MAIN PROPERTIES AND LOCAL PECULIARITIES OF RADIATIVE STRENGTH FUNCTIONS IN NEUTRON RESONANCE CASCADE GAMMA-DECAY

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The hypothesis on dependence form of the radiative strength functions of *E1*-and *M1*-transitions in heated nucleus on the excited level density was suggested and tested experimentally. For this purpose, the region of possible values of random functions of the level density and radiative strength functions which precisely reproduced experimental intensity of two-step cascades for 41 nuclei from ^{40}K to ^{200}Hg was determined.

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1. INTRODUCTION

The method for obtaining information about nuclear structure parameters by measurement of two-step gamma cascades intensity following thermal neutron captures was developed at FLNP JINR, Dubna [1,2]. Experimental spectra in this method were used for estimation values of the nucleus excited level density and the radiative strength function of gamma transition. The basic idea of Dubna method comes from dependence of two-step gamma cascade intensity on partial radiative width Γ and density ρ of excited levels:

$$I_{\gamma\gamma}(E_1) = \sum_{\lambda,f} \sum_i \frac{\Gamma_{\lambda i}}{\Gamma_\lambda} \frac{\Gamma_{if}}{\Gamma_i} = \sum_{\lambda,f} \frac{\Gamma_{\lambda i}}{<\Gamma_{\lambda i}> m_{\lambda i}} n_{\lambda i} \frac{\Gamma_{if}}{<\Gamma_{if}> m_{if}} \quad . \qquad (1)$$

Where $\Gamma_{\lambda i}$ and Γ_{if} are partial radiative widths corresponding to primary and secondary transition, $n_{\lambda i} = \rho_\lambda \Delta E_i$ is the number of excited intermediate levels in a certain interval of excitation energy ΔE_i. $\langle \Gamma_{\lambda i} \rangle$ and $\langle \Gamma_{if} \rangle$ are average values on corresponding intervals of nucleus excitation energy widths; $m_{\lambda i}$ and m_{if} are the number of levels in the same intervals.

The main advantage of Dubna method is the possibility to obtain directly information about cascade gamma decay parameters as well as expected their dependences from nuclear structure without using any assumptions. In the other existing methods for determination of ρ the model calculated parameter Γ usually input not controlled, permanent and methodically not removable error in the obtained level density data. As result [3], maximal systematic error of estimation of data on the excited levels density and the partial radiative widths of gamma-transitions Γ in all nuclei is 5-10 times less by using Dubna method than in other existing approaches [4-8].

The absence of noticeable cascades between the levels with spins $|J_\lambda - J_f| \geq 3$ provides possibility of simultaneous determination level density and mean values of partial widths Γ sums of *E1*- и *M1*-transitions (for unambiguously fixed spin window of levels) from detected $I_{\gamma\gamma}$. The specific of the Dubna method is that the parameters ρ and Γ are determined [1] as the mean values for infinite number of random functions which precisely reproduce experimental values of two-step cascade intensity. As result, Dubna's values of ρ and Γ were obtained with uncertainty which contained usual experimental error of determination of $I_{\gamma\gamma}$ as well as not removable in principle methodical uncertainty of these parameters.

2. STATUS OF MODERN EXPERIMENT FOR DETERMINATION OF RADIATIVE STRENGTH FUNCTIONS AND LEVEL DENSITY

Values of level density ρ and penetrability $T=2\pi\Gamma/D_\lambda$ can be obtained by using regime of coincidence or without coincidences regime of measurement. There are several important differences between those two techniques. In case of nuclear reaction products registration without use of coincidences regime (so call one-step reaction), the values of the measured cross sections and spectra intensity I_1 are determined by product of the level density and penetrability coefficients (partial radiative widths) of nucleus surface for evaporation nucleons or gamma-quanta:

$$I_1 \propto \rho\Gamma / \sum(\rho\Gamma). \tag{2}$$

As a consequence, the measured spectra of nuclear reaction products in one-step regime depend only on shape of energy dependence of the level density and penetrability coefficients, but do not depend on their absolute values. By use of coincidences regime (for example, two-step reaction $(n_{th},2\gamma)$) with fixation of final nucleus level, the intensity of the registered cascades is qualitatively determined by product I_1*I_2 of primary I_1 and secondary transition intensity I_2. Wherein coefficient I_2 is determined by:

$$I_2 \propto \Gamma / \sum(\rho\Gamma) \tag{3}$$

In this case, detected cascade intensity depends on both, shapes of energy dependence of Γ and ρ parameters (the value I_1), and absolute value of the level density (the value I_2). This is true only if gamma-cascades to limited number of final nucleus levels are registered. Therefore, for determination of the level density from nucleon evaporation spectra [4,5,7], for example, it is absolutely necessary to set the values of nucleus surface penetrability T (calculated up to now on the basis of primitive optical model of nucleus). Or, authors [6] used primitive optical model of the level density for determination of radiative strength functions of dipole transitions k from the total gamma-spectra. As further develop of [6], analysis of authors [8] approach requires, very small total errors in "the first generation spectra" for all intermediate levels i of nucleus. Accordingly [9], these errors must have values less (or much less) than ~1% for every points of every such gamma spectra measured by NaI(Tl) detectors. Besides, in analysis of the data of one-step reactions, the hypothesis of independence of both, ρ and Γ, on structure of wave function of nucleus excited levels [4,10,11] must be used. At present, those hypothesis contradicts to main notions of quasi-particle-phonon model (QPMN) of nucleus [12] and to the experimental results of two-step reaction $(n_{th},2\gamma)$ investigation [1,2]. For example, reanalysis [13] of the data of reaction ^{59}Co$(p,2\gamma)$ ^{60}Ni [14] allowed one, in particular, to reveal very significant increase in mean intensity of the primary *E1*-transition from *p*-resonances to two-phonon level of 2.5 MeV (qualitatively corresponding to predictions of QPMN and completely contradicting to Axel-Brink hypothesis [10,11]). But exactly determined rather significant increase of cascade population of levels in region around $0.5B_n$ for ~ 20 nuclei in mass region from 40 to 200 [2] can be explained at present time only by increase of strength functions values of any cascade gamma-transitions to intermediate levels in energy region of the second (and, possibly, following) nucleons Cooper pairs breakup threshold.

The fact about influence of nuclear structure on ρ and Γ cannot be obtained from analysis of spectra of one-step reactions even in principle because of unknown systematical error of the used model calculated parameters Γ (or T). Another situation is characteristic for any two-step reaction. As in the case of one-step reaction, the system of equations (1) connecting intensity of two-step cascades with parameters ρ and Γ is undoubtedly degenerated. However, the form (1) of functional relation of parameters with the measured spectra strongly limits the region of their possible values. That is why N values of experimental cascade intensities always can be converted in ~2N values of ρ and Γ, which satisfy conditions:

$$\rho_1 \le \rho \le \rho_2 \quad \text{and} \quad \Gamma_1 \le \Gamma \le \Gamma_2 . \qquad (4)$$

The boundary values of ρ and Γ cannot be simply determinate and correspond to some distribution with the width which depends on χ^2. By this, all the ρ and Γ values belonging to intervals (4) provide reproduction of the experimental intensities with practically same precision (χ^2<<1), and relatively small differences between minimal and maximal values of parameters. It allows one to reveal main peculiarities of change in the level density and radiative widths Γ for any values of excitation energy. Discovery [15,16] of radiative strength functions dependence on structure of the levels excited by gamma-transition allowed one to the first approach and only partially (but experimentally) to take into account such dependence. Respectively, there was necessity to develop the method for study influence of this effect to gamma-decay parameters.

3. POSSIBILITIES OF DEVELOPMENT OF THE EFFECTIVE METHOD FOR DETERMINATION OF ρ AND Γ FROM $I_{\gamma\gamma}$

The level density determined from reaction $(n_{th},2\gamma)$ is described in the best way by the Strutinsky model [17] as a superposition of density of n-quasi-particle excitations (which number n increases with increase of excitation energy of broken Cooper pairs) and variable coefficient of their enhancement owing to nucleus excitations of collective type. The use of this model [18] for description of evaporation nucleons spectra in reaction ^{181}Ta(p,n) ^{181}W [19] showed that the excellent reproduction of the Obninsk experimental data can be achieved at accounting of local significant increase of parameter T for excitation energy which does not practically depend on beam protons energy. And this enhancement of neutron emission probability in the experiment under consideration completely corresponds to rather narrow region of excitation energy of nucleus with minimal level density ρ. Such effect must appear itself in any nuclei and any nuclear reactions, only if level density in them in the best way corresponds to predictions of the Strutinsky model with correlation function of nucleon pair approximately corresponding to nucleon pairing energy. Moreover, the observed shape of energy dependence of evaporation nucleon spectrum as in ^{181}W and, for example, in ^{60}Ni can be reproduced by obtained from reaction (n,2γ) functions $\rho_{cas} = \psi(E_{ex})$ and $\Gamma_{cas} = \phi(E_1)$, which satisfy functional dependence:

$$T_{om}\,\rho_{ev} = T_{cas}\;\rho_{cas} \qquad \text{or} \qquad \Gamma_{om}/D_{ev} = \Gamma_{cas}/D_{cas} \qquad (5)$$

for the model calculated penetrability T_{om} and level density ρ_{ev}, obtained from spectrum of evaporation nucleons for chosen by authors of corresponding experiment optical potential. Usually the ρ_{ev} was close to level density of Fermi-gas model ρ_{fg} [21].

Corresponding hypothesis of the modified usual strength function K_{modif} of dipole transitions in case of gamma-quantum emission is determined from equation (5) by relation:

$$K_{\text{modif}} = k_{\text{standard}} \cdot \frac{D_{fg}}{D_i} = \frac{\Gamma_{\lambda i}}{E_\gamma^3 A^{2/3} D_\lambda} \cdot \frac{D_{fg}}{D_i} \qquad (6)$$

instead of standard presentation:

$$k_{standard} = \Gamma_{\lambda i.} / (E_\gamma^3\ A^{2/3}\ D_\lambda) . \qquad (7)$$

In this way the modified radiative function (6) is used for re-determination of existed strength function $k(E1)$ and $k(M1)$ of dipole gamma-transitions. The expression (6) includes dependence of K of density of initial as well as final nuclear level on gamma transition energy. Equation (6) can be rewritten in form:

$$K_{\text{modif}} = k_{\text{standard}} \cdot \frac{\rho_{\text{exp}}}{\rho_{fg}}. \qquad (8)$$

Function ρ_{fg} in this presentation corresponds to level density of Fermi-Gas model with parameters from [20] in case of absence of collective type excitations; function ρ_{exp} – its fitted value. At their equality to ρ_{fg} the expression (6) has standard form.

In our analysis we chose Fermi-gas model with the "back- shift" for calculating of level density ρ_{fg}. The approximated values of the level density ρ_{exp} in this variant of analysis must not exceed the model values and coincide with them under condition that the model notions on Γ coincide with experimental data, at least, in corresponding interval of excitation energy. Practical approximation of the intensity distributions obtained in Dubna was performed in frameworks of this condition.

4. SOME PECULIARITIES OF PRACTICAL APPROXIMATION OF TWO-STEP CASCADES INTENSITY FOR PROPOSED MODEL

As in previous variants of determination of the level density and the radiative strength functions from two-step reaction [1,2], the unbiased estimation of region of possible values of these parameters can be obtained only by use of completely random determination process of possible functions $\rho_{\text{exp}} = \psi(E_{ex})$ and $k_{\text{exp}} = \phi(E_1)$ in all energy intervals of excitation and gamma-quanta emission. By choosing parameters of Gauss functions [1] it is made compromise between necessity of detailed reproduction of energy dependence form of desired parameters and acceptable time for realization of calculation of each variant. The width of random solutions region $\rho_2 - \rho_1$ and $\Gamma_2 - \Gamma_1$ in given variant of analysis considerably increases as compared with the data obtained earlier [1,2] because expression (5) corresponds to infinite number of possible functions ρ_{exp} and Γ_{exp}. Besides, here also increases number of iterations which are necessary for achievement of value $\chi^2 << 1$. Usual required number of interaction is several thousands to several tens of thousands [1,2]. So, here largest permissible value of parameter χ^2, when is possible to interrupt iteration determination process of $\rho_{\text{exp}} = \psi(E_{ex})$ and $k_{\text{exp}} = \phi(E_1)$ is unambiguous: the found functions must provide reproduction of the experimental intensity in limits of its total experimental error, first of all in region of small energies of the cascade primary transitions ($E_1 \approx 0.5$-2 MeV). The examples of the obtained sets of functions ρ and K, providing typical quality of approximation of the experimental intensity for nuclei of different type are given are given in Fig. 1. The obtained level density and radiative strength functions are presented on Fig. 2.

The scatter of random values ρ_{exp} and K_{exp} is large and brings to obvious shift of level density in direction of maximal values at determination of their mean values as the average values of functions $\rho_{\text{exp}} = \psi(E_{ex})$ and $k_{\text{exp}} = \phi(E_1)$. Therefore, in given variant of analysis, logarithms of the level density (practically – entropy of nucleus) and strength functions were averaged. It is seen from Fig. 1 that the number of deviations from mean value at such averaging is approximately equal. Besides, the difference between values of ρ_{exp} and K_{exp} obtained by such variant of their determination with previous variant is minimal, as well. Moreover, in region of neutron binding energy, for some nuclei the very strong exceeding of ρ_{exp} above model value ρ_{fg} disappeared or considerably decreased as compared with the data [1,2].

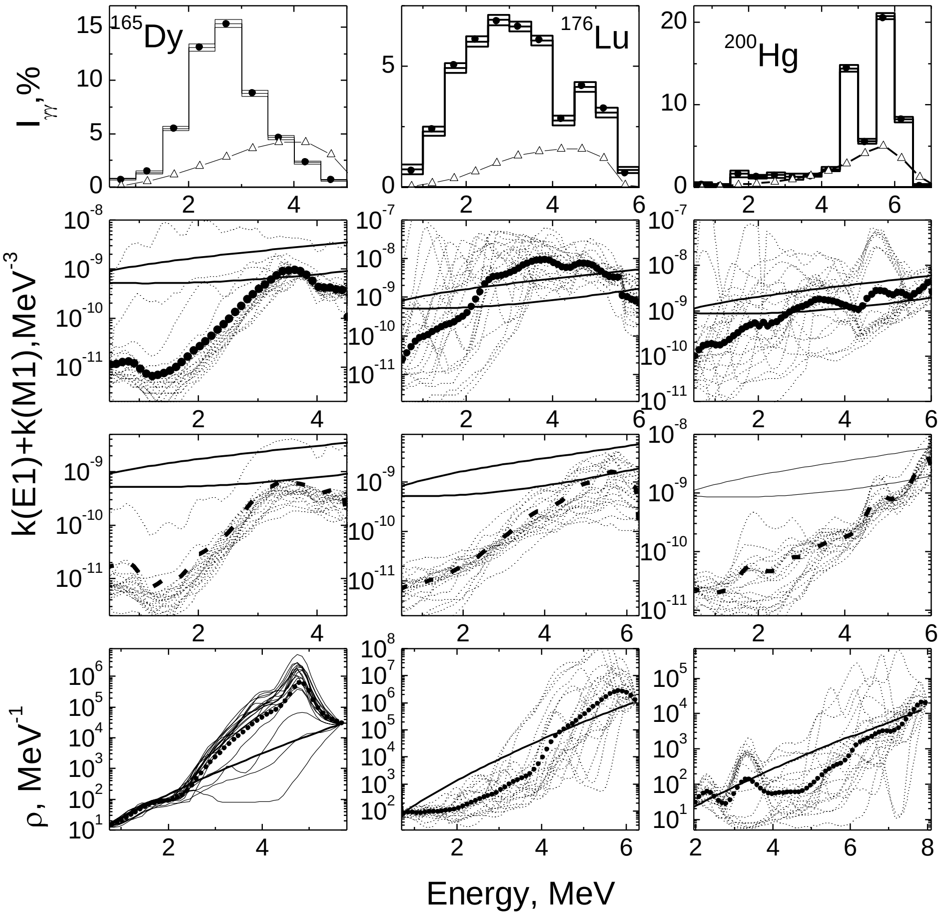

Fig.1. The examples of experimental distributions of cascade intensities approximation by random functions $\rho = \psi(E_{ex})$ and $k = \phi(E_1)$. Upper row: histogram – experimental data, full points– typical approximation, triangles – initial spectra for models [20,21] and $k(M1)$=const. Second and third rows –sum of strength functions *E1*- and *M1*-transitions (dotted curves – random functions; dark and open circles correspond to (6) and (7); lines – model data [10, 11, 21]). Down row – the most probable density of intermediate levels of two-step cascades (dotted curves – random functions, dark points – their mean value, solid line – data [21]).

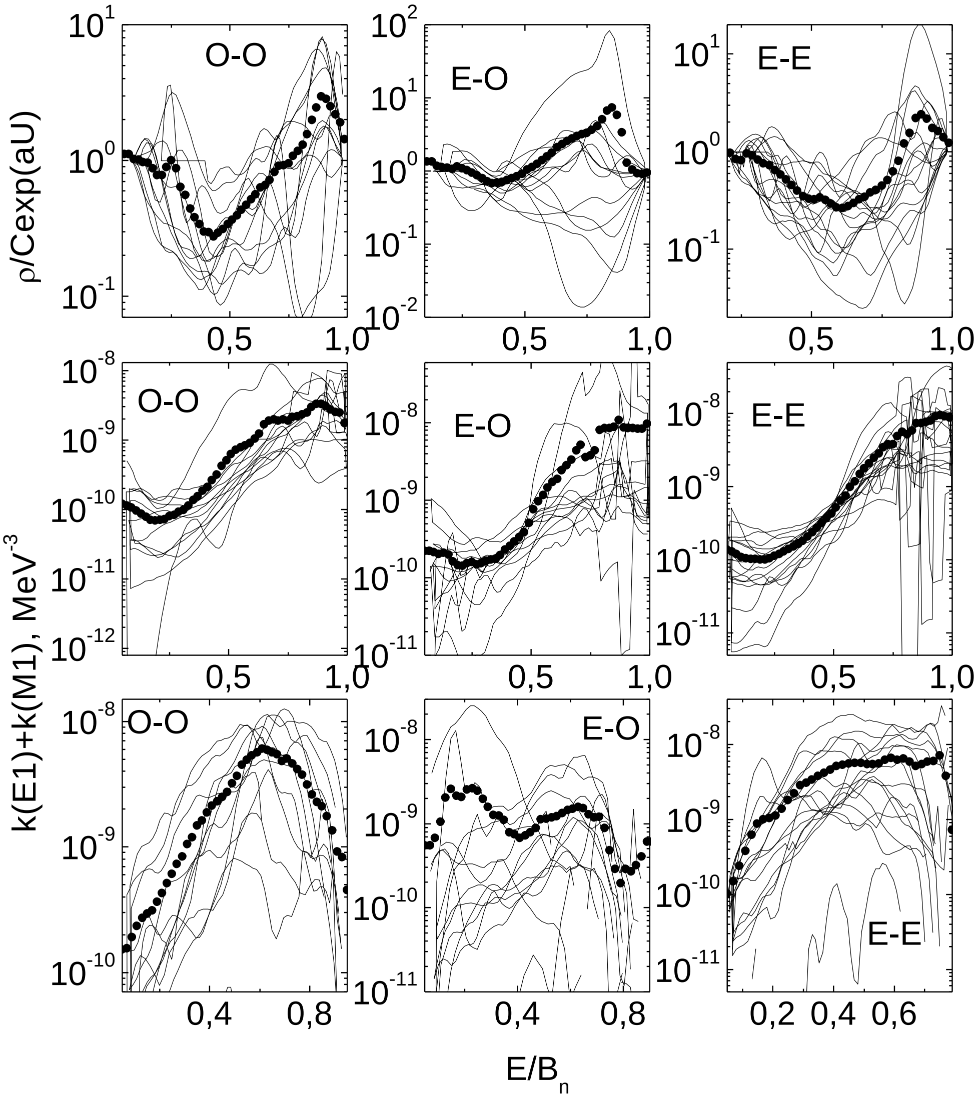

Fig.2. Upper row. Points – mean density of levels with different parity of nucleons. Thin lines – the data for nuclei studied the in reaction (n,2γ) . There is taken into account trivial exponential dependence. Middle row – the same for general trend (7) of sum of strength functions of dipole transitions. Lower row – the results of determination of their local variations. The energies of gamma-transitions and nucleus excitation are normalized to neutron binding energy $B_{n.}$

5. CONCLUSION

1. The use of hypothesis (5) does not remove step-like structure in level density below neutron binding energy. In other words – there is the fact of obvious presence of sharp change in structure of nuclei levels of different type, which at present can be interpreted as break of Cooper pair of nucleons in heated nucleus.
2. Radiative strength functions of gamma-transitions between excited levels of heated nucleus also confirm very strong influence of nucleus structure on their partial widths.

3. Intensity of two-step cascades following thermal neutron capture can be precisely reproduced under condition that the radiative strength functions of cascade transitions are considerably increased because of presence of gamma-transitions between the levels with large vibration components of wave functions. Respectively, such possibility must be taken into account at both, planning of new experiments and creation of new phenomenological models of radiative strength functions and penetrability coefficients for gamma-quanta or evaporation nucleons and light nuclei.

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