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DEPENDENCE OF THE $1/2^+$ STATE DENSITY NEAR THE NEUTRON BINDING ENERGY ON THE MASS NUMBER

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With increasing excitation energy of the atomic nucleus the density of the states increases and their structure becomes more complicated. The state density in medium and heavy nuclei near the neutron binding energy B_n is very large. Great success in the description of the density of highly excited states is due to the use of the statistical methods on the basis of the superfluid nuclear model /1/. The state density near B_n depends strongly on the mass number A. The A-dependence of the experimental values of the $1/2^+$ state density is well demonstrated in ref. /2/.

In the present paper the semi-microscopic approach is used to calculate the average spacing D between the $I^\pi = 1/2^+$ states in spherical and deformed nuclei in the region $139 \leq A \leq 205$ for the neutron binding energy B_n and at an energy $E = 6.5$ MeV, and the A-dependence of the spacing D is analysed.

In ref. /3/ a model is suggested for the description of the structure of states of intermediate excitation energy and of highly excited states in odd-mass deformed nuclei which is based on the account of the quasi-particle-phonon interaction. In ref. /4/ this model is generalized to the case when in deformed nuclei in addition to the multipole-multipole forces account is also taken of the spin-multipole- spin-multipole forces. In ref. /5/ a model is considered which is used for the description of the state structure in odd-mass spherical nuclei. In refs. /3-5/ it is shown that the number of states with given I^π in spherical nucleus or with given K^π in a deformed nucleus is equal to the sum of the poles of the following type

$$\epsilon(\nu) + \omega_{g},$$

$$\epsilon(\nu) + \omega_{g_1} + \omega_{g_2},$$

$$\epsilon(\nu) + \omega_{g_1} + \omega_{g_2} + \omega_{g_3},$$

$$\epsilon(\nu) + \omega_{g_1} + \omega_{g_2} + \omega_{g_3} + \omega_{g_4}, \qquad (1)$$

The number of states is equal to the number of poles of the type quasiparticle plus one, two, three and more phonons. In formula (1) the following notation is used: $\epsilon(\nu)=\sqrt{C^2+(E(\nu)-\lambda)^2}$ - the one-quasiparticle state energy, where C is the correlation function, λ - the chemical potential, $E(\nu)$ -the single-particle energy for the state ν; ω_g - the phonon energy, and g is equal to $\lambda\mu i$, $\lambda\mu$ is the phonon moment and its projection, i is the number of the root of the secular equation for one-phonon states [6].

In the present paper, just as in refs. [3-5], using the phonon operators we describe not only collective vibrational states but all the states with given I^{π} or K^{π}. The wave functions of many states with $\lambda > 3$ are close to the wave functions of two-quasiparticle states. in the calculations a wide configurational space has to be used. Therefore in the case of deformed nuclei we take into account multipole phonons with λ ranging from 2 and 7. In the case of spherical nuclei we take into consideration multipole and spin-multipole phonons with λ from 1 to 9 and pairing-vibrational phonons.

In the calculations use is made of the single-particle energies and the wave functions of the Saxon-Woods potential computed for deformed nuclei in ref. [7] and for spherical nuclei in ref. [8]. The constants of the interactions leading to pairing superconducting correlations and the ones of multipole-multipole interactions are taken from refs. [7-9]. The constants of multipole-multipole interaction with $\lambda > 3$ and spin-multipole - spin-multipole interaction do not noticeably affect the state density since the wave functions of such one-phonon states are close to those for two-qiasuparticle ones. In the secular

equation for the energy of the phonons of each multipolarity all the roots are calculated up to (6.5 - 7.0 MeV) excitations. After the quantities $\epsilon(\nu)$ and ω_g have been found for each nucleus the expressions of the type (1) are calculated. In all the cases the fundamental poles quasiparticle puls one, two, three and four phonons are taken into consideration. For some nuclei account is also taken of the poles quasiparticle plus five phonons. This is done so as to exhaust practically all the fundamental poles being present in a given nucleus up to B_n and 6.5. MeV.

The calculations of the average spacing between the $I^\pi = 1/2^+$ levels are performed as follows: in a given energy range from E to $E+\Delta E$ the number of fundamental poles quasiparticle plus one, two and more phonons is calculated, the summation of them results in the total number of poles by which the energy interval ΔE is divided. For example, in ^{157}Gd in the interval of 10 keV near B_n = 6.347 MeV there is the following number of the $1/2^+$ poles:

$$\begin{aligned}
&\epsilon(\nu) + \omega_g && - 8\\
&\epsilon(\nu) + \omega_{g_1} + \omega_{g_2} && - 135\\
&\epsilon(\nu) + \omega_{g_1} + \omega_{g_2} + \omega_{g_3} && - 81\\
&\epsilon(\nu) + \omega_{g_1} + \omega_{g_2} + \omega_{g_3} + \omega_{g_4} && - 17
\end{aligned} \qquad (2)$$

a total of 241 poles, therefore D = 41.5 eV. It is seen from (2) that the main fraction is the poles quasiparticle plus two and three phonons.

The calculations of this type were first performed in ref. /3/ for the ^{239}U states. These calculations have two merits compared with those of ref. /1/ the account of the collective states and direct calculation of the number of states without recourse to the methods of statistical physics.

The results of calculation of the average spacing D between the $I^\pi = 1/2^+$ states at excitation equal to the neutron binding energy and the corresponding experimental

data are given in table. There are also given the values of the parameter a calculated by the well-known formula for the level density

$$\rho = \frac{\sqrt{\pi}}{12} \cdot \frac{exp\{2\sqrt{aU_{eff}}\}}{a^{1/4} U_{eff}^{5/4}} \cdot \frac{(2j+1) exp\{-(j+1/2)^2/2\sigma^2\}}{2\sqrt{2\pi}\,\sigma^3}, \quad (3)$$

where $\sigma^2 = \frac{6}{\pi^2} <m^2> (aU_{eff})^{1/2}$, $<m^2>$ the average squared projection of the momentum near the Fermi surface, $U_{eff} = U - \delta_p$, U - excitation energy, δ_p pairing energy for protons. The a parameters in (3) are taken from ref. /16/.

It is seen from the table that in spherical nuclei with $A \leq 150$ the calculated D values for the $I^\pi = 1/2^+$ state for $E = B_n$ is by about an order of magnitude larger than the corresponding experimental values. The largest discrepancy occurs for the nuclei of the transition region ^{149}Nd and ^{149}Sm. This should just be expected since the calculation for them was carried out in the same manner as for the spherical nuclei. The softness of the nuclei of the transition region is the cause of the broad spectrum of excited states with different equilibrium deformations.

For deformed nuclei there is a very good agreement between the calculated and experimental values of D. The exception is ^{173}Yb and ^{175}Yb, where disagreement reaches 50%.

For the spherical nucleus ^{199}Hg there is observed rather good agreement between theory and experiment. However for ^{201}Hg, ^{203}Hg and ^{205}Pb calculations do not yield such a sharp increase of the D value that is observed in experiment.

The neutron binding energies B_n for different nuclei assume different values which makes it difficult to clarify the dependence of D on A. Therefore, in just the same way as in ref. /2/, the calculations of the average spacing D between the $1/2^+$ levels for all nuclei are carried out at 6.5 MeV energy. The corresponding experimental data are recalculated by the formula (3) for the energy

6.5 MeV. In Fig. 1 the recalculated experimental data for D are compared with the results of calculation at $E = 6.5$ MeV. It is seen from the figure that the theory well describes the strong increase of D in the transition from deformed nuclei to spherical ones and the increase of D as approaching to magic nuclei. For spherical nuclei with $A < 150$ the calculated values lie much above the D -values recalculated from the experimental data. This disagreement at $E = 6.5$ MeV is somewhat larger as compared with the case $E = B_n$.

In deformed nuclei there is good agreement between the calculated and the extracted from experiment D -values at $E = 6.5$ MeV. The calculations assert that the density of highly excited states is a function of the single-particle state density near the Fermi surface energy.

Figure 2 gives the values of the parameter a calculated by the formula (3) from the experimental values of the $1/2^+$ state density and the calculated values for $E = B_n$. The a values extracted from the calculations are seen to lie everywhere below the a values obtained from the experimental data, but correctly describe the general A-dependence of a.

Thus, the account of the shell and collective vibrational state effects made it possible to obtain a rather good description of the excited $1/2^+$ state density at the neutron binding energy B_n and describe the A -dependence of the average spacing between the $1/2^+$ levels at the energy 6.5 MeV.

Calculations of the state density in the framework of the method presented here continue . The dependence of the state density on the excitation energy, the angular momentum I in spherical nuclei and on the projection K in deformed nuclei is being studied. The role of the collective states in the description of the state density and other related problems are being investigated. The results of this studies will be published in the nearest time.

It should be noted that the structure of highly excited states is very complicated and they cannot be described in the framework of the simple model which is employed

for the calculation of state density. For the highly excited state structure of importance is the fragmentation process, i.e. the distribution of the single-particle state strength over many nuclear levels, which was presented in outline in ref. /17/.

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Fig. 1. The average spacing D between the $l^{\pi} = 1/2^{+}$ levels at an excitation energy $E = 6.5$ MeV. Notation: the continuous curve is the calculation; the dashed curve is the recalculation of the experimental data.

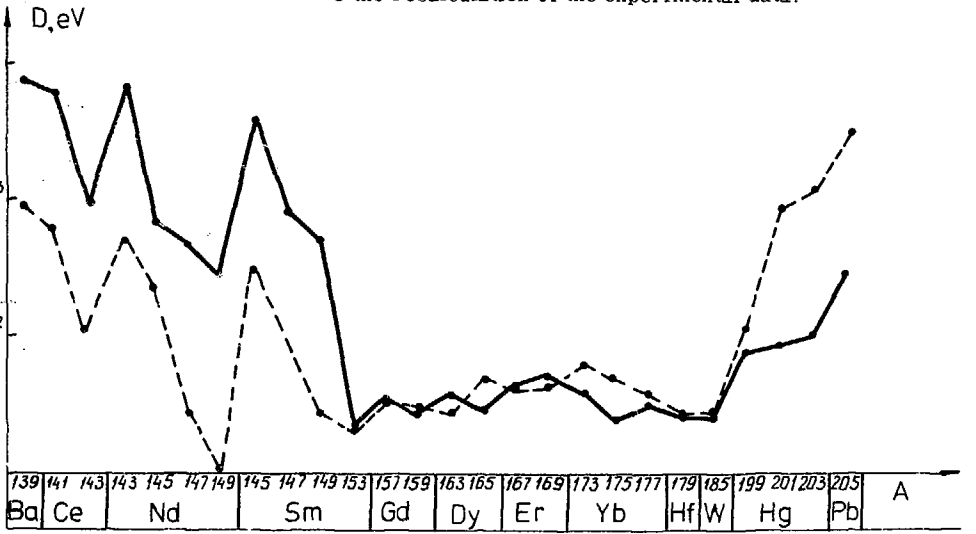
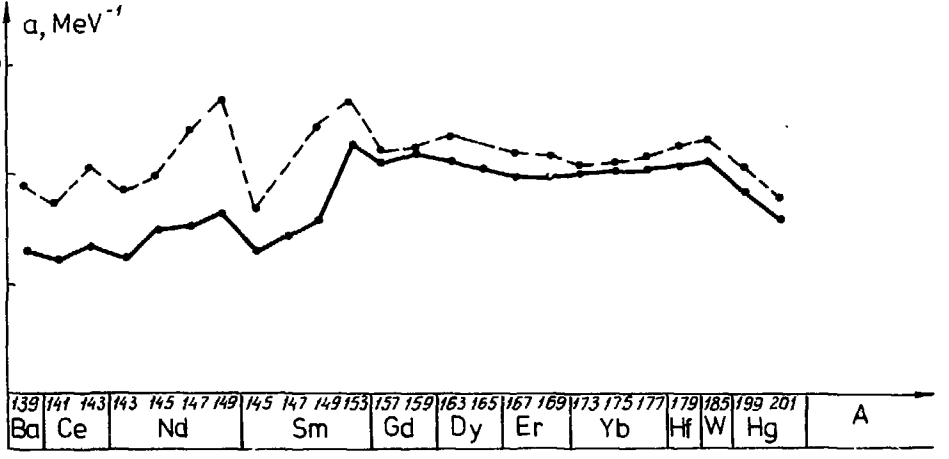


Fig. 2. The parameter a as a function of the mass number A. Notation: The continuous curve is the a values, obtained by the formula (3) from the calculated density at $E - B_n$; the dashed curve is the a values obtained by the formula (3) from the experimental data.



Table

Experimental and calculated values of the average spacing D between $1/2^+$ levels and the parameter a at the neutron binding energy B_n

Compound nucleus	B_n MeV	Experiment D, eV	Experiment a, MeV^{-1}	Ref.	Theory D, eV	Theory a, MeV^{-1}
^{139}Ba	4.720	$(9.6\pm3.4).10^3$	19.33	10	43.10^3	13.1
^{141}Ce	5.438	$(3\pm1.0).10^3$	17.8	10	$18.7.10^3$	11.8
^{143}Ce	5.113	$(1.0\pm0.2).10^3$	21.31	10	$12.5.10^3$	13.5
^{143}Nd	6.100	$(1.0\pm0.25).10^3$	18.5	11	$7.7.10^3$	12
^{145}Nd	5.970	520 ± 70	19.4	11	$1.95.10^3$	19
^{147}Nd	5.140	310 ± 43	24.4	11	$5.5.10^3$	15.3
^{149}Nd	4.940	200 ± 21	26.9	11	$2.2.10^3$	16.4
^{145}Sm	6.900	200 ± 40	18.5	11	$2.0.10^3$	12.8
^{149}Sm	5.860	90 ± 15	24.4	11	$1.66.10^3$	15.8
^{153}Sm	5.886	5.8 ± 1.5		12	63	22.3
^{157}Gd	6.347	47 ± 4	22.8	11	42	20.8
^{159}Gd	5.942	85 ± 9	22.2	11	67	22
^{163}Dy	6.253	42 ± 6	23.46	10	56	21
^{165}Dy	5.715	200 ± 38		13	133	21.1
^{167}Er	6.438	38.4 ± 0.32		14	57	19.3
^{169}Er	5.997	95.3 ± 1.7		14	117	19.4
^{173}Yb	6.480	70.3 ± 2.6		15	41	20.3
^{175}Yb	5.830	162 ± 18		15	110	20.4
^{177}Yb	5.530	185 ± 19		15	161	20.6
^{179}Hf	6.070	55 ± 8	23.05	10	58	20.8
^{185}W	5.748	93 ± 19	23.56	10	78	21.3
^{199}Hg	6.653	100 ± 30	21.32	10	84	18.3
^{201}Hg	6.227	$(1.3\pm0.1).10^3$	17.93	10	112	16.3
^{203}Hg	5.987	$2.4.10^3$		2	163	
^{205}Pb	6.730	$(2.8\pm0.7).10^3$		2	200	