THE PROBLEMS OF VIBRATIONAL LEVEL DENSITY DETERMINATION BELOW B_n IN THE FRAMEWORK OF THE MODERN MODEL NOTIONS

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Abstract

Development of practical model of neutron resonance cascade gamma-decay for extraction of maximally reliable level density and determination of the available in this case values break-up thresholds of Cooper pairs from the data on the intensities of cascades from two successive gamma-transitions from resonances to final levels with energy E_f <0.5–1 MeV brings to the conclusion on absolute necessity in further development of practical model notions on a nucleus as a system interacting bosons and fermions up to the nucleon binding energy or higher. There was obtained that for the description of the experimental data is necessary to pass from idea of collective enhancement of quasi particle density ρ_n to quite new level density model ρ_{vib} of only vibration level type.

Extraction of level density, for example, from experimental spectra for deformed nuclei below neutron binding energy B_n requires one to develop corresponding models based on some most general notions on nucleus properties. Starting from classic hypothesis on a nucleus as a system of not interacting (not formed Cooper pairs) nucleons, analysis of experiment performed the transition to the idea of presence in a nucleus of phase transition [1] and a necessity to take into account nucleon pairing through the coefficient of vibration enhancement of level density [2]. Existing model notions are enough only for reproduction of the experimental level density derived from the nucleon evaporation spectrum [3] or spectra of the primary gamma-transitions depopulating levels with different excitation energy [4].

But, methods [3,4] have common methodical error – they completely ignore a possibility of any influence of the wave function structure of the excited levels on emission probability of nucleon or gamma-quantum to the final excited level of the reaction nucleus-product. This methodical assumption contradicts to both theory and experiment of the modern generation [5] and brings to overestimation of the desired level density ρ by a factor 5-10 in the region of maximal influence of structure of the excited level on partial width Γ of emission of reaction product [6].

Development of the modern practical model of cascade gamma decay of neutron resonance for extraction of maximally reliable level density and determination of the available in this case break-up thresholds of Cooper pairs from the data on intensities of cascades from two successive gamma-transitions to final levels with energy E_f <0.5–1 MeV brings to undoubted conclusion on absolute necessity of the following development of practical models of a nucleus as a system of interacting bosons and fermions up to the neutron binding energy or higher, id est, necessity to raise models of the experiment up to the level of modern theoretical notions of quasi-particle-phonon nucleus model or model of interacting bosons and fermions.

At present this task can be partially solved by selection of phenomenological notions on the process under study and formulation of requirements to practical models of level density and radiative strength functions. Some practical developments on search for phenomenological relations between the parameters of gamma-decay process (in excitation region from 1-2 MeV to B_n) were for the first time undertaken in [7] and continued in [8].

The necessity in this activity is stipulated by:

a) the absence of level density model of vibration type excitations that includes as the parameter the break thresholds of Cooper pairs;

b) absolute absence of practical model of the strength function of *M*1-transitions for energy interval of gamma-quanta $0 < E_\gamma < B_n$;

c) and necessity to develop the absent up to now models of strength functions of dipole gamma-radiation of both electric and magnetic types for decaying and/or excited levels with mainly vibration wave function.

This conclusion unambiguously follows from the results of model-free determination of level density and radiative strength functions [5, 9] from intensities of cascades from two successive transitions between neutron resonance λ and final level *f* through intermediate one *i* with good enough precision [10]. The maximal value of energy E_f is given in [8], as well as the spectra of cascade intensity in function of energy of their primary transition [11].)

The system of nonlinear equations relating intensities of two step cascades $I_{\gamma\gamma}^{\exp}$ with unknown values of level density and radiative strength functions is degenerated and has infinite number of solutions. However, owing to absence of linear relations of parameters it may has final region of possible solutions. In studying experiment this region has rather small sizes only in case of ignoring dependence of strength functions on level structure [5] or by use for its account of additional information [9].

In general case, the size of the region of searching values Γ and ρ is so large that it does not allow one to use the obtained result [7] for development and selection of more precise than the existing models of radiative widths and level density. The only possibility for the following obtaining of reliable information on properties of nucleus matter in this situation is to develop practical model of the process under consideration that is based on phenomenological notions and existing models which provide maximally precise approximation of all the existing data. Such models are required, first of all, for practical analysis of all available experimental data on the spectra of nucleus reaction products and their cross-sections.

Earlier was obtained [12], that level density corresponding to the best reproduction of the experimental data is well approximated by level density model ρ_n for *n*-quasi-particle excitations [13]. The sum density of quasi-particle and phonon levels $\rho_{\exp}$ in analysis [8] in correspondence with [2] definited as the product $\rho_{\exp} = C_{\rm coll}\cdot\rho_n$ for phenomenological chosen coefficient $C_{\rm coll}$ of collective enhancement of level density ρ_n. This presentation is idealized but the only satisfying requirements of modern experiment.

Theoretical coefficient of vibration enhancement of level density was obtained in [12], but it does not take into account the fact of cyclic increase of quasi-particle number owing to break of Cooper pairs at different excitation energy of nucleus below B_n. Therefore instead of results [14], for analysis of cascade intensities is used phenomenology dependence $C_{\rm coll}$ on nucleus excitation $E_{\rm ex}$ and thresholds of break of Cooper pairs U_l number *l* [13]}:

$$C_{coll} = A_l \exp(\sqrt{(E_{ex} - U_l)/E_\mu} - (E_{ex} - U_l)/E_\lambda) + \beta \qquad (1)$$

The best values of parameters A_l, U_l, β, E_μ and E_λ are determined from approximation of cascade intensity spectra. The change of model notions of level density must be accompanied by correction of model notions of radiative strength functions also. The modified radiative strength function, which takes into account dependence on density of cascade intermediate levels $\rho_{\exp}$ of model function:

$k = \Gamma / (A^{2/3} \cdot E_\gamma^{3} \cdot D_\lambda)$ (2)
is set in form:
$K_{exp} = k_{mod} \cdot \rho_{mod} / \rho_{exp}$. (3)

This assumption was made on the basis of the fact that evaporation spectra of nucleons and spectra of the primary gamma-transitions are with equal precision described [6] by product of infinite number of potentially possible calculated values Γ and experimental ρ_{exp}. Concrete magnitude of ρ is usually close to level density of Fermi-gas model [15], and the existing [2] models of strength functions E_1 of gamma-transitions which are based on the some modifications of the model [16].

The obtained criteria χ^2 very close for results of two variants of approximation [8], accounting and not accounting for dependence K_{exp} on density of intermediate levels ρ_{exp}. It did not allow one to make unambiguous conclusion on nucleus parameters k_{mod} and ρ_{exp} that determine real value of modified strength function (3). There is a consequence of very large scatter of the best values of parameters A_l owing to its strong correlation with E_λ both in different nuclei and different Cooper pairs in the same nucleus.

The obtained result is in large degree affected by strong anti-correlation of parameters ρ_{exp} and K_{exp}, stipulated by the use in the analysis of the fixed value of the total radiative width of resonance. It appears, first of all, due to absence of the experimental data for K_{exp} on the low-energy primary transitions to the levels $E_i < B_n$. The mentioned factors bring unknown error in the same values of the parameters U_l and level density of vibration type for different number of broken Cooper pairs.

For these reasons, the description of level density of vibration type requires one to pass from function C_{coll} do not developed up to now level density model of vibration type ρ_{vib}. Such model must clearly depend on parameters U_l and, probably, E_λ, as the parameters determining the dynamics of phonons dumping.

Some notion on the probable form of $\rho_{vib}(E_{ex})$ can be obtained from the data on difference $\rho_{exp} - \rho_n$ from results of approximation that are analogous to that presented in в [8]. The only difference – in analysis of given work was fixed equality of positive and negative parities level densities for any nuclei and any energy of their excitation. It was done for both uniformity and for estimation of dependence degree of quality both criteria χ^2 of approximation and the best value ρ_{exp} on ratio $r = \rho^-/(\rho^+ + \rho^-)$. In the average, reproduction quality of cascade intensity changed weakly: the mean value χ^2/m for 41 studied nuclei in the accepted variant increased [8] from $\chi^2/m=2$ to $\chi^2/m=2.4$.

Hence, the total density of levels of both parities and sum $K(E1)+K(M1)$ are determined from the experimental values $I_{\gamma\gamma}^{exp}$ by use of model [8] with maximal precision even at presence of significant correlated errors of level density of different parity and strength functions of $E1$- and $M1$-transitions. And give, respectively, the most reliable at present notion on a nucleus in region of existence of super-fluid phase of nucleus matter.

The obtained values for the total level density $\rho_{exp} = \rho_n + \rho_{vib}$, or density of excitations of only vibration type ρ_{vib} (total and "partial" ones) are given in Figs. 1–3. Here should be noted, that for determination of structure of the cascade intermediate levels undoubtedly is necessary to performed in additional experiment. Because of its absence one should take into account that the shown in figures dependencies ρ_{vib} can correspond to levels of quasi-particle type. And, of course, division of level density on two items is clearly methodic approach.

This remark does not concern nuclei ^{74}Ge, ^{124}Te, ^{138}Ba ^{168}Er, ^{192}Ir and ^{198}Au, where coefficients C_{coll} for the second and following pairs equal zero. But, in this case is possible the situation that in nucleus is excited only super-fluid phase. Again, this conclusion is hypothetic and formal. For nuclei ^{140}La, ^{150}Sm, ^{156,158}Gd, ^{160}Tb, ^{163,164,165}Dy, ^{166}Ho, ^{174}Yb, ^{181}Hf, ^{182}Ta, ^{185,187} W, ^{188,191,193} Os and ^{196}Pt the obtained portion of vibration levels is very large. The reason is obvious – very large magnitudes of C_{coll} for the second and, partially, the following pairs. The main part of approximation variants in these nuclei gives not principally different magnitudes of C_{coll}. In the frameworks of the realized model and existing experimental data the appeared problem, most probably, cannot be solved.

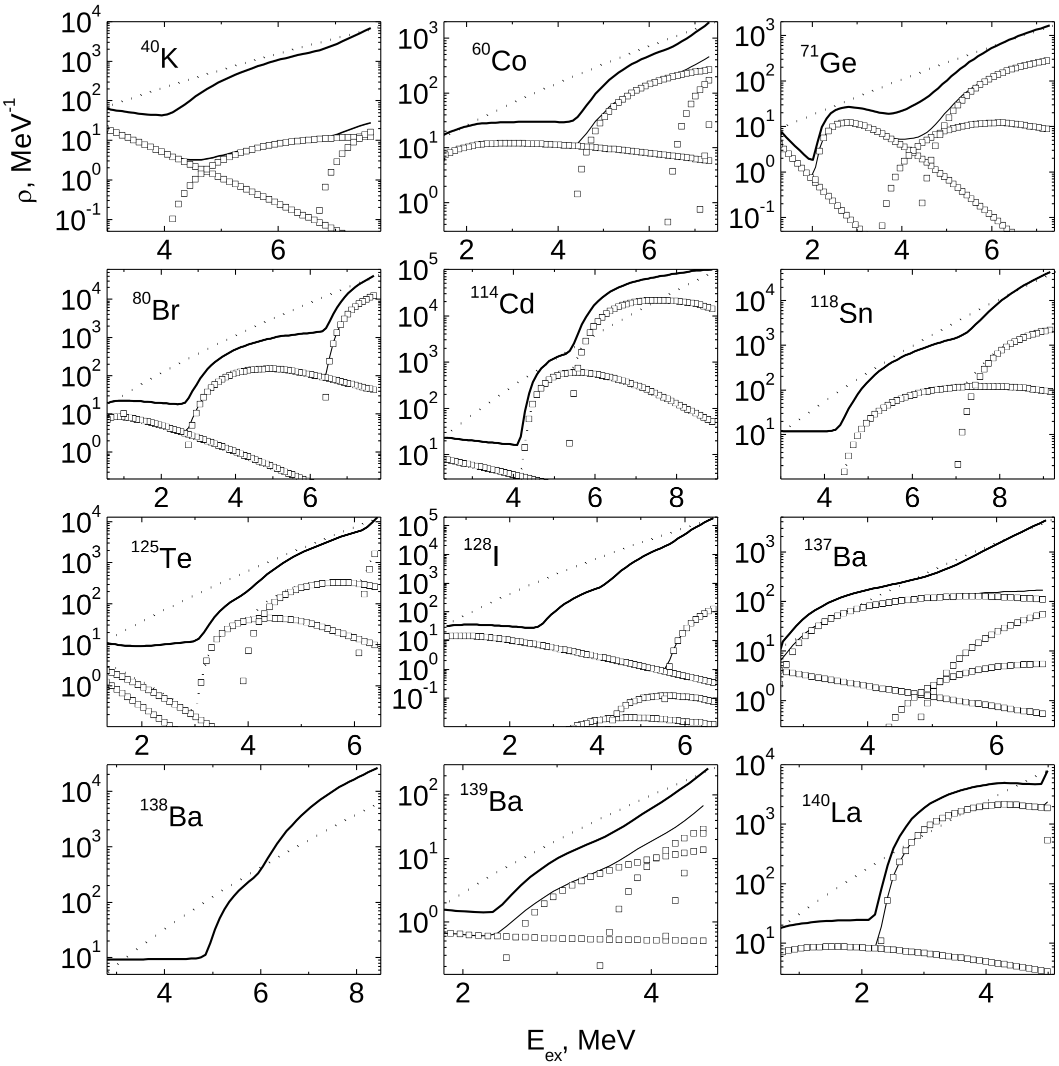

Fig.1. The data for nuclei ^{40}K, ^{60}Co, ^{71}Gr, ^{80}Br, ^{114}Cd, ^{118}Sn, ^{125}Te, ^{128}I, ^{137,138,139}Ba and ^{140}La. Dotted curve – model [15], thick curve – the best approximated value of the sum level density $\rho_n + \rho_{vib}$, open squares – sum of vibration level density for the all broken pair.

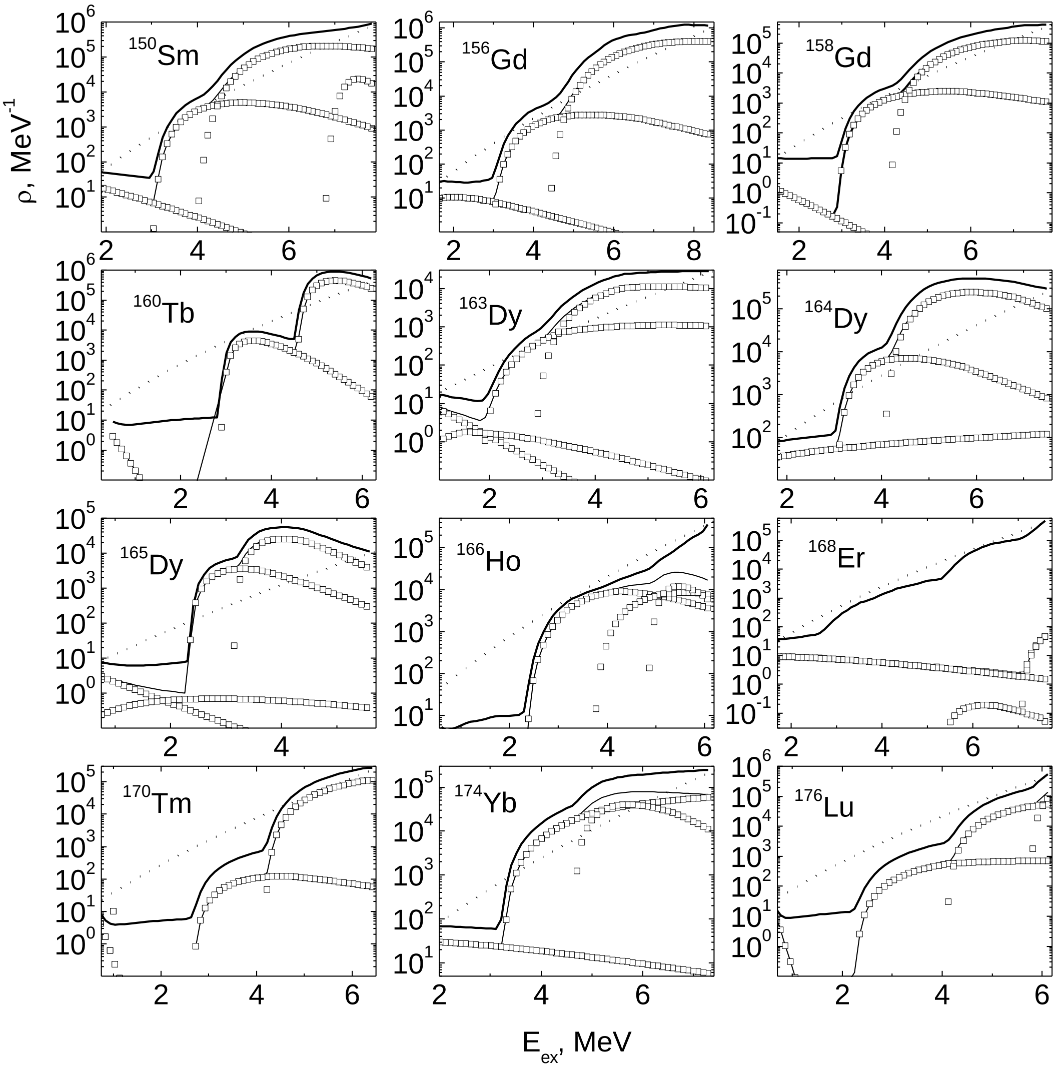

Fig.2. The same, as in Fig.1, for ^{150}Sm, ^{156,158}Gd, ^{160}Tb, ^{163,164,165}Dy, ^{166}Ho, ^{168}Er, ^{170}Tm, ^{174}Yb and ^{176}Lu.

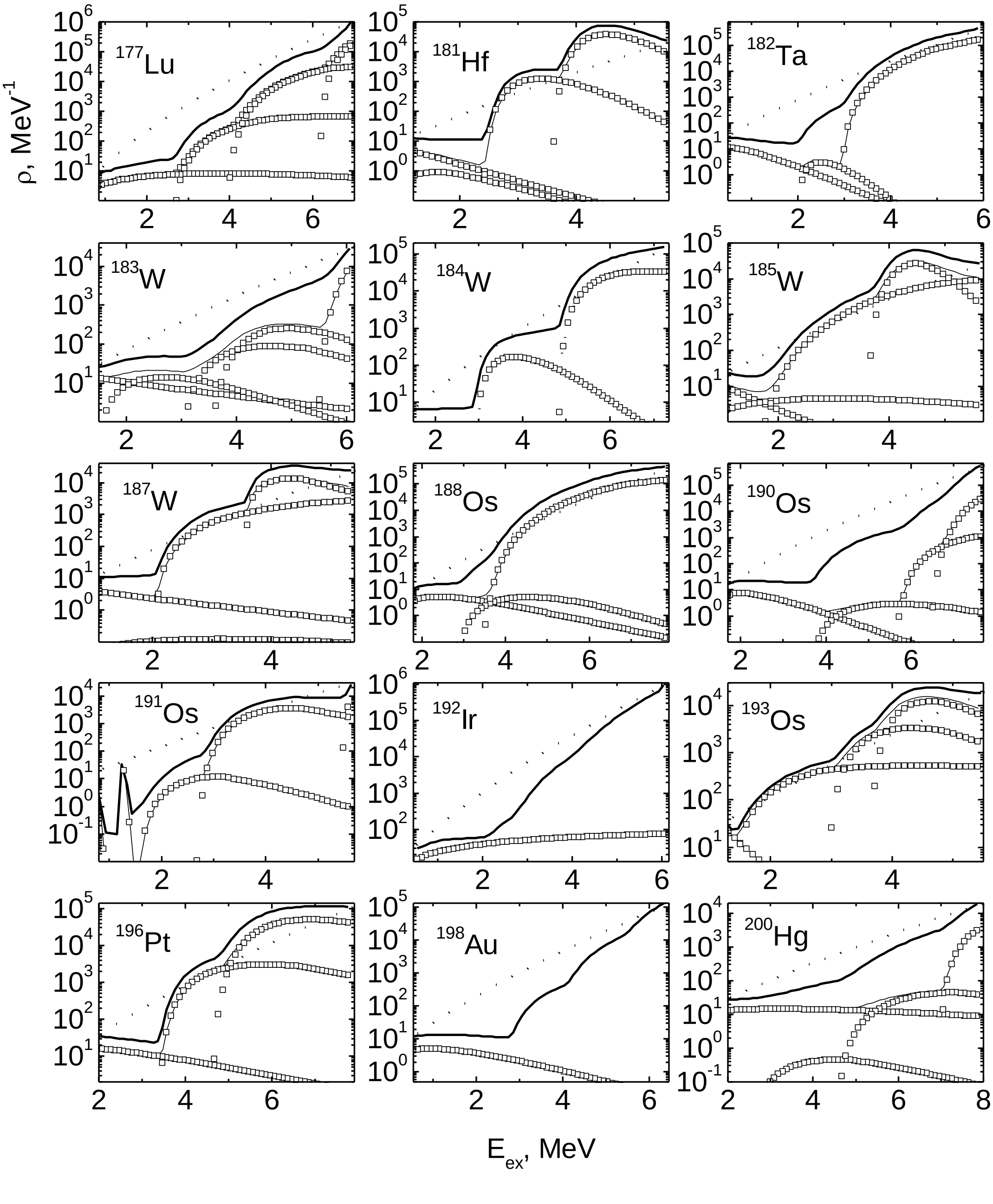

Fig.3. The same, as in Fig.1, for ^{177}Lu, ^{181}Hf, ^{182}Ta, ^{183,184,185,187}W, ^{188,190,191,193}Os, ^{192}Ir, ^{196}Pt, ^{198}Au, ^{200}Hg.

The additional to [8] variant of approximation of data on $I_{\gamma\gamma}^{\exp}$ in 41 nuclei from the mass region $40 \leq A \leq 200$ showed that accounting the difference of densities of levels of positive and negative parities gives, in the average, some better set of the parameters of the tested model. Result confirms the made earlier conclusion on influence of two nucleus phases on the process of neutron resonance cascade gamma-decay. The further investigation of super-fluidity of the heated nucleus requires developing the level density model of vibration type that determines relation of its values in the regions with different number of broken Cooper pairs.

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