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SYSTEMATICS OF THE 1^+ STATES IN DOUBLY ODD NUCLEI OF La AND Pr

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New data concerning high spin rotational bands[1-5] as well as states excited in β-decay[6-19] have become available recently for the doubly-odd nuclei in the region $50 \leq Z,N \leq 82$. They revealed extremely complicated level-spectra in which patterns of different model approaches can be recognized, none of them reproducing all features simultaneously. Recent β-decay studies of La and Pr nuclei undertaken at JINR (Dubna) in the frame of JASNAPP-1 programme were of crucial importance in this line. During the investigations of the neutron-deficient isotopes in the region of A ~ 130 many groups of allowed $0^+ \to 1^+$ Gamov-Teller (GT) β-transitions have been observed, feeding 1^+ states in the daughter odd-odd nuclei[6-10,15]. The excitation energies of 1^+ levels, the strength of GT-transitions and the deexcitation of these states to some other excited states couldn't be interpreted in the framework of the simple picture in which the wave functions of the odd-odd nucleus states are represented as a linear combination of two quasiparticles coupled to angular momentum 1^+, and the collective dynamics of the states is governed by the simple residual interaction. The complicated experimental data from β-decay and charge exchange reactions posed the problem of significantly quenched nuclear GT-matrix elements, whose origin is the subject of intensive theoretical and experimental studies (see for example Ref.20 and references therein). This effect is attributed mainly to the inadequacy of the single-particle description of the nuclear states or to the inadequacy of the one-body GT-operator.

Different theoretical calculations appeared recently which attempted to describe the collective structure of odd-odd nuclei in the framework of axially symmetric[21] or triaxial-rotor[22] core model as well as in terms of vibrational core coupled to the valence nucleons[23]. Interesting attempts to study the odd odd nuclei using dynamical symmetries have been made in Refs.24,25 and are in progress now.

It is tempting also to suggest an intimate relation between the 1^+ excitations in the odd-odd nuclei and the newly observed collective M1-mode in the deformed even-even nuclei arising from a rotational oscillation of a deformed neutron system relative to a deformed proton system[26,27].

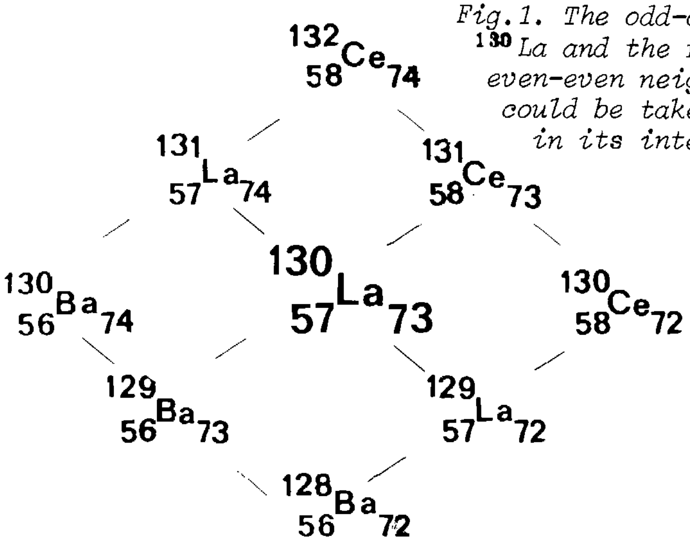

Fig.1. The odd-odd nucleus of ^{130}La and the related odd and even-even neighbours which could be taken into account in its interpretation.

As far as neither of the existing approaches is in the position to explain the whole experimental picture yet, we look in the present paper for relations between the features of the odd-odd nucleus and the corresponding eight neighbouring nuclei (shown in Fig.1 in the case of ^{130}La) in order to provide ground, by means of such a systematics, for eventual development of quantitative description for transitional odd-odd nuclei in the spirit of the Jolos approach /28/, successfully applied before to odd nuclei /29,30/. In this approach the wave function of the odd nucleus (with A+1 particles) is represented as superposition of the states of the adjacent even-even nuclei (with A and A+2 particles) yielding complete information about the particle-hole structure of the low-lying states in the odd-system. This approach is appropriate for the transitional region, where change of the core features, with change of A, is observed and the average field's symmetry is not well known. The possibility of involving the information about the eight surrounding nuclei in the calculations of the resulting even nucleus (see Fig.1) by representing its excited states as superposition of the states of only four odd-neighbours makes the extension of this approach for doubly-odd system very promising.

The region of nuclei with $50 \le Z,N \le 82$ is known to be reach of various nuclear shapes, (often coexisting in one and the same nucleus), and with the gradual shape change with the

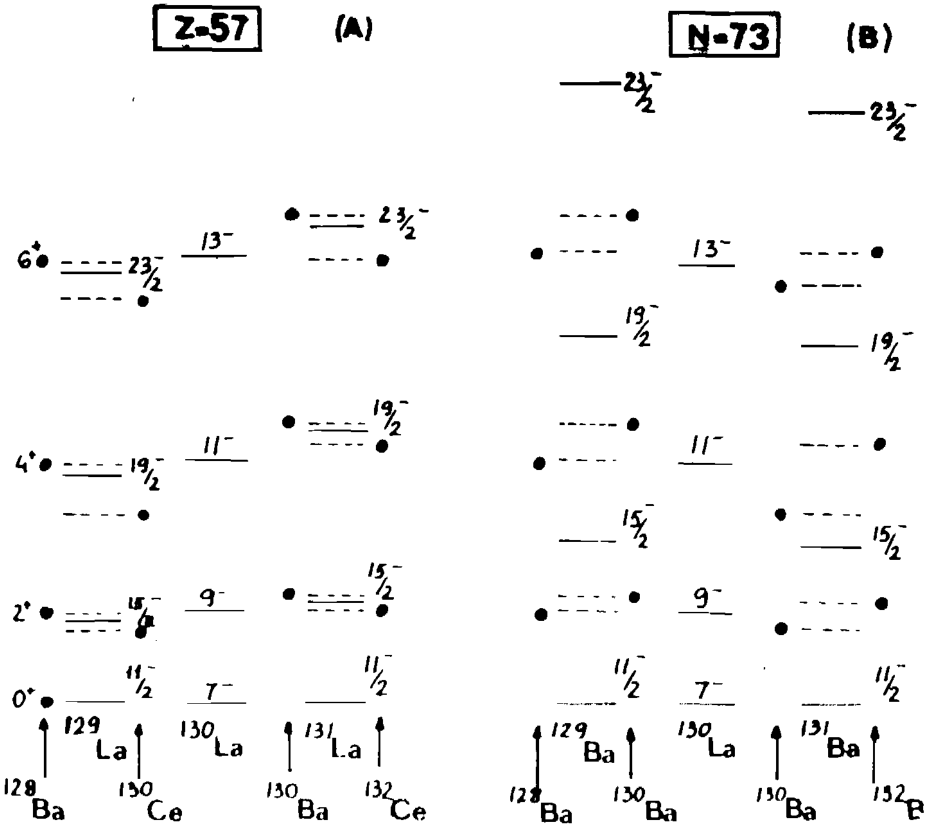

Fig.2. Comparison of the ΔJ=2 sequences of levels in ^{130}La in the related odd and even nuclei. Data are from Refs.45,46.

change of the number of valence nucleons /31,32/. It is established yet that going away of the Z=50 closed proton shell and N=82 closed neutron shell into the region of well developed deformation, nuclei exhibit various degrees of softness with respect of triaxial γ deformation as well as to quadrupole deformation β, the latter manifested for example in superdeformed bands /33-36/. Experimental investigation of the collective properties of the odd nuclei from the discussed region has revealed systematic appearance of ΔJ=1 bands built on the low lying intruder states, as well as ΔJ=2 bands built on $2d_{5/2}$, $1g_{7/2}$ and $1h_{11/2}$ quasiproton states in $^{113-126}$Sb, $^{116-127}$I, $^{118-133}$Cs, $^{125-137}$La (see for instance Refs. 36-41). For the doubly odd nuclei of the region numerous ΔJ=1 and 2 bands have been also observed. In Fig.2(A) one can see the consistency of the energy spacing in ΔJ=2 band in doubly odd nucleus of ^{130}La with that of decoupled $h_{11/2}$ proton band in neighbouring ^{129,131}La and with that of the ground state rotational bands in the related even-even core nuclei. It is interesting to note the completely different behaviour of the band upon changing the neutron number N and the proton number Z. The energy spacing remains almost the same if Z is fixed (Z=57) and N is changed (^{129,130,131}La, Fig.2(A)) while it is sensitive to change of Z when N is fixed (N=73) (^{129}Ba, ^{130}La, ^{131}Ce, Fig.2(B)). Similar effect one observes in ΔJ=1 band properties of the neighbouring odd and doubly-odd nuclei of Sb and I /42,43/, where additional sensitivity to the nature of the collectivity is implied to the two valence particles. For doubly-odd nuclei of Cs and La an abrupt change of nuclear features has been found /5/ on the basis of analysis of their ΔJ=1 bands to take place between ^{120}Cs and ^{122}Cs and between ^{124}La and $^{128-130}$La. The energies of the M1-transitions in the ΔJ=1 bands in these nuclei show staggering with parameter S= =0.12-0.14. Unfortunately for the heavier La nuclei nothing definite could be concluded about the behaviour of the γ-transitions in the band since the only available experimental study of the high-lying levels in ^{134,136}La /4/ is not complete as regards of the level spins and parities. Recent investigations of the doubly-odd nuclei of La, Pr and Pm, performed at Stony Brook Superconducting LINAK tandem accelerator via γ-ray measurements following heavy-ion-induced reactions, provided new information about high spin rotational bands in these nuclei. It has been shown that they result from the competing shape-driving forces of the $h_{11/2}$ valence proton and the correspondent neutron orbitals. Rotational bands built on the {$\pi h_{11/2} \otimes \nu h_{11/2}$} configuration and small signature splitting appear in ^{128,130}La /1,44/, ^{132,134}Pr, ^{136}Pm /2/. According to Nilsson diagram (assuming $\epsilon_2 \geq 0.25$) another configuration [$\pi h_{11/2} \otimes \nu g_{7/2}$] is also possible and found /1,2,44/ in the above mentioned nuclei with no signature splitting, which correspond to near prolate nuclear structure. Thus far enough from the magic numbers stabilizing effect of the high J quasiparticles with respect to β and γ deformation is established. The information, obtained from the high spin levels in odd odd nuclei leads us to the problem of core-polarising effect of the competing valence particles besides the problem of the interacion between particles themselves.

Let us now consider the low lying states of the odd odd La and Pr nuclei, whose typical spectrum can be seen, for exam

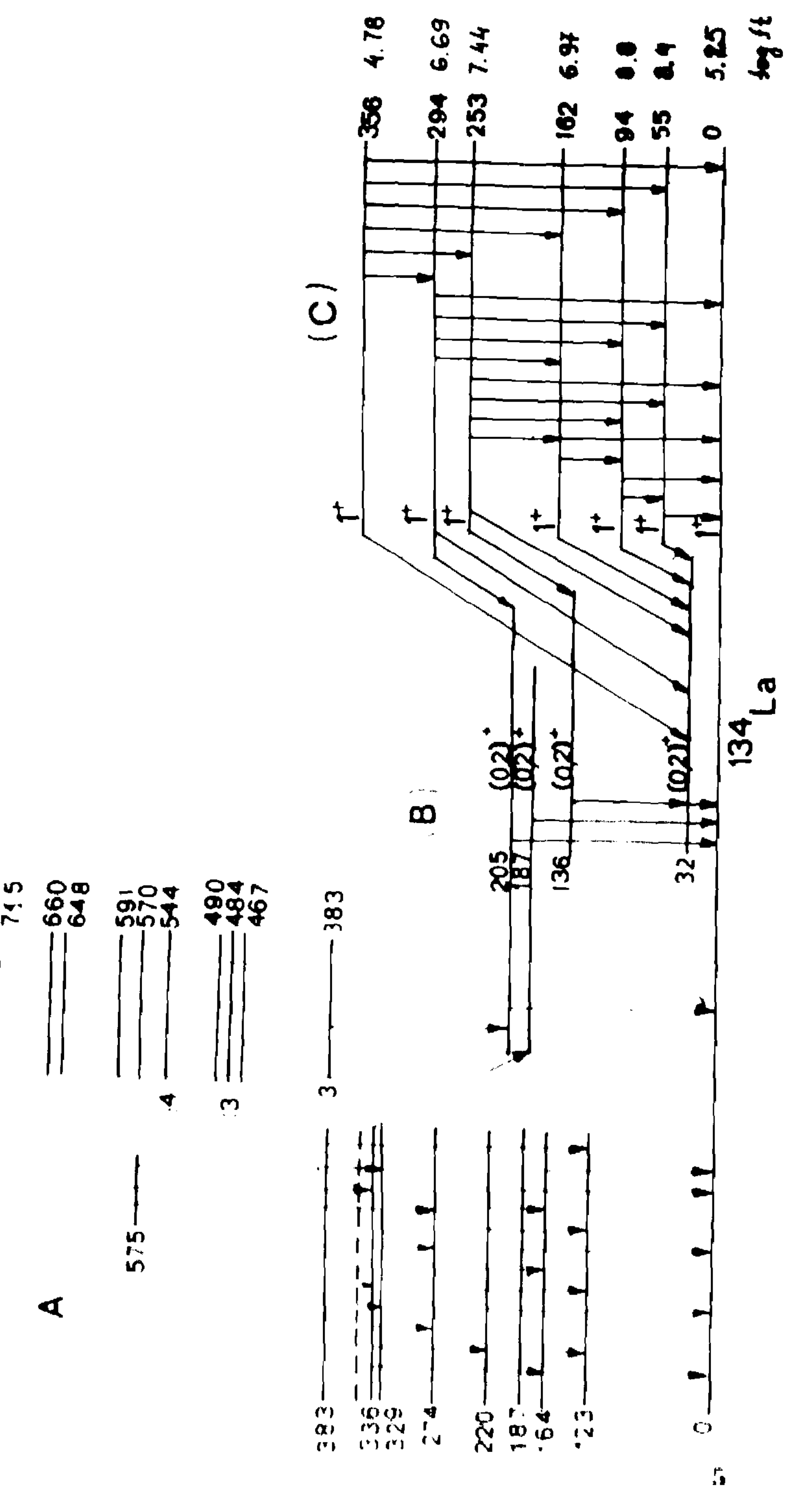

Fig.3. Partial level scheme of ^{134}La obtained by using data from Refs.4,6. One can find the level scheme of the high lying states in original paper /4/.

ple, in the case of ^{134}La, for which nucleus data are available from β-decay measurements/6/ as well as from heavy-ion measurements/4/, Fig.3. Bellow the energy of 1 MeV in the level-scheme there appear three groups of states: (A) - the states populating in the isomeric decay; (C) - the system of states with $I^{\pi}=1^{+}$ and (B) - the group of states, some of which deexcite to the levels (A), some others, populated by γ-transitions from the states in the group (C) and some, tending to develope bands with no connection with the other two groups. (The high spin states, not shown in Fig.3, can be placed on top of 29 μs isomer/4/). In the neighbouring even La and Pr nuclei such scheme of the low-lying states is only partially established.

Our attention now is focused on the 1^+ states which in the most of the discussed nuclei appear with energy spacing and log ft values forming a stable pattern with slight variation (in Z and N) in clearly distinguished trends as is shown in Fig.4. The energy spacings are obtained by subtraction from the 1^+ state energies that of the lowest 1^+ level with maximal percentage of the β-decay. The data for these lowest states are summarized in Fig.5. For Sb and La isotope chains the more available data allow us to follow the rapid drop of the energies toward the ground state and their increase after that with descrease of the neutron number. Thereby with the increase of Z the minimum approaches N=82. At the same time log ft increases with Z for fixed N. For example for ^{132}Sb log ft = 3.9 while for ^{140}Pr it is already 5.5. For the state 1324 keV in ^{132}Sb as well as for the corresponding state in ^{130}Sb configuration $[d_{3/2}, \otimes d_{5/2}]$ is known from delta-function calculation/47/. The value of log ft = 3.9 is in agreement with such a configuration as a value of the GT allowed transition between spin-orbit partner orbitals. Recently for the discussed 1^+ states in ^{120,122}Sb configuration $[\pi d_{5/2} \otimes \nu d_{3/2}]$ have been established by Fenyes/48/ in the model developed by Paar/49/ for the description of the multiplete splitting in odd odd nuclei using a dipole spin vibration and quadrupole interaction. The application of the parabolic rule for ^{122}Sb is shown in Fig.6. From the model calculations/47,48/ it is established that near doubly magic nuclei, where quadrupole excitations are not very strong, delta function interaction plays dominant role. Far away from the closed shells dominant role plays the quadrupole interaction which is the case of ^{120,122}Sb. Thus for 1_1^+ states in Sb isotopes presented in Fig.5 configuration $[\pi d_{5/2} \otimes \nu d_{3/2}]$ is obtained. This configuration is characteristic also of 1_1^+ states in La and Pr

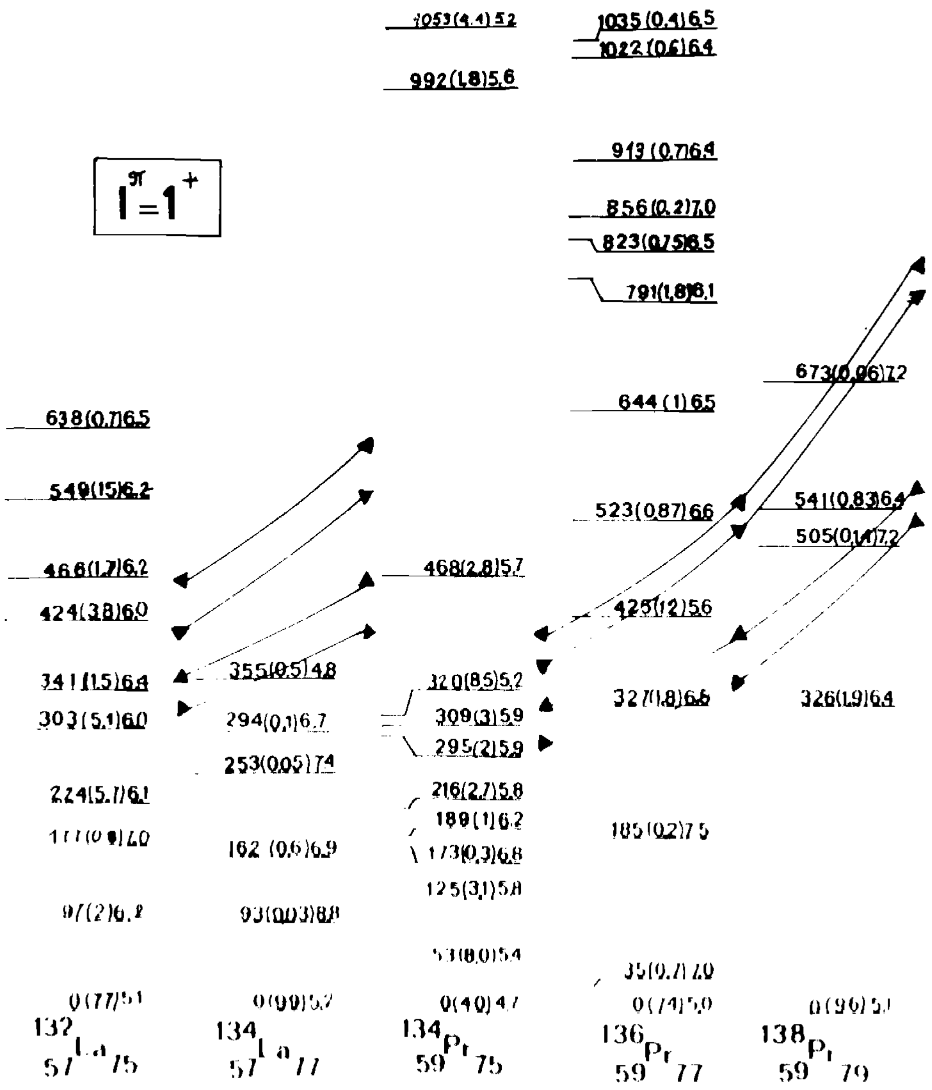

Fig.4. Energy spacing of 1^+ states of La and Pr nuclei. Levels are labelled by the energy excess above the first 1^+ state (with the maximal β decay feeding); the percentage of the β decay to the state, in brackets; and the log ft value, on the right.

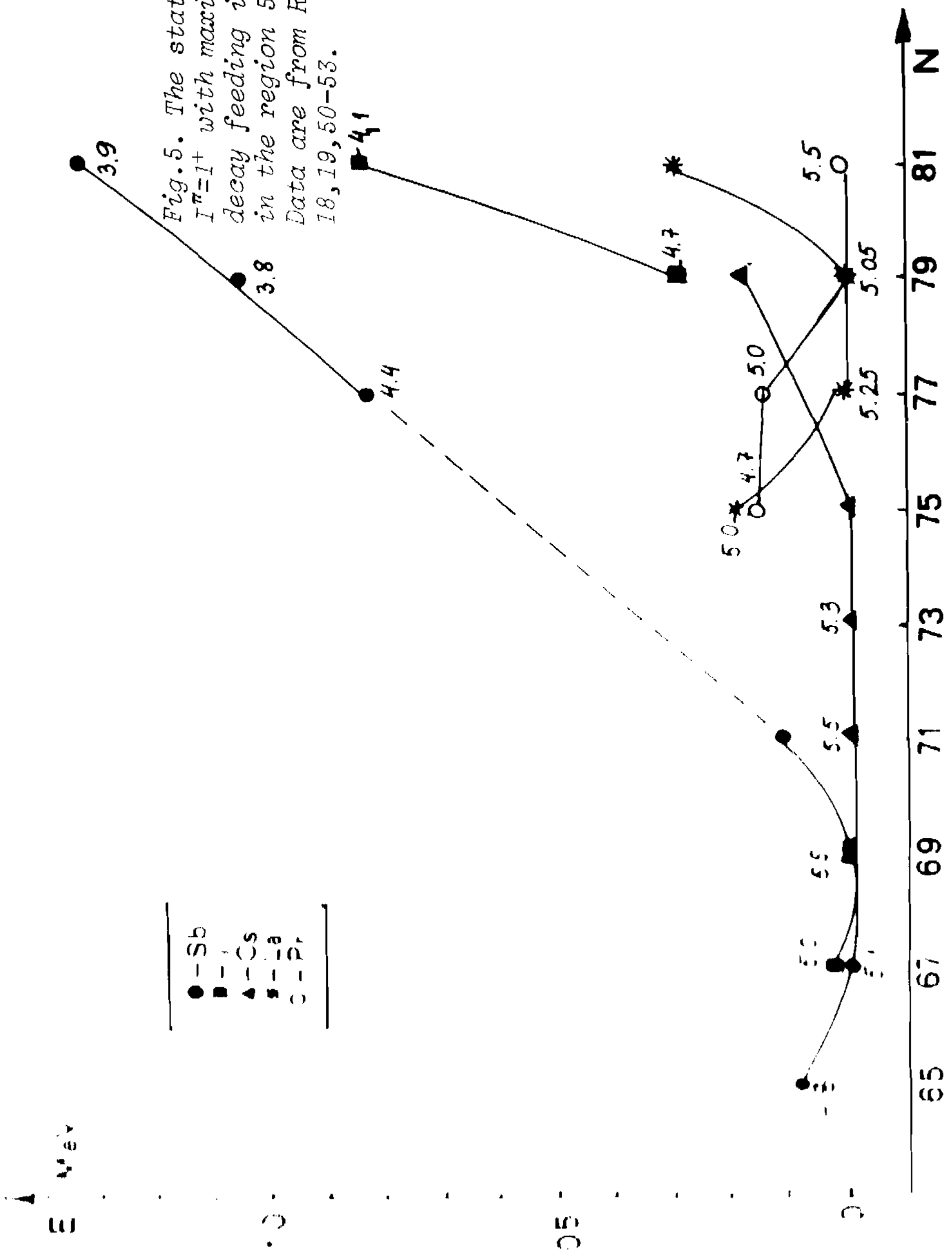

Fig.5. The states with $I^{\pi}=1^{+}$ with maximal – decay feeding identified in the region $50<Z, N\leq 82$. Data are from Refs.14,16, 18,19,50-53.

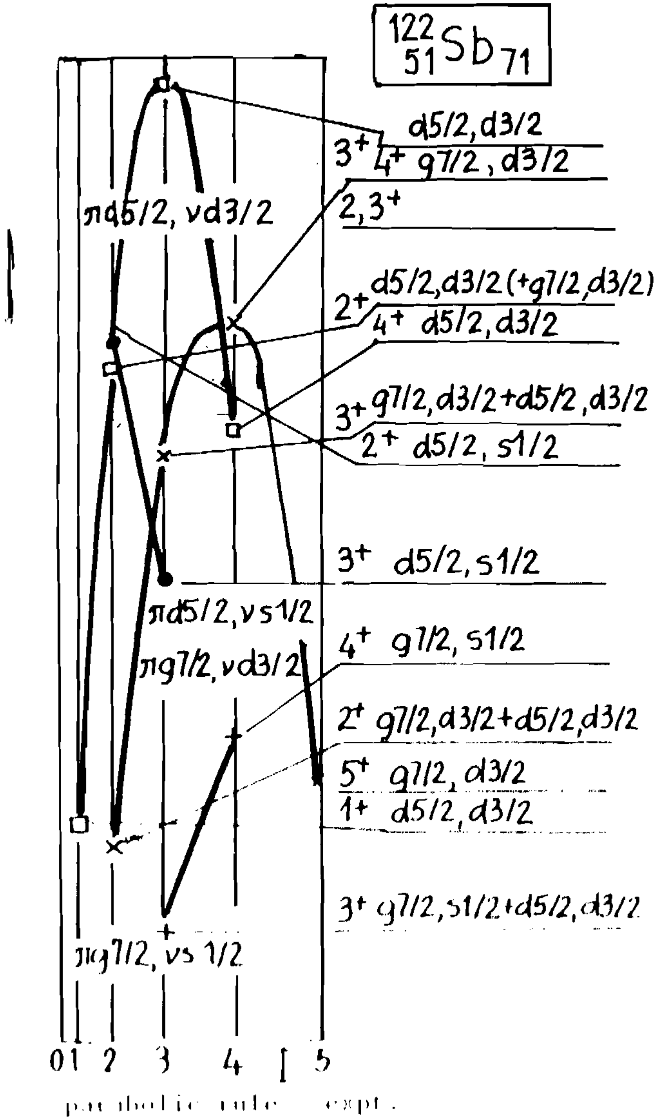

Fig.6. Application of parabolic rule for ^{122}Sb obtained in Ref.48.

nuclei. For ^{136}La this conclusion is made in Ref.4 on the ground of calculations using the formalism of Sasaki/54/ with δ-force as a residual interaction. From the typical for this region single-particle states ($2d_{5/2}$, $1g_{7/2}$) for the odd-proton and ($2d_{3/2}$, $3s_{1/2}$) for the odd-neutron one could obtain one 1^{+} state as a member of the multiplet composed by four levels with $I^{\pi} = 1^{+}$, 2^{+}, 3^{+}, 4^{+}. All this levels are identified in ^{136}La/4/ and could be ascribed to group (A) of Fig.3. The same configuration ($\pi d_{5/2}$, $\nu d_{3/2}$) for the ground state in ^{134}La is obtained by applying the parabolic rule/49/ provided positive parity is assigned tentatively to the state 183 keV. In ^{132}La additional argument for suggesting this configuration is the observed /7/ l forbidden γ transition of 26 keV situated between the states 182 and 155 keV in agreement with systematics of $d_{3/2} \to s_{1/2}$ l forbidden transitions of paper /65/. Similar suggestions about these states in Pr, as well as in La nuclei, have been made also in Ref.16.

For the excited 1^+ states some typical features could be extracted from the representation of the data given in Fig.4 and its comparison with the data for related odd and even-even nuclei. For this we use also the interpretation of the low-lying states in the neighbouring odd-mass nuclei obtained in our previous calculations /29,30,56/ in the framework of particle-anharmonic vibrations model /28/.

For nuclei with N=75,77 1^+ states with log ft value around 7.0 and β-decay feeding in the range (0.25-0.8)% appear 170 keV away from the lowest 1^+ state. This interval is close to the energy distances $\Delta E = E(5/2_1^+) - E(7/2_1^+)$ in the adjacent $^{131,133}La_{74,78}$ nuclei and $\Delta E' = E(5/2_1^+) - E(3/2_1^+)$ in the adjacent $^{131,133}Ba_{75,77}$ nuclei which suggest possible configuration $[\pi g_{7/2}, \nu[2_1^+ \otimes s_{1/2}]5/2^+\}$ which could also explain the larger log ft values of these states. One should keep in mind, however, that in the approach we used in the calculations of the related odd-nuclei (see for instance Ref.30) the state $[2_1^+ \otimes s_{1/2}]5/2^+$, which we refer to here has reacher structure in which $[2_1 \otimes s_{1/2}]5/2$ coupling is only the component with the biggest amplitude. The two states resulting from this coupling are $5/2^+$(316 and 291 keV) and $3/2^+$(288 and 302 keV) in ^{131}Ba and ^{133}Ba, respectively. In the same way, using the state $[2_1^+ \otimes s_{1/2}]3/2$ in odd-Ba nuclei and $5/2_1^+$ in odd-La nuclei we could try to roughly estimate the energy of the next 1^+ state with configuration $\{\pi d_{5/2}, \nu[2_1^+ \otimes s_{1/2}]3/2\}$. In the case of ^{132}La such states are 177 and 224 keV (Fig.4). Of course, there are other possibilities of obtaining the discussed 1^+ state as well as there are other states, participating in the multiplets not found in the experiment, but these questions should be answered by model calculations and further experiments.

The energy distance of the next group of 1^+ states from the lowest 1^+ state is of the order of the first 2^+ state energies in the neighbouring even even nuclei. The latter are marked with triangles in Fig.4. This energy distance turns out also to be close to the energy distance between the members of the $[2_1^+ \otimes d_{3/2}]$ multiplet and the $3/2_1^+$ state in the adjacent odd Ba nuclei. (A similar comparison is valid for the La nuclei.) The structure of the odd nuclear states was determined previously 30,56 . On the ground of this similarity one could speculate about the possibility of coupling the members of the multiplets $[2_1^+ \otimes d_{3/2}]$ in the odd La and in the odd Ba nuclei obtaining in this way various 1^+ states for which configurations $\{\pi[2_1^+ \otimes d_{3/2}]1/2^+, \nu[2_1^+ \otimes d_{3/2}]3/2^+\}1^+$, $\{\pi[2^+ \otimes d_{3/2}]3/2^+, \nu[2_1^+ \otimes d_{3/2}]5/2^+\}1^+$, $\{\pi[2_1^+ \otimes d_{3/2}]5/2^+$, $\nu[2^+ \otimes d_{3/2}]7/2^+\}1^+$ should appear, for example. In the case of ^{132}La possible candidates for such a configurations are the states with energies in the region 300-500 keV, which have also close log ft values and similar deexcitation /5-10/. Their characteristics change with the approach of the N=82 in agreement with the transition of the odd-nuclei to more spherical form. Unfortunately, the incomplete experimental information doesn't permit this systematics to be extended to the higher-lying 1^+ states.

Only precise model calculations, of course, could provide us with a deeper understanding of the phenomena in this field and explain in particular, the abundance of 1^+ states as well as the specific patterns of their appearance. The odd-odd nucleus states in such a model could naturally be built up from an even-even nuclear core and two particles (hole) excitations for the odd neutron and the odd proton. The intriguing peculiarities of the spectra in this region would certainly deserve the effort of their deeper study, but a model of this kind is extremely difficult to be dealt with computationally. It is desirable therefore to look for sensible simplifications. Our preliminary systematic investigation of the problem in the present work provides us with some insight and sheds light on a possible way of such a simplification. The above arguments suggest that the levels of doubly odd nuclei from this transitional region could approximately (due to the regularities of the spectra already discussed in the text above) be described as superposition of the states of the related odd nuclei and only one additional odd particle (hole) excitation. Diminishing in this way the degrees of freedom and using appropriate Hamiltonian, one could hope to overcome the immense technical difficulties and reach at least a preliminary dynamical explanation of the observed data checking thereby the possibility for the application of anharmonic treatment of the 1^+ states. This picture is, in a way, if not exactly equivalent, at least an essential approximation to the more straightforward manner of building such a states by coupling two particles to the even even core.

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