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ON THE NATURE OF THE ^{133}Ba EXCITED STATES

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1. INTRODUCTION

The $^{133}_{56}Ba_{77}$ lies at a distance of 7 neutrons from the shell closure N = 82. The low-lying levels of the adjacent even-mass Ba-nuclei (with A = 132,134) exhibit characteristics transitional between spherical and deformed, so it is reasonable to describe the odd-mass nucleus as a quadrupole, anharmonic vibrations, coupled to the various possible single-particle states of the odd-neutron.

In the present work, low-lying states of ^{133}Ba are analysed in the framework of a version of the particle-vibrational coupling (PVC) model, proposed in[1]. The choice of the model is based on the possibility to treat an odd nucleus in a natural way expanding its states over real states of the even-even anharmonic core and using creation and annihilation operators of particles. Another model advantage is the possibility to take correctly into account the particle-hole structure of the states.

Experimentally, the level scheme of ^{133}Ba has been studied in a few works[2-5]. These include the investigations of β-decay of ^{133}La[2-4] and (d, p)-reaction study[5]. Although the level scheme of this nucleus has been constructed in general in these works, quantum characteristics of many states above 500 keV should be specified[6]. In a recent paper[7] we have already reported our preliminary results from γ-ray measurements of ^{133}La-decay. Here we use them together with our new results from the conversion electron spectra of ^{133}La to deduce the spins and parities of the low-lying levels of ^{133}Ba.

2. EXPERIMENT AND DATA ANALYSIS

Radioactive sources of the La-isotopes have been obtained in the spallation reaction on a Gd-target with 660 MeV protons ($I_p \approx 2.5\ \mu A$) at the JINR-synchrocyclotron, Dubna. After chemical separation of the La-fraction, the mass A=133 has been separated in an electromagnetic mass-separator.

Conversion-electron spectra (CE) have been measured employing Si(Li)-detector with resolution 1.1 keV at 100 keV. To filter the low energy-electrons a homogeneous magnetic field of 750 Gauss has been used[7]. Comparison of our results (Table 1)

Table 1

Conversion coefficients and multipolarities deduced from its compairing with the calculated values (ref./8/)

Conversion line (KeV)	$I_\gamma(\Delta I_\gamma)$	$I_{ce}(\Delta I_{ce})$ (the Present work)	I_{ce} ref./2/	$\alpha_K(\Delta\alpha_K)$	Λ	Placement $E_i(I^\pi)\to E_f(I^\pi)$
1	2	3	4	5	6	7
302 - K	66,2(9,8)	60,4(21)	515	0,038	M1,(E2)	$302(3/2^+)\to 0(1/2^+)$
L		6,9(8)	80			
M		1,52(37)	23			
309 - K	0,55(5)	0,58(18)		0,045(14)	M1	$887(5/2^+)\to 577(7/2^+)$
324 - K	0,32(5)	$<$0,4		$<$0,05	(M1)	$1211(3/2^+,5/2^+)\to 887(5/2^+)$
328 - L	1,19(6)	0,121(25)		0,0042(8)	(M1)	$630(5/2^+,3/2^+)\to 302(3/2^+)$
339 - K	1,63(15)	1,05(31)	$<$13	0,027(8)	M1,E2	$630(5/2^+,3/2^+)\to 291(5/2^+)$
L		0,141(34)		0,0035(9)		
354 - K	0,094(6)	0,38(7)	7	0,017(4)	E2	$1211(\leq 7/2^+)\to 858(3/2^+,5/2^+)$
355 - K	1,19(5)	0,129(30)		0,0045(11)		
385 - K	3,10(10)	1,55(5)	16,5	0,021(6)	M1,E2	$676(3/2^+,5/2^+)\to 291(5/2^+)$
L		0,25(7)				
M		0,07(3)				
428 - K	0,211(33)	0,098(26)		0,019(6)	M1	$1351(3/2^+,5/2^+)\to 923(3/2^+,5/2^+$
436 - K	1,02(5)	0,26(5)	5,5	0,0106(22)	E2	$1112(7/2^+,5/2^+,3/2^+)\to 676(3/2^+,5/2^+$
442 - K	0,07(3)	0,035(12)		0,021(2)	M1	$1329(3/2+,5/2^+,7/2^+)\to 887(5/2^+)$

Table 1 (continued)

1	2	3	4	5	6	7
445 - K	0,17(1)	0,067(25)		0,016(7)	E2,M1	$1329(5/2^+,7/2^+)\to 883(9/2^+)$
469 - K	0,85(6)	0,250(30)	~7	0,0124(16)	M1	$1352(7/2^+,5/2^+,3/2^+)\to 887(5/2^+)$
482 - K	1,39(7)	0,300(37)		0,0091(12)	E2,(M1)	$1021(\leq 7/2^+)\to 676(3/2^+,5/2^+)$
527 - K	3,22(10)	0,60(5)	5	0,0079(7)	E2,M1	$539(1/2^+)\to 12(3/2^+)$
534 - K	2,00(34)	0,37(4)	4	0,0077(15)	E2,M1	$1112(7/2^+,5/2^+,3/2^+)\to 577(7/2^+)$
540 - K	0,553(23)	0,07(3)		0,0052(21)	E2,(M1)	
556 - K	5,7(12)	0,83(8)	5	0,0060(13)	E2	$858(3/2^+,5/2^+)\to 302(3/2^+)$
L		0,068(25)				
565 - K	21,6(6)	3,48(13)	35	0,0068(4)	E2,M1	$577(7/2^+)\to 12(3/2^+)$
567 - K	8,35(35)	0,97(6)	~8	0,0048(4)	E2	$858(\leq 7/2^+)\to 291(5/2^+)$
572 - K	1,08(10)	0,120(29)		0,0046(11)	E2	$862(\leq 7/2^+)\to 291(5/2^+)$
581 - K	0,48(5)	0,098(30)		0,0085(27)	M1(E2)	$1211(5/2,3/2^+)\to 630(3/2^+)$
585 - K	7,01(21)	0,977(32)	9	0,0058(3)	E2	$887(\leq 7/2^+)\to 302(3/2^+)$
592 - K	1,30(7)	0,20(5)		0,0064(16)	E2,(M1)	$883(\leq 9/2^+)\to 291(5/2^+)$
595 - K	15,93(56)	2,84(11)	30	0,0074(4)	M1	$887(7/2^+,3/2^+)\to 291(5/2^+)$
L		0,50(10)				
618 - K	32,9(10)	5,27(20)	53	0,0067(3)	M1	$630(5/2^+)\to 12(3/2^+)$
L		0,652(30)	8			
621 - K	21,5(6)	2,4(5)	22	0,0046(10)	E2	$923(\leq 7/2^+)\to 302(3/2^+)$
L		0,41(4)	3			
630 - K	5,6(2)	0,56(4)		0,0042(3)	E2	$630(5/2^+)\to 0(1/2^+)$
632 - K	39,0(12)	5,9(3)	58	0,0063(3)	M1	$923(3/2^+,5/2^+,7/2^+)\to 291(5/2^+)$
L		0,83(5)	11			
M		0,13(4)				
664 - K	3,57(10)	0,40(9)		0,0046(12)	M1,E2	$676(\leq 7/2+)\to 12(3/2^+)$
672 - K	1,40(33)	0,126(28)		0,0037(1)	E2	$1211(\leq 5/2^+)\to 539(1/2+)$
676 K	1,12(30)	0,109(27)		0,0041(15)	E2	$676(\leq 5/2^+)\to 0(1/2^+)$

Table 1 (continued)

1	2	3	4	5	6	7
733 K	0,094(15)	0,026(8)		0,0115(39)	M1	$1620(3/2^+,5/2^+,7/2^+)\rightarrow 887(5/2^+)$
751 K	1,96(4)	0,187(34)	~1	0,0039(7)	M1,(E2)	$1329(5/2^+)\rightarrow 577(7/2^+)$
775 K	0,109(25)	0,015(5)	1,2	0,0057(22)	M1	$1352(5/2^+,7/2^+)\rightarrow 577(7/2^+)$
810 K	1,69(4)	0,097(20)		0,0024(5)	E2	$1112(\leq 7/2^+)\rightarrow 302(3/2^+)$
L		0,016(4)				
821 K	0,498(21)	0,040(5)		0,0034(4)	M1	$1112(3/2^+,5/2^+,7/2^+)\rightarrow 291(5/2^+)$
846 K	18,92(62)	1,00(33)	1	0,0022(7)	E2	$858(\leq 7/2^+)\rightarrow 12(3/2^+)$
L		0,099(27)				
M		0,017(8)				
858 K	15,39(56)	0,897(34)	11	0,0024(2)	M1	$858(3/2^+)\rightarrow 0(1/2^+)$
L		0,087(15)	1,4			
M		0,032(11)				
875 K	1,66(6)	0,069(10)	0,9	0,0017(3)	E2	$887(\leq 7/2^+)\rightarrow 12(3/2^+)$
L		0,014(4)				
909 K	0,377(23)	0,021(4)		0,0023(5)	M1,E2	$1211(\leq 7/2^+)\rightarrow 302(3/2^+)$
911 K	3,88(5)	0,19(4)	2,1	0,0020(4)	E2,(M1)	$923(\leq 5/2^+)\rightarrow 0(1/2^+)$
920 K	0,771(22)	0,051(10)		0,0027(5)	M1	$1211(3/2^+,5/2^+)\rightarrow 291(5/2^+)$
933 K	0,513(34)	0,034(9)		0,0027(7)	M1	$1563(3/2^+,5/2^+,7/2^+)\rightarrow 630(5/2^+)$
1010 K	2,80(13)	0,128(12)	1,6	0,0019(2)	E2,M1	$1021(\leq 7/2^+)\rightarrow 12(3/2^+)$
L		0,016(4)				
1038 K	0,273(23)	0,015(4)		0,0023(6)	M1	$1329(3/2^+,5/2^+,7/2^+)\rightarrow 291(5/2^+)$
1043 K	0,333(25)	0,016(4)		0,0020(5)	M1	$1620(5/2^+,7/2^+)\rightarrow 577(7/2^+)$
1061 K	3,38(20)	0,109(10)	1,7	0,00134(4)	E2	$1352(\leq 9/2+)\rightarrow 291(5/2^+)$
L		0,022(4)				
1099 K	7,7(4)	0,241(23)	3,4	0,0013(2)	E2	$1112(\leq 7/2^+)\rightarrow 12(3/2^+)$
L		0,026(3)				
M		0,011(3)				
1199 K	0,83(5)	0,0279(30)	0,8	0,00140(7)	M1	$1211(\leq 5/2^+)\rightarrow 12(3/2^+)$

with conversion-electron spectrum obtained in /3/ , (Table 1, column 4) shows generally good agreement. An additional information about 20 γ-transitions has been obtained. The internal conversion coefficients (ICC) were estimated assuming that γ-transition 302 keV has $\alpha_k = 0.038$. Column 6 of Table 1 contains multipolarities deduced with the use of theoretical conversion coefficients from /8/ . In the most cases the multipolarities from our data do not differ essentially from those previously obtained and this does not allow one to remove the existing ambiguities in spins and parities. Our final conclusions are presented in column 7 of Table 1 and used further in comparison of the calculated energies with the experimental ones.

3. CORE-PARTICLE COUPLING MODEL AND ITS APPLICATIONS TO ^{133}Ba

As the model has been described in details in /1/ only a brief discussion will be given here.

The PVC-scheme used incorporates both anharmonicities in the core vibrations and pairing effects in the odd-neutron motions.

The total Hamiltonian of the coupled system is:

$$H = \sum_{jm} E_j a^+_{jm} a_{jm} - \frac{G}{4} p^+ p - \kappa \sum_{\mu} Q^+_{2\mu} Q_{2\mu} . \qquad (1)$$

Here $a^+_{jm}(a_{jm})$ are particle (hole) creation (annihilation) operators, E_j are the single-particle energies for the odd particle, (jm) are the quantum number of the odd particle states. The second and third terms correspond to the pairing and quadrupole-quadrupole interactions, respectively.

The simultaneous consideration of the pairing and quadrupole correlations leads to the dependence of the coefficients U_j, V_j upon the considered (In) states of even-even core and J-states of odd nucleus. So in the model are introduced new coefficients p^J_{Inj}, h^J_{Inj} by which this effect is taken into accoubt, instead of the usual U_j, V_j coefficients, determined by BCS-methods. (For details see ref. /1/).

The wave function is written in the form:

$$\psi^A_{JM} = \sum_{Inj} C^{JM}_{IMjm} [p^J_{Inj} a_{jm} \psi^{A-1}_{IM} - (-1)^{j-m} h^J_{Inj} a_{j-m} \psi^{A+1}_{IM}] ,$$

where p^J_{Inj} and h^J_{Inj} are the amplitudes of the probability that the state ψ^A_{JM} contains a particle coupled with the collective core state ψ^{A-1}_{IM} and, respectively, a hole coupled with the core state ψ^{A+1}_{IM}. (A±1) denotes (A±1) nucleons in the cores considered.

Table 2

B(E2) experimental transition rates and quadrupole moments in ^{134}Ba

$Q_{2_I^+}$ (eb)	−0,64(I4) /9/ * −0,3I(II) /I0/	$B(E2;2_I^+\to 0_I^+)$ $(eb)^2$	+0,I34(3) /9/ +0,I40(3) /II/*
$B(E2_2^+\to 0_I^+)$ $(eb)^2$	0,00I3(2) /II/	$B(E2;2_2^+\to 2_I^+)$ $(eb)^2$	0,207(24) /II/
$B(E2;4_I^+\to 2_I^+)(eb)^2$	0,2I4(22) /II/	$B(E2;4_I^+\to 2_2^+)$ $(eb)^2$	<0,00024 /II/

The odd-mass system energies E^J and eigenvector coefficients p^J_{Inj}, h^J_{Inj} are obtained further by solving the Schroedinger equation for the Hamiltonian (1). In the numerical calculations the following set of input parameters has been used:

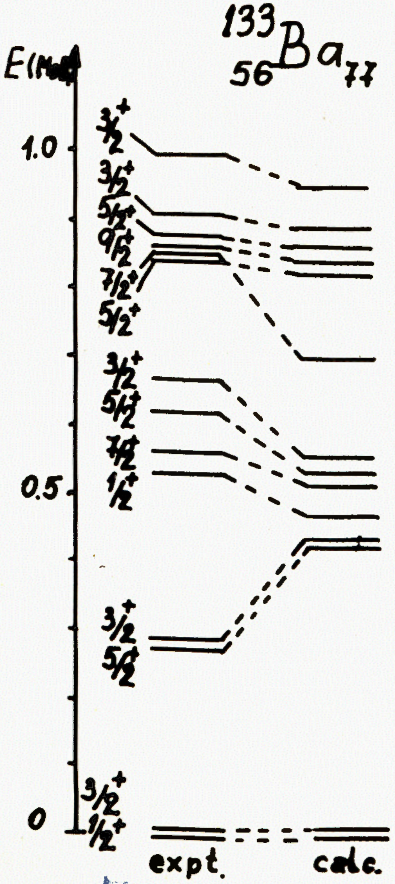

Fig. 1.

◀ Comparison of the experimental and calculated level spectra of ^{133}Ba.

1) The spherical single-particle states $s_{1/2}$, $d_{3/2}$, $d_{5/2}$ and $g_{7/2}$ with their energy-spacings $\Delta E(d_{3/2}-s_{1/2}) = 0.6$ MeV, $\Delta E(d_{5/2}-g_{7/2}) = 0.2$ MeV. The Fermi-level λ has been adjusted to the experimental level schemes and it has been found to lie close to $d_{3/2}$ in accordance with the results in ref. /5/.

2) The four collective core excitations 0_I^+, 2_I^+, 2_2^+, 4_I^+ have been taken from the neighbouring even-even core nuclei ^{132,134}Ba.

3) The reduced quadrupole matrix elements have been obtained from the experimental transition rates and the quadrupole moments of the core nuclei. In Table 2 all available data about neighbouring even-even Ba-nuclei are listed. Marked values are those, for which the best fit is obtained.

Although the reduced matrix elements are not considered as adjustable parameters in the model, we have varied their values in the whole range of the available data not firmly establishes so far. The final results are shown in Fig. 1.

4. RESULTS AND DISCUSSION

Comparison of the experimentally established positive-parity levels in ^{133}Ba and calculated ones, show a good agreement: 13 lowest levels in ^{133}Ba are reproduced within rms-deviation about 0.07 MeV. It shoud be noted, that in the cases when the spins of the levels are not firmly established (it takes place for the levels above 600 keV), we assumed some of them. For these we used present data for conversion electrons. For 887 keV excited state we find experimentally $I^\pi = 5/2^+$ and this is in full agreement with the calculated value.

Table 3

The wave-function components in ^{133}Ba

ground state $(I^\pi = I/2^+)$	1^{st} excited state$(I^\pi = 3/2^+)$
(33%p + 3I% h) $[0\otimes s_{1/2}]$	(36%p + 32% h) $[0\otimes d_{3/2}]$
(9%p + I7% h) $[2_1\otimes d_{3/2}]$	(I0%p + I8% h) $[2_1\otimes d_{3/2}]$
8% h $[2_1\otimes d_{5/2}]$	...
...	

The analysis of the wave-functions demonstrates a considerable mixing in all states, even in the ground state (Table 3). Note, that a good test for the model-wave functions is the B(M1)-estimation. So, we calculated B(M1), $3/2^+_1 \xrightarrow{12\,KeV} 1/2^+_{gr.st.} = 0.31\mu_N^2$, using the wave functions obtained in the present paper, and gyromagnetic ratios: $g_l = 0$, $g_s = 0.6\ g_s^{free}$ and $g_R = Z/A$. The value obtained is in a reasonable agreement with the experimental one $(3.73\mu_N^2)$ /12/.

A more detailed analysis of the results obtained in calculations would be possible if more experimental information about transition rates and quantum characteristics of the excited states of this nucleus were available.

In conclusion we believe that this version of the PVC-model has every chance to provide a good description of typical odd-transitional nuclei.

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О природе возбужденных состояний ^{133}Ba

При помощи Si(Li) β-спектрометра измерены электроны внутренней конверсии из распада ^{133}La и сделаны выводы о мультипольностях ряда γ-переходов. Экспериментально установленные характеристики возбужденных состояний ^{133}Ba сравниваются с результатами теоретических расчетов энергии и волновых функций уровней ^{133}Ba, проделанных в рамках модели взаимодействия нечетной частицы с ангармоничным вибрационным остовом. Получено удовлетворительное согласие для 13 нижайших уровней, а также для вероятности М1-перехода с энергией 12 кэВ / $B(M1, 3/2^+_1 \xrightarrow{12\ \text{кэВ}} 1/2^+_1)^{calc.} = 0{,}31\,\mu_N^2$/, который в оболочечной модели является ℓ-запрещенным.

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On the Nature of the ^{133}Ba Excited States

Using Si(Li) β-spectrometer, the internal conversion electrons from the ^{133}La decay were measured and conclusions were made of the multipolarities of a number of γ-transitions. The experimentally obtained ^{133}Ba excited state characteristics are compared with the results of theoretically calculated energies and wave functions of ^{133}Ba levels. The calculations have been performed within the model of interaction of an odd particle with anharmonic vibrational core. A satisfactory agreement is obtained for 13 lowest levels as well as for 12 keV M1-transition probability ($B(M1, 3/2^+_1 \xrightarrow{12\text{keV}} 1/2^+_1)^{calc.} = 0.31\mu_N^2$), which is ℓ-forbidden in the shell-model.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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