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ROTATION EFFECT ON THE LEVEL DENSITY OF DEFORMED NUCLEI

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In the study of the model for describing the structure of intermediate and highly excited states [1] a direct and relatively simple method has been suggested for the calculation of the level density at different excitation energy and different spins.

This method has then been used in ref. [2] to calculate the $1/2^+$ state density at the neutron binding energy B_n and at 6.5 MeV energy, as well as to investigate the A-dependence of the level density. In ref. [3] the level density has been calculated for spherical nuclei at different spins and energies.

In ref. [4] density for states with fixed $I^{\pi} = K^{\pi}$ has been calculated near B_n and the dependence of the density on the excitation energy and the K angular momentum projection has been studied. In paper [4] the contribution of rotational excitations to the level density has been disregarded and therefore for the levels with $I \geq 1$ the calculated value of the density is smaller than the experimental one. A rough acoount of the rotational motion makes the description of the density of the states with $I \geq 1$ better. Recently much attention [5] has been devoted to the effect of the rotational motion on the excited state density, therefore we find useful to pubsish the results of our calculations on the density of states with $I \geq 1$ in which the rotational motion is roughly taken into account.

In the present paper we investigate the effect of the rotational motion on the excited state density and consider the spin dependence of the density in deformed nuclei.

The average value of D between the levels with fixed $I^{\pi} = K^{\pi}$ is calculated in the following manner: in a given energy interval we calculate the number of the states of the type

$$\omega_{g_1} + \omega_{g_2} + \dots \qquad (1)$$

in doubly even nuclei and of the type

$$\varepsilon(\nu) + \omega_{g_1} + \omega_{g_2} - \mathcal{E}_0(\nu_0) \qquad (2)$$

in odd-A nuclei and find the average spacing D between these states. Here ω_g is the phonon energy, $g = \lambda\mu j$, $\lambda\mu$ are the multipolarity and its projection, j is the number of the root of the secular equation for the phonon, $\varepsilon(\nu)$ the quasiparticle energy, $\mathcal{E}_0(\nu_0)$ the ground-state energy of an odd-A nucleus. In the calculations the single-particle energies and the wave functions of the Saxon-Woods potential are used. The pairing constants and the multipole-multipole force constants and the equilibrium deformation parameters are the same as in ref./4/. All these quantities are fixed in the study of the low-lying states of deformed nuclei.

Satisfactory experimental data on the level density are obtained near B_n . Therefore we give the results of calculations obtained at the neutron binding energy. If the target-nucleus spin I_0 is different from zero then one measures the total density of the S -wave neutron resonances with spins $I_0 \pm 1/2$. Therefore we calculate the average D according to the formula:

$$D(\mathcal{E}, I_o \pm 1/2) = \{\rho(\mathcal{E}, I_o - 1/2) + \rho(\mathcal{E}, I_o + 1/2)\}^{-1} . \qquad (3)$$

Strictly speaking, it is unknown how the rotation of a nucleus in the highly excited state proceeds. However, we make use of the usual formula for the rotational motion energy

$$E_{rot} = \frac{1}{2\mathcal{J}}[I(I+1) - K^2] . \qquad (4)$$

In the calculations of the level density by means of statistical methods (see refs.[6,7]) one often uses the rigid rotation moment of inertia $\mathcal{J}_{rig} = \frac{2}{5} m A R^2$. If we take into account the rotational motion, following (4), then the level density at an excitation energy with a fixed I^{π} is

$$\rho(\mathcal{E}, I^{\pi}) = \sum_{K=K_o}^{I} (1 - \delta_{K,0} \cdot \delta_{\pi,(-1)^{I+1}}) \rho(\mathcal{E} - \frac{1}{2\mathcal{J}}[I(I+1) - K^2], K^{\pi}) , \qquad (5)$$

where K_o is zero or 1/2. In ref.[5] the following approximate expression for the level density

$$\rho(\mathcal{E}, I_o \pm 1/2) \approx \rho(\mathcal{E}, I=K) \cdot (I_o + 1/2) \qquad (6)$$

is suggested.

We have tabulated the experimental data and the following results of calculations of the average spacing D between the levels at $\mathcal{E} = B_n$:

i) without the account of the rotational motion at $I=K$ ii) with the account of the rotational motion by the formula (5) with the rigid rotation moment of inertia, iii) with the

Table

The average spacing D between the levels with given I^{π} for $I \geq 1$ calculated with and without the account of the rotational motion

Compound nucleus	B_n, MeV	I^{π}	D, ev Exp.	D ev, for $I=K$	Calculation with the account of the rot. lev. by eq.(5)	eq.(6)
^{156}Gd	8.527	$1^-, 2^-$	1.99 ± 0.32	3.5	2.0	1.8
^{158}Gd	7.929	$1^-, 2^-$	6.3 ± 0.6	8.7	4.8	4.4
^{162}Dy	8.204	$2^+, 3^+$	2.55 ± 0.38	11.1	3.9	3.7
^{164}Dy	7.657	$2^-, 3^-$	9.6 ± 1.6	19.6	11.8	6.5
^{168}Er	7.770	$3^+, 4^+$	4.0 ± 0.4	26.6	7.2	6.7
^{174}Yb	7.440	$2^-, 3^-$	7.81 ± 0.93	13.6	6.5	4.5
^{177}Lu	6.890	$13/2^-, 15/2^-$	2.37 ± 0.27	14.5	2.1	1.9
^{178}Hf	7.620	$3^-, 4^-$	3.2 ± 0.2	11.1	3.1	2.8
^{180}Hf	7.330	$4^+, 5^+$	5.8 ± 0.5	18	4.5	3.6
^{182}Ta	7.640	$15/2^+, 17/2^+$	1.5	4.1	0.8	0.5
^{236}U	6.467	$3^-, 4^-$	0.67 ± 0.13	1.4	0.6	0.4
^{244}Cm	6.720	$2^+, 3^+$	-	2.2	0.9	0.7

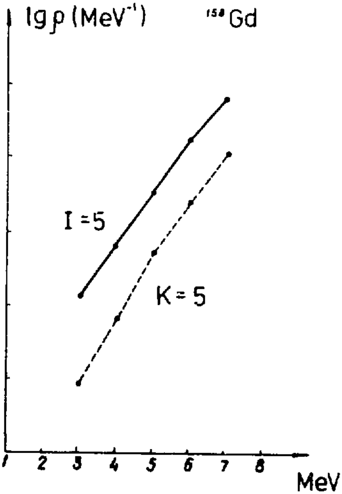

Fig. 1. The $\mathcal{E}$-dependence of ρ for the states with $I^{\pi} = 5^{-}$ (continuous curve) and with $I^{\pi} = K^{\pi} = 5^{-}$ (dashed curve) in ^{158}Gd

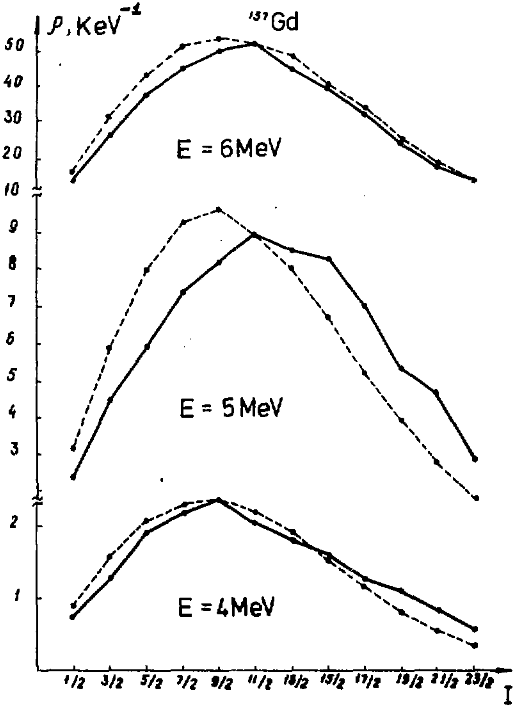

Fig. 2. The I-dependence of ρ for the states with positive parity in ^{151}Gd. The plot represented by the continuous line is obtained by eq.(5). The plot represented by the dashed line is obtained by eq.(7).

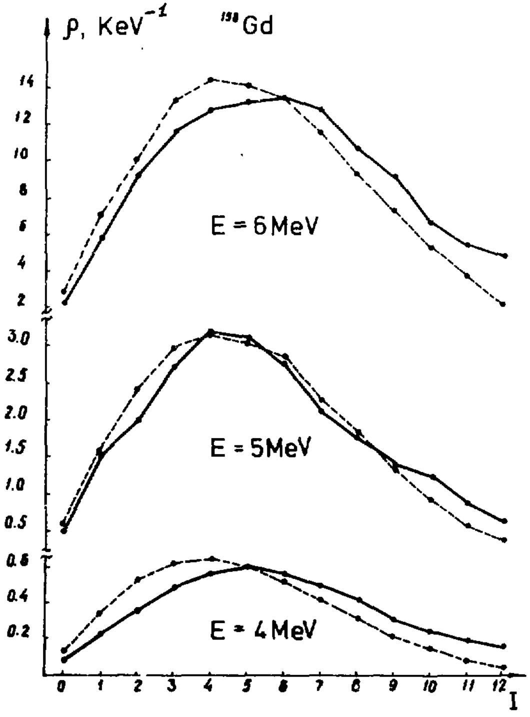

Fig. 3. The I-dependence of ρ for the states with negative parity in ^{158}Gd. The plot represented by the continuous curve is obtained by eq.(5).
The plot represented by the dashed curve is obtained by eq.(7).

account of the rotational motion by the formula (6). The experimental data are taken from the same papers as in ref.[4]. It is seen from the table that accounting for the rotational motion has resulted in a noticeably better agreement of the results of calculations with experiment, especially for states with high spins. The difference between the semi-microscopic calculations by eq.(5) and more qualitative calculations by eq.(6) is nonessential. If the moment of inertia is taken to be half the rigid rotation one then, according to the calculations by eq.(5), the density at $\mathcal{E}=B_n$ decreases by less than 10%. For the $I=5$ states at $\mathcal{E}=4$ MeV the decrease of the level density by 20%, etc.

Thus, the account of the vibrational and rotational motions leads to a good description of the nuclear level density of deformed nuclei at the neutron binding energy B_n.

Let us study how the excitation energy dependence of the level density changes when the rotational motion is taken into account by eq.(5) compared with the density at $I=K$. Fig.1 gives the behaviour of the density for the $I^{\pi}=5^-$ states in ^{158}Gd calculated by eq.(5) and the density of the $I^{\pi}=K^{\pi}=5^-$ states. These curves are seen to be shifted with respect to each other by about a constant value. They confirm the validity of eq.(6).

We investigate the spin dependence of the level density at different excitation energy. Figs.2 and 3 give the spin dependence for ^{157}Gd and ^{158}Gd at an energy 4,5 and 6 MeV calculated by eq.(5). Comparing the spin I dependence given in

Figs.2 and 3 and the K dependence given in Figs.6 and 7 in ref.[4] we see that $\rho(I)$ essentially differs from $\rho(I=K)$. Figs.2 and 3 give the spin dependence calculated by the formula

$$\rho(\mathcal{E}, I) = \frac{2I+1}{2\sqrt{2\pi}\,\sigma^3}\,\rho(U)\exp\left\{-\frac{I(I+1)}{2\sigma^2}\right\} \tag{7}$$

with the values

$$\sigma^2 = 8{,}88\cdot 10^{-2}(aU)^{1/2}A^{2/3}$$

corresponding to the choice of the rigid rotation moment of inertia, where U the excitation energy minus the pairing energy. The parameter a was chosen such that the densities calculated by eqs.(5) and (7) coincide at the maximum of the curves calculated by eq.(5). It is seen from these figures that the semi-microscopic calculations taking into account the vibrational and rotational motion give the spin dependence close to that which is obtained by the statistical model.

It should be noted that in the semi-microscopic description of the excited level density there is not a single free parameter, since all the parameter were fixed earlier in studying the low-lying states of deformed nuclei.

The semi-microscopic calculations taking into account the vibrational and rotational motions give a good description of the density of states with different spins at the neutron binding energy B_n in deformed nuclei. They lead practically to the same spin dependence which follows from the statistical model.

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