ERNEST GRODNER

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Ernest Grodner

2 . Diplomas, scientific/artistic degrees - including name, date and place of issue together with the doctoral dissertation title:

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Master degree given by Faculty of Physics, University of Warsaw, June 2002

b. PhD degree obtained in December 2006 at the Faculty of Physics, University of Warsaw. Doctoral dissertation title:" Lifetime measurements of excited states in 132La and 128Cs as a test of the chiral symmetry breaking".

3. Information on previous employment in scientific / artistic units:

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b. University of Warsaw, March 2007 - March 2009, research associate

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d. University of Warsaw, March 2009 - March 2017, research associate

e. National Centre for Nuclear Research, since March 2017, research associate

4. Indication of the achievement* resulting from art. 16 sec. 2 of the Act of 14 March 2003 on academic degrees, academic titles, and degrees and titles in the field of art (Dz. U. 2016 r. poz. 882 ze zm. w Dz. U. z 2016 r. poz. 1311.):

a. Title of the scientific achievement:

"Verification of the hypothesis of chiral symmetry breaking in atomic nuclei."

b. List of publications:

[H1] E. Grodner, J. Srebrny, U. Rybicka,
"Jądra atomowe spontanicznie łamią symetrię odwracania czasu"
Foton 132, Wiosna 2016

[H2] E. Grodner, J. Srebrny, A. A. Pasternak, Ch. Droste, M. Kowalczyk, M. Kisieliński, J. Mierzejewski, M. Gołębiowski, T. Marchlewski, T. Krajewski, D. Karpiński, P. Olszewski, P. Jones, T. Abraham, J. Perkowski, Ł. Janiak, J. Samorajczyk, J. Andrzejewski, J. Kownacki, K. Hadyńska-Klęk, P. Napiorkowski, M. Komorowska, S. F. Özmen
"Spontaneous Time-reversal Symmetry Breaking in 124 Cs"
American Institute of Physics Conf. Proc. 1491, 140 (2012)

[H3] E. Grodner,
"Staggering of the B(M1) value as a fingerprint of specific chiral bands structure"
International Journal of Modern Physics E Vol. 20, No. 2, 380–386 (2011)

[H4] E. Grodner
"DSA lifetime measurements in 132 La in the context of spontaneous chiral symmetry breaking accompanied by the new S-symmetry."
Journal of Physics: Conference Series 366 012022 (2012)

[H5] E. Grodner, S.G. Rohoziński, J. Srebrny
"Simple picture of the nuclear system diverging from the strong chiral symmetry breaking limit"
Acta Physica Polonica B38, No. 4, 1411 (2007)

[H6] E. Grodner
"Quest for the chiral symmetry breaking in atomic nuclei"
Acta Physica Polonica B39, No. 2 ,531 (2008)

[H7] 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
"Partner bands of ^{126}Cs – first observation of chiral electromagnetic selection rules"
Physics Letters B703, 46-50 (2011)

[H8] E. Grodner, A.A. Pasternak, J. Srebrny, M. Kowalczyk, J. Mierzejewski, M. Kisieliński, P. Decowski, Ch. Droste, J. Perkowski, T. Abraham, J. Andrzejewski, K. Hadyńska-Klęk, Ł. Janiak, A. Kasparek, T. Marchlewski, P. Napiorkowski, J. Samorajczyk
"DSA lifetime measurements of ^{124}Cs and the time-reversal symmetry"
Journal of Physics: Conference Series, 381, 012067 (2012)

[H9] E. Grodner, J. Srebrny, Ch. Droste, L. Próchniak, S. G. Rohoziński, M. Kowalczyk, M. Ionescu-Bujor, C. A. Ur, K. Starosta, T. Ahn, M. Kisieliński, 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, J. Meng
"First Measurement of the g Factor in the Chiral Band: The Case of the ^{128}Cs Isomeric State"
Physical Review Letters 120, 022502 (2018)

c. Omówienie celu naukowego ww. pracy/prac i osiągniętych wyników wraz z omówieniem ich ewentualnego wykorzystania.

Verification of the hypothesis of chiral symmetry breaking in atomic nuclei

1 Chirality - a concept used in several science areas

The phenomenon of chirality is known in many fields of physics as well as in chemistry and biology. Chirality concept in general means the existence of two states with opposite handedness - the left-handed $|L\rangle$ and the right-handed $|R\rangle$, which describe a given phenomenon or structure of objects. The term chirality refers to the Greek word 'cheir' meaning hand. In this context, chirality refers to the left- or to the right-hand. Transforming the left hand into the right one and vice verse is not possible only by rotation, it requires mirroring. Therefore, the geometric structure of the left hand is not identical to the geometric structure of the right one.

An example of geometric chirality is the structure of certain chemical molecules that occur in two forms (enantiomers): left-handed or right-handed, fig. 1 [1]. The basic description of the molecular chirality can

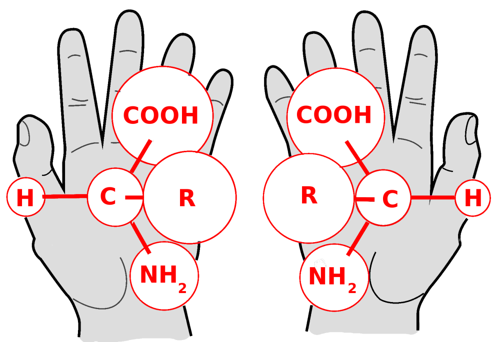

Figure 1: An example of enantiomers i.e. two molecules with the same composition and with mirror reflected geometry.

be reduced to a space-inversion operator (parity) and to a system of three position vectors spanning the three-dimensional space. These vectors may form the left- or the right-handed reference frame and the superposition of space-inversion P and pi-rotation R_π transforms the left-handed system into the right-handed one and vice-verse $R_\pi P|L\rangle = |R\rangle$. The chemical composition of the right- and the left-handed molecules is the same, which makes it difficult to determine their structure with chemical methods. In this context, the human sense of smell is a curiosity, since it is able to distinguish the handedness of certain aromatic molecules. The human 'nose' feels the right-handed molecule of the citrus fruits aroma - fig. 2 - like the aroma of a fresh fruit, whereas the left-handed form of this molecule smells as an acrid odor similar to turpentine [2].

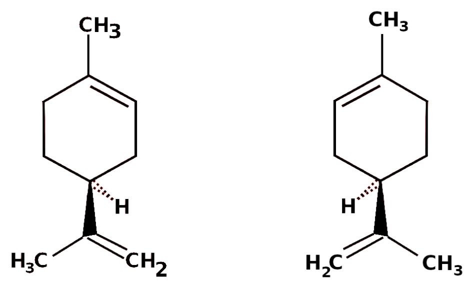

Figure 2: The left- and the right-handed citrus fruits aroma molecules. The human sense of smell distinguishes the molecules' handedness by feeling different fragrances.

In the molecular chirality research an effective 'nose' which is able to distinguish the handedness of a molecule is based on polarized beams of light. It is worth to mention that the chirality phenomenon is present in the field of optics as well. In a quantum picture the chirality of a laser beam with a specific wavelength and wave vector $\vec{k}$ is defined as $\chi = \hbar ck \left(\hat{N}^L - \hat{N}^R\right)$, where $\hat{N}^L$ or $\hat{N}^R$ is the photon number with left- or right-handed circular polarization constituting the beam [3],[4]. The maximum chirality i.e. the maximum right/left handedness of the optical beam occurs when it consists only of photons with one circular polarization R/L. Therefore, there is an important aspect of optical chirality which is similar to the chirality in the field of nuclear physics described here i.e., there can be a smooth change of the handedness between two extreme values depending on the number of L or R circular polarized photons present in the beam. Circular polarization of photon is determined by the spin projection $\vec{s}$ on the momentum vector $\vec{p}$: $\vec{s} \cdot \vec{p}$, therefore the handedness in the optical chirality phenomenon relates to a 'screw'. For this reason, the handedness is often referred to as 'helicity'.

In the field of weak interactions, the particle handedness, similarly to the circular polarization of photons, is defined as the projection of the particles spin on the momentum vector $\vec{s} \cdot \vec{p}$, which also leads to the concept of chirality. The weak interaction is based on the weak-current. An interesting aspect of the weak-current is that it is purely left-handed for massless particles $J^W_\mu = \bar{\psi}\gamma_\mu(1+\gamma_5)\psi = 2\bar{\psi}_L\gamma_\mu\psi_L$ [5]. One can say that in the case of weak interaction of massless particles the chirality do not need a 'nose' because nature itself chooses only the left-handed form of the interaction.

Chirality which is present in quantum chromodynamics is also an important phenomenon that is relevant in the description of the strong interactions.

In all of the above-mentioned chirality phenomena, the operator which reverses the handedness is the combination of pi-rotation R_π and space inversion P. Therefore, these phenomena are closely related to the concept of parity . Nuclear chirality is a phenomenon other than the mentioned above and it is not related to parity.

2 Nuclear chirality

The phenomenon of nuclear chirality which is discussed here relates to odd-odd nuclei, i.e. the nuclei consisting of an odd number of protons and an odd number of neutrons. Such nuclei can be described as a coupling of three elements: even-even core R, an odd neutron n, and an odd proton p. Each of these elements can have its own angular momentum vector, therefore, in the discussed add-odd nuclei we deal with the arrangement of three angular momentum vectors j: of the core j_R, of the odd neutron j_n and of the odd proton j_p. In analogy to molecular chirality, these three angular momentum vectors can create the right-handed $|R\rangle$ or the left-handed $|L\rangle$ reference frame, which is shown in fig. 3. Unlike to the vectors

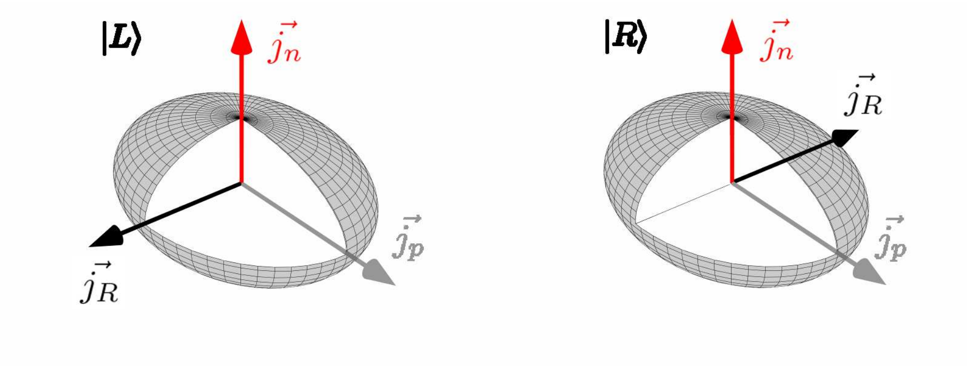

Figure 3: Three mutually perpendicular angular momentum vectors: of the even-even core $\vec{j_R}$, of the odd proton $\vec{j_p}$ and of the odd neutron $\vec{j_n}$ may form the left- $|L\rangle$ or the right-handed $|R\rangle$ reference frame.

of atoms positions in a molecule, the angular momentum is a pseudo-vector, i.e. it changes the sign with the time-reversal T. Therefore, in contrast to chirality concepts in other fields of science, the reversion of the handedness of three angular momentum vectors is related to the time-reversal T instead to the space-inversion P. This makes the nuclear chirality a unique phenomenon that, instead of parity, involves the time-reversal symmetry. The operator commonly used in the nuclear chirality is the superposition of pi-rotation R_π^Y and time-reversal T. The superposition $R_\pi^Y T$ calls the chiral symmetry operator, or simply the chiral operator. Similar to molecular chirality and chirality based on helicity concept, where pi-rotation and space inversion $R_\pi P$ changes the object's handedness to the opposite value, so in the field of nuclear chirality, the superposition $R_\pi^Y T$ reverses the handedness of the three angular momentum vectors $R_\pi T|R\rangle = |L\rangle$, $R_\pi T|L\rangle = |R\rangle$ - see fig. 4. The hypothesis of nuclear chirality, i.e. the existence of the handedness defined by three angular momentum vector in an atomic nucleus has been formulated for the first time in ref.[6]. Chirality phenomenon in the odd-odd nucleus occurs when the three angular

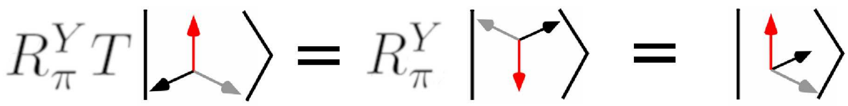

Figure 4: Acting with the chiral symmetry operator $R_\pi^Y T$ on three angular momentum vectors forming the left-handed system. The time-reversal T reverses all angular momentum vectors while the pi-rotation R_π^Y leads finally to the right-handed arrangements of these vectors.

momentum vectors span the three-dimensional space and thus form a system with definite handedness. Not all odd-odd nuclei allow such angular momentum vectors coupling. The chirality phenomenon occurs when **three conditions** corresponding to core deformation and its interaction with odd nucleons are met.

Nucleons forming the even-even core resemble molecules forming a drop of a liquid. In frame of the classical physics, the core would have a hydrodynamic character rather than the character of a solid-state body. The nucleon-nucleon interactions has both a short-range character, responsible for nucleons correlations (pairing), as well as long-range character, responsible for the collective features of the core like its shape. In nuclear physics, the shape of the core is defined by deformation associated with the deviation from the spherical shape.

The first condition for the occurrence of nuclear chirality is the significant triaxial deformation of the core, which roughly corresponds to the shape of the non-axial ellipsoid. Such an ellipsoid possesses three principal axes: short, intermediate and long axis, see fig. 5. In case of triaxially deformed solid body the greatest moment of inertia occurs for rotation around the short axis. However, the core has a hydrodynamic character and the largest moment of inertia occurs for rotation around the intermediate axis [7]. Therefore, it is expected that the core angular momentum vector is oriented close to the direction

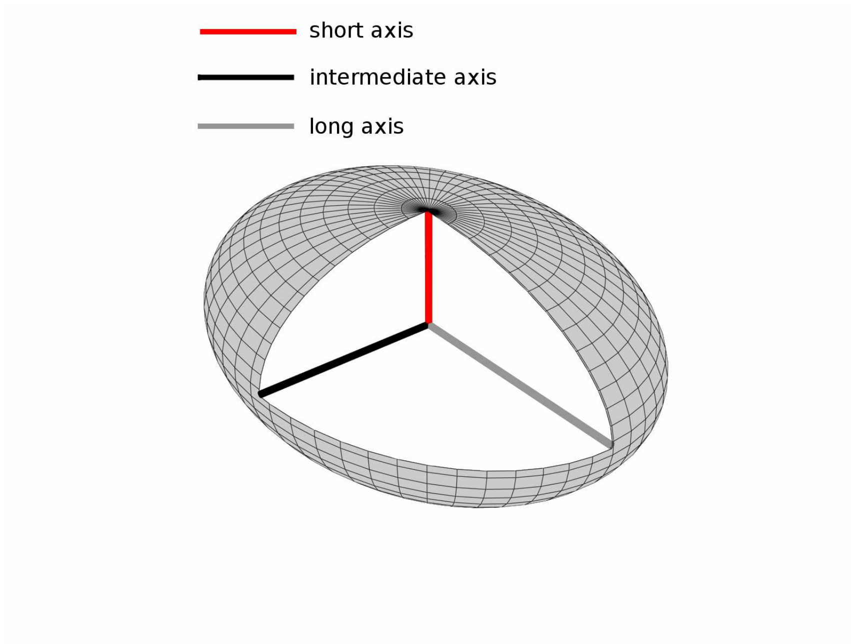

Figure 5: Triaxial shape of an even-even core corresponds to a non-axial ellipsoid where three principal axes can be distinguished: the short axis marked in red , the intermediate axis marked in black and the long axis marked in grey colour.

defined by the intermediate axis.

Attractive nuclear forces are responsible for binding the odd nucleons to the core. Therefore, an odd nucleon will choose a state which spatially overlaps with the shape of the core as much as possible. Since nucleons are subject to Pauli's rule, they can only choose states that are not occupied. In the case of a large number of unoccupied states in the shell, an odd nucleon will choose one with a large spatial overlap with the core. In the frame of quantum many-body problem with pairing, such a nucleon has a particle character and its state lies above the Fermi level. In opposite, if the shell is almost fully occupied, then the odd nucleon will choose the state at the top of the shell with a small spatial overlap with the core. This state is below the Fermi level and has the character of a hole.

The second condition for the occurrence of nuclear chirality discussed in this work, is that the odd proton has a particle character, i.e. it occupies a state above the Fermi level. It is expected that the energy of the proton-core system will be minimized for the maximum spatial overlap of these objects. In such a situation, the angular momentum vector of the proton will be close to the direction of the short core deformation axis.

The third condition refers to an odd neutron and is the opposite of the condition for the odd proton. Ideally, in a completely filled shell (by n-n pairs) there should be only one neutron missing. The state of such an unpaired odd neutron is then located at the top of the shell and has the hole-like character. In such a scenario there is a minimum overlap of the odd-neutron state with the core wave function and the angular momentum vector of the odd-neutron aligns close to the long axis of the core deformation.

Meeting the three above conditions means that the minimum energy of the system will occur for three nearly perpendicular angular momentum vectors j_R, j_p, j_n - leading to the phenomenon of nuclear chirality. It should be noted that the above-described interaction of odd nucleons with the even-even core maintains the chiral configuration at low nuclear excitation energies. For high excitation energy the mechanism described above may not be valid and the nucleus usually loses its chiral character. The chirality research presented in this work relate to isotopes produced in the nuclear fusion reaction. Nuclei produced in this way are highly excited. These nuclei cool down by emitting particles and radiation. Only when the energy of excitation approaches the energy of the ground state, the configuration of three angular momentum vectors can become chiral. The three angular momentum vectors spontaneously form a left-handed or right-handed system. Such a spontaneous choice of one of two equivalent handednesses is called the spontaneous chiral symmetry breaking in nuclear physics [8].

Spontaneous symmetry breaking is an important phenomenon mainly in the field of particle physics and fundamental interactions. It is worth quoting the Nobel document [9] where a Lagrangian with the potential in the form of a Mexican hat has been discussed - see fig. 6. In this situation, there are an

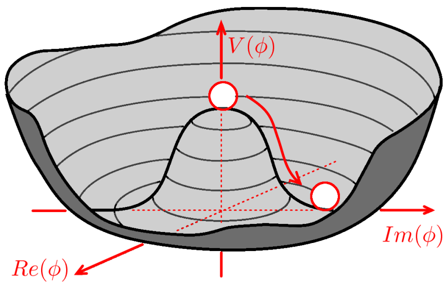

Figure 6: Part of the Nobel document [9] presenting the Lagrangian potential in the form of a Mexican hat. The vacuum breaks the symmetry spontaneously by selecting one place in the potential minimum – this has been marked with a red coloured arrow.

infinite amount of equivalent minima lying on a ring with a non-zero radius. Spontaneous selection of one minimum, like it is shown in figure 6, means that the vacuum violates the symmetry spontaneously by choosing the specific value ϕ of the field. It is worth emphasizing that fundamental symmetry still exists in the sense that all the minima at the bottom of the hat are equivalent. However, the selected vacuum state, by choosing one particular position in the hat, no longer has symmetry. This phenomenon is called the spontaneous symmetry breaking.

Another Nobel document [10] is fully devoted to the phenomenon of spontaneous symmetry breaking. It is worth to quote a fragment containing a real life analogy of the spontaneous symmetry breaking phenomenon:

> *"There are also perfectly symmetric situations in life where we must break the symmetry to proceed. At a round dinner table with napkins placed between the plates, should one take the one to the left or the one to the right? Both situations represent identical results. Someone has to start, however, by breaking the symmetry. Once this is done, everyone knows which side to choose. We shall see that this phenomenon occurs at the fundamental levels of physics, too."*

This fragment contains few important notes. The first is the existence of two equivalent situations before the start of the meal: the napkin on the left as well as the napkin on the right are available. The existence of these two equivalent possibilities means that the table (which is an analogy of nature) preserves the symmetry fundamentally and does not distinguish any of the two possibilities. The second is that it is not the table, but guests who violate the symmetry by spontaneous selection of napkins from one side. Guests are here the analogy of a specific quantum state. The third important information is that the symmetry must be broken in order to proceed with the dinner. This is the analogy of an object that has to choose one of many equivalent possibilities and break the symmetry spontaneously to reach the lower excitation energy.

Nuclear chirality is also based on the phenomenon called the spontaneous symmetry breaking in nuclear physics [8]. The energy of an odd-odd chiral nucleus can be depicted as a double potential well in the parameter of handedness. The value of the handedness parameter is defined by the mixed vector product which is normalized to unity

$$o = \frac{(\vec{j}_\pi \times \vec{j}_\nu) \cdot \vec{j}_R}{\sqrt{j_\pi^2 j_\nu^2 j_R^2}}. \tag{1}$$

In case of three mutually perpendicular angular momentum vectors there are two opposite values of the handedness parameter $o = 1$, $o = -1$ corresponding to left- or right-handed reference frame that is formed by these vectors (see fig. 7). Such a configuration would be an ideal case of nuclear chirality. However, the condition of mutual orthogonality of the momentum vectors is not necessary. To distinguish two opposite handednesses, it is enough for the three angular momentum vectors to span a three-dimensional space. So, the handedness parameter usually does not reach the extreme values of ± 1 but gets closer to a zero value. Therefore, the nuclear chirality phenomenon occurs for the three angular momentum vectors spanning

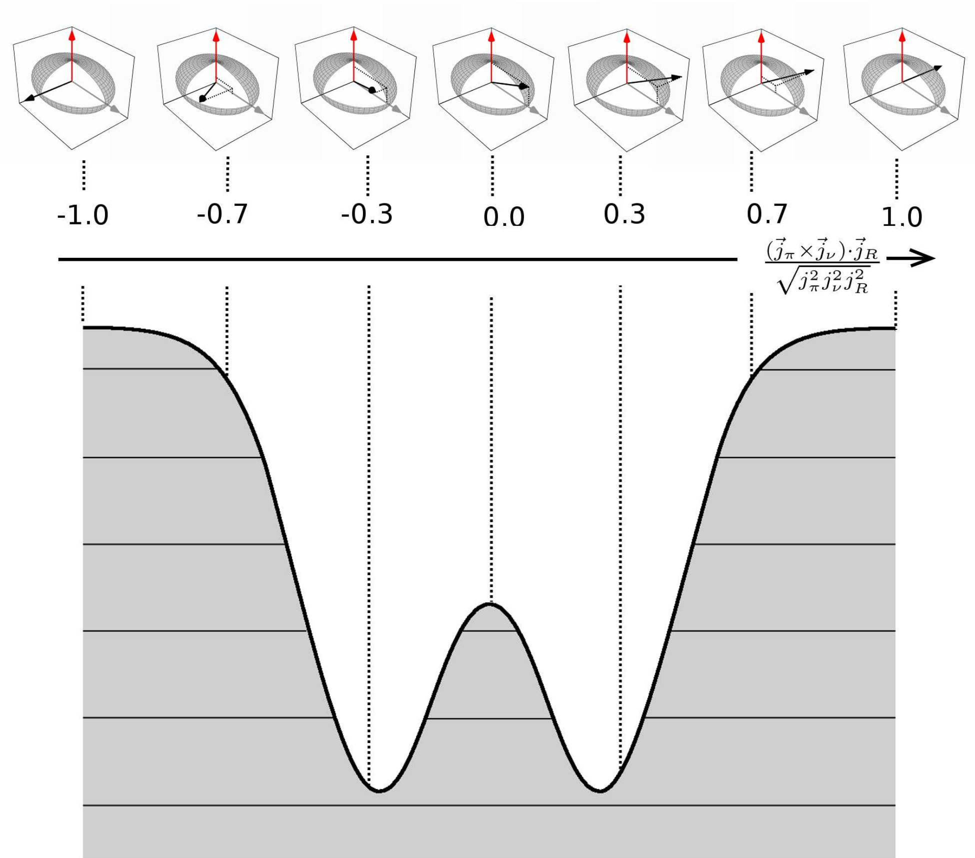

Figure 7: The double potential well in the handedness parameter of three angular momentum vectors system. An example vectors arrangement is shown at the top of the picture.

the three-dimensional space where the handedness parameter is significantly different from zero. This is called the chiral configuration $|L\rangle$ or $|R\rangle$ of the nucleus. In opposite, if these vectors roughly span only the two-dimensional space, i.e. all three are located almost in one plane, we're talking about a planar $|P\rangle$ or non-chiral configuration. The planar configuration has no handedness, therefore, the nuclear chirality does not occur and the value of the handedness parameter is close to zero $o \approx 0$. Similarly to the handedness in optical chirality the value of the handedness parameter in the nuclear chirality can change smoothly in the range $o \in [-1, 1]$. The total energy of the nucleus as a function of the handedness parameter has the form of a symmetric double potential well (fig. 7).

A highly excited nuclei which are produced in a fusion reaction usually have various nucleon configurations that do not satisfy the three conditions required for the occurrence of the nuclear chirality phenomenon. Therefore, the produced nuclei are initially not chiral. However, the nature of the nuclei changes when the excitation energy decreases and the transition to lower energies is only possible when the three conditions mentioned above are fulfilled. Then the wave function gets trapped in one of the minima in the double potential well, fig. 8. The handedness of the three angular momentum vectors appears and the spontaneous chiral symmetry breaking occurs [7].

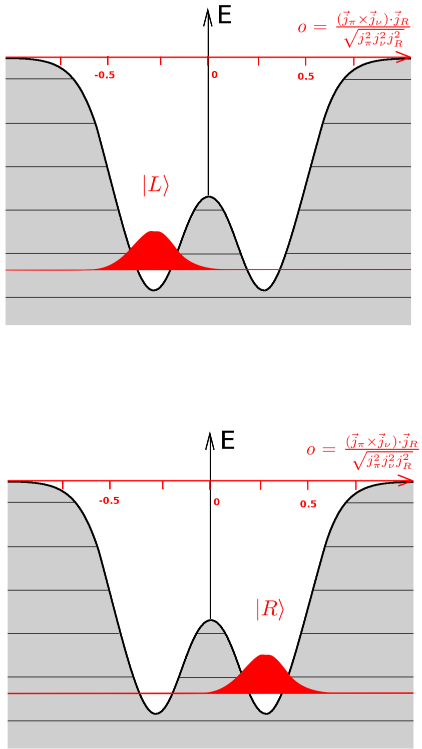

Figure 8: Reaching the excitation energy comparable to the value of the barrier separating the minima with opposite handedness leads to localization of the non-stationary wave function in one of the two minima. Spontaneous selection of the handedness of three angular momentum vectors occurs.

The spontaneous chiral symmetry breaking phenomenon in an atomic nucleus is not identical with that present in the field theory and fundamental interactions. However, there are similarities in the mathematical description, what is shown in the fragment of the Nobel document[9]

> *"Another remarkable development came around 1960 when Yoichiro Nambu (Nobel Prize 2008) extended ideas from superconductivity to particle physics. He had previously shown that the BCS ground state has spontaneously broken*

gauge symmetry. This means that, while the underlying Hamiltonian is invariant with respect to the choice of the electromagnetic gauge, the BCS ground state is not."

In the case of an atomic nucleus, the Hamiltonian (which is an analog of a table in the document [10]) is also invariant with respect to the chiral symmetry operator $(R_\pi T)^\dagger H R_\pi T = H$ However, the wave function $|L\rangle$, $|R\rangle$ of the chiral nucleus (which is an analogy of the guests at the table) is no longer invariant

$$R_\pi T|L\rangle = |R\rangle \quad (2)$$

$$R_\pi T|R\rangle = |L\rangle. \quad (3)$$

The double potential well in fig. 8 is symmetric what reflects the invariance of the nuclear Hamiltonian with respect to the chiral symmetry operator $R_\pi T$. This feature also has a deeper meaning related to the fundamental conservation of the time reversal symmetry in the area of low energy nuclear excitations. I have published an instructive discussion of these phenomena in the popular science article [H1].

3 Nuclear chirality - observables

One of the biggest differences between the nuclear chirality and the chirality concept in other science areas is the way of observing the left or the right-handed system. In case of the weak interactions of massless particles, the weak current has pure left-handed form, so the nature of the process selects itself a specific handedness which therefore does not have to be detected. In the case of optical chirality, the handedness measurement (left- or right-handed circular polarization of the beam of light) can be performed with the use of appropriate polarizers. As described in the first chapter, the handedness of some aromatic molecules can be determined using the human nose. The nuclear chirality does not have such a nose, i.e. there is no way to detect the specific handedness formed by the three angular momentum vectors. Moreover, even if such a nose existed it would be useless, because all quantities are observed in the stationary states of the nucleus with unspecified handedness parameter. Thus experimentalists face a seemingly paradoxical situation in which the observation of the handedness of the non-stationary states $|L\rangle$ or $|R\rangle$ with $o \neq 0$ has to be done from the decay of the stationary states with unspecified handedness where the expectation value is always $o = 0$. It is an unbreakable barrier in the present nuclear spectroscopy research due to the way of observing the excited chiral nuclei, usually by registration of gamma quanta emitted by electromagnetic transitions between excited nuclear levels. Each excited state has an average lifetime. As it turns out, lifetimes of excited states in a chiral nucleus are in the picoseconds (10^{-12} s) range. This is one of two characteristic time intervals that can be called the 'observation time' in the research of nuclear chirality. The second characteristic interval results from the finite value of the energy barrier separating the minima with the opposite handedness - see fig. 8. The non-stationary state with a definite handedness is represented by the wave function located in one of the minima of a double potential well. This wave function tunnel after some time - around 10^{-19} s - through the barrier to the other minimum. The second characteristic time is the tunneling interval. So the tunneling process takes place with a period many orders of magnitude shorter than the lifetime of the excited nuclear level. This disproportion of the two characteristic intervals causes that only the stationary states are observed, which are always 'distributed' equally in the two minima of the double potential well. The stationary wave function has no specific handedness, thus the handedness information is not carried out by gamma quanta emitted from the decay of these states. So, the disproportion of the tunneling period and the observation time causes that the localized wave function $|L\rangle$ or $|R\rangle$ of a non-stationary state with definite handedness is not visible. Instead, the stationary states of the double potential well $|+\rangle$ and $|-\rangle$ are available for the experimental research. The $|+\rangle$ and $|-\rangle$ states are approximately the linear combinations of the $|L\rangle$ and $|R\rangle$ ones fig. 9. It is worth

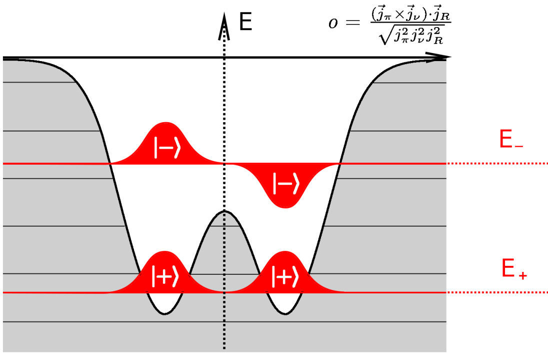

Figure 9: The so called chiral doublets $|+\rangle$, $|-\rangle$ are observed experimentally. These are the eigenstates of the double potential well. The chiral doublets wave function is approximately a linear combination of the non-stationary $|L\rangle$, $R\rangle$ wave functions.

considering two cases of the potential energy barrier separating the minima of the opposite handedness. In the first case, we consider the infinite barrier limit. Then the two lowest stationary states $|+\rangle$, $|-\rangle$ in the double potential well correspond to a symmetric and antisymmetric combinations of the $|L\rangle$ and $|R\rangle$ states, which are also stationary in this limit:

$$|+\rangle = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \tag{4}$$

$$|-\rangle = \frac{i}{\sqrt{2}}(|L\rangle - |R\rangle) \tag{5}$$

In this case, the tunneling is not present and the wave functions $|+\rangle$, $|-\rangle$ and $|L\rangle$, $|R\rangle$ constitute two equivalent basis sets. In the second case, the barrier has a finite value so that the states $|L\rangle$, $|R\rangle$ are no longer stationary and do not constitute a basis set alternative to stationary states $|+\rangle$, $|-\rangle$. In this case, the observed states $|+\rangle$, $|-\rangle$ also have the form of a linear combinations

$$|+\rangle = \frac{1}{\sqrt{2}N_+}(|L\rangle + |R\rangle) \quad (6)$$

$$|-\rangle = \frac{i}{\sqrt{2}N_-}(|L\rangle - |R\rangle). \quad (7)$$

These formulae are valid in the approximation of in a significant separation of the two minima. The main difference in relation to the infinite barrier limit is the normalizing factor $N_\pm$, which reflects the possibility of a non-zero overlap of the localized wave functions $\langle L|R\rangle \neq 0$. The chiral symmetry is broken spontaneously, which means that the two potential minima with opposite handedness are identical and the double potential well is symmetric as a function of the handedness parameter $o = 0$. This feature is mathematically expressed by the commutator $[R_\pi T, H] = 0$. The energies of the stationary states are the Hamiltonian expectation values, which through the commutator $[R_\pi T, H] = 0$ and the approximation of a significant separation of the two minima take the form

$$E_+ = \langle +|H|+\rangle = \frac{Re\langle L|H|L\rangle + Re\langle L|H|R\rangle}{N_+^2} \quad (8)$$

$$E_- = \langle -|H|-\rangle = \frac{Re\langle L|H|L\rangle - Re\langle L|H|R\rangle}{N_-^2}. \quad (9)$$

These are doublet states with the energy separation $\Delta E = E_- - E_+$ proportional to the $Re\langle L|H|R\rangle$ factor associated with the tunneling frequency $f = \Delta E/h$. The energy splitting ΔE of around 100 keV gives the $2 \cdot 10^{19}$ Hz tunneling frequency and the tunneling interval in the order of 10^{-19} s. Observation of almost degenerate doublet states indicates the spontaneous chiral symmetry in an atomic nucleus. In conclusion, instead of a localized wave function with definite handedness $|L\rangle$ or $|R\rangle$, the chiral doubles are observed suggesting the existence of the double potential well in the parameter of handedness o. It is said that the chiral symmetry in nuclear physics is broken strongly when the energy barrier is significant and the doublets are almost degenerate - the energy splitting of the chiral doublets is then in the 0-200 keV limits. Weak chiral symmetry breaking occurs for a lower energy barrier giving the doublet splitting about 200-500 keV. In the case of a small barrier, the splitting of doublets is comparable to the typical energy differences between the nuclear excited states - in the order of 1MeV. In this case, we are talking about chiral vibrations in the structure of an atomic nucleus.

At the beginning of the nuclear chirality research the experiments were focused on the search for the existence of the chiral doublets. A certain facilitation in search for such a doublet states is the nuclear rotation required for the development of the angular momentum vectors in question. Nuclear rotation gives the characteristic sequences of the excited levels - the so-called rotational bands - which can be identified in the nuclear excitation level schemes. The rotational bands are created on both $|+\rangle$ and $|-\rangle$ states, see fig. 10. Observation of two almost degenerate rotational bands indicates the existence of

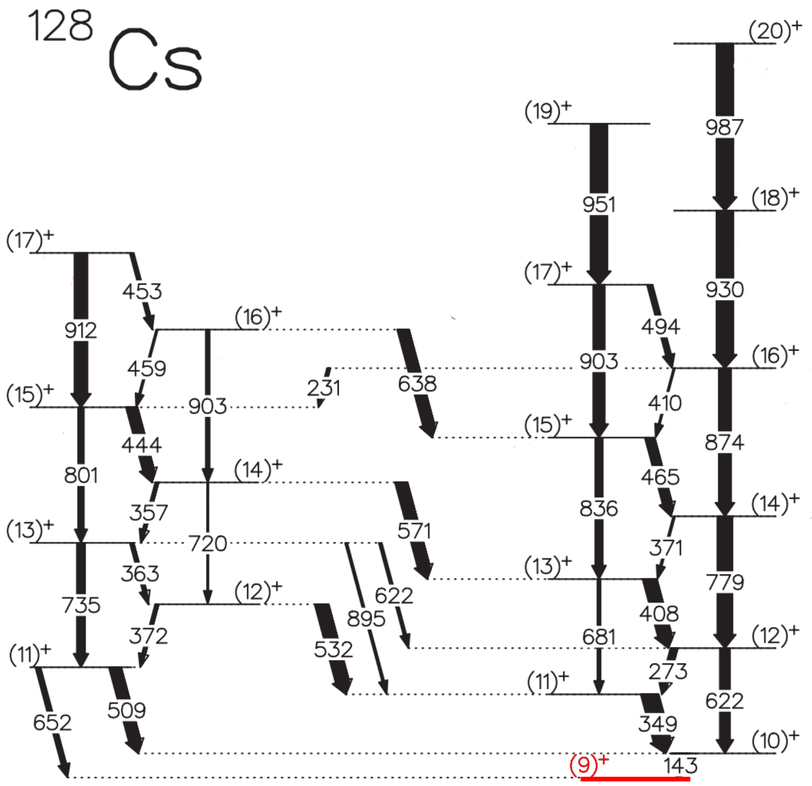

Figure 10: An example of two rotational excitation level sequences built on $|+\rangle$ and $|-\rangle$ chiral doublets. Such rotational bands are called chiral partner bands. The 9^{+} state marked in red colour calls the bandhead of chiral partner bands.

chiral symmetry breaking. Such observation in ^{134}Pr nucleus contributed to formulation of the chiral symmetry breaking hypothesis in nuclear physics in 1997 [4]. Two rotational bands with similar energies of corresponding levels were called the chiral partner bands. In the following years, chiral partner bands were found in odd-odd atomic nuclei in the mass around A = 130 [7], [11]. However, it soon turned out that the existence of the partner bands can be the result of a phenomena other than the nuclear chirality. Doubts about the interpretation of the partner bands were published in ref.[12] entitled:

> *"Risk of Misinterpretation of Nearly Degenerate Pair Bands as Chiral Partners in Nuclei. The insufficiency of the near-degeneracy criterion to trace nuclear chirality is emphasized."*

Therefore, there was an urgent need to measure observables other than energies of the levels in the partner bands. Doubts about the interpretation of the partner bands as chiral ones appeared more or less at the beginning of the present millennium. The phenomenon of signature splitting is one of the possible alternative interpretations of the bands. It is based on Coriolis force appearing in the non-inertial system associated with the rotating atomic nucleus. Coriolis force causes the Kramer's degeneration to vanish. Magnetic substates become splitted and levels energies are described by a new quantum number called signature. In the ref.[H2] I have published an article about the risk of a wrong interpretation where signature splitting can be taken as the nuclear chirality phenomenon. Therefore, we have undertaken a subsequent measurements that were complementary to the study of the level energies in partner bands. Because these bands are observed through the emission of gamma quanta from the decays of the levels belonging to them, it was natural to determine these levels lifetimes and the corresponding gamma transition probabilities.

4 Indirect chirality research - the gamma transition probabilities measurements

In 2001 I have initiated the measurements of electromagnetic transition probabilities in chiral partner bands - long before the appearance of ref.[H2]. From the very beginning of the nuclear chirality research the experimental works were ahead of the theoretical interpretations. In many cases, the experimental results were obtained a few years before the appearance of their proper interpretation what resulted in significant delays and difficulties in the results publication. Publication of large dozen-page works was often impossible due to dynamically developing theoretical models and changes in theoretical interpretation. Just a few quotes from contemporary articles are enough to show that this situation continues to this day: in ref.[13] a paradox present in a previous interpretation vanishes in the new theoretical approach:

> *"The paradox on the previous interpretation for the nuclear chiral geometry based on the effective angle has been clarified by reexamining the system with the particle-hole configuration* $\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$ *and rotor with deformation parameter* $\gamma = 30°$*"*

On the other hand, in ref.[14] the energy splitting of the chiral doublets is reinterpreted in a model that takes into account the chiral and the non-chiral configurations of a nucleus:

> *"Three- and two-level mixing models are proposed to understand the doubling of states at the same spin and parity in triaxially-deformed atomic nuclei with odd numbers of protons and neutrons."*

In ref.[15] a new representation of the chiral geometry was proposed:

"Understanding the chiral geometry with K-plot and azimuthal-plot"

In 2002 and 2003, we obtained the first results of electromagnetic transition probabilities in chiral partner bands. At that time, the interpretation of these probabilities was not yet established, as shows the fragment of ref.[16]:

> *"Because of the complexity and generality of nuclear chirality, the behavior of electromagnetic transition probabilities or the selection rules are not yet understood."*

A few years later I have published the first article containing the fundamental analysis of these data, i.e. based on model-independent fundamental symmetries [H3]. The $R^Y_\pi T$ commutation relations with Hamiltonian and with electromagnetic transitions operator led to the conclusion that the electromagnetic transition probabilities for corresponding levels in both bands should be similar. It turned out that nearly equal values of gamma transition probabilities in both bands result from the commutators $[R_\pi T, M1] = 0$ and $[R_\pi T, E2] = 0$ similarly to degeneration of chiral doublets energies which result from $[R_\pi T, H] = 0$ commutator. It is interesting that the very well known text book which is considered to be the canon of nuclear spectroscopy field [17] also contains a mathematical description of the chiral symmetry operator $R^Y_\pi T$ properties. The book has been published in 1969 and the possibility that rotational bands may be built on the chiral doublets $|+\rangle$, $|-\rangle$ was not known at that time. Therefore the hypothesis of the chiral character of the rotational states (as a linear combinations of $|R\rangle$ and $|L\rangle$ states with specified handedness) was then overlooked.

In order to get the gamma transition probabilities in chiral partner bands, it was necessary to measure these bands' excited states lifetimes. The transition probability is inversely proportional to a levels' lifetime. For a long lifetimes - in the order of 10^{-7} s and more - a measurement of a decay curve giving the half-life can be performed. However, chiral doublets are rotational states. These are collective excited states with very short lifetimes around 10^{-13} - 10^{-12} s. The experimental challenge of such a short lifetimes measurement is best reflected by the fact that the light travels around 1 millimeter distance in such a short time intervals. Currently, it is not possible to get a decay curve measurement in this time scale. It was necessary to use another experimental method, the so-called DSA (*Doppler Shift Attenuation*), which is based on a comparison with the method's characteristic time of 10^{-12} s. In the DSA method, the recoils' stopping time in a target matter is such a characteristic time at the level of 10^{-12}. We have determined the precise value of the stopping time in our stopping power measurements which results I have published in ref.[18]. The chiral nuclei discussed here are produced in a fusion reaction, where the

^{14}N or ^{10}B projectiles hit the target nucleus (tin or cadmium isotope). The projectile's energy is above the coulomb barrier and allows to create the final nucleus - called the recoil nucleus. The recoil inherits the entire projectile's momentum and moves in the target with the initial velocity of around $v_{max} = 1\%$ c. This momentum is lost in an average time interval of 10^{-12} s which is the required characteristic time of the method. The lifetime measurements of the chiral excited states are based on the Doppler effect, which correlates the recoils' stopping time with the Doppler shift of the observed gamma radiation. In case where the lifetime of the excited level is short - e.g. less than 10^{-13} s nearly all gamma quanta are emitted from the recoil moving almost with the initial velocity $v_{max} = 1\%$ c. The energy E_{max} of these quanta has a maximum Doppler shift. If, however, the lifetime of the excited level exceeds 10^{-12} s then nearly all gamma quanta are emitted from the nuclei at rest. The energy E_0 of such gamma quanta are no longer subject to the Doppler shift. These are two limiting cases that allow the levels' lifetime estimation. The sensitivity of the method, which allows the lifetime determination lies between these limits, in the 10^{-13} s - 10^{-12} s range. If the lifetime of the level in question falls within this range, then an energy spectrum (called the Doppler disturbed peak) ranging from E_0 to E_{max} is registered as the result of the level decay - fig. 11.

The shape analysis of the Doppler disturbed peak is a complicated process, which I've described in ref.[19] and allows precise lifetime determination of an excited nuclear state. As shown in ref. [19] we've extended the standard DSA technique in a way allowing the application of thick targets that play simultaneously the role of the stopper. In this way we obtained the data statistics higher by an order of magnitude than in the case of a standard DSA technique which uses a thin target with a thick stopping material backing. We applied this innovative DSA method in lifetime measurements of ^{132}La isotope where partner bands were previously observed [7], [20]. According to literature ^{132}La was the first nucleus that was subjected for lifetime measurements of the states belonging to possible chiral partner bands. DSA measurement turned out to be extremely important because the results obtained totally denied the earlier chiral interpretation of the partner bands in ^{132}La what I published in refs. [21], [22], [23]. According to ref.[H3] the gamma transition probabilities in both partner bands should be similar provided the bands' chiral character. The obtained data revealed that these probabilities differ approximately by an order of magnitude in the ^{132} La isotope . It should be emphasized here that the interpretation of electromagnetic transition probabilities in chiral partner bands had not yet been well established at that time. That's why papers [21], [22], [23] are conference articles, while the full interpretation appeared only 6 years later - in 2011. That year I have published the discussion of the electromagnetic transition probabilities in the context of their final interpretation in my paper [H4].

Basing on the experience we gained in the DSA technique we had quickly performed another experiment

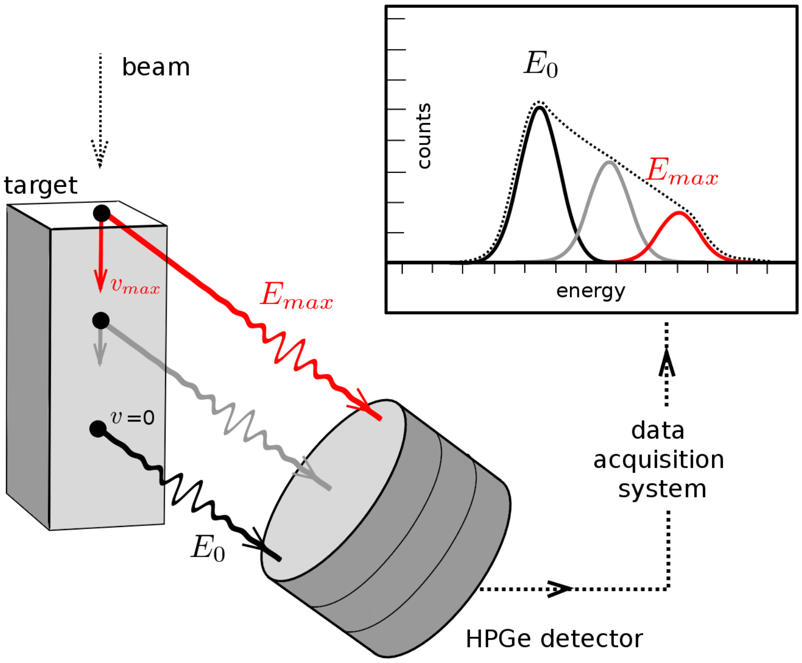

Figure 11: The Doppler Shift Attenuation method used for lifetime measurements in 0.1 ps - 1.0 ps region. Nuclear fusion reaction of the projectile and the target nucleus is used in the DSA method. The produced nuclei - called recoils – have an average initial velocity around v_{max} =1%c. Recoils lose their kinetic energy with a simultaneous radiation of gamma quanta from their excited states. If a level-lifetime is shorter that 0.1 ps then the gamma quanta are emitted almost at the initial velocity of the recoil (red colour). In opposite, if the level-lifetime is longer than 1.0 ps then the gamma emission occurs after the recoil has stopped in the target (black colour). For the level lifetimes within 0.1-1.0 ps range the gamma emission occurs at various recoils velocities within 0-v_{max} limits. In such a scenario a Doppler shifted energy distribution (called the Doppler disturbed peak) is observed for a given electromagnetic transition. The lineshape analysis of such a Doppler disturbed peak allows precise determination of the levels lifetime.

aimed to lifetime measurements in partner bands of ^{128}Cs. We obtained the first data already at the end of 2003. It turned out that the gamma transition probabilities are similar in both partner bands in ^{128}Cs, see fig. 12, which clearly indicated their chiral nature. However, there also was a unexplained observation that had no interpretation at that time.

In the collective rotational bands in ^{131}La and ^{132}La which I studied earlier, see refs.[19], [21], [22], [23], the obtained M1 transition probabilities are a smooth function of the spin value. Moreover, many

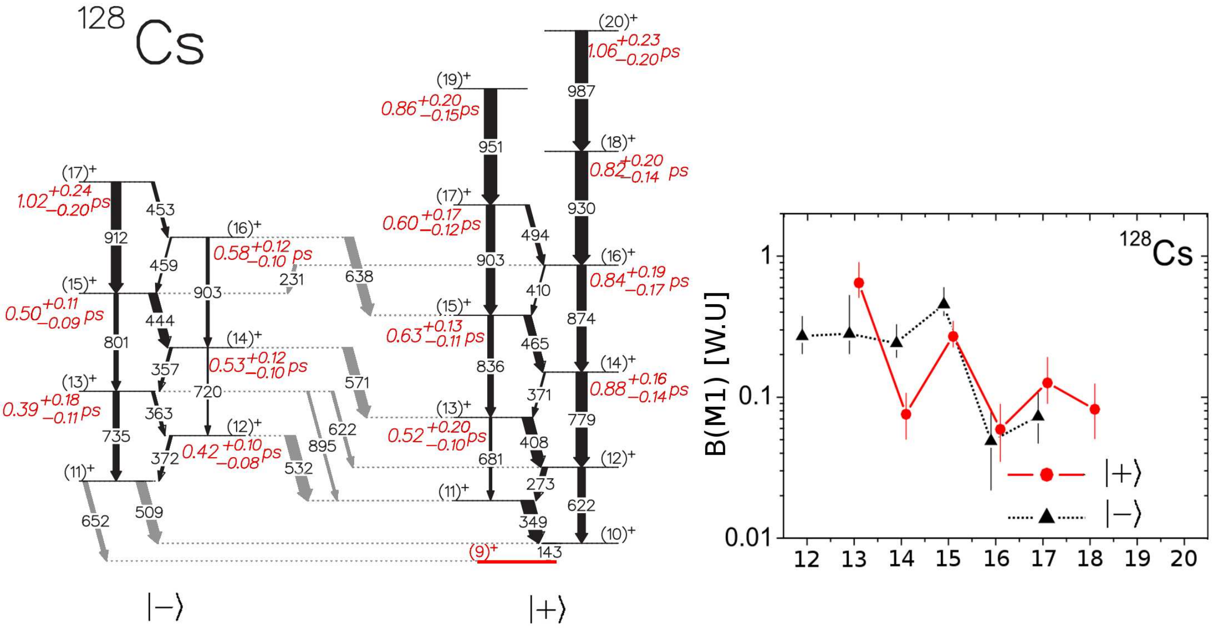

Figure 12: Left - lifetime measurements results in the chiral partner bands in ^{128}Cs isotope. The lifetimes are marked in red colour close to the corresponding levels. The lowest level belonging to the chiral bands - the so called chiral bandhead - is marked in red colour as well. Right - the reduced M1 transition probabilities resulting from the measured lifetimes. The transition probabilities are similar in both partner bands above the $I = 13\hbar$ level spin. The alternate large and small values of the M1 transition probabilities have been observed for the first time. Such an alternate M1 transition probabilities dependence is called the B(M1) staggering.

collective nuclear models at that time predicted a smooth dependence of the M1 transition probabilities on the level spin in a rotational band. It turned out that the M1 probabilities in the partner bands of ^{128} Cs have a different character. Instead of smooth changes of the M1 probability as a function of the level spin, we observed the so called *B(M1) staggering* i.e., alternately small and large M1 transition probability values. We collected the data in a ready-to-publish manuscript but the observation of the B(M1) staggering forced us to re-analyze the data in order to exclude the possibility of a methodological error. However, a fortunate coincidence allowed us to publish this data quickly. In parallel to our experimental chirality research a theoretical analyses and calculation were independently conducted which resulted in publication of ref. [16] where the B(M1) staggering in a chiral partner bands was predicted for the first time. It turned out that the B(M1) staggering is a characteristic feature of nuclear chirality and reflects the M1 selection rules in chiral partner bands where some additional conditions are fulfilled (maximum and rigid three-axial deformation, odd nucleons are in a single-j shell). This opened the way for the publication of my main result from that phase of the nuclear chirality research [24]. As shown in the title of the ref. [24] *"128Cs as the Best Example Revealing Chiral Symmetry Breaking"*, the ^{128}Cs isotope was considered as the best case of nuclear chirality world-wide. It was the first documented observation of the B(M1) staggering in chiral partner bands and a confirmation of the predicted chiral M1 selection rules. Ref. [24] can be considered as the first significant experimental result in favor of the existence of nuclear chirality in nature and was the first motivation to seek B(M1) Staggering in other nuclei being a chiral candidates. Still however , the theoretical picture of the B(M1) staggering in chiral partner bands was not complete. The main problem was the condition of rigid triaxial deformation which was assumed in ref. [16]. This condition was inconsistent with other observations indicating that the nuclei in question - including ^{128}Cs - posses very soft triaxial deformation.

The next step were theoretical considerations aimed to analyze the rigid deformation condition and divergence form the strong chiral symmetry breaking limit. I've presented a discussion of the properties of a nucleus which is not perfectly chiral in the following articles [H5], [H6]. These works are based on 'purely algebraic' approach and do not depend on model calculations. The quoted references were a kind of the attempt to define parameters for assessing the degree of chiral symmetry violation. In parallel to the theoretical considerations, I have performed further experiments to verify the existence of the B(M1) staggering in other nuclei with a soft triaxial deformation. For this purpose, we have done DSA measurements in partner bands of ^{126}Cs nucleus. Despite the fact that the ^{126}Cs isotope, similarly to the previously studied ^{128}Cs, contradicts the rigid triaxial deformation condition we have observed and confirmed the full set of chiral M1 selection rules (B(M1) staggering) predicted in ref. [16]. The obtained results were a significant contribution to the study of the nuclear chirality but their publication was delayed due to uncertain interpretation based on ref. [16]. I made a model independent analysis of the electromagnetic transition probabilities in chiral bands of ^{126}Cs using a commutation rules of the respective transition operators. The so-called phase convention which was analyzed in this work turned out to be very important. The phase convention states that all observed quantities should be a real values of corresponding matrix elements. To meet this condition, the phases of the chiral doublets $|+\rangle$ and $|-\rangle$ had to be chosen properly. The correct application of the phase convention forced the introduction of the imaginary unit in the $|-\rangle$ wave function, which was previously overlooked. There were significant conclusions resulting from this modification what enabled me the publication of ref. [H7] containing the experimental results measured in ^{126}Cs. The M1 transition probabilities measured in ^{126} Cs confirmed the complete set of M1 selection rules predicted in ref. [16] i.e., the existence of two B(M1) staggerings.

One of the staggerings corresponds to intraband M1 transitions - transitions that link the excited states within one chiral band. The other staggering corresponds to the interband M1 transitions - the transitions linking the two chiral bands with each other. These two staggerings have opposite phase as a function of the level spin i.e., for large M1 probability for the transition within the band there is little probability for the transition between the bands and vice-verse - see fig.13. Thanks to the proper application of the phase convention I was able to explain the opposite phase of the staggerings as a domination of the real part of complex matrix element (inband transition) over the imaginary part of the same matrix element (interband transition) and vice-verse. This observation led me to publish the results in refs. [H3], [H7]. It should be noted that the chiral origin of B(M1) staggering in the context the soft triaxial deformation

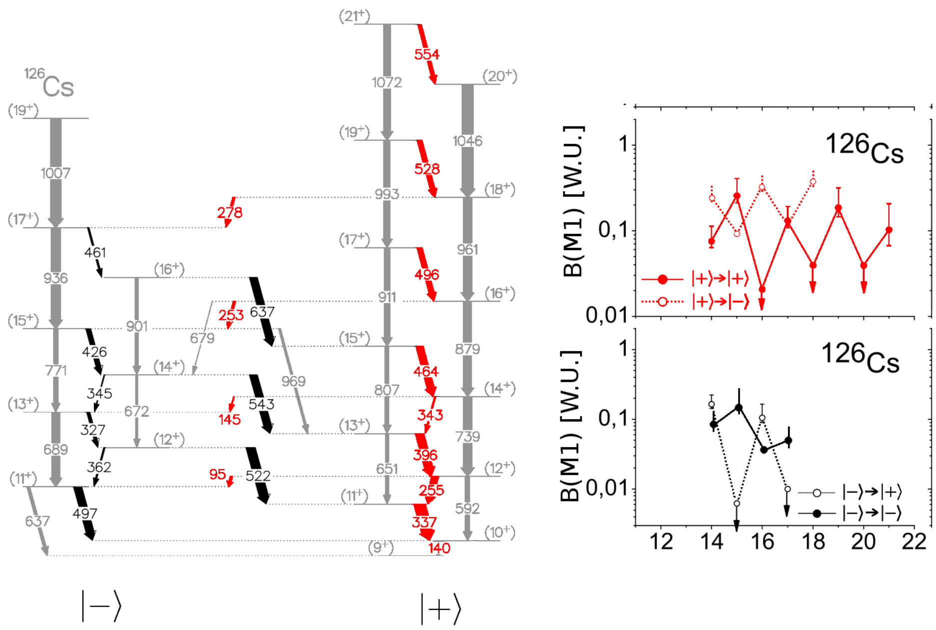

Figure 13: Left - chiral partner bands observed in ^{126}Cs nucleus. The intraband $|+\rangle \rightarrow |+\rangle$ as well as interband $|+\rangle \rightarrow |-\rangle$ M1 transitions are marked in red colour. Black colour indicates the intraband $|-\rangle \rightarrow |-\rangle$ and interband $|-\rangle \rightarrow |+\rangle$ M1 transitions. Right- the M1 transition probabilities marked in corresponding colours. The intraband B(M1) staggering is in opposite phase to the interband B(M1) staggering.

contradiction was not yet solved, which led to alternative explanations of the M1 selection rules. This situation hindered the publication of subsequent results and lasted until 2011 when it was shown for the first time [25], [26] that the B(M1) staggering should occur in some chiral nuclei with a soft triaxial deformation. Such a B(M1) staggering is interpreted as a manifestation of nuclear chirality coexisting with a new symmetry that has not been studied before as stated in a fragment of ref. [25]:

> *"It turns out that such staggering, obtained by numerical calculations, can be explained by a kind of selections rules following a new, not discussed as yet, symmetry of the model."*

This new symmetry is a generalization of the model presented earlier in ref. [16] to nuclei with soft triaxial deformation. The conditions necessary for the additional symmetry to exist are met in all of the Cs isotopes studied by us. Finally, the B(M1) staggering turned out to be a peculiar hallmark of chiral nuclei, proving in an almost eyewitness way the existence of the chiral symmetry breaking in atomic nuclei. This undoubted success in the theory of nuclear chirality prompted us to look for chiral M1 selection rules also in the ^{124}Cs isotope. The obtained preliminary results, confirm the existence of the B(M1) staggering, what I published in ref. [H8]. To this day, the ^{128,126,124}Cs isotopes examined by us are the only cases presenting the B(M1) staggering among about 60 chiral nuclei. These are the only data indicating the existence of nuclear chirality in such a significant manner.

Observation of two partner bands with almost degenerate rotational states as well as similar electromagnetic transition probabilities and B(M1) staggering reveal the effects of the chiral symmetry breaking. These quantities are not directly related to the concept of handedness of the three angular momentum vectors in question. Therefore, in accordance with the title of this chapter, I call these measurements the *indirect chirality research.* Despite the successes in the interpretation of the indirect chirality research results, still there are hypotheses claiming that the observed properties are the result of other, not yet known phenomena. These doubts motivated me to develop a new type of research - the direct chirality research.

5 Direct nuclear chirality research - magnetic dipole moment measurements

Since 2007, in parallel to the indirect chirality research, I was looking for a new method that allows to determine the geometry of the three angular momentum vectors j_R, j_p, j_n in the chiral nucleus. It turned out that the g-factor (and the associated magnetic dipole moment) measurement is an excellent solution, which allows direct insight into the geometry of the three angular momentum vectors in question. Therefore, I call this new type of measurements the *direct chirality research.*

I submitted the first proposal aimed to measure the magnetic moments of several excited levels in ^{132}La already in 2008 at Laboratori Nationali di Legnaro (Italy). The proposed method - called *Recoil In*

Vacuum - was based on strong magnetic fields on the level of kT originating from ionized electronic shells. The method allows the magnetic moment measurement of several key excited stated in partner bands of ^{132}La with short lifetimes (in the order of 10^{-12} s).

This idea, however, was not accepted by PAC, since the performance of such an experiment could cause a high consumption of materials inside the accelerators and the need of a two-week maintenance work after performing the experiment. In the same year, I've modified the experimental method and submitted a new proposal at IPN Orsay (France) where it was accepted by PAC. The new method allowed the g-factor measurement in only one state I=9$\hbar$ which is the lowest level in the ^{128}Cs chiral partner bands - this level is marked in red in Figs.10 and 12.

The I=9$\hbar$ level is called the isomeric state, i.e. a state with long lifetime (in the order of 10^{-7} s). It is worth to look on the direct chirality research described here from the perspective of the recent (2017) main theoretical publication dedicated to nuclear chirality [27] where we read:

> *"Experimental and theoretical studies provide a new insight into possible interpretations of the doublet bands as the quest for observables uniquely identifying nuclear chirality continues".*

This shows that the direct chirality research I proposed in 2008 was ahead of theoretical analyzes by a decade, which again resulted in delays in the publication process. Part of the work was not accepted for publication at all due to the lack of a theoretical interpretation of observed phenomena. This is supported by a referee review conclusion for our last submitted manuscript:

> *"In conclusion, the present manuscript contains experimental results of improved accuracy but no physical interpretation of these results has been offered to the reader and no new information on the structure of ^{128}Cs has been gained. The manuscript shall be considered as an investigation of low lying level-scheme of ^{128}Cs without any discussion about the derived results and therefore does not deserve publication in Phys. Rev. C."*

However, ten years of intense cooperation of the experimental and theoretical groups made it possible to publish the first results of the direct chirality research where the configuration of the three angular momentum vectors in the ^{128}Cs isotope has been determined.

According to what has been described in Chapter III, the observation of the $|L\rangle$ or $|R\rangle$ handedness of the three vectors system is not possible within the present experimental techniques. Only the $|+\rangle$ and $|-\rangle$ chiral doublets with the handedness expectation value equal to zero, which are linear combinations of the $|L\rangle$ or $|R\rangle$ states, can be examined experimentally. In this context, measuring the mutual orientation of three angular momentum vectors seemed to be impossible. The way out of this apparent dead end is to notice that the minima with opposite handedness in the double potential well are identical. Therefore, it is not important in which of these two minima the non-stationary wave function is located. It is important that the handedness parameter of such a wave function is located around a value other than zero, regardless of its sign. In the geometric picture, this means that regardless of the sign of the handedness parameter it is important to distinguish whether the three angular momentum vectors span the three-dimensional space - the chiral geometry or only the two-dimensional space - the non-chiral geometry. In order to answer this question, it is enough to measure a certain linear combination of expected cosines of mutual angles of the three angular momentum vectors. If the chiral doublets comes from the chiral $|L\rangle$ and $|R\rangle$ states where the handedness parameter o is close to $o = +1$ or $o = -1$ the expected cosines should be close to zero because the three vectors will be almost perpendicular to each other. Cosine function does not distinguish the system's handedness, thus bypassing the fundamental experimental limitation of inability to determine the handedness at which the non-stationary wave function is temporarily located. Therefore the direct chirality research is based on the measurement of a certain linear combination of three scalar products expectation values: $j_R \cdot j_p$, $j_p \cdot j_n$, $j_n \cdot j_R$, which gives the information whether the three angular momentum vectors span the 3D-space (chirality) or just the 2D-space (non-chirality). It turned out that the measurement of the g-factor, and the corresponding magnetic dipole moment - is just the experimental way to get the required linear combination of the scalar products expectation values.

An analysis of the dipole magnetic moment as a result of the coupling of only two angular momentum vectors [28] can be found in literature. I call these theoretical calculations the *two-component model*. Unlike the two-component model the nuclear chirality is based on coupling of three angular momentum vectors. So, in the first step I had to perform a generalization of the two-component model to a model which is able to describe the system of three spin-vectors. I made such a generalization in 2008 and called it the *three-component model* of the dipole magnetic moment. In nuclear spectroscopy experiments, only the gyromagnetic factor ($g - factor$) is measured directly, which is associated with a dipole magnetic moment. The g-factor is a unitless value that represents the numerical value of the magnetic moment μ of the given excited state per unit of the total angular momentum J, $g = \frac{\mu}{J}$ where μ and J are expressed in μ_N and $\hbar$ units respectively. In the derived three-component model the gyromagnetic factor g is given by the formula, which I have included in my recent article [H9]:

$$
\begin{aligned}
g \;=\; & \frac{1}{2}\Bigg[(g_p + g_n + g_R) + \frac{\langle j_p^2\rangle}{\langle J^2\rangle}(g_p - g_n - g_R) \\
& + \frac{\langle j_n^2\rangle}{\langle J^2\rangle}(g_n - g_p - g_R) + \frac{\langle j_R^2\rangle}{\langle J^2\rangle}(g_R - g_p - g_n)\Bigg] \\
& - \frac{1}{\langle J^2\rangle}\left(g_p\langle \vec{j}_n \cdot \vec{j}_R\rangle + g_n\langle \vec{j}_p \cdot \vec{j}_R\rangle + g_R\langle \vec{j}_p \cdot \vec{j}_n\rangle\right), \qquad (10)
\end{aligned}
$$

where the g_p, g_n, g_R are the gyromagnetic factors of the odd-proton, odd-neutron and the even-even core, respectively, and J is the total angular momentum of the excited states which is the sum of the j_p, j_n and j_R. It is worth noting that the component in square brackets does not depend on the mutual orientation of angular momentum vectors $\vec{j_p}$, $\vec{j_n}$ and $\vec{j_R}$. Marking this component as g^{chiral} leads to the following formula

$$g = g_{chiral} - \frac{1}{\langle J^2 \rangle} \left(g_p \langle \vec{j_n} \cdot \vec{j_R} \rangle + g_n \langle \vec{j_p} \cdot \vec{j_R} \rangle + g_R \langle \vec{j_p} \cdot \vec{j_n} \rangle \right). \tag{11}$$

which is easier to interpret. The point in this formula is the presence of a linear combination of the three expectation values of the scalar products of angular momentum vectors. In the case of the ideal chiral geometry, the three angular momentum vectors are mutually perpendicular and span the three-dimensional space. In this case, the linear combination of the scalar products is close to zero. The gyromagnetic factor of the nucleus then has the value marked as g^{chiral}. Any deviation from g^{chiral} means that the three angular momentum vectors are not perpendicular to each other. The maximum deviation occurs when the vectors are located in one plane and instead of the three-dimensional (3D), they only span the two-dimensional (2D) space. In this way we have obtained a unique tool to verify whether an atomic nucleus breaks the chiral symmetry (three angular momentum vectors span the 3D space) or there is no nuclear chirality (three vectors span the 2D space). The great advantage of measuring the g-factor in a chiral nucleus is that the theoretical predictions are based on the set of magnetic moments g_R, g_p and g_n of the core and of the odd nucleons. These are well known data determined with high accuracy in previous experiments in even-even and even-odd neighboring nuclei.

In the case of a non-complicated wave functions, the g-factor can be calculated even analytically. Such a wave function is a *single coupling scheme* of three angular momentum vectors to the total spin J of the excited level. In a single coupling scheme we first add two angular momentum vectors e.g. j_p and j_n to a single specific value of j_{pn}. Then we add the j_{pn} with the third angular momentum vector j_R to create the total spin J of the excited state. The state representing such a sequential single coupling scheme can be written as $|(j_p j_n) j_{pn} j_R; JM\rangle$. Nuclear excited states $|JM\rangle$ usually consist of many single coupling schemes since there are many possible orientations of three angular momentum vectors j_R, j_p and j_n that make up the same value of the total spin J. Nevertheless, the use of single coupling schemes gives a clear explanation of the previously discussed paradox seemingly appearing in the definition of nuclear chirality within the quantum angular momentum algebra. In the quantum physics the angular momentum vector is represented by two quantum numbers $|IM\rangle$ corresponding to the vector's length and its projection on the quantization axis. Representation through these two values excludes the possibility of simultaneous determination of three spatial components of an angular moment vector. In this perspective, the correctness of the nuclear chirality concept was discussed which requires the directions of the angular momentum vectors in the 3D-space to be known. The use of the single coupling schemes allow to clarify these doubts. There are analytical formulas for all three scalar products expectation values $\langle \vec{j_n} \cdot \vec{j_R} \rangle$, $\langle \vec{j_p} \cdot \vec{j_R} \rangle$, $\langle \vec{j_p} \cdot \vec{j_n} \rangle$ in a single coupling scheme, which correspond to three mutual orientations of the angular momentum vectors in a chiral nucleus. These formulae are not yet published, therefore they are fully included in the appendix.

The three-component model allows for an instant prediction of the g-factor value expected for I=9^+ state of ^{128}Cs in frame of a semi-classical approach. It turned out that in the case of non-chiral geometry, where three angular momentum vectors span only the two-dimensional space, the expected g-factor has two limiting values $g = 0.4$ and $g = 0.6$. Any other configuration of the three angular momentum vectors leads to the g-factor value located within these limits. Especially for the ideal chiral geometry, where the three angular momentum vectors span the three-dimensional space and are mutually perpendicular the g-factor takes the value $g = g^{chiral} = 0.5$. These semi-classical predictions were sufficient to submit an experiment proposal for the g-factor measurement of the isomeric state I=9^+ in ^{128}Cs isotope at IPN Orsay. Ultimately, however, instead of the semi-classical predictions it was necessary to perform a complicated quantum model calculations, in which the isomeric state is represented by a composition of many coupling schemes. Nuclear models allow to calculate coefficients of such a single coupling schemes composition and the calculation of the expected g-factor in a fully quantum way. The well-known model calculations at the time, e.g. Core Particle Hole Coupling (CPHC) [29] predicted almost the ideal chiral configuration of the three angular momentum vectors with the g-factor value $g^{theory} \approx g^{chiral} = 0.5$. With that knowledge wee started to prepare the experiment.

6 The g-factor measurement of the I=9^+ isomeric state in ^{128}Cs isotope

Our experiment is historically the first one where the gyromagnetic factor of an excited state belonging to the chiral partner bands was determined. The small difference between the g-factor $g = 0.5$ expected in the limit of ideal chiral geometry and the g-factor $g = 0.4$ or $g = 0.6$ expected in the non-chiral limit was a huge experimental challenge. Therefore the maximum precision was required, which motivated us to establish a large international experiment collaboration. The core of the experimental group consisted of two teams from the Faculty of Physics and the Heavy Ion Laboratory of the University of Warsaw. These two groups were responsible for preparing the experiment, the ^{122}Sn isotopic target, large part of the electronics needed for DAQ and two HPGe detectors for high energy gamma quanta registration. Cooperation with supplementary teams covered the following tasks:

-consultations with the experimental group that has indicated the existence of chiral partner bands in ^{128}Cs for the first time (USA, Canada, Japan),

-preparations of the GAMIPE reaction chamber suitable for g-factor measurements (Romania),

-preparations of special type HPGe detectors - LEPS - suitable for precise registration of low energy gamma radiation (Italy),

- delivery of high-quality pulsed beam using tandem accelerator (France),

-making model calculations in frame of Particle-Rotor-Model (PRM) under direction of Jie Meng - one of the two discoverers of nuclear chirality [6] (China).

Despite the large logistic challenge the experiment has been prepared within 10 days before the beam time. The 9^+ is the lowest state of the chiral partner bands in ^{128}Cs - fig. 14. Such a state is often called the *bandhead*.

The bandhead in ^{128}Cs is a long living state since the transition to lower energies requires the microscopic structure of the nucleus to be changed. The half-life of the 9^+ level is $T_{1/2}$=56 ns and is suitable for very precise g-factor measurement method - the Time Dependent Angular Distribution (TDPAD) method. The fusion reaction of the projectile and the target nucleus is used in this method. According to the angular momentum conservation principle the final nucleus has a spin which is almost perpendicular to the momentum vector of the projectile. Spin of the produced nuclei is aligned in the plane perpendicular to beam direction. The non-isotropic spin alignment results in the non-isotropic distribution of the emitted gamma radiation. In our experiment, the ^{10}B beam and the ^{122}Sn target 22 mg/cm^2 thick were used. The 22 mg/cm^2 target thickness was chosen to ensure that all produced ^{128}Cs nuclei will be stopped in the reaction chamber. The target has been put in a 2.2-T magnetic field attained with help of the GAMIPE chamber. The magnetic field of 0.6 T was produced by an electromagnet and then was focused using iron poles of the GAMIPE chamber in a small area where the target was mounted. The magnetic field strength of the electromagnet was multiplied 4 times (up to 2.2 T) at the target area by using this technique. The interaction of the dipole magnetic moment of the nucleus with the external magnetic field leads to the nuclear spin precession around the B-field direction. The spin precession is

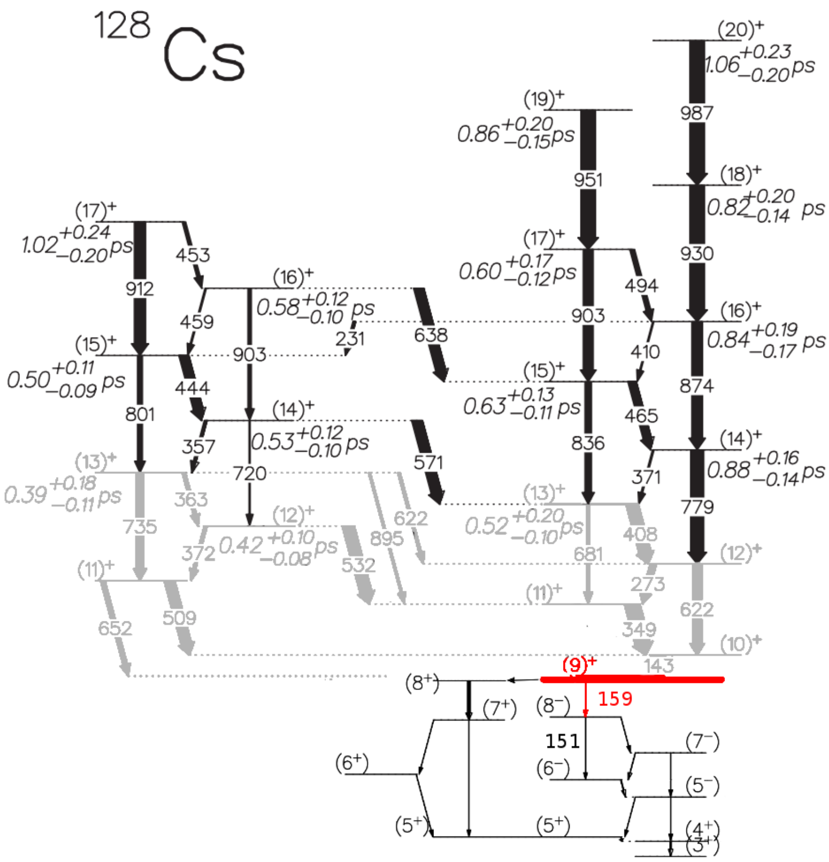

Figure 14: Relevant part of the ^{128}Cs level scheme. The isomeric 9^+ state which is the chiral bandhead has been marked in red colour. Black colour used above the isomeric states indicates the levels and transition probabilities which chiral interpretation has beed obtained with previous indirect chirality research. Gray colour shows the part of the level scheme where chiral or non-chiral configuration of ^{128}Cs has not yet been determined. The 9^+ isomeric state decay was used to reconstruct the bottom part of the level scheme.

observed through the precession of the non-isotropic gamma rays distribution - fig. 15. The precession frequency allows to get g-factor value of the state from which the gamma quanta are emitted. That's why the pulsed beam of high quality is required. The studied level is fed by a short beam pulse while its decay and the precession of the emitted gamma radiation is observed between beam pulses. In our experiment, the beam pulse lasted 1ns with the repetition period of 400ns. Such a long gap between beam pulses allowed the observation of several precession periods -fig. 16- and getting precise g-factor value of the 9^+

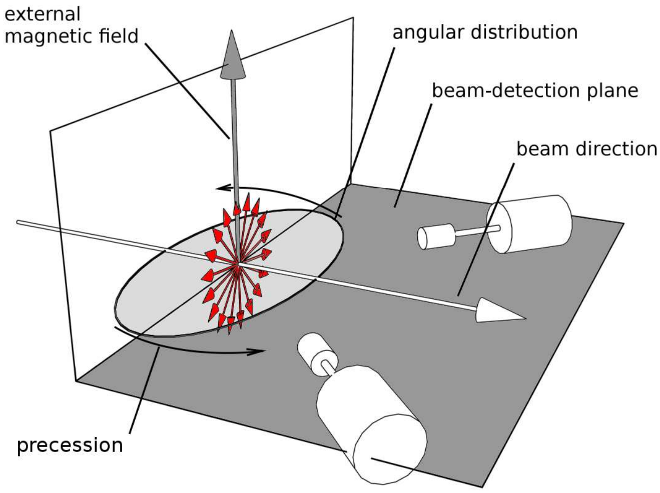

Figure 15: The Time Dependent Perturbed Angular Distribution (TDPAD) method used for dipole magnetic moment measurement. Read colour - non-isotropic spin alignment of the final nuclei produced with nuclear fusion reaction. The spin alignment in the plane perpendicular to the beam direction results in the non-isotropic gamma emission. The external magnetic field vector is perpendicular to the beam direction (vertical in the picture). Interaction of the nuclear magnetic moment with the applied external magnetic field results in the spin precession and the corresponding precession of the non-isotropic gamma radiation around the external magnetic field vector. The precession frequency is observed via oscillations of the gamma radiation intensity registered by two detectors located in the beam-detection plane.

state.

I've finished the experimental data analysis already in 2011 with the precise result of the g-factor $g = 0.59(1)$. However it turned out that such a value was a big surprise at least for two reasons. First of all, this result indicated the non-chiral configuration of chiral bandhead in ^{128}Cs isotope. This first direct observation of the geometry formed by the three angular momentum vectors in a chiral nucleus indicated that these vectors only span a two-dimensional space. Secondly, this result was inconsistent with all model calculations available at the time. These calculations pointed to an almost ideal chiral geometry, where the three angular momentum vectors in question span a three-dimensional space being almost mutually perpendicular with a g-factor value $g = g_{chiral} = 0.5$.

The discrepancies between experimental observation and theoretical calculations once again delayed the results publication. During the next few years different interpretations of those differences were presented. One of them was, for example, the hypothesis about the necessity of a transition from the

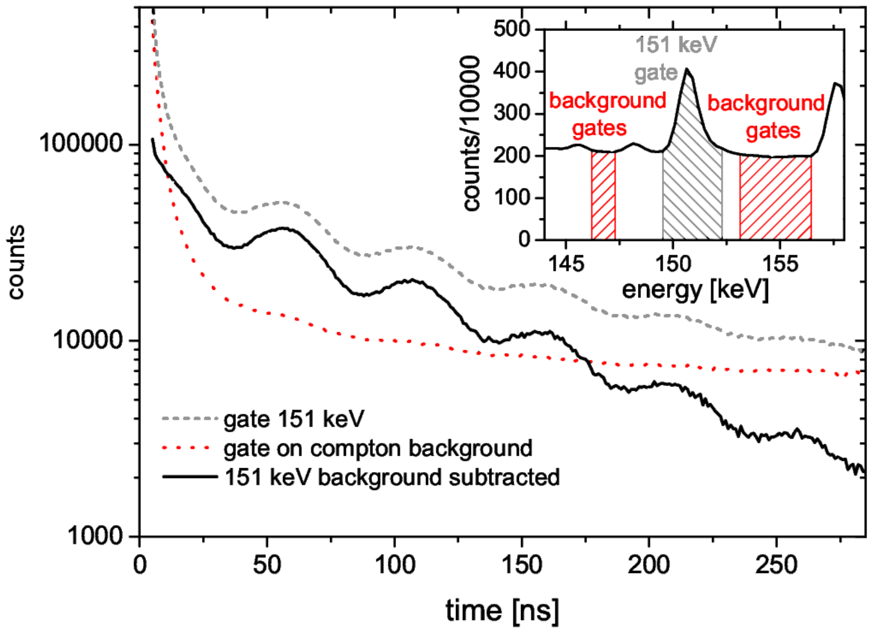

Figure 16: Oscillations of the gamma radiation emitted by 151 keV transition - gray colour. Red-colour - the background radiation intensity. Black colour - Gamma radiation oscillations of 151 keV transition after background subtraction.

quantum state (sparse composition of single coupling schemes) to the classical state (a wave packet with a rich composition of single coupling schemes) in order to achieve the non-chiral geometry of a nucleus. Fortunately, these hypotheses were not published and after some years of discussion they turn out not to be true. Intensive cooperation with a Chinese group of theoreticians finally brought effects in 2016 and 2017. A new, more complicated version of the PRM model (*Partition-Rotor-Model*) was used in the calculations, where odd nucleons may occupy different states within the same nuclear shell. Some of these occupation configurations reproduce the experimental g-factor $g = 0.59(1)$ and the way for results publication was no logner blocked. I have published the final conclusions of the first direct research of the nuclear chirality in the letter [H9] entitled *"First Measurement of the g-Factor in the Chiral Band: The Case of the* ^{128}*Cs Isomeric State"*

7 Conclusions from the first direct nuclear chirality research

In contrast to indirect nuclear chirality research (where symptoms of the nuclear chirality phenomenon like the existence of the chiral partner bands and characteristic electromagnetic transition probabilities in these bands are observed) the direct nuclear chirality research by g-factor measurements allows to draw some undoubted conclusions. The key conclusion is the rejection of the 9^+ state interpretation within the two-component model. The two-component model assumes that the bandhead involves only the lowest state of the core, i.e. $j_R = 0$. The two-component hypothesis is based on the assumption that the total $I = 9$ spin value is built chiefly by coupling only two angular momentum vectors of the odd nucleons j_p and j_n. The analysis presented in ref.[H9] clearly shows that it is not possible to reproduce the experimental result $g = 0.59(1)$ within the two-component model. The core angular momentum value must be $j_R = 4\hbar$ in order to reproduce the experimental observations. So, the core angular momentum $j_R \approx 4\hbar$ in the bandhead of ^{128}Cs is similar to angular momentum of the odd nucleons $j_p = j_n = \frac{11}{2}\hbar$. This result is even ahead of today's theoretical analyses in which $j_R \approx 0\hbar$ is still considered to be true as the following fragment of ref.[13] shows:

> *"Further study for the angular momentum shows that the paradox is caused by the fact that the angular momentum of the rotor is much smaller than those of the proton and the neutron near the bandhead."*

Another important conclusion is based on earlier indirect chirality research of the ^{128}Cs isotope where chiral electromagnetic selection rules (the B(M1) staggering) have been observed in partner bands for the spin range $I \geq 13\hbar$. The direct chirality research through the g-factor measurement revealed, however, that the chiral $I = 9\hbar$ bandhead is not chiral. This observation indicates that the ^{128}Cs nucleus undergoes a transition from the non-chiral configuration at the bandhead to chiral configuration for spins higher than 13 $\hbar$. Such a phenomenon has already been predicted in 2004 in ref.[30] as the critical frequency for nuclear rotation that needs to be exceeded in order for the three angular momentum vectors to form the chiral geometry. Despite the experimental premises demonstrating the existence of a chiral critical frequency, which I published in 2012 in ref.[H2], this phenomenon has not been observed until today. Model calculations aimed at finding the value of the chiral critical frequency are currently the subject of intense theoretical research [13].

The obtained g-factor result indicating the non-chiral geometry of the ^{128}Cs bandhead is particularly interesting in the context of the recent achievements in the nuclear chirality theory [14],[27]. In these works, the contribution of the non-chiral geometry to the wave function of the partner bands levels nas been studied for the first time. It allows a deeper understanding of the nuclear chirality phenomenon by using the following non-stationary states as the basis set for model calculations:

- chiral $|L\rangle$ and $|R\rangle$ states where the handedness parameter $o \neq 0$ and three angular momentum vectors span the three-dimensional space
- non-chiral $|P\rangle$ states where the three angular momentum vectors only span the two-dimensional space with the handedness parameter $o = 0$. This theoretical research constitutes a contemporary context for the g-factor results we obtained in ^{128}Cs case. It again shows that the experimental results are ahead of the theoretical development for several years. To this day it is the main reason for delays in the results publications.

8 Conclusions and future perspectives

The aim of this work is a brief presentation of nuclear chirality experimental research in the context of current progress in the theoretical description of this phenomenon. These studies can be divided into two stages:

- the indirect chirality research, in which the effects of spontaneous chiral symmetry breaking are observed such as the existence of two almost degenerate rotational bands and characteristic selection rules of electromagnetic transitions between the states in these bands.

- the direct chirality research with the goal to determine the geometry of the system formed by three angular momentum vectors in question.

The direct chirality research described here relate to the first g-factor measurement in the state belonging to chiral partner bands world-wide. Despite the fundamental inability to determine the handedness of the three angular momentum vectors, we succeeded to perform a measurement that is able to verify whether these vectors span the three-dimensional space - a chiral case, or only a two-dimensional space - a non-chiral case. The result of the experiment indicates the non-chiral configuration of the $I = 9^+$ chiral bandhead in ^{128}Cs isotope. In the context of previous indirect chirality research this result suggests the existence of the chiral critical frequency which was earlier predicted theoretically. This year's (2018) theoretical achievement [13] based on complex nuclear models also indicates the existence of the chiral critical frequency. The experiments aimed at finding the chiral critical frequency are the most likely future perspective of experimental research in the field of nuclear chirality. To this end, the nature of the excited states lying directly above the chiral bandhead should be verified. In ^{128}Cs isotope, these are rotational levels in partner bands with the spin values of 10^+, 11^+ and 12^+. The first measurement of the 10^+ state has already been carried out with a new Fast-Timing technique (not described here) [31] and the new experimental setup called EAGLE-EYE - fig. 17. I have constructed the EAGLE-EYE setup in 2017 and 2018 in cooperation with NCBJ (Poland), ŚLCJ (Poland), RHOSPHERE (Romania), FATIMA (UK, France, Germany). A return to the Recoil in Vacuum technique is also planned to measure g-factors of

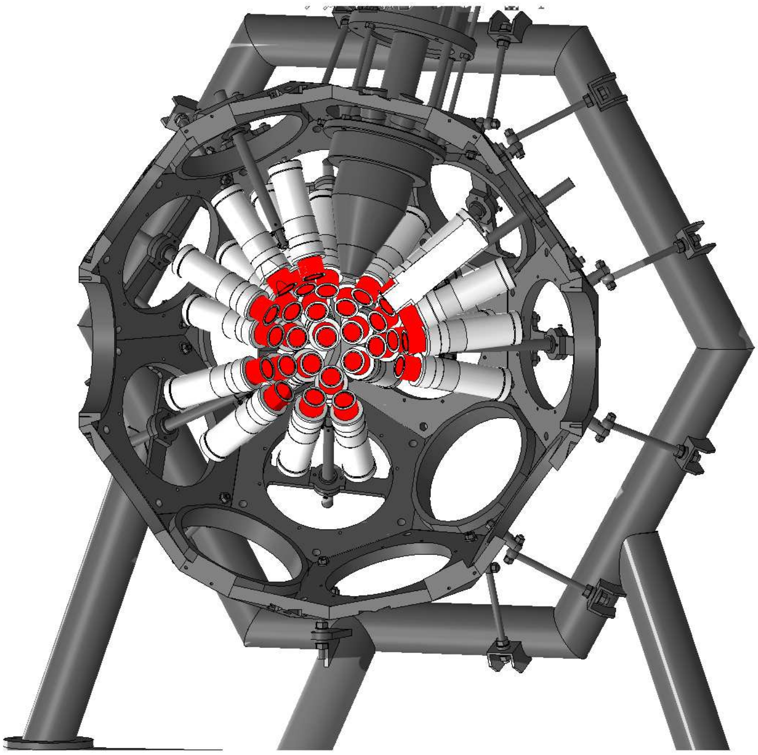

Figure 17: The EAGLE-EYE setup consists of many fast LaBr detectors that are put into the EAGLE array equipped with 16 high-efficiency HPGe anti-compton shielded spectrometers. The location of the LaBr crystals is marked in red colour. The first experiment aimed at lifetime measurement of low laying chiral band levels in ^{128}Cs was performed in February 2018 with 24 LaBr detectors obtained from FATIMA and RHOSPHERE collaborations.

low-lying states in partner bands of ^{132}La isotope.

9 appendix - scalar products expectation values of angular momentum vector pairs

This appendix contains analytical formulae that are used for simple wave functions, i.e. those represented by the single coupling schemes. These formulae allow to calculate the expectation values of scalar products of angular momentum vectors pairs in the chiral nucleus and will be discussed in an article planned to be released in 2019.

$$\langle (j_p' j_n') j_{pn}' j_R'; J'M' | \vec{j}_p \cdot \vec{j}_n | (j_p j_n) j_{pn} j_R; JM \rangle = \delta_{J'J} \delta_{M'M} \delta_{j_p' j_p} \delta_{j_n' j_n} \delta_{j_R' j_R} \delta_{j_{pn}' j_{pn}} (-1)^{j_p + j_n + j_{pn}}$$

$$\times \sqrt{j_p(j_p+1)(2j_p+1) j_n(j_n+1)(2j_n+1)} \left\{ \begin{array}{ccc} j_p & j_n & j_{pn} \\ j_n & j_p & 1 \end{array} \right\}, \tag{12}$$

$$\langle (j_p' j_n') j_{pn}' j_R'; J'M' | \vec{j}_p \cdot \vec{j}_R | (j_p j_n) j_{pn} j_R; JM \rangle = \delta_{J'J} \delta_{M'M} \delta_{j_p' j_p} \delta_{j_n' j_n} \delta_{j_R' j_R} (-1)^{j_R + j_p + j_n + J + 1}$$

$$\times \sqrt{(2j_{pn}+1)(2j_{pn}'+1)} \sqrt{j_p(j_p+1)(2j_p+1)} \sqrt{j_R(j_R+1)(2j_R+1)}$$

$$\times \left\{ \begin{array}{ccc} j_p & j_{pn} & j_n \\ j_{pn}' & j_p & 1 \end{array} \right\} \left\{ \begin{array}{ccc} j_{pn} & j_R & J \\ j_R & j_{pn}' & 1 \end{array} \right\}, \tag{13}$$

$$\langle (j_p' j_n') j_{pn}' j_R'; J'M' | \vec{j}_n \cdot \vec{j}_R | (j_p j_n) j_{pn} j_R; JM \rangle = \delta_{J'J} \delta_{M'M} \delta_{j_p' j_p} \delta_{j_n' j_n} \delta_{j_R' j_R} (-1)^{j_R + j_p + j_n + J + 1 + j_{pn} + j_{pn}'}$$

$$\times \sqrt{(2j_{pn}+1)(2j_{pn}'+1)} \sqrt{j_n(j_n+1)(2j_n+1)} \sqrt{j_R(j_R+1)(2j_R+1)}$$

$$\times \left\{ \begin{array}{ccc} j_n & j_{pn} & j_p \\ j_{pn}' & j_n & 1 \end{array} \right\} \left\{ \begin{array}{ccc} j_{pn} & j_R & J \\ j_R & j_{pn}' & 1 \end{array} \right\}. \tag{14}$$

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5. Discussion of other scientific and research achievements.

The most important achievement, which is not included in the habilitation paper presented here, is my research on the fundamental violation of SU4 symmetry in collective states of N = Z nuclei. Such collective states may have a character described by four types of bosons. These bosons presents a generalization of the classic SU4 symmetry which gives the Wigner multiplets. The existence of collective bosons may manifested itself as an existence of super-allowed Gamow-Teller transitions. I carried out an innovative analysis of this phenomenon, which I concluded in the following letter:

E.Grodner, A.Gadea, P.Sarriguren, S.M.Lenzi, J.Grebosz, J.J.Valiente-Dobon, A.Algora, M.Gorska, P.H.Regan, D.Rudolph, G.de Angelis, J.Agramunt, N.Alkhomashi, L.Amon Susam, D.Bazzacco, J.Benlliure, G.Benzoni, P.Boutachkov, A.Bracco, L.Caceres, R.B.Cakirli, F.C.L.Crespi, C.Domingo-Pardo, M.Doncel, Zs.Dombradi, P.Doornenbal, E.Farnea, E.Ganioglu, W.Gelletly, J.Gerl, A.Gottardo, T.Huyuk, N.Kurz, S.Leoni, D.Mengoni, F.Molina, A.I.Morales, R.Orlandi, Y.Oktem, R.D.Page, D.Perez, S.Pietri, Zs.Podolyak, A.Poves, B.Quintana, S.Rinta-Antila, B.Rubio, B.S.Nara Singh, A.N.Steer, S.Verma, R.Wadsworth, O.Wieland, H.J.Wollersheim

"Hindered Gamow-Teller Decay to the Odd-Odd N=Z 62Ga: Absence of Proton-Neutron T=0 Condensate in A=62"
Physical Review Letters 113, 092501 (2014)

ERNEST GRODNER