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COLLECTIVE STATES IN ^{230}Th: BAND STRUCTURE

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Experimental data for the excited states in the deformed nucleus ^{230}Th studied in the (p, t) reaction are analyzed. Sequences of the states are selected which can be treated as rotational bands and as multiplets of excitations. Experimental data are compared with the interacting boson model (IBM) and the quasiparticle-phonon model (QPM) calculations.

Keywords: collective bands, moments of inertia, interacting boson model, quasiparticle-phonon model.

1. Introduction

In the paper [1] the details of the experimental techniques, the DWBA analysis of the experimental data from the high-precision, high-resolution study of the ^{232}Th(p, t)^{230}Th reaction, and the results of identification of about 200 levels in ^{230}Th are given. As prolongation of this study we present in this paper theoretical analysis of the obtained experimental data and some conclusions on the structure of the excited states in ^{230}Th.

A full microscopic description of low-lying excitations in deformed nuclei has eluded theoretical studies to date. Along with the interplay of collective and single-particle excitations, which takes place in deformed rare earth nuclei, additional problems arise in the actinide region because of the reflection asymmetry [2]. Evidently the nature of the first excited 0^+ states in the actinide nuclei is different from that in the rare earth region where they are due to the quadrupole vibration [3]. Octupole degrees of freedom have to be important in the actinides. One has then to expect a complicated picture at higher excitations: residual interactions could mix the one-phonon and multiphonon vibrations of quadrupole and octupole character with each other and with quasiparticle excitations. Detailed experimental information on the properties of such excitations is needed for comparison with theory. On the experimental side, the (p, t) reaction is very useful. On the theoretical side, a microscopic approach such as the quasiparticle-phonon model (QPM) is necessary, in order to account for the number of states detected and to make detailed predictions on their properties.

2. Some conclusions on the structure of excited states

A. Collective bands in ^{230}Th

After the assignment of spins to all excited states in ^{230}Th [1] the sequences of states can be distinguished which show the characteristics of a rotational band structure. An identification of the states attributed to rotational bands was made on the following conditions:

a) the angular distribution for a state as band member candidate is fitted by the DWBA calculations for the spin necessary to put this state in the band;

b) the transfer cross section in the (p, t) reaction to the states in the potential band has to decrease with increasing spin;

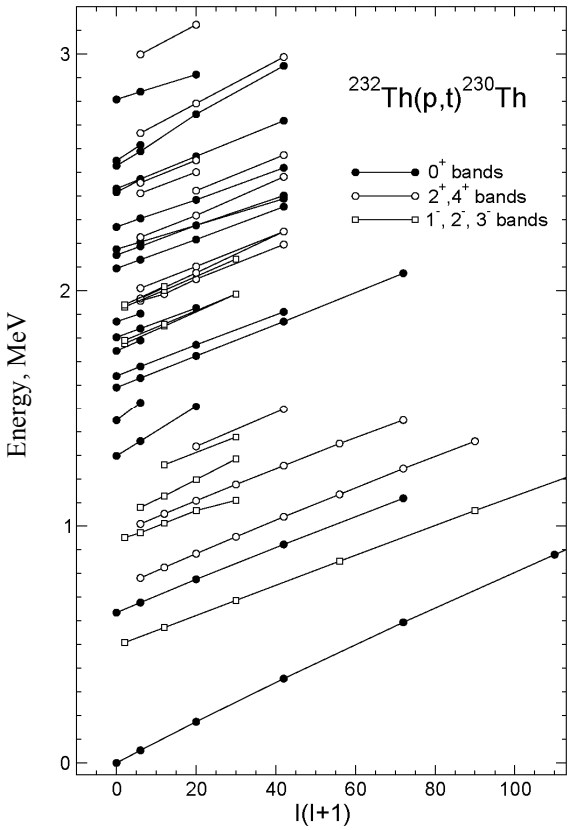

Fig. 1. Collective bands based on the 0^+, 2^+, 4^+, 1^-, 2^- and 3^- excited states in ^{230}Th as assigned from the DWBA fit of the angular distributions from the (p, t) reaction.

c) the energies of the states in the band can be fitted approximately by the expression for a rotational band $E = E_0 + AI(I + 1)$ with a small and

smooth variation of the inertial parameter *A*. Collective bands identified in such a way are shown in Fig. 1 and are listed in Table 1 (for a calculation of the moments of inertia). The procedure can be justified in that some sequences meeting the above criteria are already known from gamma-ray spectroscopy to be rotational bands, so other similar sequences are very probably rotational bands too. The straight lines in Fig. 1 strengthen the argument for these assignments. For example the mean deviation of the experimental energies from the calculated rotational values for the longest newly assigned band based on the state 0^+ at 1589 keV is only 1.0 keV; for the band based on the 0^+ state at 2093.9 keV it is 1.3 keV; and for the band above the 0^+ state at 2268.9 keV it is 3.9 keV. Even for the band above the 0^+ state at 2426.4 keV assigned tentatively the deviation is less than 1 keV. The observed deviations are all consistent with the stretching effect typical for rotational bands. Nevertheless additional information (on E2 transitions at least) is needed to confirm these assignments.

Table 1. **The sequences of states qualifying as candidates for rotational bands (from the CHUCK fit, the (p, t) cross sections and the inertial parameters). The energies taken in brackets correspond to the sequences assigned tentatively**

0^+	1^+	2^+	3^+	4^+	5^+	6^+	7^+	8^+	
0.0		53.2		174.0		356.3		593.8	
634.9		677.5		775.5		923.0		1117.5	
		781.4	825.6	883.9	955.1	1039.6	1134.2	1243.3	
		1009.6	1052.3	1107.5	1176.1	1255.5	1349.3	1448.7	
1297.1		1359.5		1507.4		1496.0			
				1337.2					
1447.9		1524.8							
1589.8		1630.1		1723.5		1868.9		2073.2	
1638.5		1679.1		1770.7		1910.0			
(1744.9)		1789.4							
1802.5		1839.6		1926.0					
(1868.9)		1902.7	1985.4	2048.7		2194.8			
		1956.4		2074.9		2249.9			
		1966.9		2102.0		2249.9			
		2010.1							
2093.9		2130.7		2216.0		2354.8			
2150.5		2187.1		2276.0		2402.0			
2175.1		2205.4		2276.0		2388.4			
		2226.0		2317.7		2481.3			
2268.9		2305.4		2383.8		2519.3			
(2422.7)		2474.3		2422.7		2573.2			
(2426.4)		2467.2		2562.9		2712.9			
		2411.6		2501.1					
		2461.0		2556.2					
2528.1		2589.1		2746.2		2950.5			
2549.8		2616.0		2791.5		2987.9			
		(2666.0)							
2808.1		2841.3		2913.6					
		2999.0		3124.7					
	1^-	2^-	3^-	4^-	5^-	6^-	7^-	8^-	9^-
	508.2		571.7		686.7		851.9		1065.9
	951.9	972.1	1012.5	1065.9	1109.0				
		1079.4	1127.8	1196.8	1283.6				
			(1259.2)		1376.7				
	(1789.4)		1858.6		1985.4				
	(1775.2)		1849.6		1985.4				
	(1931.1)		2000.9		2133.2				
	(1939.8)		2017.3						

It is worth mentioning that the tentative assignment 0^+ for the state at 2426.4 keV is supported by a sequence of 3 other states (2^+, 4^+, 6^+) on top of it. Three other tentative 0^+ states (1745.3, 1868.9, and 2422.7 keV) have only one tentative state (2^+) on top of them and the band sequence is not based on γ-ray transition but on energy arguments. In Table 2 we present moments of inertia (MoI) obtained by fitting the level energies of the bands displayed in Fig. 1 by the expression $E = E_0 + + AI(I+1)$. In upper part of the Table those sequences are presented which are connected by

Table 2. **Moments of inertia for the bands in ^{230}Th as assigned from the angular distributions from the ^{232}Th(p, t)^{230}Th reaction. Results derived from the sequences having only 2 levels or assigned tentatively are given in lower part of the Table**

E, keV	J(0^+)	E, keV	J(2^+)	E, keV	J(1^-,3^-)
0.0	56.8	781	67.5	508	78.3
635	70.1	1009	70.0	951	98.5
1297	47.8	1956	62.9	1079	61.7
1589	74.0	1967	64.5	1259	79.4
1639	75.7	2010	75.7	1789	72.0
1802	80.5	2226	76.0	1931	71.3
2093	81.2	2666	55.5		
2150	81.6				
2175	98.5				
2269	81.8				
2426	74.0				
2528	49.0				
2808	89.5				
1448	40.0	2412	78.0	1259	79.4
1745	67.2	2461	73.1		
1868	88.4	2999	55.4		
2422	58.0				
2550	45.7				

known γ-ray transitions or have at least 3 levels and in lower part of the Table the sequences having only 2 levels or tentatively assigned are presented. The obtained MoI cover a broad range, from ~50 MeV^{-1} to ~100 MeV^{-1}. The negative parity bands based on the states with spin 1^- interpreted as the octupole-vibrational bands [6] have high MoI (the 1^- band at 951 keV has the largest). The 0^+ band at 1297 keV, considered as β-vibrational band, has the smallest MoI. At this stage, it is difficult to make a complete correlation between the intrinsic structure of the bands and the magnitude of their MoI. Nevertheless one can assume also for the 0^+ bands that the largest MoI could be related to the octupole phonon structure and the smallest MoI could be related to the one-phonon quadrupole structure. The bands with the intermediate values of the MoI could be based on the two-phonon quadrupole excitations.

If the moments of inertia do indeed carry information on the inner structure of the bands, then the numbers of excitations with different structure are comparable. This would be in contradiction with the IBM calculation which predicts predominantly the octupole two-phonon structure of 0^+ excitations (see below). The nature of 0^+ excitations, derived from calculations in the framework of the QPM as predominately quadrupole, is in contradiction with both the IBM calculation and with the above mentioned empirical observation (see below).

B. Excited states with spins higher than 0^+

Other states, mainly with spins 2^+, 4^+ and 6^+ are intensively excited in the (p, t) reaction. The nature of these states may only be assumed. Some of these states could belong to the collective bands based on 0^+ states. Some of the 2^+ states could be quadrupolar (one-phonon) vibrational states with correspondence to 0^+ excited states, since in deformed nuclei every excitation of angular momentum I^π splits into states distinguished by their K quantum numbers ranging from 0 to I. Some 4^+ excited states could be hexadecapole vibrational excitations and 2^+ and 0^+ states should correspond to this class of states for the same reason. If this speculation reflects reality then the number of 0^+ states has to be the largest. However, the observation is in contradiction with this conjecture unless very weak 0^+ excitations are not seen in the (p, t) reaction. Attributing the underlying structure to each of the observed states is not possible with the presently available experimental data. To give at least a hint for the structure of these states the experimental energy distribution of the (p, t) transfer strength for the 0^+, 2^+ and 4^+ excitations is plotted in Fig. 2.

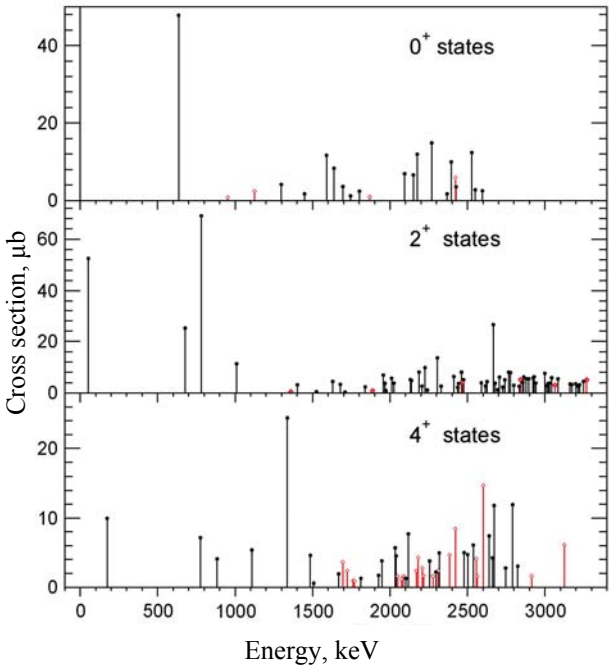

Fig. 2. Experimental distribution of the (p, t) strength integrated in the angle region 0° - 45° for 0^+, 2^+ and 4^+ states in ^{230}Th. The levels identified reliably are indicated by filled circles and those identified tentatively are indicated by open diamonds.

A most remarkable feature in Fig. 2 is the most strongly excited 4^+ state at 1337 keV, which can be related to the strongly excited 0^+ state at 635 keV and 2^+ state at 781 keV. The inertial parameters derived from the bands based on these states are practically the same. The only explanation is that these states have the same structure. One can assume that these states are a triplet originating from an excitation of multipolarity 4 as in the case of a

quadrupole two-phonon excitation. However, a corresponding strongly excited one phonon quadrupole excitation with spins 0^+ and 2^+ are not observed at lower energy. Indeed, the 0^+ state at 1297 keV, which was identified as the β-vibrational state [6], is rather weak. Thus quadrupole two-phonon excitations have to be excluded. On the assumption that these states have a two-phonon octupole structure a quadruplet of states has to be observed with spins from 0^+ to 6^+. Experimentally a state with spin 6^+ is identified at 1653 keV, although its excitation is only of 0.9 μb, i.e. much weaker than the other states. If this assumption is correct, then the interpretation of the first 0^+ state as a two-phonon excitation obtains some confirmation. This quadruplet of states and the corresponding bands are displayed in Fig. 3. Note however, that the moments of inertia derived from the band based on the states of the multiplet are somewhat smaller than the ones derived for the bands based on negative parity states (see Table 2).

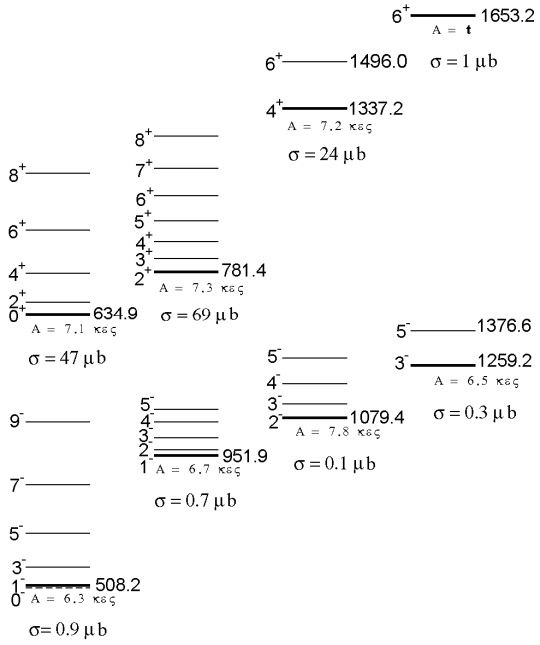

Fig. 3. Assumed multiplets of states of the octupole one-phonon (bottom) and the octupole two-phonon (top) excitations and corresponding collective bands.

An indirect confirmation of the above assumption would be the existence of another quadruplet. The 1^- levels at 508 keV and 952 keV and the 2^- level at 1079 keV were interpreted as members of a quadruplet of octupole shape oscillations with $K^\pi = 0^-$ to 3^- [6]. The 3^- level at 1259 keV identified from the (p, t) reaction in the present study can be the missing member of this quadruplet, as shown in Fig. 3. The energy separation between the $K^\pi = 0^-$ and $K^\pi = 1^-$ and between the $K^\pi = 1^-$ and $K^\pi = 2^-$ band heads differ strongly. This was explained by a strong coupling of the bands based on the last two states [6]. The energy separation between the 3^- level at 1259 keV and the 2^- level is close to the one between the second 1^- and 2^- levels, which can also be attributed to the coupling of these three states.

3. Discussion

A. 0^+ excitations

The structure of excited 0^+ states in deformed even-even nuclei is still a matter of controversial discussion despite intensive investigation. Traditionally the first excited 0^+ state has been interpreted as the β-vibrational excitation of the ground state. However, in many nuclei the 0^+_2 state has only weak transitions to the ground-state band, while strong electric quadrupole transitions to the gamma band have been found [8]. This contradicts the traditional interpretation, since a transition from a β-vibrational state to the gamma band is suppressed due to the destruction of a beta phonon, and, at the same time, the creation of a gamma phonon. The unclear situation led to an intense debate about the structure of low-lying 0^+ states.

Maher et al. [3] were the first who noticed an interesting feature of 0^+ excited states in the actinides. The strong excitations of the first excited 0^+ states in the (p, t) reaction, combined with all other available evidence (rather weak E2 transitions to the ground-state band, strong α decays leading to them, the strong Coulomb excitation of the associated collective bands) suggest that these states represent a new and stable collective excitation, different in character from the most common formulation of the pairing vibration as well as from the β-vibration usually found in the deformed rare-earth nuclei. The second excited 0^+ states in actinides (firmly assigned) demonstrate completely different features [6, 9, 10]. Weak excitation in the (p, t) reaction, relatively strong *E2* transitions to the ground-state band and a small B(E1)/B(E2) ratio for transitions to 2^+ and 1^- states give evidence that they could be the usual β-vibrational states. For ^{230}Th this is the case for the level at 1297.8 keV [6]. Otsuka and Sugita [11] applied the *spdf*- interacting boson model to the actinide nuclei, aiming to get a unified description of quadrupole-octupole collective states. They suggested the first excited 0^+ band be referred to as the "super β band" thus emphasizing the difference of the structure of this state from that of the usual β-vibrational state. They also predicted the existence of the second excited 0^+ band to be the usual β band that was confirmed later. There are evidences for the first 0^+ state in ^{230} Th (quadruplet of states, large moment of inertia comparable to that

for the octupole-vibrational bands, together with the features noticed by Maher et al. [3] and listed above) to carry the two-phonon octupole nature. However, the B(E1)/B(E2) ratio for transitions to the 1^- and 2^+ states is even smaller for this state than for the state at 1297 keV: $\sim 4 \cdot 10^{-7}$ fm^{-2} compared to $\sim 7 \cdot 10$-^{7} fm $^{-2}$ [6]. Intuitively one would expect that a large B(E1)/B(E2) ratio might be characteristic for a two-octupole-phonon excitation, whereas a small ratio might indicate a β shape oscillation. That is true for the state at 1297 keV (which indeed is a β-vibrational state), but not true for the first excited state. Moreover, the IBM and the QPM predict one phonon quadrupole nature for this state (see below). Therefore the available data do not allow the firm conclusion on the nature of this state.

Understanding of the structure of the higher excited states remains a challenge for further experimental studies (e.g. γ spectroscopy in the (p, tγ)-reaction) and for nuclear theory. The first attempt to explain experimental data of a large number of 0^+ excited states in ^{158}Gd [12] was a phenomenological approach [13] based on the extended interacting boson model *(spdf-IBM),* which accounted for a large fraction of the observed states. The importance of the octupole degrees of freedom was revealed. The first microscopic approach was performed in the framework of the projected shell model (PSM) [16], using a restricted space spanned by two and four quasiparticle states. The IBM calculation reproduced satisfactorily all energy levels in ^{158}Gd and gave small E2 decay strengths for them. Soloviev and co-workers [14, 15] applied the quasiparticle-phonon model (QPM) to get a microscopic understanding of low-lying 0^+ states. The QPM was also applied to ^{158}Gd [17]. It predicts an sizable fraction of the 0^+ states to have large or dominant two-phonon components, mainly built from collective octupole phonon components, in agreement with the IBM calculations [13].

No extended calculations have yet been carried out for the excitation of the two-quasiparticle (2QP) modes, which are expected to occur at excitation energies of about twice the pairing gap energy, i.e. about 1.5 MeV in our case. Only very restricted microscopic calculations for low energies were attempted by Ragnarsson and Broglia [7]. It would be desirable to extend these calculations to higher energies. Just above 1.5 MeV, exactly in the range 2.0 - 2.5 MeV, a bump in the distribution of the (p, t) transfer strength is observed (see Fig. 2). At least some of these excitations could be of 2QP-nature. A model by Rij and Kahana [19] describing the 0^+ state as a pair of holes in the oblate 1/2[501] Nilsson level should also be mentioned.

The monopole pairing vibration state for neutron-pair excitation (n-MPV) is expected to be strongly excited in the (p, t) reaction because of the large overlap of the wave function of such a state with that of the target nucleus ground state. A dominant (p, t) cross section for a single state in the spectrum (besides the ground and the first excited states) is observed in some nuclei. In ^{229}Pa the cross section for the $L = 0$ transfer to the state at 1500 keV is about 15 % of that for the ground state and comparable to that for the first excited 0^+ state in ^{230}Th [5]. However, this behavior is unexpected, since this energy corresponds more to that of the proton-pair excitation (p-MPV), where the cross section is expected to be much weaker. At the same time, a dominant cross section in ^{228}Th is observed for a single state at about 2.1 MeV, much higher than in ^{229}Pa, which can be considered as being due to the ^{228}Th core plus a proton. These facts, as well as practically no correspondence of the energy distribution of the (p, t) strength in these two nuclei, need a theoretical explanation. No dominant excitation at higher energies is observed in ^{230}Th. In the case of a relatively dense spectrum of 0^+ states, fragmentation of the n-MPV state to nearby states is possible. Such a group of states in ^{230}Th around 1600 keV could be a result of such fragmentation. The summed cross section of this group is about 13 % of that for the ground state. A similarly dense spectrum occurs also in ^{228}Th and ^{229}Pa; nevertheless, these nuclei demonstrate dominant excitation of individual states.

B. IBM calculations

Although ^{230}Th is considered a vibrational-like nucleus, the inclusion of the octupole degree of freedom in the description of its properties turned out to be important [6]. The role of the octupole degree of freedom in deformed actinide nuclei and the related description with bosons added to the IBM in the *sd* boson space *(sdf-IBM)* has been studied in [21]. Despite reproducing reasonably well the main features of the observed low-lying negative parity states in the rare earth nuclei [20], the *sdf-IBM* was not so successful for the actinide nuclei. A better reproduction of the relevant data is obtained if a *p* boson is included in addition to the boson without seeking an understanding of its physical nature [22].

The full experimental spectrum of the 0^+ states in ^{230}Th, including relatively firm and tentative assignments, and the results of *spdf-IBA* calculations are compared in Fig. 4. In the energy ranges covered experimentally, the IBM predicts seven excited 0^+ states of pure *sd* (quadrupolar) bosonic structure, and twelve excited 0^+ states which have two bosons in the *pf* boson space. They could be related to octupole two phonon excitations (OTP). The nature of the states according to the calculations is indicated in Fig. 4.

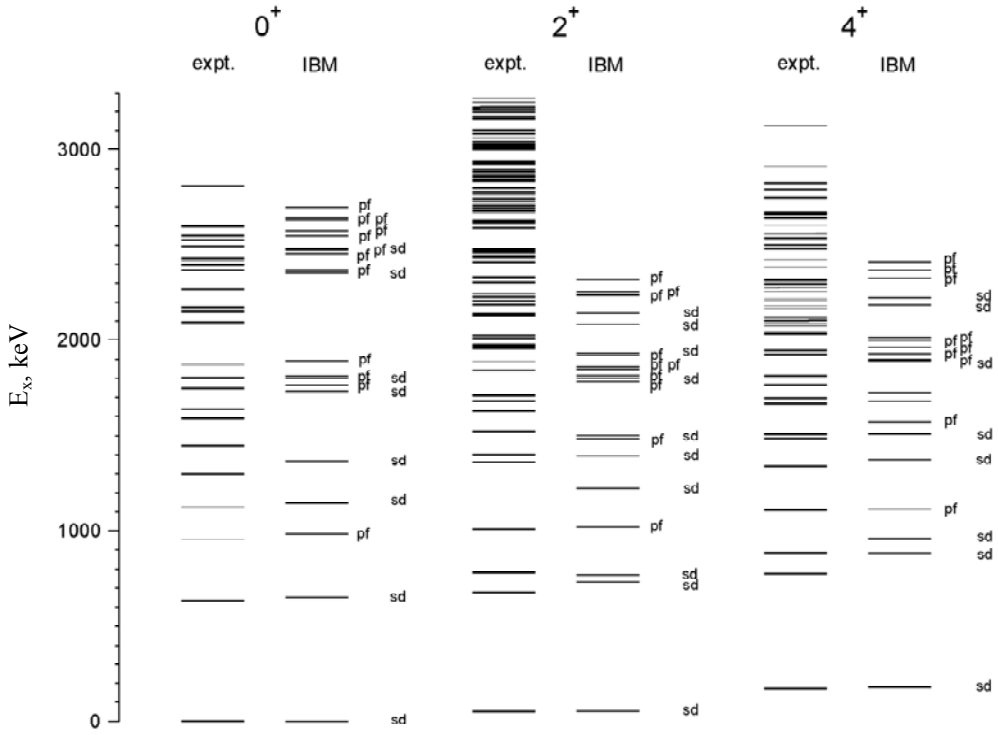

Fig. 4. Energies of all experimentally assigned excited 0^+, 2^+ and 4^+ states in ^{230}Th in comparison with *spdf*-IBM calculations. The structure of the states derived from calculations is indicated to the right of the corresponding lines. The firmly assigned states are shown by thick lines, while tentatively assigned states are indicated by thin lines.

We can see a reasonable correlation in excitation energy between experiment and calculation up to 1.4 MeV. The calculation predicts the first excited 0^+ state as a quadrupole excitation in the *sd* space at an energy close to the experimental state at 635 keV. The second excited 0^+ state is predicted as an octupole two-phonon excitation and could correspond to the tentative assigned 0^+ state at 953 keV. The following two are predicted to have a quadrupole structure and correspond energetically to the tentative assigned 0^+ state at 1126 keV and to the 0^+ state at 1297 keV, respectively. The latter was, indeed, considered the β-vibrational state in Ref. [6].

Thus the IBM calculation with the parameterizations used predicts for ^{230}Th 20 excited 0^+ states in the energy range below 2.7 MeV. Accounting in addition for the presence of monopole pairing vibrational states, two-quasiparticle states and perhaps a state from hexadecapole collectivity, not included in the calculation, we can consider 24 observed 0^+ excitations as nearly perfect agreement with calculated number of such excitations. But there is no clarity concerning the nature of these excitations without additional experimental information.

A calculation in the framework of the *spdf-IBM* gives 20 levels of spins 2^+, 4^+ and 6^+ in comparison with 40, 32 and 11 identified levels of these spins in the energy region below 2.7, 2.3 and 2.4 MeV, respectively. The spectrum of 2^+ and 4^+ states in comparison with the *spdf-IBM* calculation is given in Fig. 4. Most of the 6^+ states could not be observed in the (p, t) reaction because of their low cross section. As far as 2^+ and 4^+ states are concerned, the number of experimental levels is much higher than the prediction of the *spdf IBM* model.

C. QPM calculations

The ability of the QPM to describe multiple 0^+ states (energies, $E2$ and $E0$ strengths, two-nucleon spectroscopic factors) was demonstrated for ^{158}Gd [17]. An extension of the QPM to describe the 0^+ states in the actinides [18] was made after our publication on the results of a preliminary analysis of the experimental data [4]. The present calculations aim to explain the results of the detailed analysis of the experimental data for ^{230}Th.

In the QPM [23] the Hamiltonian in a separable generalized form is adopted to generate the quasiparticle RPA phonons described by the operators

$$Q^{\dagger}_{i\nu} = \frac{1}{2}\sum_{q_1 q_2}(\varphi^{i\nu}_{q_1 q_2}\alpha^{\dagger}_{q_1}\alpha^{\dagger}_{q_2} - \phi^{i\nu}_{q_1 q_2}\alpha^{\dagger}_{q_2}\alpha^{\dagger}_{q_1}). \qquad (1)$$

The Hamiltonian expressed in terms of these phonon operators is diagonalized in the space spanned by one- and two-phonon states. The QPM eigenstates have the structure

$$\Psi_{nK} = \sum_i C_i^{(n)} Q^\dagger_{i\lambda K} \mid 0\rangle + \sum_{\nu_1\nu_2} C^{(n)}_{\nu_1\nu_2} [Q^\dagger_{\nu_1} \otimes Q^\dagger_{\nu_2}]_K \mid 0\rangle \,, \quad (2)$$

where λK label the multipolarity and magnetic component of the phonon operator. Each of these states represents the intrinsic component of the total wave function

$$\Psi^I_{nMK} = \sqrt{\frac{(1+\delta_{K0}0)(2I+1)}{16\pi^2}} \times$$

$$\times [D^I_{MK}\Psi_{nK} + (-1)^{I+K} D^I_{M-K}\Psi_{nK}] \,, \quad (3)$$

where D^I_{MK} is the Wigner matrix. No free parameters are used in these calculations, all physical input quantities and constants are determined by an independent fit to the experimental data in neighboring odd nuclei. For details see [18].

The experimental spectra of the 0^+, 2^+ and 4^+ states in ^{230}Th are compared with the results of the QPM calculations in Fig. 5. The QPM considers only vibrational 2^+ and 4^+ excitations in the even-even nuclei, therefore all other excitations have to be excluded from the comparison. Only the 2^+ and 4^+ states not belonging to rotational bands (see Sec. 2 A) are included in Fig. 5, i.e. these states are assumed to be mainly of vibrational structure. The QPM generates 23 0^+ states below 2.8 MeV in fair agreement with the 24 identified states. At the same time the QPM yields less 2^+ and 4^+ excited states than the ones observed experimentally. The numbers of 2^+ and 4^+ states generated up to 3 MeV are 20 and 17, respectively, considerably less than the observed 50 and 27 corresponding experimental levels (see Fig. 5). It seems that taking into account the two-quasiparticle and pairing vibrational states not excluded from consideration (there are problems in their identification) cannot explain this large difference. Beside the ground state, experiment reveals one very strong peak for every of 0^+, 2^+ and 4^+ state and small strengths for other states. The calculation correctly yields strong peaks close in magnitude and position to the experimental ones for the 0^+, 2^+ and 4^+ states. These strong peaks form the suggested multiplet are shown in Fig. 3. The calculation correctly yields small strengths for other peaks in the case of 0^+ excitations. At the same time, besides the first strongn peaks, the QPM predicts for the 2^+ and 4^+ states two other strong peaks not observed experimentally.

In contrast to the *spdf-IBM,* the QPM is able to reproduce the two-neutron transfer strength. The wave functions (3) can be used to compute the (p, t) normalized transfer spectroscopic factors

$$S_n(p,t) = \left[\frac{\Gamma_n(p,t)}{\Gamma_0(p,t)}\right]^2 , \quad (4)$$

where the amplitudes are given by [24]

$$\Gamma_n(p,t) = \langle \Psi^I_{nMK}, N-2 \mid \sum_{q_1q_2} r^I Y_{IK} \alpha_{q_1}\alpha_{q_2} \mid \Psi_0, N\rangle \,. \quad (5)$$

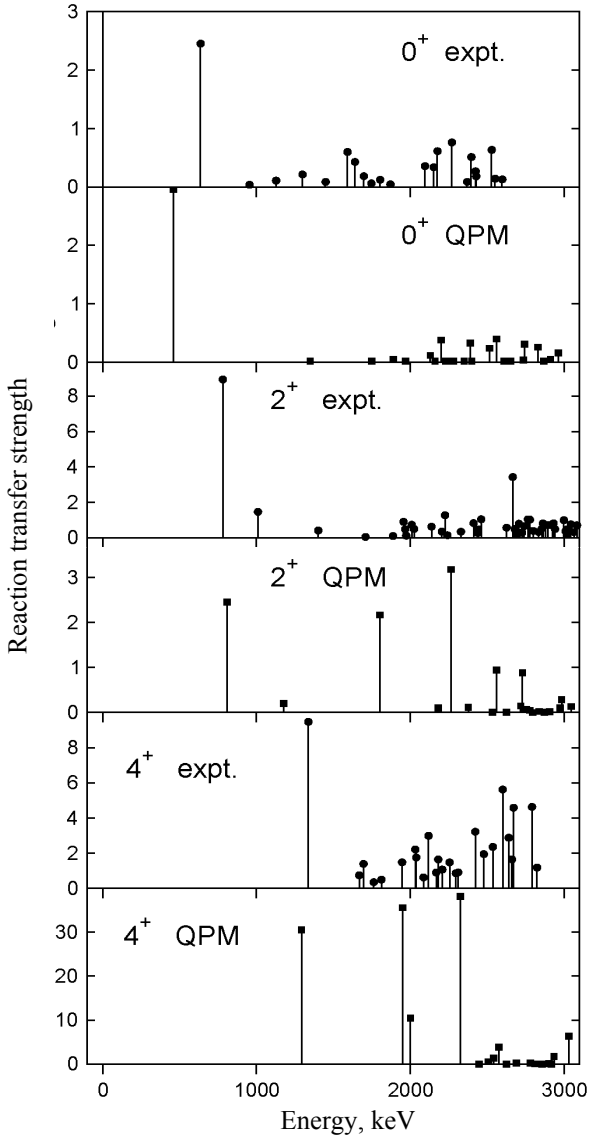

Fig. 5. Comparison of experimental and calculated (QPM) 0^+, 2^+ and 4^+ relative level reaction strengths for the (p, t) reaction. The 2^+ and 4^+ states assumed to belong to rotational bands (see Sec. 2 A) are not included. The experimental strengths for $0^+_{g.s.}$, 2^+_1 and 4^+_1 being rotational states are normalized to 10 (the latter two are not shown in Figure).

The amplitude Γ_0(p, t) refers to the transitions to the I members of the ground state rotational band [18]. In Fig. 6 we present the increments of the (p, t) strength to the 0^+, 2^+ and 4^+ states and that of the spectroscopic factors derived from the DWBA analysis for these states. They are given relative to those for corresponding states of the ground state band and are compared with the calculated normalized spectroscopic factors. Since the DWBA analysis for the 0^+ states included different configurations of the transferred neutrons, only the (p, t) strength ratio is given in Fig. 6 for these states.

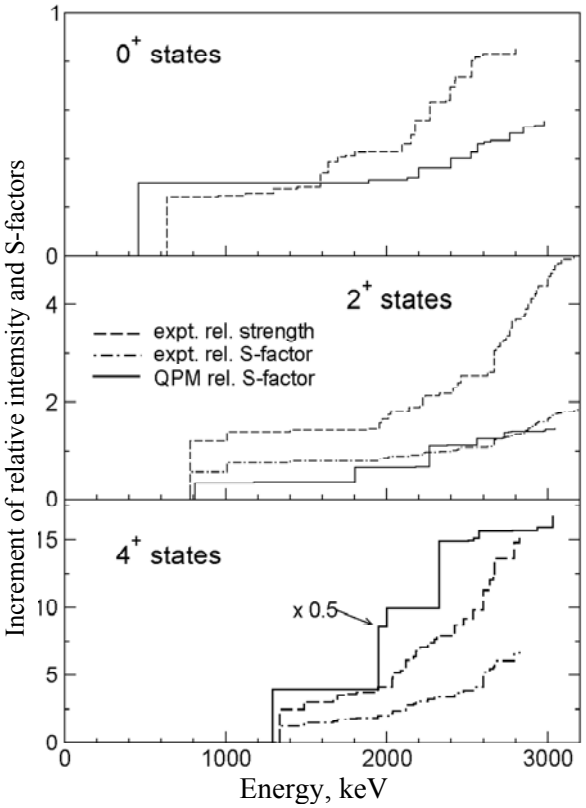

Fig. 6. Experimental increments of the (p, t) strength in comparison with the QPM calculations. The 2^+ and 4^+ states assumed as belonging to rotational bands (see Sec. 2 A) are not included.

For other states only the $(2g_{9/2})^2$ neutron configuration was accepted. According to the DWBA formalism in the case of the same neutron configuration and the direct one-step transfer the strength ratios have to be close to the spectroscopic factor ratios. This is not the case for ^{230}Th, since a considerable difference of these two ratios is observed.

As one can see, the calculations of 0^+ for the (p, t) strength ratio are in fair agreement with the experiment. For the 2^+ states the calculations are in good agreement with the measured spectroscopic factor ratios, however almost two times smaller than the measured strength ratios. We have to note that the (p, t) strengths for the 0^+ and 2^+ states not firmly assigned are small and do not influence considerably the results of comparison. At the same time withdrawal of these states from consideration will only improve the agreement with the calculations. For the 4^+ states the calculated spectroscopic factors are more than two times larger than the experimental strength and spectroscopic factor ratios. The difference possibly stems from the change of the (p, t) cross section caused by the inclusion of additional two-step paths of the neutron transfer for the 2^+ and 4^+ members of the ground state band. The angular distributions for these states differ considerably from those for direct one-step transfer and can be fitted only by an inclusion of a two-step excitation number which is the largest for the 4^+ state. For the 0^+ states, where only the one-step transfer is possible, the agreement between calculation and experiment is good. For both 2^+ and 4^+ states the energies at which the experimental strength first appears agrees with the calculated ones. This means that the energies of the first vibrational 2^+ and 4^+ excitations predicted by the QPM are in fair agreement with the experiment (recall that the states belonging to the rotational bands are excluded from this comparison).

The nature of 0^+ excitations as well as for 2^+ and 4^+ states in the QPM differs greatly from that in the *spdf-IBM*. In all low-lying states quadrupole phonons are dominant and the octupole phonons are predicted to play a relatively modest role. This might be acceptable in the vibration-like ^{230}Th, but the same is predicted for the octupole soft ^{228}Th. The spectrum is explained from the QPM calculation procedure (Pauli principle) as a redistribution of the strength of the lowest two-octupole phonons among many closely packed QPM 0^+ states [13]. To assess this aspect, calculations for octupole deformed lighter isotopes of Th would be important.

Other predictions of the QPM can be tested experimentally only for the lowest states. The measured values of $B(E2;0_1^+ \to 2_0^+) = 1.1$ W.u. is close to the computed value of 1.7 W.u. At the same time the calculated monopole transition strength $\rho^2(E0;0_1^+ \to 0_g^+) = 1.48 \cdot 10^{-3}$ is two orders of magnitude smaller than the experimental value of $126(13) \cdot 10^{-3}$ [6]. Again, we would like to stress the necessity of systematic measurements of electromagnetic properties of higher excited 0^+ states to understand their nature.

4. Conclusion

Assignments made in the experimental part of this study [1] allowed the identification of sequences of states which have the features of rotational bands with definite inertial parameters. The 2^+, 4^+ and 6^+ states not included in these bands have been considered as vibration-like excitations. The experimental data are compared with *spdf*-IBM and QPM calculations. Giving an approximately correct number of 0^+ states, these models provide different predictions for the structure of these states. They are also in conflict with the apparent structure of the states inferred from the moments of inertia of the rotational bands built on them. More specifically, as follows from the moments of inertia, the 0^+ states have different intrinsic structures, which is in contradiction with the predictions of both the IBM

(predominantly octupole bands) and the QPM (predominantly quadrupole bands). A remarkable feature of the QPM is the prediction of strong first vibrational excitations close in magnitude and position to the experimental ones. The numbers of 2^+ and 4^+ states are underestimated by both theories. Spectroscopic factors from the (p, t) reaction, and the trend in their change with the excitation energy, are approximately reproduced by the QPM for the 0^+ and 2^+ states and overestimated by theory for the 4^+ states. The lack of additional information does not allow for final conclusions on the validity of the theoretical approaches. Therefore we hope that our new data will stimulate further experimental and theoretical studies. Accurate experiments and a detailed analysis similar to the present work are desirable for other nuclei in this region. Challenging experiments on gamma spectroscopy following (p, t) reactions would give much needed information.

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КОЛЕКТИВНІ СТАНИ В ^{230}Th: СТРУКТУРА СМУГ

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Виконано аналіз експериментальних даних для збуджених станів у ядрі ^{230}Th, одержаних у реакції (p, t). Виявлено послідовності станів, що можуть трактуватись як ротаційні смуги та як мультиплети збуджень. Експериментальні дані порівнюються з розрахунками в рамках моделі взаємодіючих бозонів та квазічастинково-фононної моделі.

Ключові слова: колективні смуги, моменти інерції, модель взаємодіючих бозонів, квазічастинково-фононна модель.

КОЛЛЕКТИВНЫЕ СОСТОЯНИЯ В ^{230}Th: СТРУКТУРА ПОЛОС

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Выполнен анализ экспериментальных данных для возбужденных состояний в ядре ^{230}Th, полученных в реакции (p, t). Обнаружены последовательности состояний, которые могут трактоваться как ротационные полосы и как мультиплеты возбуждений. Выполнено сравнение экспериментальных данных с расчетами в рамках модели взаимодействующих бозонов и квазичастично-фононной модели.

Ключевые слова: коллективные полосы, моменты инерции, модель взаимодействующих бозонов, квазичастично-фононная модель.

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