Vol. 39 (2008) ACTA PHYSICA POLONICA B No 2

QUEST FOR THE CHIRAL SYMMETRY BREAKING IN ATOMIC NUCLEI*

E. Grodner

Nuclear Physics Division, Institut of Experimental Physics, Warsaw University
Hoża 69, 00-681 Warsaw, Poland

(Received January 17, 2008)

The phenomenon of chiral symmetry breaking is discussed and a review of a wide spectrum of the experimental data is given. In addition to the basic description of this phenomenon an analysis of the level schemes and electromagnetic properties observed in nuclei expected to show the chiral symmetry breaking is presented.

PACS numbers: 21.10.Re, 21.10.Tg, 23.20.–g

1. Introduction

The chiral symmetry breaking, further also referred to as chirality phenomenon, has been discussed already for ten years. The formulation of the chirality hypothesis in 1997 [1] was followed by several waves of experimental studies aimed at finding this new phenomenon in nature. After numerous reports on the existence of the so-called chiral partner bands published at the beginning of the current decade [2–5], the need to determine the electromagnetic properties of these bands became obvious. New data on the gamma-transition probabilities are progressively collected allowing nowadays to verify the interpretation of the observed level structure. Almost ten years after formulation of the chirality hypothesis the full evidence for chiral symmetry breaking phenomenon in ^{128}Cs nucleus [6] has been reported. This result renewed the interest in the experimental as well as theoretical study of the chirality phenomenon. The present paper gives a review of experimental data concerning the nuclear properties expected to reveal chiral symmetry breaking and a summary of the studies made in this field so far. In addition to the obtained experimental results a simple description of the chirality phenomenon is presented.

* Presented at the XXX Mazurian Lakes Conference on Physics, Piaski, Poland, September 2–9, 2007.

2. Breaking of symmetry and the chiral dynamical variable

The spontaneous breaking of symmetry in a state of a quantum system means, roughly speaking, that this state, which certainly is not an eigenstate of the Hamiltonian, is changed under the action of the corresponding symmetry operator. A good example of this mechanism is represented by the breaking of translational symmetry by a finite quantum object (like a nucleus). Such a finite object can be described by a wave pocket with a well defined localization in the physical space. This wave pocket is not eigenfunction of Hamiltonian meaning that its localization is not time-constant — it is dynamical variable which changes under the action of the translation operator (symmetry operator). Therefore the states of the broken symmetry should be referred to as localized states (in terms of dynamical variables).

A similar mechanism is used to describe the chiral symmetry breaking nuclei. In the simplest case, these nuclei can be treated as a system of three components: the even–even triaxial core, the odd proton (particle) and the odd neutron (hole). It is expected that the energy of such a system is minimal when the angular momenta vectors of these three components are mutually perpendicular. Two frames can then be formed by means of these vectors: the right- or left-handed one and the nucleus can be described by the localized (in a parameter of the handedness) wave functions: either $\Phi_{\rm L}$ — for the left-handed or $\Phi_{\rm R}$ for the right-handed frame. This localization changes under the action of the so-called chiral operator [7] (chiral symmetry operator) R_yT:

$$R_yT\Phi_{\rm L} \;=\; \Phi_{\rm R}\,, \tag{1}$$

$$R_yT\Phi_{\rm R} \;=\; \Phi_{\rm L}\,, \tag{2}$$

which, according to the definitions given at the begining of the present section, means the breaking of the chiral symmetry.

Though the chiral symmetry breaking has already been studied for many years, the theoretical grounds for describing this phenomenon have not yet been fully established. For the translational and rotational symmetries the dynamical variables are well defined quantities: the position and the orientation angle, respectively. On the contrary, the chiral dynamical variable (quantity describing the handedness) is not yet well established. One of the possible definitions of this quantity has been given in Ref. [7] where the handedness of the system is defined as the expectation value of operator $\hat{\sigma}$:

$$\hat{\sigma} = \frac{(\hat{j}_p \times \hat{j}_n)\cdot \hat{j}_{\rm R}}{\sqrt{j_p(j_p+1)\cdot j_n(j_n+1)\cdot j_{\rm R}(j_{\rm R}+1)}}\,, \tag{3}$$

$\hat{j}_{\rm R}$, $\hat{j}_p$, $\hat{j}_n$ being the angular momenta vector operators of the core, the proton and the neutron, respectively. In fact, the expectation value of this operator could be a good measure of the handedness since it takes opposite values (± 1) for left- or right-handed systems.

3. Symmetry restoration and experimentally observed properties

The instruments used in nuclear spectroscopy experiments are often unable to determine all dynamical variables of the given nucleus. This means that direct observation of the spontaneous breaking of symmetry is often impossible. Thus the question what is measured in the experiments and what information is obtained on the symmetry can be answered starting from one of the basic rules of quantum mechanics, *i.e.* the uncertainty principle. According to this principle, it is impossible to measure the values of complementary (not commuting with each other) variables simultaneously: either the value of one variable or its complementary counterpart can be precisely determined. In the case of translational symmetry this means that either the position or the momentum can be measured. The same is valid for the rotational symmetry. If angular orientation is not observed, then the variable complementary to it — the angular momentum — can be determined. Indeed, in the experimental level schemes the rotational bands built on excited levels with a well defined angular momentum are clearly observed.

In the experiments aimed to observe the chiral symmetry breaking, the value of the chiral dynamical variable – handedness σ — is not measured, while the states (chiral doublets) with the well defined variable that is complementary to it — chirality Σ — are observed. The precise definitions of quantities σ and Σ have not been established yet, which gives an opportunity for further theoretical investigations. The above considerations show an important property common for all kind of symmetries: the objects studied experimentally are described by wave functions (in the laboratory reference frame) not localized in the dynamical variables. This means that these wave functions do not violate the symmetries. For instance, the rotation of a deformed nucleus (breaking the rotational symmetry) is observed by the occurrence of rotational band whose levels have a well defined angular momentum. The wave functions of these levels have therefore an undefined angular orientation (which is the corresponding complementary dynamical variable). Therefore such (not localized) laboratory wave functions do not violate the rotational symmetry. Transformation from the localized (symmetry breaking) wave functions to the corresponding laboratory ones (conserving the symmetries) can be found by the well known GCM projection technique [8]. The GCM procedure is also often called restoration of the broken symmetries. This restoration is necessary to obtain theoretical predictions which can then be compared with the experimentally measured quantities.

The restoration of symmetry in the spirit of the GCM technique leads to the conclusion that for the chiral symmetry breaking systems doublet of states (with $\Sigma = \pm 1$) should be observed for a given spin I:

$$|\Psi^I_{\Sigma=+}\rangle = \frac{1}{\sqrt{2(1+\mathrm{Re}\langle\Phi_{\mathrm{L}}|\Phi_{\mathrm{R}}\rangle)}}(|\Phi_{\mathrm{L}}\rangle + |\Phi_{\mathrm{R}}\rangle)\,, \tag{4}$$

$$|\Psi^I_{\Sigma=-}\rangle = \frac{i}{\sqrt{2(1-\mathrm{Re}\langle\Phi_{\mathrm{L}}|\Phi_{\mathrm{R}}\rangle)}}(|\Phi_{\mathrm{L}}\rangle - |\Phi_{\mathrm{R}}\rangle)\,. \tag{5}$$

By calculating the expectation values of a given operator in these states the theoretical predictions of the quantities observed experimentally can be obtained. The values of these quantities depend on the degree of chiral symmetry breaking. Therefore their experimental investigation is a possible way of empirical study of the chirality phenomenon.

4. Chiral symmetry breaking limits and experimental observations

The situation where all the three angular momenta vectors $\vec{j}_p$, $\vec{j}_n$ and $\vec{j}_{\mathrm{R}}$ are mutually perpendicular ($\sigma = \pm 1$) corresponds to the ideal case of the chiral configuration. This probably does not often take place in real nuclei where the angles between the angular momenta vectors can deviate from 90°. In such a situation σ will take values between -1 and $+1$ with the value 0 corresponding to orientation of the three vectors in one plane. The quantity σ is not a good quantum number and therefore the handedness can change and the nucleus can tunnel from the left-handed state to the right-handed one. This tunneling effect together with the distribution of the localized wave functions in the σ variable are the main factors describing the limits of the chiral symmetry breaking. In the case of a strong chiral symmetry breaking limit the left-handed state is separated from the right handed one which means that $\langle\Phi_{\mathrm{L}}|\Phi_{\mathrm{R}}\rangle = 0$. Also a high potential energy barrier prevents the tunneling effect $\langle\Phi_{\mathrm{L}}|H|\Phi_{\mathrm{R}}\rangle = 0$. On the contrary, in the case of a weak chiral symmetry breaking limit the distribution of the localized states in the variable σ gives non-vanishing overlap $\langle\Phi_{\mathrm{L}}|\Phi_{\mathrm{R}}\rangle \neq 0$. The tunneling effect can also be strong in this case which means that $\langle\Phi_{\mathrm{L}}|H|\Phi_{\mathrm{R}}\rangle \neq 0$ and can lead in the extreme situation to the chiral-vibrational modes. The limits of the chiral symmetry breaking determine the properties observed experimentally. This can be shown by calculating the expected energy of the chiral doublets. The Hamiltonian H and the symmetry operator R_yT fulfill the following commutation relation:

$$[H, R_yT] = 0 \tag{6}$$

leading to the following formulae for energies of the chiral doublets

$$\left\langle \Psi^I_{\Sigma=+}|H|\Psi^I_{\Sigma=+}\right\rangle \;=\; \frac{E_0+\Delta E}{1+\epsilon}\,, \tag{7}$$

$$\left\langle \Psi^I_{\Sigma=-}|H|\Psi^I_{\Sigma=-}\right\rangle \;=\; \frac{E_0-\Delta E}{1-\epsilon}\,, \tag{8}$$

where $\Delta E = \mathrm{Re}\langle \Phi_\mathrm{L}|H|\Phi_\mathrm{R}\rangle$, $\epsilon = \mathrm{Re}\langle \Phi_\mathrm{L}|\Phi_\mathrm{R}\rangle$ and $E_0 = \mathrm{Re}\langle \Phi_\mathrm{L}|H|\Phi_\mathrm{L}\rangle$. The parameters ΔE and ϵ (see also [9]) vanish in the strong limit of chiral symmetry breaking which makes the energies of the doublets equal. These parameters become non-zero values in the case of a weak breaking limit, and the resulting energy splitting between the chiral partner bands appears. The first experimental studies of the chirality phenomenon aimed to find the partner bands in the level schemes gave also information on the discussed splitting which is presented in Fig. 1 for selected nuclei. The data presented in this figure can be classified in two ways: the value of the energy splitting itself and the spin dependence of this splitting. Regarding the former value, both, the ^{128}Cs and ^{126}Cs isotopes as well as the ^{134}Pr nucleus (for spins greater than 13) are close to the strong limit of the chiral symmetry breaking since the energy splitting is small (less than 200keV). The dependence of the

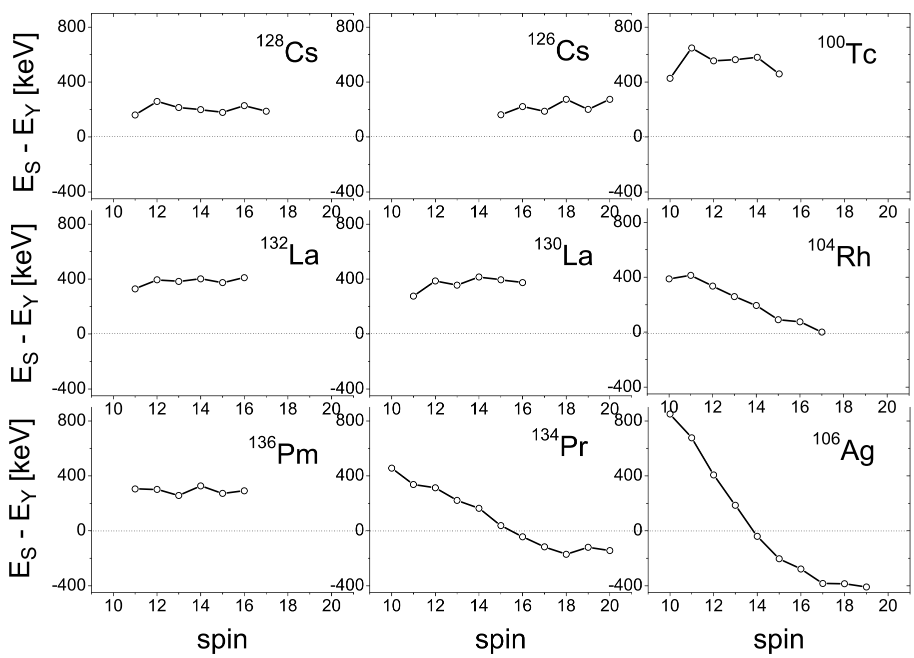

Fig. 1. Energy difference $E_\mathrm{S}-E_\mathrm{Y}$ between chiral doublets (energy of the side band level E_S minus the corresponding one of yrast level E_Y) as a function of spin.

splitting on the spin value should be constant, otherwise the level spacing in both bands differ. The monotonic spin dependence of the energy splitting, like the one observed in ^{134}Pr, indicates different moments of inertia in each band which makes the chiral interpretation unlikely. Nevertheless, ^{134}Pr was considered as the best nucleus presenting the chirality phenomenon.

Also other observables would be doubly degenerated if only they were expectation values of operators fulfilling the same commutation relation as the Hamiltonian. As it has been reported in Ref. [9] (see also [10]) the electromagnetic transition operator $B(\lambda\mu)$ also commutes with the R_yT symmetry operator, $[B(\lambda\mu), R_yT] = 0$ for $\lambda\mu = $ M1, E2, M3, E4, ... This means that the transition probabilities can be described by formulae (7, 8), where the gamma transition operator $B(\lambda\mu)$ is used instead of the Hamiltonian

$$\left\langle \Psi^{I}_{\Sigma=+} || B(\lambda\mu) || \Psi^{I_i}_{\Sigma=+} \right\rangle = \frac{B_0 + \Delta B}{1+\epsilon}\,, \tag{9}$$

$$\left\langle \Psi^{I}_{\Sigma=-} || B(\lambda\mu) || \Psi^{I_i}_{\Sigma=-} \right\rangle = \frac{B_0 - \Delta B}{1-\epsilon}\,. \tag{10}$$

The parameters $\Delta B = \mathrm{Re}\langle \Phi_{\mathrm{L}} || B(\lambda\mu) || \Phi_{\mathrm{R}} \rangle$, $\epsilon = \mathrm{Re}\langle \Phi_{\mathrm{L}} | \Phi_{\mathrm{R}} \rangle$ vanish in the limit of strong symmetry breaking and the resulting γ-transition probabilities from the members of the chiral doublet would be equal. This leads to the conclusion that the electromagnetic properties observed in partner bands should be similar. The smaller the difference of the reduced transition probabilities measured in the two bands the stronger the evidence in favour of existence of the chirality phenomenon. The reduced transition probabilities as a function of the spin value of the initial level are plotted in Fig. 2. The surprising conclusion resulting from this picture is that the ^{132}La nucleus cannot be interpreted as one breaking the chiral symmetry as it was previously suggested [11] since a huge difference in the electromagnetic properties between the partner bands of ^{132}La is observed [12, 13].

Among the available experimental data on the level lifetimes, the most interesting case is related to the ^{128}Cs nucleus whose electromagnetic transition probabilities observed in the partner bands agree with those calculated for the ideal chiral configuration [14]. The data in Fig. 2 show that the limit of strong symmetry breaking is not achieved since a small difference in B(E2) and B(M1) values between the partner bands in ^{128}Cs is present. However, the absolute values of B(M1) probability as a function of spin show very characteristic feature — B(M1) staggering [6, 13, 15] observed in the partner bands for the first time. According to Ref. [4, 14] this indicates that the degree of the chiral symmetry breaking in ^{128}Cs is very close to the strong breaking limit. The ^{128}Cs isotope is now considered as the best example presenting the chirality phenomenon.

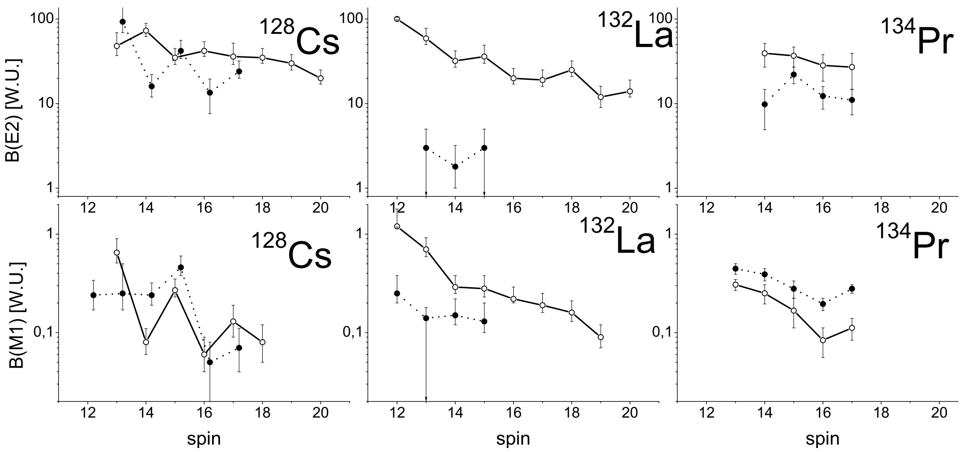

Fig. 2. Reduced E2 (upper part) and M1 (lower part) transition probabilities as a function of the initial spin value. Solid and dotted lines correspond to yrast and side band, respectively.

Having the experimental values of the reduced transition probabilities $B^{\rm exp}(\lambda\mu; I_i \to I)$ we can calculate matrix elemets appearing in equations (9) and (10) by using the following formula

$$\left\langle \Psi_\Sigma^I || B(\lambda\mu) || \Psi_\Sigma^{I_i} \right\rangle = \pm\sqrt{(2I_i+1)B^{\rm exp}(\lambda\mu; I_i \to I)}\,. \tag{11}$$

In the following calculations the sign + is chosen (see Ref. [9]). It is also assumed that the yrast band is built of $|\Psi_+^I\rangle$ and the side band — of $|\Psi_-^I\rangle$ states. Other cases are discussed in Ref. [9]. By using the above assumptions and equation (11), formulae (9) and (10) get the form

$$\sqrt{(2I_i+1)B^{\rm exp}_{\rm yrast}(\lambda\mu; I_i \to I)} \;=\; \frac{B_0+\Delta B}{1+\epsilon}\,, \tag{12}$$

$$\sqrt{(2I_i+1)B^{\rm exp}_{\rm side}(\lambda\mu; I_i \to I)} \;=\; \frac{B_0-\Delta B}{1-\epsilon}\,. \tag{13}$$

It is usefull to construct the following experimental quantity

$$\epsilon(\lambda\mu, I_i) = \frac{\sqrt{(2I_i+1)B^{\rm exp}_{\rm yrast}(\lambda\mu; I_i \to I)} - \sqrt{(2I_i+1)B^{\rm exp}_{\rm side}(\lambda\mu; I_i \to I)}}{\sqrt{(2I_i+1)B^{\rm exp}_{\rm yrast}(\lambda\mu; I_i \to I)} + \sqrt{(2I_i+1)B^{\rm exp}_{\rm side}(\lambda\mu; I_i \to I)}}\,. \tag{14}$$

As it can be proved, this quantity is related to ϵ, B_0 and ΔB by the equation

$$\epsilon(\lambda\mu, I_i) = \frac{\Delta B - \epsilon B_0}{B_0 - \Delta B \epsilon} \tag{15}$$

and it describes two important phenomena for two limiting cases: $\epsilon \to 0$ or $\Delta B \to 0$. In the first case ($\epsilon \to 0$) information on $\Delta B = \mathrm{Re}\langle \Phi_{\mathrm{L}} || B(\lambda\mu) || \Phi_{\mathrm{R}} \rangle$ can be obtained

$$\lim_{\epsilon \to 0} \epsilon(\lambda\mu, I_i) = \frac{\Delta B}{B_0}\,. \tag{16}$$

To change the handedness in the chiral configuration, one of the three spins must be inverted. This cannot be done by M1 or E2 transitions since a larger spin difference is required. On the contrary, the ΔB quantity for M1 and E2 transition types can have large values for near planar orientation of the three angular momenta vectors. In the second case ($\Delta B \to 0$) the $\epsilon(\lambda\mu, I_i)$ gives information on the mutual overlap of the wave functions with the defined handedness, $\epsilon = \mathrm{Re}\langle \Phi_{\mathrm{R}} | \Phi_{\mathrm{L}} \rangle$

$$\lim_{\Delta B \to 0} \epsilon(\lambda\mu, I_i) = -\epsilon \tag{17}$$

which is also expected to be small for the chiral configuration and large for the planar one. In both cases the following values of $\epsilon(\lambda\mu, I_i)$ are expected

$$\begin{array}{lcll} |\epsilon(\lambda\mu, I_i)| & \approx & 0 & \text{for chiral configuration} \\ |\epsilon(\lambda\mu, I_i)| & \approx & 1 & \text{for planar configuration}\,. \end{array}$$

The plot of the experimentally obtained values of $\epsilon(\lambda\mu, I_i)$ as a function of spin I_i is shown in Fig. 3. One can see that both $\epsilon(E2)$ and $\epsilon(M1)$ values are close to zero for ^{128}Cs and ^{134}Pr which suggests that the chiral symmetry breaking is close to the strong breaking limit in these nuclei. The deviation of the $\epsilon(E2)$ and $\epsilon(M1)$ experimental points from zero can

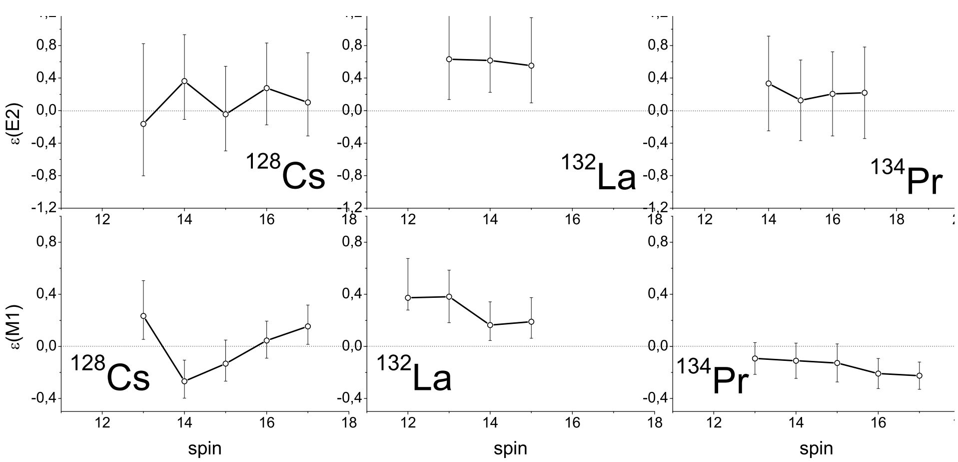

Fig. 3. The ϵ(E2) (upper part) and ϵ(M1) (lower part) experimental values as a function of spin. See text for explanation.

be expressed by the statistical χ^2 quantity. The χ^2 values for $\epsilon(M1)$ are: $\chi^2_{\rm M1}(^{128}{\rm Cs})$=1.26; $\chi^2_{\rm M1}(^{132}{\rm La})$=2.46; $\chi^2_{\rm M1}(^{134}{\rm Pr})$=1.98. These values suggest that among these three nuclei ^{128}Cs is the closest to the strong breaking limit of chiral symmetry.

5. Conclusions

The recent results of the lifetime measurements show that the presence of partner bands is not a sufficient argument to prove whether or not the chirality phenomenon is observed. The similar level schemes of ^{132}La and ^{128}Cs indicate that both nuclei may be interpreted in terms of chiral symmetry breaking. However, the measured transition probabilities show a striking difference in electromagnetic properties observed in these nuclei. The characteristic B(M1) staggering as a function of spin value is neither observed in ^{132}La nor in ^{134}Pr. Among the three nuclei whose level lifetimes have been measured, ^{128}Cs nucleus is so far the only one showing full agreement with the predictions based on of the chirality phenomenon. The measured level energies and transition probabilities suggest the chiral symmetry breaking in ^{128}Cs. This conclusion could be supported by other observables which are expected to be doubly degenerated in the partner bands. Other type of experiments should therefore be planned to explore new quantities, namely the expectation values of operators NEW fulfilling the commutation relation $[NEW, R_yT] = 0$.

I would like to appreciate the permanent support by S.G. Rohoziński of the Institute of Theoretical Physics of the University of Warsaw. I express my gratitude to Ch. Droste, T. Morek and J. Srebrny for their help in preparing and performing the experiments. Thanks are also due to the operating staff of the U200P cyclotron of Heavy Ion Laboratory of the University of Warsaw.

REFERENCES

[1] S. Frauendorf, Jie Meng, *Nucl. Phys.* **A617**, 131 (1997).

[2] K. Starosta, T. Koike, C.J. Chiara, D.B. Fossan, D.R. LaFosse, A.A. Hecht, C.W. Beausang, M.A. Caprio, J.R. Cooper, R. Krücken, J.R. Novak, N.V. Zamfir, K.E. Zyromski, D.J. Hartley, D.L. Balabanski, Jing-ye Zhang, S. Frauendorf, V.I. Dimitrov *Phys. Rev. Lett.* **86**, 971 (2001).

[3] T. Koike, K. Starosta, C.J. Chiara, D.B. Fossan, D.R. LaFosse *Phys. Rev.* **C63**, 061304 (2001).

[4] T. Koike, K. Starosta, C.J. Chiara, D.B. Fossan, D.R. LaFosse, *Phys. Rev.* **C67**, 044319 (2003).

[5] C. Vaman, D.B. Fossan, T. Koike, K. Starosta, I.Y. Lee, A.O. Macchiavelli, *Phys. Rev. Lett.* **92**, 032501 (2004).

[6] E. Grodner, J. Srebrny, A.A. Pasternak, I. Zalewska, T. Morek, Ch. Droste, J. Mierzejewski, M. Kowalczyk, J. Kownacki, M. Kisieliński, S.G. Rohoziński, T. Koike, K. Starosta, A. Kordyasz, P.J. Napiorkowski, M. Wolińska-Cichocka, E. Ruchowska, W. Płóciennik, J. Perkowski, *Phys. Rev. Lett* **97**, 172501 (2006).

[7] K. Starosta, C.J. Chiara, D.B. Fossan, T. Koike, T.T.S. Kuo, D.R. LaFosse, S.G. Rohoziński, Ch. Droste, T. Morek, J. Srebrny, *Phys. Rev.* **C65**, 044328 (2002).

[8] P. Ring, P. Schuck, *Nuclear Many-Body Problem*, Springer-Verlag, 1975.

[9] E. Grodner, S.G. Rohoziński, J. Srebrny *Acta Phys. Pol. B* **38**, 1411 (2007).

[10] A. Bohr, B. Mottelson *Nuclear Structure*, vol. I, W.A. Benjamin, New York 1969.

[11] K. Starosta, C.J. Chiara, D.B. Fossan, T. Koike, T.T.S. Kuo, D.R. LaFosse, S.G. Rohoziński, Ch. Droste, T. Morek, J. Srebrny, *Phys. Rev.* **C65**, 044328 (2002).

[12] E. Grodner, J. Srebrny, Ch. Droste, T. Morek, A.A. Pasternak, J. Kownacki, *Int. J. Mod. Phys.* **E13**, 243 (2004).

[13] J. Srebrny, E. Grodner, T. Morek, I. Zalewska, Ch. Droste, J. Mierzejewski, A.A. Pasternak, J. Kownacki, J. Perkowski, *Acta Phys. Pol. B* **36**, 1063 (2005).

[14] T. Koike, K. Starosta, I. Hamamoto, *Phys. Rev. Lett.* **93**, 172502 (2004).

[15] E. Grodner, I. Zalewska, T. Morek, J. Srebrny, Ch. Droste, M. Kowalczyk, J. Mierzejewski, M. Sałata, A.A. Pasternak, J. Kownacki, M. Kisieliński, A. Kordyasz, P. Napiorkowski, M. Wolińska, S.G. Rohoziński, R. Kaczarowski, W. Płóciennik, E. Ruchowska, A. Wasilewski, J. Perkowski, *Int. J. Mod. Phys.* **E14**, 347 (2005).