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SYMPLECTIC CLASSIFICATION OF THE EVEN-EVEN NUCLEI AND NUCLEAR SPECTRA

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1. INTRODUCTION

The introduction of the F-spin in the framework of IBM-2 /1/ makes it possible to consider, in a unified way, the properties of sequences of atomic nuclei. Thus in /2, 3/ series of even-even nuclei are united in F-spin multiplets. The empirical investigation carried out in these papers shows that the low-lying energy levels of the ground and γ-bands of the nuclei belonging to a given F-spin multiplet depend slightly, almost constantly, on the third projection of the F-spin.

In this paper, as an extension of this approach, we propose to consider in a unified way all even-even nuclei with valence nucleons belonging to a given major nuclear shell. This gives a possibility to deal with the entire spectrum of each shell, which allows to reveal both the existing regularities and the typical features of the different shells. The extension proposed leads to a classification of the even-even nuclei in symplectic multiplets.

It should be noted, that the classification scheme given below uses, as a starting point, some of the concepts of IBM-2, but, at the same time, differs essentially from it. The spectrum is discussed in an empirical way. The problem of the adequate theoretical description of the energy levels will be discussed separately in a forthcoming paper.

2. ALGEBRAIC CONSTRUCTION OF Sp(24, R)

In IBM-2 two types of boson creation π_a^+ and ν_a^+ and annihilation π_a and ν_a operators (a = 0,1,...,5) are introduced. The bilinear products $\pi_a^+\pi_b$ and $\nu_a^+\nu_b$ generate the "proton" and "neutron" U(6) groups, i.e. $U_\pi(6)$ and $U_\nu(6)$. The operators $\pi_a^+\nu_b$ and $\nu_a^+\pi_b$ extend the $U_\pi(6)\oplus U_\nu(6)$ algebra to U(12). With the help of boson operators one can define only the most symmetric representations of $U_\pi(6)$, $U_\nu(6)$ and U(12) labelled by N_π, N_ν and N respectively. From the generators of U(12) one can construct the sums $\pi_a^+\pi_b + \nu_a^+\nu_b$, which generate the "mixed" group $U_{\pi\nu}(6)$, and also the operators

$$F_+ = \sum_{a=0}^{5} \pi_a^+\nu_a \; ; \qquad F_- = \sum_{a=0}^{5} \nu_a^+\pi_a \; ;$$

$$F_0 = \frac{1}{2}\sum_{a=0}^{5}(\pi_a^+\pi_a - \nu_a^+\nu_a) \equiv \frac{1}{2}(N_\pi - N_\nu).$$

which generate the F-spin group — $SU_F(2)$. This corresponds to the decomposition $U(12) \supset U_{\pi\nu}(6) \oplus SU_F(2)$.

The extension of U(12) to Sp(24,R) can be done in a natural way (the common case of Sp(4k,R) is discussed in /4/). The boson representation of Sp(24,R) /5/ is obtained by the addition of the raising $\pi_a^+\pi_b^+$, $\nu_a^+\nu_b^+$, $\pi_a^+\nu_b^+$ and decreasing $\pi_a\pi_b$, $\nu_a\nu_b$, $\pi_a\nu_b$ operators to the generators of U(12). All the most symmetric representations of U(12), labelled by N, act in spaces, whose direct sum coincides with the space $\mathcal{H}$ of the boson representation of Sp(24,R). The latter is reducible and decomposes in two irreducible ones. The first one acts in the space $\mathcal{H}_+$, where the spectrum of N is even, while the second one acts in the space $\mathcal{H}_-$ where N is odd ($\mathcal{H} = \mathcal{H}_+ \oplus \mathcal{H}_-$).

The groups $SU_F(2)$ and $U_{\pi\nu}(6)$ are mutually complementary /6/ which leads to the following relation for their second order Casimir operators — $C_2^{(6)} = 2F^2 + 4N + (1/2)N^2$. Hence, when N is fixed the eigenvalues $F(F+1)$ of F^2 give the irreducible unitary representations (IURs) of both $SU_F(2)$ and $U_{\pi\nu}(6)$. Further, it is obvious, that when N and F are fixed there arise $2F+1$ equivalent representations of $U_{\pi\nu}(6)$ labelled by $F_0 = -F,\dots,F$. Thus one obtains the following reduction scheme:

$$Sp(24,R) \xrightarrow{N} U(12) \xrightarrow{F^2} SU_F(2) \oplus U_{\pi\nu}(6) \xrightarrow{F_0} U_{\pi\nu}(6). \qquad (2.1)$$

On the other hand in the space $\mathcal{H}$ there acts a reducible unitary representation, namely the ladder representation of the algebra U(6,6) /7,8/. The corresponding Weyl generators of U(6,6) are: $\pi_a^+\pi_b$, $\pi_a^+\nu_b^+$, $-\nu_a\pi_b$, $-\nu_a\nu_b^+$. This representation splits in irreducible ones (ladders), labelled by the first order Casimir operator of U(6,6): $C_1^{(6,6)} = 2F_0 - 6$. In the space of each ladder (F_0 — fixed) there acts an infinite set of IURs of the algebra $U_\pi(6) \oplus U_\nu(6)$ (steps) labelled by N. The reduction $U_\pi(6) \oplus U_\nu(6) \supset U_{\pi\nu}(6)$ can be obtained by means of $\vec{F}^2(C_2^{(6)})$. Finally, instead of (2.1) one has

$$Sp(24,R) \xrightarrow{F_0} U(6,6) \xrightarrow{N} U_\pi(6) \oplus U_\nu(6) \xrightarrow{\vec{F}^2} U_{\pi\nu}(6). \qquad (2.2)$$

From a mathematical point of view both schemes (2.1) and (2.2) are equally appropriate for the description of all IURs of $U_{\pi\nu}(6)$ acting in $\mathcal{H}$.

Reduction scheme (2.1) is written in terms of algebra. We recall that the IURs of the group U(n) and the corresponding irreducible representations of the algebra U(n) act in the same spaces.

The splitting of the spaces $\mathcal{H}_\pm$ corresponding to the reductions

$$\begin{tikzcd}
 & Sp(24,R) \arrow[dl, dash, "F_0"'] \arrow[dr, "N"] & \\
U(6,6) \arrow[dr, dash, "N"'] & & U(12) \arrow[dl, dash, "F_0"] \\
 & U_\pi(6) \oplus U_\nu(6) &
\end{tikzcd}$$

is shown schematically in Fig. 1, where the columns represent the ladders defined by F_0 and the rows — the IURs of U(12) defined by N. Each cell corresponds to a given IUR of $U_\pi(6) \oplus U_\nu(6)$.

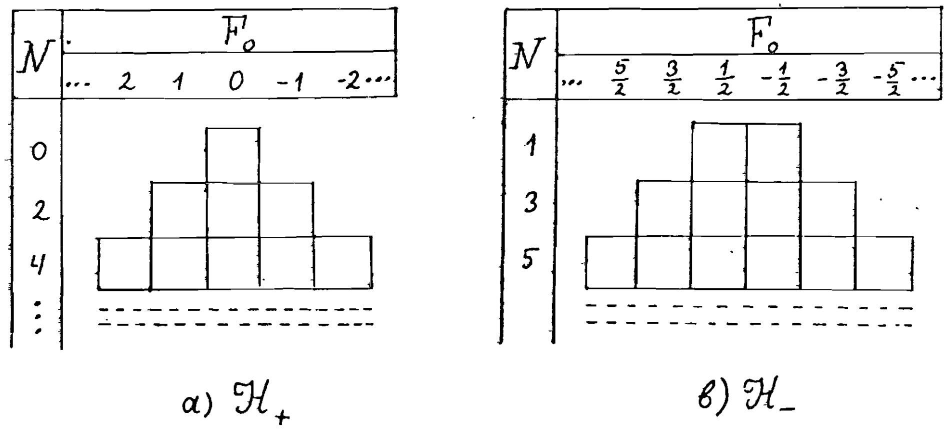

Fig. 1. The splitting of $\mathcal{H}_+$ (N – even) and $\mathcal{H}_-$ (N – odd) corresponding to the reductions Sp(24,R) ⟶ U(6,6) ⟶ $U_\pi(6) \oplus U_\nu(6)$ and Sp(24,R) ⟶ U(12) ⟶ $U_\pi(6) \oplus U_\nu(6)$.

3. PHYSICAL INTERPRETATION OF N AND F_0

In IBM-2 the proton and neutron boson numbers N_π and N_ν are found by counting the valence proton and neutron pairs (or hole pairs) of a given even-even nucleus from the nearest closed shell. The quantities N and F_0 are defined by

$$N = N_\pi + N_\nu, \qquad F_0 = \frac{1}{2}(N_\pi - N_\nu).$$

In various papers dealing with IBM-2 the following four possibilities to count N_π and N_ν are used:

i) From proton and neutron particles. In this case one has

$$N_\pi = \frac{1}{2}(N_p - N_p^{mag}), \qquad N_\nu = \frac{1}{2}(N_n - N_n^{mag}), \qquad (3.1)$$

where N_p and N_n are the total proton and neutron numbers in the nucleus and N_p^{mag} and N_n^{mag} are the corresponding magic numbers. Therefore

$$N = \frac{1}{2}(A - A^{mag}), \qquad F = \frac{1}{2}(M_T - M_T^{mag}), \tag{3.2}$$

where $A = N_p + N_n$ is the mass number and $M_T = \frac{1}{2}(N_p - N_n)$ is the third projection of the isospin.

ii) From proton and neutron holes. Then

$$N = \frac{1}{2}(A^{mag} - A), \qquad F_0 = \frac{1}{2}(M_T^{mag} - M_T), \tag{3.3}$$

and the difference between this case and the previous one is not essential.

iii) From proton particles and neutron holes. Then

$$N = M_T - M_T^{mag}, \qquad F_0 = \frac{1}{4}(A - A^{mag}).$$

iv) From proton holes and neutron particles. Then

$$N = M_T^{mag} - M_T, \qquad F_0 = \frac{1}{4}(A^{mag} - A).$$

Here we do not stick to the interpretation of N_π and N_ν as numbers of real nucleon pair excitations in nuclei. The physical sense of N and F_0 is revealed by their expressions in terms of A and M_T. From this point of view it is obvious that the physical meaning of N and F_0 in cases i) and ii) compared with cases iii) and iv) is exchanged. But in order to describe the even-even nuclei in a unified way a uniqueness in the understanding of N and F_0 is necessary. Moreover, we want to introduce a classification scheme, according to which the even-even nuclei from a given major shell are united in common multiplets. For this reason it is not acceptable to assume that in the first half of the shell N and F_0 are given by (3.2) and in the second half — by (3.3). That is why we have to choose one from the four possibilities described above to count N and F_0. At that, all even-even nuclei from a given major shell are enumerated one-to-one by the values of the pair N and F_0.

4. CLASSIFICATION SCHEME

A major nuclear shell is defined by a pair of double magic numbers (N'_p, N'_n) and (N''_p, N''_n), where $N'_p < N''_p$ and $N'_n < N''_n$. The even-even nuclei, whose valence nucleons belong to this shell can be united in two symplectic multiplets in the following way.

The double magic number (N'_p, N'_n) corresponds to the vacuum state (N=0) in $\mathcal{H}$. Using formulae (3.1) and (3.2) one finds N_π and N_ν and N and F_0. Then each nucleus under consideration corresponds to a definite cell in the space $\mathcal{H}_+$ or $\mathcal{H}_-$, which represents a given IUR of $U_\pi(6) \oplus U_\nu(6)$ (see fig. 1). The symplectic multiplets obtained in this way will be noted by $(N'_p, N'_n | N''_p, N''_n)_+$ if N is even and by $(N'_p, N'_n | N''_p, N''_n)_-$ if N is odd. In $\mathcal{H}_+$ and $\mathcal{H}_-$ these multiplets form closed figures restricted by the conditions $0 \le N \le \frac{1}{2}(N''_p - N'_p)$ and $0 \le N \le \frac{1}{2}(N''_n - N'_n)$ so that $0 \le N \le \frac{1}{2}(A'' - A')$. In other words the space of the even-even nuclei from a given major shell is mapped onto two finite subspaces of $\mathcal{H}_+$ and $\mathcal{H}_-$ respectively. The spectrum of F_0 within these figures is also restricted: $\frac{1}{4}(N'_n - N''_n) \le F_0 \le \frac{1}{4}(N''_p - N'_p)$. This quantity runs all its admissible values $F_0 \le -(N/2),\dots,(N/2)$, if and only if $N_\nu \le \frac{1}{2}(N''_n - N'_n)$ and $N_\pi \le \frac{1}{2}(N''_p - N'_p)$. The sides of the figures correspond to proton or neutron closed shells. Each row consists of nuclei belonging to a given isobar, and each column — of nuclei belonging to a given isofer.

5. LOW-LYING ENERGY SPECTRUM

The numbers N_π and N_ν determine the nuclei belonging to a given Sp(24,R) multiplet. Hence, the Hamiltonian, which should describe the energy spectrum of the multiplet as a whole, will depend on N_π and N_ν, or, which is the same — on N and F_0. That is why it is of interest to investigate empirically the N and F_0 dependence of the excited energy levels of the nuclei of a given multiplet. As an illustration Figs. 2 and 3 show the N dependence at F_0 fixed of the 2^+-levels of the ground bands of the nuclei belonging to the multiplets $(50, 82 | 82, 126)_+$ and $(50, 82 | 82, 126)_-$ (see Tables 1 and 2). The experimental data are from /9/.

The picture of the spectrum presented so far shows the expedience of the unification of the even-even nuclei in Sp(24,R)- multiplets. The curves obtained (Figs. 2, 3) demonstrate a differentiation of the separate U(6,6)-submultiplets and show an existence of a stable periodical structure in the shell, expressed in the similar behaviour of the different U(6,6)-curves. Note that the neighbouring nuclei in the U(6,6) multiplets differ in an α-particle, which is consistent with the hypotesis of α-clustering in nuclei /10/. A slight (almost constant) dependence on N is observed in the middle of the curves corresponding to the rotational nuclei. It should be noted that in /3/ the rotational nuclei ^{156}Dy - ^{184}Hg ($F_0 = 2$) and ^{158}Dy - ^{182}Pt ($F_0 = \frac{3}{2}$) were united in two F-spin multiplets, where N and F_0 are defined as in case iii). The levels $E_{2^+} \simeq 70$ KeV for ^{162}Gd and 73 KeV $\le E_{2^+} \le$ 82 KeV for ^{172}Er and ^{168}Dy are predicted by interpolation.

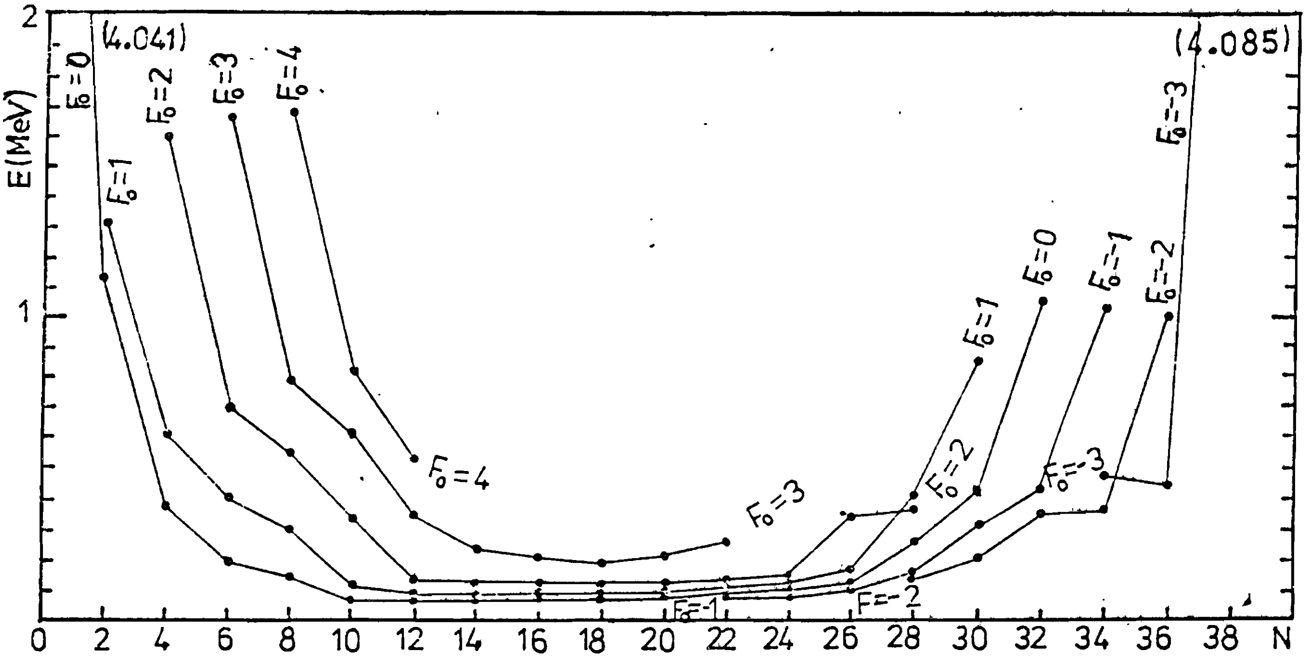

Fig. 2. Multiplet (50, 82 | 82, 126$)_+$. Dependence of the 2^+-levels on N at fixed F_o (see Table 1).

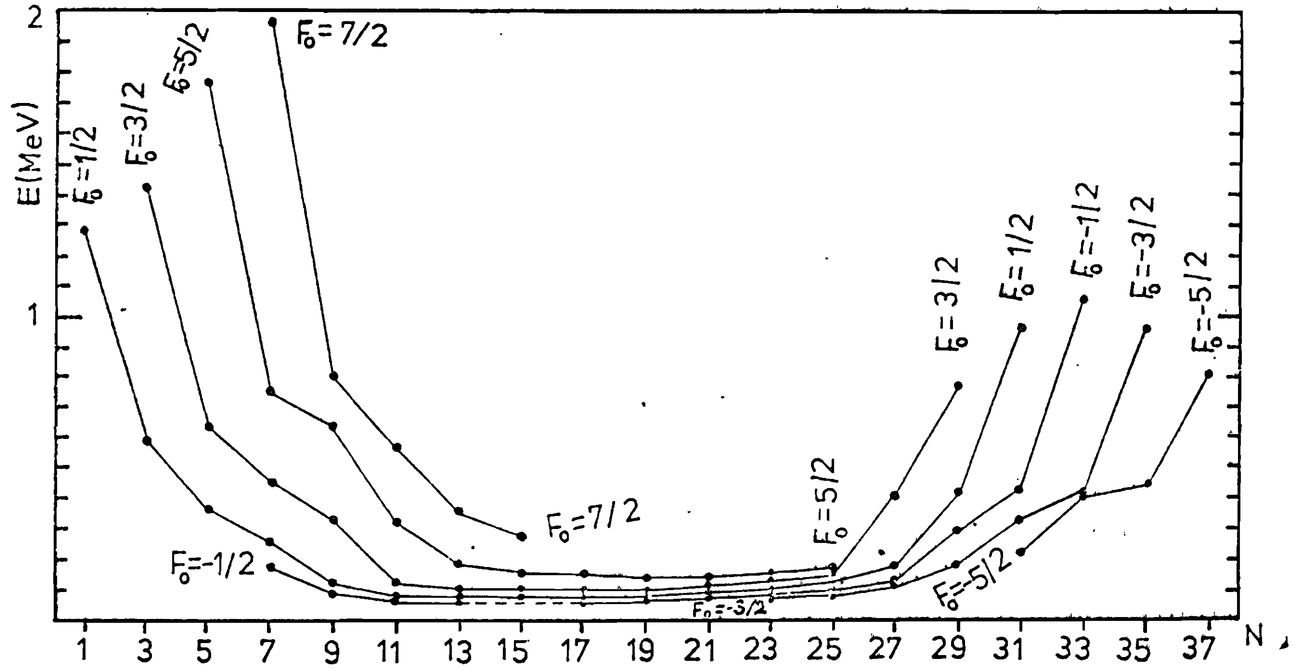

Fig. 3. Multiplet (50, 82 | 82, 126$)_-$. Dependence of the 2^+-levels on N at fixed F_o (see Table 2).

Table 1

Multiplet $(50,82|82,126)_+$.

N	F_0 = 5	4	3	2	1	0	−1	−2	−3
0						^{132}Sn			
2					^{136}Xe	^{136}Te			
4				^{140}Ce	^{140}Ba	^{140}Xe			
6			^{144}Sm	^{144}Nd	^{144}Ce	^{144}Ba	^{144}Xe		
8		^{148}Dy	^{148}Gd	^{148}Sm	^{148}Nd	^{148}Ce	^{148}Ba		
10	^{152}Yb	^{152}Er	^{152}Dy	^{152}Gd	^{152}Sm	^{152}Nd	^{152}Ce		
12	^{156}Hf	^{156}Yb	^{156}Er	^{156}Dy	^{156}Gd	^{156}Sm			
14	^{160}W	^{160}Hf	^{160}Yb	^{160}Er	^{160}Dy	^{160}Gd			
16	^{164}Os	^{164}W	^{164}Hf	^{164}Yb	^{164}Er	^{164}Dy			
18	^{168}Pt	^{168}Os	^{168}W	^{168}Hf	^{168}Yb	^{168}Er	^{168}Dy		
20		^{172}Pt	^{172}Os	^{172}W	^{172}Hf	^{172}Yb	^{172}Er		
22			^{176}Pt	^{176}Os	^{176}W	^{176}Hf	^{176}Yb		
24			^{180}Hg	^{180}Pt	^{180}Os	^{180}W	^{180}Hf		
26			^{184}Pb	^{184}Hg	^{184}Pt	^{184}Os	^{184}W	^{184}Hf	
28				^{188}Pb	^{188}Hg	^{188}Pt	^{188}Os	^{188}W	
30					^{192}Pb	^{192}Hg	^{192}Pt	^{192}Os	
32						^{196}Pb	^{196}Hg	^{196}Pt	^{196}Os
34							^{200}Pb	^{200}Hg	^{200}Pt
36								^{204}Pb	^{204}Hg
38									^{208}Pb

Table 2.

Multiplet $(50,82|82,126)_-$.

N	F_0 = $\frac{11}{2}$	$\frac{9}{2}$	$\frac{7}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{3}{2}$	$-\frac{5}{2}$	$-\frac{7}{2}$
1						^{134}Te	^{134}Sn			
3					^{138}Ba	^{138}Xe	^{138}Te			
5				^{142}Nd	^{142}Ce	^{142}Ba	^{142}Xe			
7			^{146}Gd	^{146}Sm	^{146}Nd	^{146}Ce	^{146}Ba			
9		^{150}Er	^{150}Dy	^{150}Gd	^{150}Sm	^{150}Nd	^{150}Ce			
11	^{154}Hf	^{154}Yb	^{154}Er	^{154}Dy	^{154}Gd	^{154}Sm	^{154}Nd			
13	^{158}W	^{158}Hf	^{158}Yb	^{158}Er	^{158}Dy	^{158}Gd	^{158}Sm			
15		^{162}W	^{162}Hf	^{162}Yb	^{162}Er	^{162}Dy	^{162}Gd			
17		^{166}Os	^{166}W	^{166}Hf	^{166}Yb	^{166}Er	^{166}Dy			
19		^{170}Pt	^{170}Os	^{170}W	^{170}Hf	^{170}Yb	^{170}Er			
21			^{174}Pt	^{174}Os	^{174}W	^{174}Hf	^{174}Yb			
23			^{178}Hg	^{178}Pt	^{178}Os	^{178}W	^{178}Hf	^{178}Yb		
25				^{182}Hg	^{182}Pt	^{182}Os	^{182}W	^{182}Hf		
27				^{186}Pb	^{186}Hg	^{186}Pt	^{186}Os	^{186}W		
29					^{190}Pb	^{190}Hg	^{190}Pt	^{190}Os	^{190}W	
31						^{194}Pb	^{194}Hg	^{194}Pt	^{194}Os	
33							^{198}Pb	^{198}Hg	^{198}Pt	
35								^{202}Pb	^{202}Hg	
37									^{206}Pb	^{206}Hg

As for the rest of the shells, when $N_p \geq 20$ and $N_n \geq 20$, the spectrum of the low-lying energy levels of the ground and quasi-ground bands has, in general, an analogical behaviour, but in particular cases there exist some peculiarities. The similarity of the curves inspires the search of an explicit form of the dependence of the Hamiltonian on N and F_0. All these problems will be discussed in a forthcoming paper.

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Георгиева А. и др. E4-87-927

Симплектическая классификация четно-четных ядер и их спектров

Предложено обобщение подхода, согласно которому спектры четно-четных ядер объединяются в F-спиновых мультиплетах. Все четно-четные ядра с валентными нуклонами, принадлежащими одной оболочке, рассматриваются как единый симплектический мультиплет. Предложенная модель использует некоторые основополагающие концепции модели IBM-2, но в то же время существенно отличается от нее. На этом этапе обсуждаются только феноменологические черты спектров четных ядер.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1987

Georgieva A. et al. E4-87-927

Symplectic Classification of the Even-Even Nuclei and Nuclear Spectra

In this paper an extension of the approach, classifying the even-even nuclei spectra in F-spin multiplets is proposed. One considers in a unified way all even-even nuclei with valence nucleons belonging to a given major shell. This extension leads to a classification of the even-even nuclei in symplectic multiplets.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1987