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SIMPLE PICTURE OF THE NUCLEAR SYSTEM DIVERGING FROM THE STRONG CHIRAL SYMMETRY BREAKING LIMIT*

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It is emphasised that the chiral symmetry operator, R_yT, commutes not only with the Hamiltonian but also with the electromagnetic transition operators $M(\sigma\lambda)$ for $\sigma\lambda =$M1, E2, *etc.* This fact is used to illustrate possible differences in electromagnetic properties between the two chiral partner bands. On the basis of the ^{132}La lifetime data an example is shown where differences in the transition probabilities observed in the partner and in the yrast band can be described in the chiral picture.

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1. Introduction

The breaking of chiral symmetry has been a subject of intense discussions for the last 10 years. Characteristic observables (structure of the level scheme [1] and the electromagnetic properties [2]) have been predicted for the spontaneous formation of chirality. The theoretical predictions gave rise to a series of experimental activities aimed to verify whether this new phenomenon is observed in nature. Such experiments were performed at the Warsaw cyclotron with the use of the OSIRIS II multidetector array. The

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lifetimes (in the picosecond range) of the excited states of ^{128}Cs and ^{132}La were obtained by the Doppler Shift Attenuation method and published in Ref. [3]. The results presented therein have shown that ^{128}Cs is so far the only known nucleus in which the energies of levels as well as the transition probabilities are close to the chiral picture. To study the nuclear system diverging from the strong chiral symmetry breaking we concentrate in the present paper on the other nucleus, ^{132}La, investigated in [3].

It has been shown in Ref. [1] that in an odd–odd triaxial nucleus the angular momenta of the odd proton, the odd neutron and the even–even core can form two systems of the opposite chiralities $\eta = L$ or $\eta = R$. This corresponds to the formation of two states $|L\rangle$ and $|R\rangle$, localised in parameter η. In such a case the chiral symmetry is broken since the $|L\rangle$ and $|R\rangle$ states are not eigenstates of the chiral symmetry operator R_yT:

$$R_yT|R\rangle = |L\rangle\,, \tag{1}$$

$$R_yT|L\rangle = |R\rangle\,. \tag{2}$$

The restoration of chiral symmetry in the spirit of the GCM technique, leads to conclusion that the following doublet of states $|\pm\rangle$ of definite symmetry should be observed:

$$|+\rangle = \frac{1}{\sqrt{N_+}}\left(|L\rangle + |R\rangle\right)\,, \tag{3}$$

$$|-\rangle = \frac{i}{\sqrt{N_-}}\left(|L\rangle - |R\rangle\right)\,, \tag{4}$$

$$N_\pm = 2(1 \pm \mathrm{Re}\langle L|R\rangle)\,. \tag{5}$$

The phases of $|+\rangle$ and $|-\rangle$ states are chosen in accordance with the phase convention given in [4], namely

$$R_yT|\pm\rangle = +1|\pm\rangle\,. \tag{6}$$

Two rotational bands (the chiral partner bands) are built on the $|+\rangle$ and $|-\rangle$ states. In the case of strong breaking of chiral symmetry the energies of corresponding levels as well as the transition probabilities should be the same along both bands. Possible candidates for the chiral partner bands were found in the level schemes of more than ten nuclei [5–7]. However, there are cases in which the electromagnetic transition probabilities deviate from the values predicted for the strong chiral symmetry breaking [3, 8]. It is, therefore, of great importance to present a description being able to deal with different degrees of chiral symmetry breaking. In the present paper we give a simple picture approaching this problem.

2. Hamiltonian and M($\sigma\lambda$) electromagnetic transition operators

In chiral-symmetric systems the symmetry operator R_yT commutes with the Hamiltonian

$$[R_yT, H] = 0\,. \tag{7}$$

If so, the energies (expectation values of the Hamiltonian) of the $|+\rangle$ and $|-\rangle$ states can be written in the form

$$\frac{\langle +|H|+\rangle}{\langle +|+\rangle} = \frac{\mathrm{Re}\langle L|H|L\rangle + \mathrm{Re}\langle L|H|R\rangle}{1+\mathrm{Re}\langle L|R\rangle}\,, \tag{8}$$

$$\frac{\langle -|H|-\rangle}{\langle -|-\rangle} = \frac{\mathrm{Re}\langle L|H|L\rangle - \mathrm{Re}\langle L|H|R\rangle}{1-\mathrm{Re}\langle L|R\rangle}\,. \tag{9}$$

If we denote $\mathrm{Re}\langle L|H|L\rangle$, $\mathrm{Re}\langle L|H|R\rangle$ and $\mathrm{Re}\langle L|R\rangle$ as E_0, ΔE and ε, respectively, the above equations take the form

$$\frac{\langle +|H|+\rangle}{\langle +|+\rangle} = \frac{E_0 + \Delta E}{1+\varepsilon}\,, \tag{10}$$

$$\frac{\langle -|H|-\rangle}{\langle -|-\rangle} = \frac{E_0 - \Delta E}{1-\varepsilon}\,. \tag{11}$$

Since the same commutation relations are also fulfilled for the electromagnetic transition operator $M(\sigma\lambda)$, where $\sigma\lambda$ is M1, E2, M3, E4, ... (see Eqs. (1A-73) and (3C-10) in Ref. [4]), H can be replaced by $M(\sigma\lambda)$ in equations (7), (10), (11):

$$[R_yT, M(\sigma\lambda)] = 0\,, \tag{12}$$

$$\frac{\langle +|M(\sigma\lambda)|+\rangle}{\langle +|+\rangle} = \frac{M_0 + \Delta M}{1+\varepsilon}\,, \tag{13}$$

$$\frac{\langle -|M(\sigma\lambda)|-\rangle}{\langle -|-\rangle} = \frac{M_0 - \Delta M}{1-\varepsilon}\,, \tag{14}$$

where $M_0 = \mathrm{Re}\langle L|M(\sigma\lambda)|L\rangle = \mathrm{Re}\langle R|M(\sigma\lambda)|R\rangle$, $\Delta M = \mathrm{Re}\langle L|M(\sigma\lambda)|R\rangle = \mathrm{Re}\langle R|M(\sigma\lambda)|L\rangle$. Equations (13) and (14) are also valid for the reduced matrix elements of $M(\sigma\lambda)$. When the system deviates from the strong chiral symmetry breaking limit, the parameters ΔE and ε become non-vanishing. In this case the energies of the $|+\rangle$ and $|-\rangle$ states become not equal. It follows from equations (13), (14) that a similar phenomenon can be expected also for the electromagnetic matrix elements. The fact that the ΔM and ε parameters have non-zero values leads to different magnitudes of the electromagnetic transitions within the chiral partner bands. This could explain systematic difference in the transition probabilities observed in the partner bands of ^{132}La. Similar rules are expected for other observables, which are the expectation values of operators commuting with R_yT.

3. Determination of the parameters M_0 and ΔM from the experimental lifetime data

The reduced matrix elements of the electromagnetic transition operator $M(\sigma\lambda)$ can, in compliance with formula

$$\langle I||M(\sigma\lambda)||I_{\rm i}\rangle = \pm\sqrt{(2I_{\rm i}+1)B(\sigma\lambda; I_{\rm i}\to I)}\,, \tag{15}$$

where $I_{\rm i}$ is the initial spin, be calculated from the reduced transition probabilities $B(\sigma\lambda)$ determined experimentally. The sign in Eq. (15) depends on the choice (once for all) of sings of the initial and final wave functions for each $I_{\rm i}$ and I. According to this rule, the sign + will be chosen for all matrix elements of the M1 operator. Further, only the M1 transitions will be considered. For a given pair of spins $I_{\rm i}$ and I, the matrix element $\langle I||M({\rm M1})||I_{\rm i}\rangle$ calculated from the experimental value of B(M1) for the yrast band will be denoted as $M_{\rm exp}^{\rm yrast}({\rm M1})$. In the same way $M_{\rm exp}^{\rm side}({\rm M1})$ denotes similar quantity for the side band. In this notation, equations (13) and (14) take the form

$$M_{\rm exp}^{\rm yrast}({\rm M1}) = \frac{M_0+\Delta M}{1+\varepsilon}\,, \tag{16}$$

$$M_{\rm exp}^{\rm side}({\rm M1}) = \frac{M_0-\Delta M}{1-\varepsilon}\,, \tag{17}$$

where the yrast levels are assumed to be built on the symmetric $|+\rangle$ state and the side band levels on the antisymmetric $|-\rangle$ state. The opposite assignment of the bands is discussed later. By eliminating parameter ε from equations (16) and (17) we obtain

$$M_0 = A_0(2+\Delta M\, A_1)\,, \tag{18}$$

where A_0 and A_1 are parameters which can be extracted from experimental data, *viz.*

$$A_0 = \frac{M_{\rm exp}^{\rm yrast}({\rm M1})\, M_{\rm exp}^{\rm side}({\rm M1})}{M_{\rm exp}^{\rm yrast}({\rm M1}) + M_{\rm exp}^{\rm side}({\rm M1})}\,, \tag{19}$$

$$A_1 = \frac{M_{\rm exp}^{\rm yrast}({\rm M1}) - M_{\rm exp}^{\rm side}({\rm M1})}{M_{\rm exp}^{\rm yrast}({\rm M1})\, M_{\rm exp}^{\rm side}({\rm M1})}\,. \tag{20}$$

It is now clear that from the two B(M1) values measured for both bands and given initial and final spins, a linear dependence of M_0 on ΔM can be established. Considering the uncertainties of the measured B(M1) values, a corridor of possible M_0 and ΔM values will be obtained instead of the line. For another pair of initial and final spins, another corridor of possible M_0 and ΔM values can be found. The mutual overlap of all the found corridors defines the area of the M_0 and ΔM parameters describing observed electromagnetic properties of the partner bands in the framework of the chiral picture. When the assignment of the bands is inverted (*e.g.* the yrast band corresponds to the antisymmetric $|-\rangle$ and the side band to the symmetric $|+\rangle$ state) the parameter A_1 will change its sign $A_1 \rightarrow -A_1$. This will also change the sign of parameter ΔM in the found $(M_0, \Delta M)$ area, namely $(M_0, \Delta M) \rightarrow (M_0, -\Delta M)$. In conclusion, the $(M_0, \Delta M)$ area and the mirror reflected one, $(M_0, -\Delta M)$, correspond to the two possibilities of band assignment.

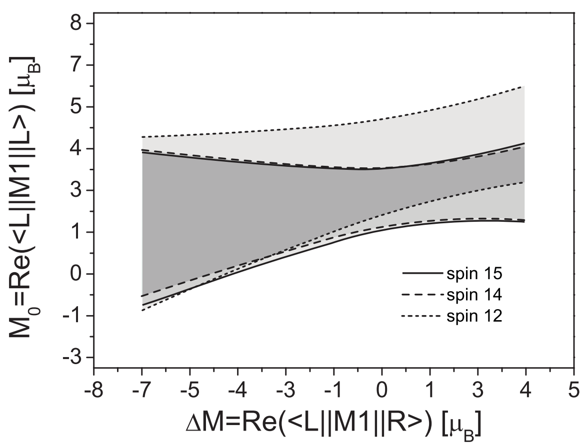

Fig. 1. Plot of the three experimentally found $M_0, \Delta M$ corridors for ^{132}La. The mutual overlap is coloured dark grey.

The procedure described above applied to the case of ^{132}La, shows how the differences in electromagnetic properties of the partner bands can be explained in the framework of the chiral picture in which the system deviates from the strong breaking limit of chiral symmetry. The B(M1) values are measured in both bands of ^{132}La for initial spins $I_{\mathrm{i}} = 12$, 14, 15. The resulting corridor in the M_0 *versus* ΔM plot is calculated for each spin (see Fig. 1). Each pair of values of $M_0, \Delta M$, taken from the mutual overlap of corridors, describes the observed B(M1) values in the two bands. This shows that even for the case when the transition probabilities are not similar in both bands it is possible to find parameters describing observed differences in the framework of the chiral picture.

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