do not prefer any of the two possible systems meaning that the spin-chiral symmetry is fundamentally conserved. However, selection of one handedness minimizes the energy and breaks the symmetry spontaneously. Actually, spin-chirality is equivalent to spontaneous time-reversal symmetry breaking since the symmetry operation that reverses handedness is a combination of $\pi$-rotation and time reversal. As it was written in Ref.[16] observation of the handedness through the $\gamma$-radiation is not possible since the eigenstates are symmetric or antisymmetric combinations of the left- and right- handed systems. Those combinations form chiral doublets on which two rotational bands – called chiral partner bands – develop. In the first experimental study of nuclear chirality only the chiral partner bands were searched for. It turned out that observation of the partner bands is not a sufficient argument to confirm the presence of the chiral symmetry breaking and the measurement must be augmented by determination of the level lifetimes in the partner bands. The DSA experiments [17, 18] revealed remarkable gamma-selection rules in the $^{128,126}$Cs isotopes as presence of specific $B(M1)$ staggering confirming the spin-chiral symmetry breaking. Here, first DSA results in $^{124}$Cs nucleus are presented.

4. $^{124}$Cs DSA lifetime measurements

![Figure 2](image_url)

**Figure 2.** Entry-states population of $^{124}$Cs (left) and cross-sections (right) as a function of $^{14}$N beam energy bombarding the $^{114}$Cd target calculated using the COMPA code.

The $^{124}$Cs was produced in the $^{114}$Cd($^{14}$N,4n)$^{124}$Cs reaction at the beam energy of 73MeV. The $^{114}$Cd target, 34 mg/cm$^2$ thick played also the role of the stopper. The $^{14}$N beam was provided by the U200P cyclotron located at the Heavy Ion Laboratory of the University of Warsaw [19]. Fig. 2 shows entry-states population of $^{124}$Cs produced in the above reaction calculated using the COMPA code [20]. It is expected that levels close to the yrast (and also to side-band) are mostly populated considering short feeding times. Calculated cross-sections of different reaction channels as a function of $^{14}$N beam energy are also presented in Fig.2. The $\gamma - \gamma$ coincidences were measured by the EAGLE array equipped with 12 ACS germanium spectrometers of around 25% efficiency each.

Fig.3 shows relevant part of the level scheme as observed in our experiment together with preliminary lifetime data and an example of the Doppler disturbed peak. Level spin and parity assignment follows Ref.[21]. The DSA analysis was performed with the COMPA, GAMMA and SHAPE codes described in details in Ref.[20]. Fig.4 presents $B(M1)$ transition probabilities in the yrast band. The presence of two rotational bands, with almost degenerate spin and parity
levels indicates spontaneous breakdown of the chiral symmetry in $^{124}$Cs. Though we report here the B(M1) staggering only in the yrast band, it agrees with the chiral scenario of $^{124}$Cs due to possible occurrence of the S-symmetry [22]. According to Ref.[22], the S-symmetry may appear together with the chiral symmetry breaking and indicates the $\gamma = 30^{\circ}$ triaxial deformation.

5. From spin-chirality back to fundamental time-reversal symmetry
The electromagnetic selection rules observed in the partner bands of $^{128,126}$Cs and in the yrast band of $^{124}$Cs suggest that the spin-chiral symmetry appears in nature. The symmetry is
not broken ideally since the energy separation between the chiral doublets is around 150keV. However, there are other nuclei where the energy separation of the doublets (claimed to be chiral ones) is around 10keV [23, 24]. These doublets may be used for the measurement of the fundamental time-reversal symmetry breaking. An example of use of doublet states for study of the time-reversal symmetry is given in Ref.[25] in which the Electric Dipole Moments had been measured. In the chiral scenario the EDM is substituted by a specific magnetic moment related to spin-configuration. Measurements of magnetic moments of short lived states are extremely complicated, therefore here we concentrate on γ-correlation methods. An extensive description of the γ−γ correlation methods used to study the time-noninvariant components of the strong interaction is given in Ref.[26]. The main principles of these methods are based on the fact that the phase convention making values of all electromagnetic matrix elements real breaks down due to the presence of T-violating terms in the strong interactions. In such a scenario there should be a complex phase \( e^{i\phi} \) difference between the matrix elements which can be determined through the measurement of the mixed (M1/E2) gamma radiation. Such a measurement has been reported in Refs.[27, 28, 13] where the T-violating contributions to the nuclear Hamiltonian were investigated. Today, the knowledge of the existence of two different states with opposite chiralities \( |I, +\rangle, |I, -\rangle \) which are the eigenstates of the \( R_y T \) operator, can be utilized. Due to the presence of T-violating interactions the \( R_y T \) symmetry is also broken and none of these states is a true chirality eigenstate. In fact, the mixing of the doublets can be calculated in the first order perturbation theory as

\[
|I, +\rangle_\text{mixed} = |I, +\rangle + \frac{|I, -\rangle \langle I, -| H_{R_y T} |I, +\rangle}{E_+ - E_-} = |I, +\rangle + \delta |I, -\rangle \quad (1)
\]

\[
|I, -\rangle_\text{mixed} = |I, -\rangle + \frac{|I, +\rangle \langle I, +| H_{R_y T} |I, -\rangle}{E_- - E_+} = |I, -\rangle + \delta |I, +\rangle \quad (2)
\]

where \( H_{R_y T} \) denotes the T-violating part of the Hamiltonian. Note that the sum over all intermediate states has been truncated to a single state by assuming the doublet members to be very close in energy. If the relative contribution of the T-violating terms into the total Hamiltonian is on the level of \( 10^{-n} \) then the \( \langle I, -| H_{R_y T} |I, +\rangle \) non-diagonal matrix element constitutes \( 10^{-n} \) part of the typical energy of the strong interaction, i.e. \( 10^{-n} \) MeV. Without using doublet states, the mixing amplitude \( \delta \) will be also in the order of \( 10^{-n} \). In a chiral doublet with the energy degeneracy of round 10 keV, the mixing amplitude will increase two orders of magnitude to \( 10^{-n+2} \) because of the small denominator in eqs.(1,2). It gives favorable conditions for the fundamental time-reversal symmetry study.

6. Summary
The chiral scenario was not predicted for light Cs isotopes, however, the preliminary results of the DSA lifetime measurements in \(^{124}\text{Cs}\) show possible presence of the spin-chiral symmetry breaking. Although the requirement of nearly particle-hole configuration of the chiral partner bands in odd-odd Cs nuclei is not fully met in \(^{124}\text{Cs}\) (the odd neutron does not possess the pure hole-like character) the chiral features of the partner bands are observed. It seems that location of the odd nucleons with respect to the Fermi level may not strictly fulfill the theoretical conditions for the spin-chiral symmetry to be broken. This gives rise for the search of the chiral phenomena in the nuclei that are not considered as chiral ones by model calculations. Another reason for the detailed examination of spin-chirality is the possibility of the fundamental time-reversal symmetry study where the chiral doublets are involved. In such a case the unique features of the nuclear structure may be used to magnify the symmetry breaking effects in the fundamental quantum mechanics.
6.1. Acknowledgments
This work was supported in part by the Polish Ministry of Science under contract No. N N202 169736.

References
[1] E. Schrödinger, Annalen der Physik 79, 361 (1926)
[2] E. Schrödinger, Annalen der Physik 79, 489 (1926)
[3] E. Schrödinger, Annalen der Physik 79, 734 (1926)
[4] E. Schrödinger, Annalen der Physik 80, 437 (1926)
[5] E. Schrödinger, Annalen der Physik 81, 109 (1926)
[6] L. Broglie, Comptes Rendus 183, 272 (1926)
[7] V. Fock, Z. Phys. 38, 242 (1926)
[8] W. Gordon, Z. Phys. 40, 117 (1926)
[9] O. Klein, Z. Phys. 37, 895 (1926)
[10] J. Kudar, Annalen der Physik 81, 632 (1926)
[11] P. A. M. Dirac, Proc. Roy. Soc. A117, 610 (1928)
[12] P. A. M. Dirac, Proc. Roy. Soc. A118, 351 (1928)
[13] J.L. Gimlett, H.E. Henrikson, F. Boehm, Phys. Rev. C25, 1567 (1982)
[14] C. R. Christenson, Phys. Rev. Lett. 13, 138 (1987).
[15] S. Frauendorf, Jie Meng, Nucl. Phys. A617, 131 (1997).
[16] E. Grodner, Int. J. Mod. Phys. E20, 380 (2011).
[17] 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. Kolke, K. Starosta, A. Kordyasz, P. J. Napierkowski, M. Woźnińska-Cichocka, E. Ruchowska, W. Płóciennik, J. Perkowski, Phys. Rev. Lett. 97, 172501 (2006).
[18] 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. Król, K. Wrzosek Phys. Lett. B703, 46 (2011).
[19] Heavy Ion Laboratory, www.slcj.uw.edu.pl
[20] 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, M. Woźnińska, Eur. Phys. J A27, 325 (2006).
[21] A. Gizon, J. Timár, J. Gizon, B. Weiss, D. Barnéoud, C. Foin, J. Genevey, F. Hannachi, C.F. Liang, A. Lopez-Martens, P. Paris, B.M. Nyakó, L. Zolnai, J.C. Merdinger, S. Brant, V. Paar, Nucl. Phys. A694, 63 (2001).
[22] L. Próchniak, S.G. Rohoziński, Ch. Droste, K. Starosta, Acta Phys. Pol. B42, 465 (2011).
[23] K. Starosta, in Nuclei at the Limits, edited by T. L. Khoo and D. Seweryniak, AIP Conf. Proc. No. 764 (AIP, New York, 2005), p. 77.
[24] C. Vaman, D. B. Fossan, T. Kolke, and K. Starosta, Phys. Rev. Lett. 92, 032501 (2004)
[25] N. Auerbach, Nucl. Phys. A787, 532c (2007)
[26] B.A. Jacobson, E.M. Henley, Phys. Rev. 113, 234 (1959).
[27] N. K. Cheung, H.E. Henrikson, F. Boehm, Phys. Rev. C16, 2381 (1977)
[28] J.L. Gimlett, H.E. Henrikson, N.K. Cheung, F. Boehm, Phys. Rev. Lett. 42, 354 (1979)