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A.L.Komov, L.A.Malov, V.G.Soloviev, V.V.Voronov

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The semi-microscopic approach allowing one to take into account the contribution of the vibrational and rotational motions has been suggested [1-6] for the calculation of the level density. The calculations of the level density for nuclei in the region $50 \leq A \leq 202$ have been performed. The investigations showed that the collective modes of the nuclear motion affect essentially the level density. Thus, they should be taken into account to describe the level density correctly. The aim of the present paper is to calculate the level density near the neutron binding energy B_n in the region $230 \leq A < 254$ and to investigate the dependence of the level density on the excitation energy. The nuclei of the considered region are rather intensively investigated experimentally.

In the semi-microscopic approach the average spacing between the levels D with the given values of the angular moment projection onto the symmetry axis of the nucleus K and parity π in some energy interval $\Delta\xi$ is obtained by a direct calculation of the number of states in the given interval $\Delta\xi$. The semi-microscopic approach for the calculation of the level density is described in papers [1-5]. The equations for the energies of quasiparticle and vibrational states and the methods of their solution are given in the monograph [7]. To take into account the rotation, the rotational band with the excitation energy

$$E_{rot} = \frac{1}{2J}[\,I(I+1) - K^2\,] \qquad (1)$$

is constructed on each state with the given values of K^π.

The level density at the excitation energy $\tilde{\varepsilon}$ for the states with spin I and parity π are calculated by the formula:

$$\rho(\tilde{\varepsilon}, I^{\pi}) = \sum_{K=K_0}^{I} \rho(\tilde{\varepsilon} - E_{rot}, K^{\pi}), \qquad (2)$$

where K_0 is the minimal value of K contributing to the state with the given spin. The value of the moment of inertia is usually taken to be equal to the rigid rotation moment of inertia J_{rig} as the level density with low spins depends weakly on the value of the moment of inertia/5,6/. When calculating the wave functions and single-particle energies we have used the Saxon-Woods potential. The potential parameters, the pairing constants and the equilibrium deformation parameters are the same as in ref./8/. All these quantities are fixed in the study of the low-lying states of deformed nuclei, and there is no free parameter when calculating the level density.

The calculation results of the level density at the neutron binding energy B_n and the corresponding experimental data taken from refs./9,10/ are given in the *Table*. We give the calculation results only for those nuclei for which there are the experimental data. For most of the nuclei the calculation results are in good agreement with the experiment. For the isotopes of americium and curium this agreement is less satisfactory.

As is known the statistical methods are widely used in the calculations of the level density/9,11,12/. In refs./9,11/ in the considered region of nuclei the level density near B_n was calculated by means of the statistical methods taking account of rotation. The obtained results describe better the corresponding experimental data than those in ref./11/. On the average the agreement of our calculations with the experimental data is the same as of the calculations/9/ without the account of the vibrational motion. It should be noted that the calculated level density is larger than the experimental one in ^{239}Pu, ^{243}Am and ^{246}Cm as in ref./9/, though in this paper the calculations have been performed with the single-particle energies of the Nilsson potential.

Table. The experimental and calculated values of the average spacing between the levels $\mathcal{D}$ at the neutron binding energy B_n.

compound nucleus	B_n MeV	I^π	D, eV	
			experiment	calculation
^{230}Th	6,79	$2^+,3^+$	0,6	0,7
^{231}Th	5,12	$1/2^+$	11,0	18
^{233}Th	4,79	$1/2^+$	16,7	22,5
^{232}Pa	5,56	$1^-,2^-$	0,44	0,7
^{234}Pa	5,20	$1^-,2^-$	0,8	0,9
^{233}U	5,74	$1/2^+$	4,2	5,9
^{234}U	6,84	$2^+,3^+$	0,61	0,83
^{235}U	5,31	$1/2^+$	12,3	11,4
^{236}U	6,47	$3^-,4^-$	0,67	0,6
^{237}U	5,12	$1/2^+$	15,4	9,1
^{238}U	6,14	$0^+,1^+$	2,5	6,5
^{239}U	4,78	$1/2^+$	20,8	20,6
^{238}Np	5,48	$2^+,3^+$	0,72	0,9
^{239}Pu	5,40	$1/2^+$	9,5	6,0
^{240}Pu	6,53	$0^+,1^+$	2,3	2,1
^{241}Pu	5,24	$1/2^+$	12,5	10,0
^{242}Pu	6,30	$2^+,3^+$	1,2	1,2
^{243}Pu	5,04	$1/2^+$	15	22,9
^{242}Am	5,53	$2^-,3^-$	0,58	0,2
^{243}Am	6,38	$9/2^-,11/2^-$	0,6	0,3
^{244}Am	5,36	$2^-,3^-$	0,67	0,25
^{245}Cm	5,69	$1/2^+$	12,6	6,3
^{246}Cm	6,45	$3^+,4^+$	1,5	1,0
^{247}Cm	5,16	$1/2^+$	38	13
^{248}Cm	6,21	$4^+,5^+$	1,33	0,8
^{249}Cm	4,71	$1/2^+$	35	56
^{253}Cf	4,79	$1/2^+$	16	20,8

The available experimental data on the nuclear level density cover only two regions of nuclear excitation energy, namely the region of low-lying states and that of neutron resonances. The experimental data on the energy dependence of density are rather fragmentary though they may serve as a good test for any theory of the description of the level density.

The energy dependence for the total level density in ^{230}Th obtained experimentally is given in ref. /13/. Knowing the density for the given values of I^{π} one can easily calculate the total density

$$\rho(\mathcal{E}) = \sum_{\pi, I} \sum_{K=K_0}^{I} \rho(\mathcal{E} - E_{rot}, K^{\pi}) = 2 \sum_{I,K} \rho(\mathcal{E} - E_{rot}, K^{\pi}) . \qquad (3)$$

The factor 2 is due to the assumption on the equality of the level densities with different parity which is correct for the deformed nuclei /3/. When calculating $\rho(\mathcal{E})$ the summation over I has been performed up to the value $I_{max} = 16$. This makes it possible to take into account the contribution of all partial densities $\rho(\mathcal{E}, I)$, as even for $I \geq 12$ the density $\rho(\mathcal{E}, I)$ decreases sharply /5/ and gives no considerable contribution to $\rho(\mathcal{E})$. Our calculation results are given in *fig. 1*. It is seen from the figure that in the low-lying region the use of the rigid rotation moment of inertia results in overestimate of the level densities. If the moment of inertia is taken to be equal to J_{cr} obtained by means of the cranking model with the account of pairing /7/, one obtains a good description of the experimental data. The value of the total density depends on the moment of inertia, since the partial densities $\rho(\mathcal{E}, I)$ for $I > 7$ when changing the moment of inertia by a factor of two may be changed by a factor of 1.5-3. This dependence in $\rho(\mathcal{E})$ is weaker than in $\rho(\mathcal{E}, I)$ (formula (2)) due to the fact that about 50% of the value $\rho(\mathcal{E})$ is exhausted by the partial densities with the small values of the spin $I \leq 5$. *Figure 1* also shows the energy dependence of the total level density calculated with the same single-particle spectrum by the statistical model /12/ with the program taken from ref. /14/. The difference is due to the fact that in the given version of the statistical model

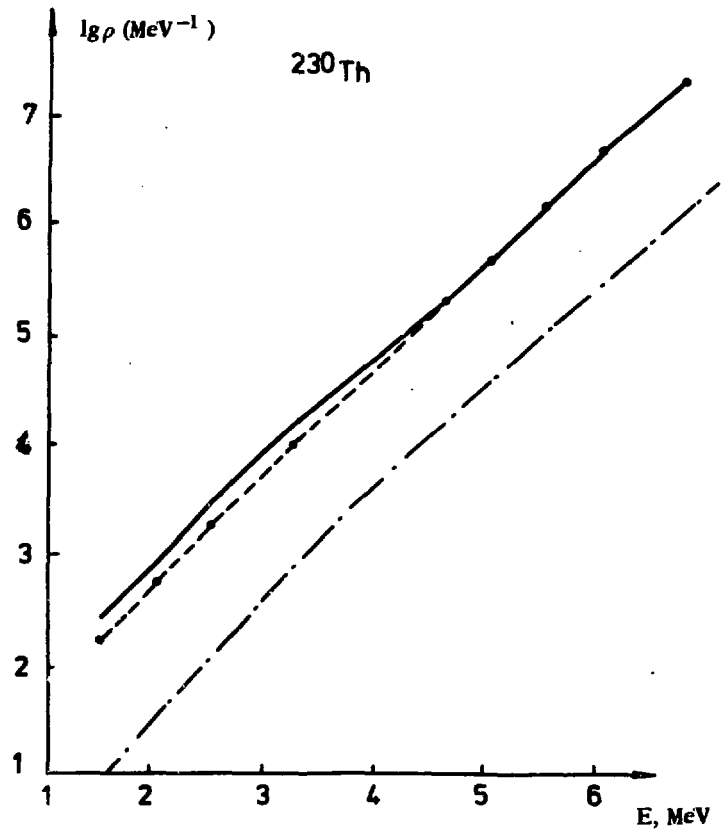

Fig. 1. The total level density in ^{230}Th *as a function of the excitation energy; circles represent the experimental values from ref.* /13/, *the continuous line represents our calculations with* $J = J_{rig}$; *the dashed line represents our calculations with* $J = J_{cr}$; *the detdash line represents our calculation by means of the statistical model with the program from ref.* /14/.

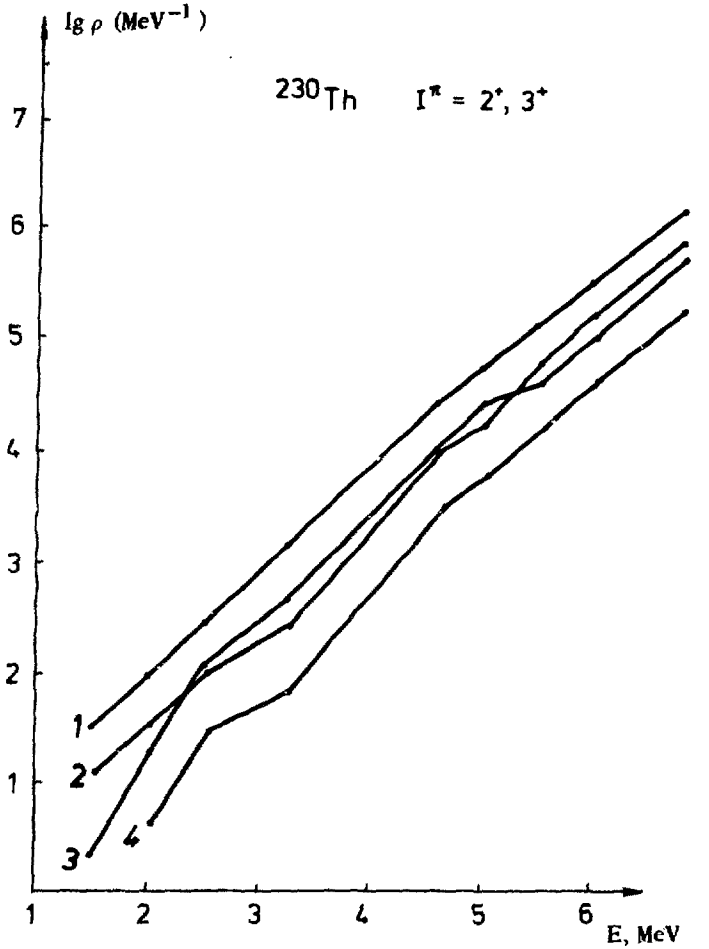

Fig. 2. The total density of states with $I^{\pi} = 2^{+}, 3^{+}$ *in* ^{230}Th. *The calculation results. 1 - with the account of vibrational and rotational motions; 2 - without the account of the vibrational motion; 3 - without the account of rotational motion; 4 - without the account of vibrational and rotational motions.*

the contribution of collective motions is not taken into account. To what extent the contribution of vibrational and rotational motions is essential one can see from *fig. 2* for the energy dependence of the density $\rho(\mathcal{E}, 2^+, 3^+)$ of states with $I^\pi = 2^+, 3^+$ in ^{230}Th. The account of the vibrational motion results in the increase of the density by a factor of 3 on the energy interval from 2 to 7 *MeV*. Approximately such an increase of the density provides the account of rotation.

The present calculations show that the calculations by means of the semi-microscopic method give a satisfactory description of the experimental data on the nuclear level density at the binding energy and provide correctly the energy dependence of the total level densities.

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