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NUCLEAR LEVEL DENSITY AT A=110-125

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Abstract: The analysis of (p,n)-reaction neutron evaporation spectra and neutron resonance density in the range A=110-125 using a generalized superfluid model results in a strong dependence of the ground state correlation function Δ_0 and the asymptotic level density parameter $\tilde{a}$ on nucleon composition. Its origin is associated with the effect of the spherical proton shell Z=50 on Δ_0, and the deformed neutron shell N≈66 on $\tilde{a}$.

(nuclear level density, neutron spectra, shell correction)

The advance in the description of excited level density is rather slow regardless of its essential role in practical application of the statistical nuclear reactions theory. The status of this problem is ascertained by major problems in the theory and difficulties in obtaining experimental data on level density. A wide-spread occurrence of empirical and semi-empirical systematics /1-3/ whose parameters are devoid of any definite physical sense is inherent for it. The implementation of more realistic approaches to the level density description for the experimental data analysis is vital in this connection. This can be done with a use of generalized superfluid model (GSM) /4/, consistently taking into account pairing correlations of nucleons and phenomenologically collective growth of level density and shell effects. The model was tested in the description of neutron resonance density and nuclear fission probability in the range A>150 /4,5/, and even a greater number of characteristics in the region A≈50 /6/. This paper is focused on the analysis of experimental data on neutron evaporation spectra (NES) and neutron resonance density (NRD) in the range of nuclei with the average atomic weight A=110-125.

Within the GSM the level density as a function of excitation energy U and angular moment J of the nucleus is expressed by ratio

$$\rho(U,J)=\rho_{in}(U,J)\cdot K_{rot}(U)\cdot K_{vib}(U), \qquad (1)$$

where $\rho_{in}(U,J)$ is a density of inner (guasiparticle) excitations described by the superfluid model with the level density parameter

$$a(U,Z,A)=\begin{cases}\tilde{a}(A)(1+\delta W(Z,A)f(U-E_c)/(U-E_c)) & \text{for } U>U_c\\ a(U_c,Z,A) & \text{for } U\leqslant U_c,\end{cases} \qquad (2)$$

$$\tilde{a}(A)=\alpha_v A+\alpha_s A^{2/3}, \qquad (3)$$

$$f(U-E_c)=1-\exp(-\gamma(U-E_c)), \qquad (4)$$

$$E_c=0.152a_c\Delta_0^2, \quad U_c=0.472a_c\Delta_0^2 , \qquad (5)$$

$$\Delta_0=12A^{-1/2}. \qquad (6)$$

$K_{rot}(U)$ and $K_{vib}(U)$ are the coefficients of rotating and vibrating increase of level density. In ratios (2)-(6) $\tilde{a}$ is an asymptotic value of a(U) (at large U), corresponding to the drop model, δW is a shell correction for the nuclear deformation energy (mass) /7/, $f(U-E_c)$ is a phenomenologically determined function taking into account reconstruction of shells with energy, α_v=0.073, α_s=0.115, γ=0.064 MeV^{-1} are the parameters obtained through adjustment of (1) to the observed values of NRD in the region A>150 /4/, E_c, U_c are a condensation energy and a critical energy of phase transition from the superfluid state ($U\geqslant U_c$) to the normal one ($U>U_c$) for even-even nuclei, Δ_0 is a correlation function of the ground state.

For the level density description within the GSM a rotating coefficient K_{rot} dependence on deformation is essential, which abruptly changes in the adiabatic approximation at the transition from spherical nuclei $K_{rot}=1$ to axial-symmetric deformed ones $K_{rot}=\sigma_{\perp}^{2}=\mathcal{F}_{\perp}t$, where $\mathcal{F}_{\perp}$ is a perpendicular moment of inertia, t is a nuclear temperature. The effect of vibrating coefficient K_{vib} on the level density is less essential /4/.

The systematic analysis of NES within GSM was initiated in /8/. The present work is based on Weisskopf's approximation (like in /8/)

$$N(E_n)=\text{const}\cdot E_n\sigma_c^{*}(E_n,U)\cdot\rho(E^{*}-B_n-E_n,0) \qquad (7)$$

and the experimental data on neutron spectra $N(E_n)$ of (p,n)-reaction /9,10/. In (7) $\sigma_c^{*}(E_n,U)$ is a reverse reaction cross-section taken equal to the compound nucleus formation cross-section $\sigma_c(E_n,0)$, E^{*} is a compound nucleus (A+1,Z+1) excitation energy at the absorption of a proton with the energy E_p by the target nucleus (A,Z), $U=E^{*}-B_n-E_n$ is a residual nucleus (A,Z+1) excitation energy. The subject of analysis was level densities $\rho(U,0)$ constructed according to (7) using the data on $N(E_n,E_p)$ for E_p=6-10 MeV /9/, E_p=7-14 MeV /10/.

When describing the energy dependences $\rho(U,0)$, whose examples are given in Fig.1, the values Δ_0 and $\tilde{a}$ were applied as free parameters. A comparison of the recovered level density with an independent source of information with the known values of NRD also shown in Fig.1 in the form $\rho(B_n,0)$ served as a test. The values Δ_0 and $\tilde{a}$ are defined for 11 residual nuclei: ^{57}Co, ^{94}Nb, ^{107,109}Cd, ^{115}Sn, $^{116-119,122}$Sb, ^{181}W. The dependences of the values $\Delta_0 A^{1/2}$ and $\tilde{a}/A$ as functions of mass number A are shown in Fig.2. All the nuclei except the heaviest one ^{181}W suggested to be spherical according to the available data on the low-lying levels spectra. The curves corresponding to the GSM systematics, i.e. ratios (3) and (6), are shown in

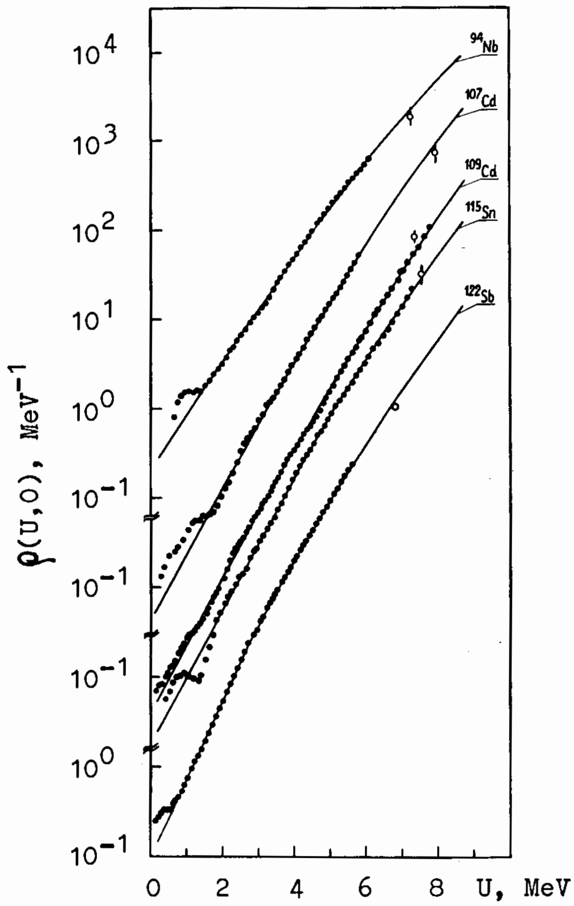

Fig.1. Energy dependence of absolute level density $\rho(U,0)$ for nuclei ^{94}Nb-^{122}Sb. The dots stand for experimental level densities reconstructed from (p,n)-reaction neutron spectra. The solid curves for $\rho(U,0)$ calculation with the parameters $\tilde{a}$ and Δ_0 obtained from analysis of experimental level densities. The circles for $\rho(B_n,0)$ level densities corresponding to the data on neutron resonances.

Fig.2 with dash-dotted lines. The values obtained from the NES for ^{57}Co, ^{94}Nb and ^{181}W are in a satisfactory agreement with (3) and (6), but at the section A=110-125 they systematically deviate from them. This result is not surprising for the parameter Δ_0. The formula (6) giving a global description of a very great amount of data /11/ does not claim the details associated with individual features of nuclei, e.g. their shell structure. The minimum $\Delta_0(A)$ can be seen to be formed by the nuclei close to the filled proton shell Z=50 on the basis of the comparison with solid and dashed

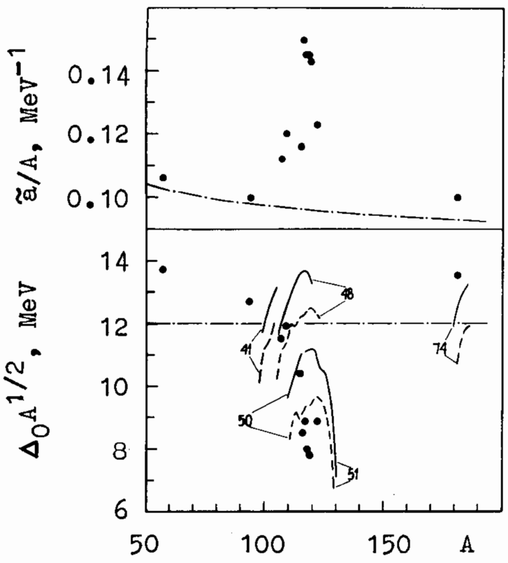

Fig.2. Parameters $\Delta_0 A^{1/2}$ and $\tilde{a}/A$ as functions of the mass number A. The dots stand for evaporation neutron spectra analysis of (p,n)-reaction within the GSM. The dash-dotted curves for behaviour of the parameters $\Delta_0 A^{1/2}$ and $\tilde{a}/A$ to be found according to systematics /4/. The solid (even neutron number), dashed (odd) curves for the results of calculations Δ_0 (8) with Δ_{0N} and Δ_{0Z} from /13/. The numbers denote the changes of nuclei under question.

curves in Fig.2 calculated according to /12/

$$\Delta_0^2=(\Delta_{0N}^2+\Delta_{0Z}^2(Z/N)^{1/3})/(1+(Z/N)^{1/3}). \quad (8)$$

The values Δ_{0N} and Δ_{0Z} have been calculated with a microscopic theory /13/.

The origin of maximum $\tilde{a}(A)$ in Fig.2 is more difficult to understand, primarily due to essential deviations from (3) (or roughly from $\tilde{a}/A$=const) being completely incompatible with the very notion of the asymptotic liquid-drop parameter $\tilde{a}$. In particular, it cannot be related to the incorrect account of shell effects in (2), as far as $\gamma|\delta W(Z, A)| \ll 1$ and $\tilde{a} \approx a$ in the mentioned nuclear range. The maximum $\tilde{a}/A$ observed is detected by diverse data and all the known systematics of the level density parameter, i.e. undependently on the experimental data source and the employed model. Fig.3 illustrates this, representing the a/A parameter values obtained from the

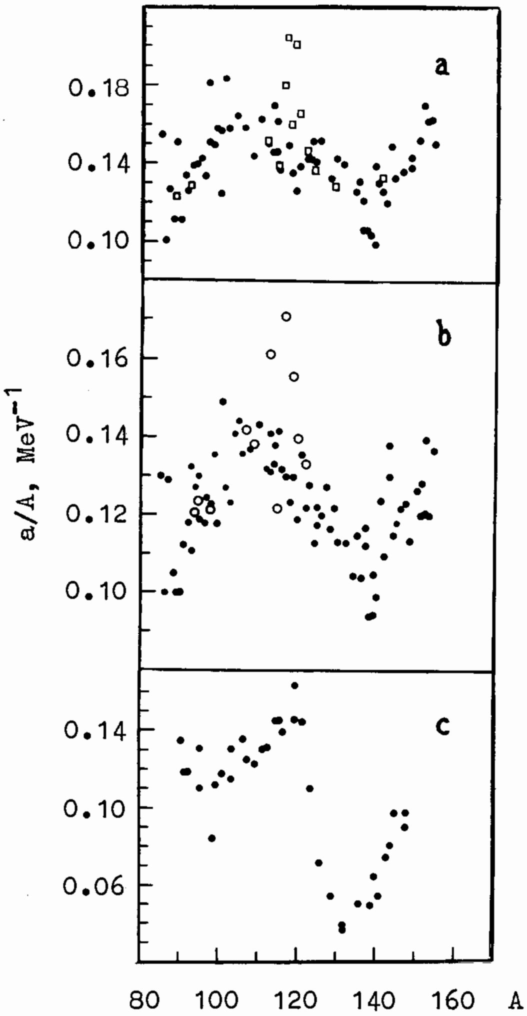

Fig.3. Dependence of a/A on A according to standard Fermi-gas model (a), back-shift Fermi-gas model (b) and data obtained from fission neutron spectra (c). □,○– the results of (p,n)-reaction neutron spectra analysis in /10/ and /9/, respectively.

data on the NRD and NES with a use of a standard Fermi-gas model /2/ and a back-shift Fermi-gas model /3/ as well as from the fission neutron spectrs /14/. It is evident that the reason should be sought in the incompleteness of the applied description of level density common for all the models including the GSM.

Fig.4 shows one of the trends of the search in the discussed anomaly $\tilde{a}(A)$ interpretation, illustrating the values $\tilde{a}/A$ shown against the number of neutrons N obtained with the GSM both from NRD and NES and a portion of the contour map of the neutron shell correction $W(\beta, N)$

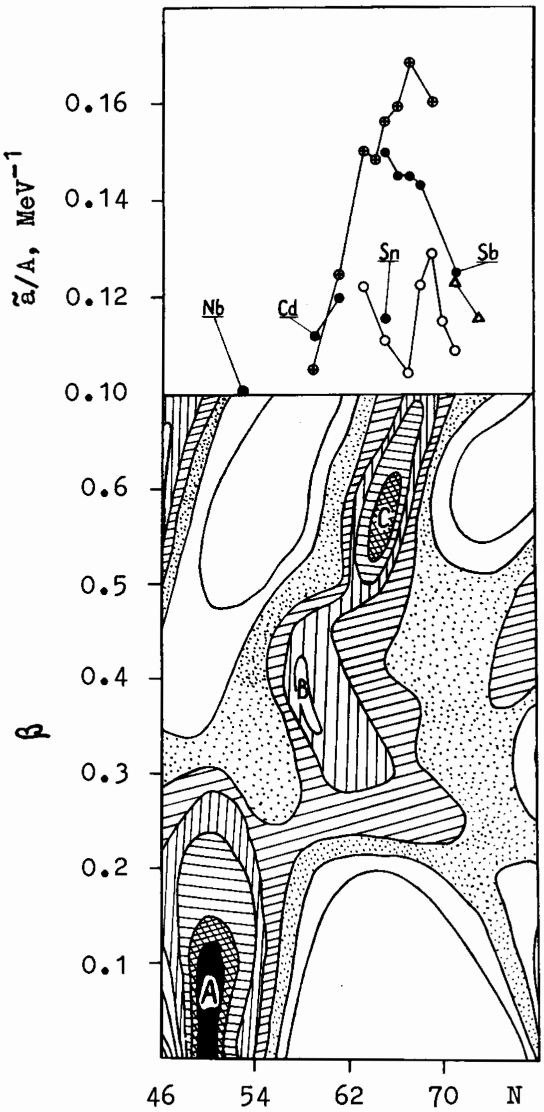

Fig.4. Parameter $\tilde{a}/A$ for isotope-chains in region Z=50 as a function of neutron number N and contour map of the neutron shell correction W(β,N) /15/. The values for nuclei ^{48}Cd(⊕—⊕), ^{50}Sn(○—○), ^{51}Sb(Δ—Δ) are obtained from the data on the observed neutron resonance density, ●- the results of (p,n)-reaction neutron spectra analysis.

from /15/, where β is a parameter of quadrupole deformation. The $\tilde{a}/A$ maximum position can be seen to correspond to a ruther deep minimum W(β,N) with N≈66 and β≈0.57. This feature W(β,N) can result in the formation of the second deformation energy minimum (the first one corresponds to β=0) or to such its variation, that the contribution of deformed states will be predominant with the growth of U (due to the difference in value K_{rot} as compared to the spherical ones). In the analysis performed at a fixed deformation (β=0) this effect would result in the growth of parameter $\tilde{a}$.

The occurrence of "excited deformed shells" and their enhancement as the role of pairing decreases with energy were first discussed by V.M.Strutinsky /16/. The evaluations of the effect on the basis of a particular calculation for ^{116}Sn nucleus in /17/ improve confidence in the suggested interpretation.

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