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GENERAL TREND AND LOCAL VARIATIONS OF NEUTRON RESONANCE CASCADE GAMMA-DECAY RADIATIVE STRENGTH FUNCTIONS

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Генеральный тренд и локальные вариации радиационных силовых функций каскадного гамма-распада нейтронных резонансов

Предложена и проверена новая гипотеза о зависимости формы радиационных силовых функций электрических и магнитных дипольных гамма-переходов на возбужденные уровни нагретых ядер. Для этой цели определена область возможных случайных значений плотности уровней и радиационных силовых функций, точно воспроизводящих экспериментальную интенсивность двухквантовых каскадов для 41 ядра от ^{40}K до ^{200}Hg. Показано, что, как следствие коллективных эффектов, предлагаемая гипотеза может обеспечивать максимальное увеличение значений радиационных силовых функций на порядок величины по сравнению с существующими представлениями. Результат указывает на необходимость принимать во внимание такую возможность как в существующих, так и в будущих моделях радиационных силовых функций.

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General Trend and Local Variations of Neutron Resonance Cascade Gamma-Decay Radiative Strength Functions

A new hypothesis on dependence of the form of the radiative strength functions of electric and magnetic dipole gamma transitions in heated nucleus on the excited level density was suggested and tested experimentally. For this purpose, the region of possible values of random values 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. It was obtained that the suggested hypothesis can provide the maximal increase of radiative strength functions values by order of magnitude in comparison with existing notations as a result of collective effects enhancement. This result points to the necessity to take into account this possibility in existing and future models of radiative strength functions.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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1. INTRODUCTION

The method for obtaining information about nuclear structure parameters by measurement of two-step gamma cascade 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, partial radiative width of the cascade gamma decay and the radiative strength function of gamma transition. The basic idea of the Dubna method comes from dependence of two-step gamma cascade intensity on partial radiative width Γ and density ρ of excited levels:

$$I_{\gamma\gamma}(E_1) = \sum_{\lambda,f}\sum_{i}\frac{\Gamma_{\lambda i}}{\Gamma_\lambda}\frac{\Gamma_{if}}{\Gamma_i} = \sum_{\lambda,f}\frac{\Gamma_{\lambda i}}{\langle\Gamma_{\lambda i}\,\rangle\; m_{\lambda_i}}\, n_{\lambda_i}\frac{\Gamma_{if}}{\langle\Gamma_{if}\rangle\; m_{if}}, \qquad (1)$$

where $\Gamma_{\lambda i}$ and Γ_{if} are partial radiative widths correspond to primary and secondary transition; $n_{\lambda i} = \rho_\lambda \Delta E_i$ is a 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 numbers of levels in the same intervals.

The main advantage of the 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. So, the measurement of two-step gamma cascade intensities is effective tools for checking theoretical prediction. 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 a result [3], by using the Dubna method maximal systematic error of estimation of data on the excited levels density and the partial radiative widths of gamma transitions Γ (in nuclei with arbitrary spacing D_λ between neutron resonances) is 5–10 times less than in other existing approaches [4–8].

The absence of noticeable cascades between the levels with spins $|J_\lambda - J_f| \geqslant 3$ provides possibility of simultaneous determination of level density and mean values of partial widths Γ sums of $E1$- and $M1$-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 as the mean values for infinite number of random functions (concentrated in finite region of possible level densities and strength function values) which precisely reproduce experimental values of two-step cascade intensity. As a 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.

In this analysis, information about the validity of new hypothesis that predicts functional dependence of radiative strength functions of electric and magnetic dipole gamma transitions in heated nucleus on the excited levels density was tested. For this purpose, ability for receiving data about this dependence from obtained early $I_{\gamma\gamma}$ experimental values was analyzed and it is shown that the most reliable results can be obtained only by measuring of the two-step gamma cascade intensity. Method for practical estimation of nuclear structure influences on cascade gamma-decay parameters from measurement of $I_{\gamma\gamma}$ are presented in this work. Based on it, there is a possibility to obtain phenomenological description on dependence of radiative strength functions and the excited levels density on real structure of nucleus.

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

The value of resolution parameter FWHM of modern spectrometers used for charged particles and gamma-quanta detection is many times larger than the mean spacing D_i between excited levels in main part of excited levels energy region in arbitrary nucleus. Therefore, the level density and penetrability $T = 2\pi\Gamma/D_\lambda$ of nucleus surface for reaction products can be found only by fitting the measured spectra (cross sections) to their model set value. That is a major problem for accurate and reliable determination of those parameters values.

Values of parameters ρ and Γ can be obtained by measurement of the reaction products spectra by single detector (one-step reaction), or by coincidences between two (or more) detectors (two-step reaction). There are several important differences between these two techniques. In case of nuclear reaction products registration without using of coincidence regime (the so-called one-step reaction), the values of the measured cross sections and spectra intensity I_1 are determined by the product of the level density and penetrability coefficients (the 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 detected 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. It means that the total probability of emission of given product per one decay of a nucleus is equal to unity. Therefore, the precision of cross-section reproduction is determined only by the product of these variables but not by absolute values [7] of ρ and Γ.

Using of regime coincidences (for example, two-step reaction $(n_{\rm th}, 2\gamma)$) with fixation of final nucleus level, the intensity of the registered cascades is qualitatively determined by the product $I_1\ I_2$ of the primary I_1 and the secondary I_2 transition intensities, 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 Γ and ρ parameters energy dependence (the value I_1) and absolute value of the level density (the value I_2). This is true only if gamma cascades of limited number of final nucleus levels are registered. Dependence of I_2 on ρ is nonlinear, ambiguous and relatively weak. Nevertheless, just this connection (3) provides the maximal reliability (at the present time) of ρ and Γ determination, but with their nonzero asymptotical uncertainty.

Deviation of any parameter from the desired value in case of one-step reaction is effectively compensated by deviation of the other one, practically for infinite region of their possible values. In case of two-step gamma cascades such a compensation is really possible only for relatively small deviations of both level density and partial widths from experimental magnitudes. This conclusion is completely conserved by using in approximation process the absolute values of the low-lying level density, neutron resonances space and experimental penetrability T or radiative strength function. The value of the last parameter is usually known only for a few levels of reaction nucleus-product. This means that the obtained region of the ρ and Γ values reproduced experimental data with the same precision in the case of two-step reaction, is always many times less than in the possible ones in one-step reaction.

Therefore, for determination of the level density from nucleon evaporation spectra $[4, 5, 7]$, it is absolutely necessary to set the values of nucleus surface penetrability T (practically calculated up to now on the basis of primitive optical model of nucleus). Accordingly, the authors of [6] used primitive models of the level density for determination of radiative strength functions of dipole transitions k from the total gamma spectra. Approach of authors [8], using the same experimental data, requires a very small total experimental uncertainty in «the first generation spectra» for all intermediate i levels of nucleus. These uncertainty [9] must have values less (or much less) than $\sim 1\%$ 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, this hypothesis contradicts the main notions of quasi-particle–phonon model (QPMN) of nucleus [12] and the experimental results of two-step reaction $(n_{\rm th}, 2\gamma)$ 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 the Axel–Brink hypothesis [10, 11]). And 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 of, probably, vibration-type excitation in energy region of the second (and, possibly, following) nucleons Cooper pairs breakup threshold.

The fact about the effect of nuclear structure on ρ and Γ cannot be obtained from analysis of spectra of the one-step reactions because of unknown systematic errors of parameters Γ (or T) calculated with the used model. For any two-step reaction another situation is characteristic. 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. Therefore, unambiguous determination of ρ and Γ from measured spectra $I_{\gamma\gamma}$ is impossible. 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 $\sim 2N$ values of ρ and Γ, which satisfy the conditions:

$$\rho_1 \leqslant \rho \leqslant \rho_2, \quad \Gamma_1 \leqslant \Gamma \leqslant \Gamma_2. \tag{4}$$

The boundary values of ρ and Γ cannot be simply determined and they 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 the same precision ($\chi^2 \ll 1$) 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. This means, there are impossibility (even in principle) to obtain the unique values of decay parameters ρ and Γ of highly-excited nucleus level with negligibly acceptable uncertainty. However, the problem reduced to determination of size of limited region of infinite number of their possible values. It is evident that the experimental errors of cascade intensities transform to additional fluctuations of random functions ρ and Γ and increasing differences $\rho_2 - \rho_1$ and $\Gamma_2 - \Gamma_1$.

Discovery [2] 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 this dependence. This was done by inclusion of experimental values of cascade population $P = i_1 i_2 / i_{\gamma\gamma}$ of some tens of intermediate levels below excitation energy $\sim 0.5B_n$ in approximation process. Insufficiency of experimental data on absolute intensities of primary i_1 and secondary i_2 gamma transitions of cascades with high enough excitation energy of decaying level i did not allow one to apply this method for a half of nuclei in which intensity $i_{\gamma\gamma}$ of resolved two-step cascades following thermal neutron capture was determined. There are mainly odd–odd compound nuclei and isotopes with small thermal neutron capture cross sections.

Up to now, the presence of regions of strong influence of nucleus structure on reaction product emission probability was experimentally confirmed in [2]. Respectively, there was necessity to develop the method for study the influence of this effect on gamma-decay parameters.

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

The main defect of the existing methods for determination of ρ and Γ is absolute lack of model ideas on form of functional relation of these parameters with each other and with real structure of nucleus. Perspective models of ρ and Γ, as it follows from the Dubna data on these parameters [15–17], must take into account both, coexistence of levels of phonon and quasi-particle types and inevitable difference between radiative strength functions of gamma transitions between them (as coefficients T of nucleons or light nucleus evaporation emission). Modern models of a nucleus (like QPMN or IBMF) to more or less extent take this difference into account (but, unfortunately, in form which is unfit for practical analysis of the experimental data). Therefore, it is necessary to develop phenomenological models for description of experimental set values of nuclear structure parameters. At present, this can be partially performed for radiative strength functions of cascade gamma transitions.

The level density determined from reaction $(n_{\mathrm{th}}, 2\gamma)$ is described most precisely by the Strutinsky model [18]. This means, as a superposition of density of n-quasi-particle excitations (which number n increases with increase of excitation energy number of broken Cooper pairs) and variable coefficient of their enhancement owing to nucleus excitations of collective type. The use of this model [19] for description of evaporation nucleons spectra in reaction $^{181}\mathrm{Ta}(p,n)^{181}\mathrm{W}$ [20] 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. Practically, as a minimum, the lowest ρ value is observed in region of break threshold of the second nucleons Cooper pair in even–even compound nucleus (or threshold of appearance of four- and five-quasi-particle excitations in odd–odd and even–odd compound nuclei). The effect must appear itself in any nuclei and any nuclear reactions, only if level density in them corresponds to predictions of the Strutinsky model with correlation function of nucleon pair approximately equal 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 $(n, 2\gamma)$ reaction $\rho_{\rm cas} = \psi(E_{\rm ex})$ and $\Gamma_{\rm cas} = \phi(E_1)$ functions, which satisfy functional dependence:

$$T_{\rm om}\ \rho_{\rm ev} = T_{\rm cas}\ \rho_{\rm cas} \text{ or } \Gamma_{\rm om}/D_{\rm ev} = \Gamma_{\rm cas}/D_{\rm cas} \tag{5}$$

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

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

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

instead of standard presentation

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

Thus, the modified radiative function (6) is used for redetermination of existed strength function $k(E1)$ and $k(M1)$ of dipole gamma transitions. 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 the form:

$$K_{\rm modif} = k_{\rm standard} \frac{\rho_{\rm exp}}{\rho_{\rm fg}}. \tag{8}$$

Function $\rho_{\rm fg}$ in this presentation corresponds to level density of Fermi-gas model with parameters from [21] in case of absence of collective type excitations; function $\rho_{\rm exp}$ is its fitted value. At their equality to $\rho_{\rm fg}$ expression (6) has a standard form.

In our analysis we chose Fermi-gas model with the «back-shift» for calculating of level density $\rho_{\rm fg}$. The approximated values of the level density $\rho_{\rm exp}$ 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

Compound nucleus mass A, maximal energy E_f of measured cascade final levels and their sum intensities $I_{\gamma\gamma}$ (percent per decay)

A	E_f, MeV	$I_{\gamma\gamma}$	A	E_f, MeV	$I_{\gamma\gamma}$
^{40}K	1.64	67(23)	^{60}Co	1.005	71(3)
^{71}Ge	0.000	32(2)	^{74}Ge	2.165	36(2)
^{80}Br	0.288	23(7)	^{114}Cd	0.558	26(1)
^{118}Sn	1.230	31(1)	^{124}Te	0.603	20(2)
^{125}Te	0.671	31(1)	^{128}I	0.434	33(2)
^{137}Ba	0.279	59(4)	^{138}Ba	1.436	26(5)
^{139}Ba	1.082	81(6)	^{140}La	0.322	48(2)
^{150}Sm	0.773	12(1)	^{156}Gd	0.288	23(5)
^{158}Gd	0.261	19(2)	^{160}Tb	0.279	23(3)
^{163}Dy	0.250	22(1)	^{164}Dy	0.242	29(1)
^{165}Dy	0.184	53(1)	^{166}Ho	0.522	31(1)
^{168}Er	0.995	27(4)	^{170}Tm	0.648	23(2)
^{174}Yb	0.253	22(1)	^{176}Lu	0.595	44(1)
^{177}Lu	0.637	16(1)	^{181}Hf	0.332	52(4)
^{182}Ta	0.360	19(1)	^{183}W	0.209	28(1)
^{184}W	0.364	35(1)	^{185}W	1.068	62(1)
^{187}W	0.303	34(1)	^{188}Os	0.633	59(3)
^{190}Os	0.756	49(3)	^{191}Os	0.815	76(2)
^{192}Ir	0.415	27(6)	^{193}Os	0.889	80(1)
^{196}Pt	0.688	37(5)	^{198}Au	0.495	42(1)
^{200}Hg	0.368	59(2)			

least, in corresponding interval of excitation energy. Practical approximation of the intensity distributions obtained in Dubna was performed in the framework of this condition. The values of two-step cascades final levels maximal energy and their total intensity are given in the Table. Their experimental dependence on cascade primary transition energy is presented in the works published earlier.

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

As in the 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 using completely random determination process of possible functions $\rho_{\rm exp} = \psi(E_{\rm ex})$ and

$k_{\rm exp} = \phi(E_1)$ in all energy intervals of excitation and gamma-quanta emission. Parameters of Gauss functions [1] in this case are chosen to find a compromise between necessity of detailed reproduction of energy parameters and acceptable time for realization of calculation of each variant. The width of random solution regions $\rho_2 - \rho_1$ 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 $\rho_{\rm exp}$ and $\Gamma_{\rm exp}$. Besides, here also increase a number of iterations which are necessary for achievement of value $\chi^2 \ll 1$. Usual required number of interaction is several thousands to several tens of thousands [1, 2]. So, here the largest permissible value of parameter χ^2 is unambiguous, when it is possible to interrupt iteration determination process of $\rho_{\rm exp} = \psi(E_{\rm ex})$ and $k_{\rm exp} = \phi(E_1)$. 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 results for nuclei of different type are given in Fig. 1. The obtained level density and radiative strength functions are presented in Figs. 2–8.

The results presented here have considerable difference relative to the data of [1, 2]. Condition (5) increases very strongly the values $\rho_2 - \rho_1$ and $\Gamma_2 - \Gamma_1$ in case of using practically unrealistic initial values of these parameters. It resulted to increasing the minimum χ^2 values for each of the 42 studying nuclei. Therefore, in performed analyses, only model radiative widths [10, 11] and level density [18, 21] were used as the set of initial values of ρ and Γ. In this case, discrepancy between the input data and the mean values of set of the obtained random functions $\rho = \Psi(E_{\rm ex})$ and $k = \phi(E_1)$ is quite large. From this follows that the models mentioned above cannot give a satisfactory description of the modern experiment results.

Value of the correlation coefficient between the searching level density of positive and negative parities varied from 10 to 90% for different variants of fitting process.

The unsolved problem is the question on position of points of minimal density (break threshold U_n of the next Cooper pair of nucleons) for levels with parity π^+ and π^-. These levels can be excited by primary transitions of unambiguously fixed multipolarity as well as by cascades of two and more transitions. This means that multipolarities of primary and any next gamma transitions ending at given nucleus level can be different.

Dipole $E1$ or $M1$ gamma transitions between states of vibration type, according to selection rule, are possible only by condition that the structure of wave functions of levels with different parity contains phonons of suitable multipolarity. Taking into account the different energy of quadrupole and octupole phonons (which excited by the $E1$ or $M1$ transitions), in region around U_n, suggests the existence of possibility for local fluctuations of the level density for different

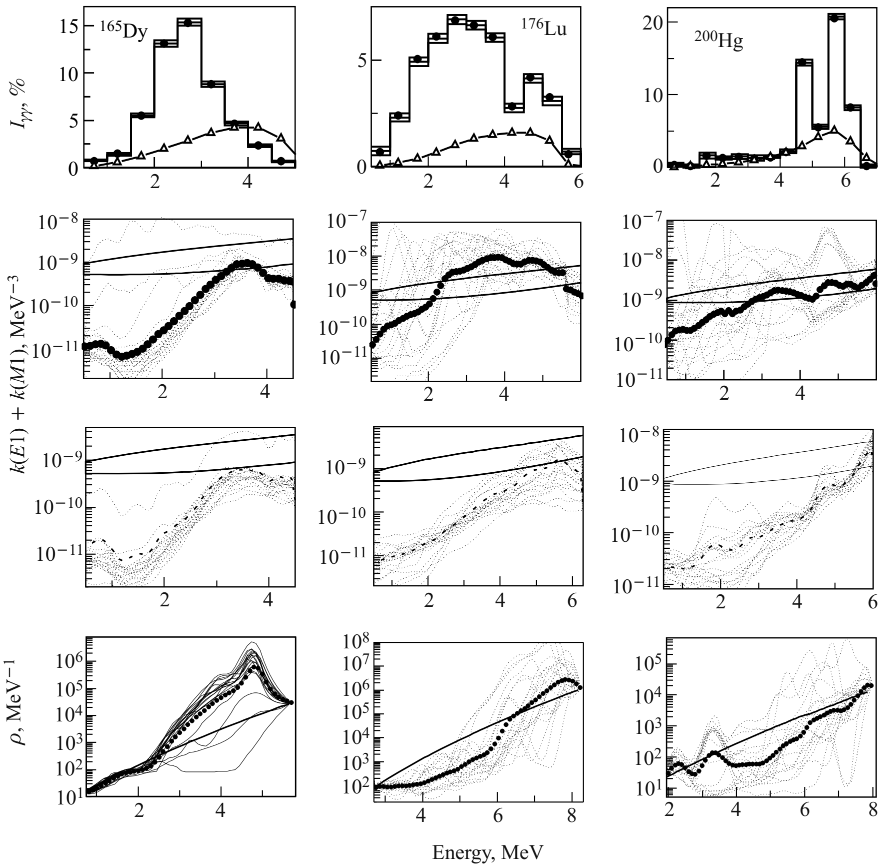

Fig. 1. The examples of experimental distributions of cascade intensities approximation by random functions $\rho = \psi(E_{\mathrm{ex}})$ and $k = \phi(E_1)$. Upper row: histogram — experimental data, filled circles — typical approximation, triangles — initial spectra for models [21, 22] and $k(M1) = \mathrm{const}$. The second and third rows — sum of strength functions $E1$ and $M1$ transitions (dotted curves — random functions; dark and dashed lines correspond to (6) and (7); lines — model data from [10, 11, 22]). Bottom row — the most probable density of intermediate levels of two-step cascades (dotted curves — random functions, dark points — their mean value, solid line — data from [22]). The very strong change of $I_{\gamma\gamma}$ in the function of nucleus mass is influenced by the structure of levels connected to cascade gamma transitions

parities excited by these transitions, correspondingly. In practice, it is impossible to reproduce this very complicated picture of gamma-decay process because of lack of necessary experimental data. Therefore, the condition (5) was used for transitions of any type ending at levels near U_n.

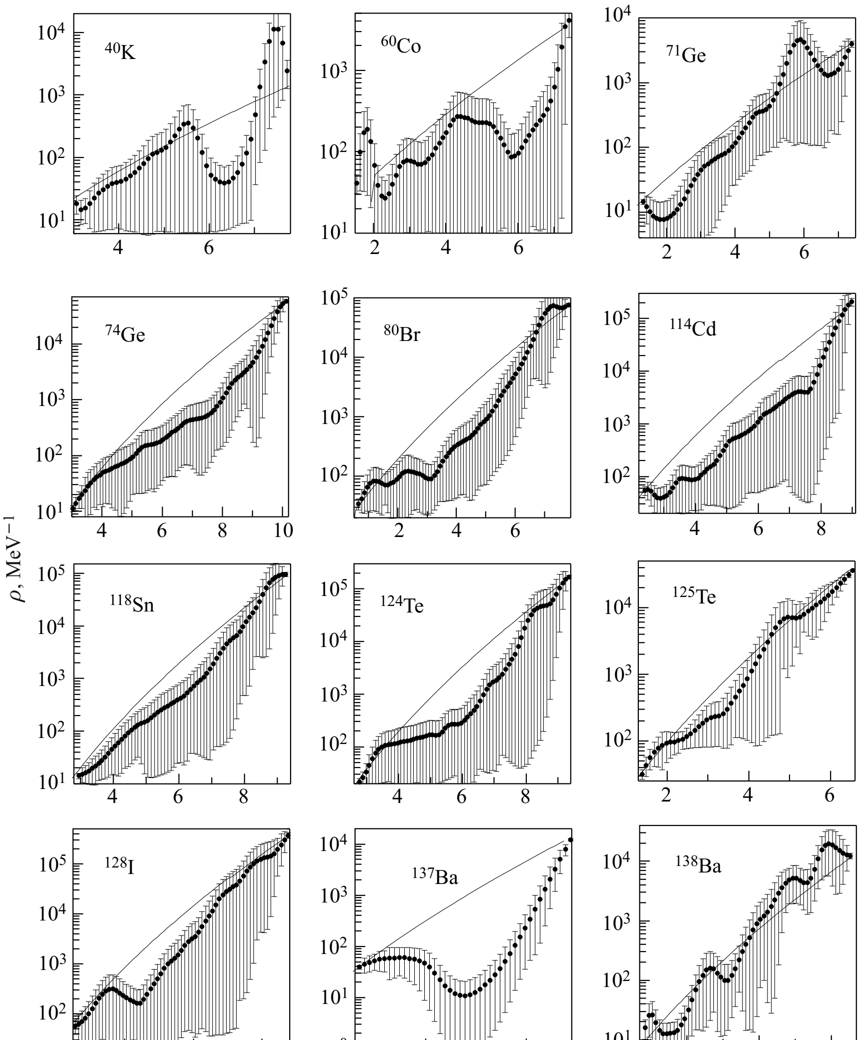

Fig. 2. Points with error bars — mean value of density of intermediate levels of two-step cascades in ^{40}K, ^{60}Co, ^{71,74}Ge, ^{80}Br, ^{114}Cd, ^{118}Sn, ^{124,125}Te, ^{128}I and ^{137,138}Ba. Thin solid lines — level density of Fermi-gas model

The examples of the obtained sets of functions ρ and K, providing typical quality of approximation of the experimental intensity are given in Fig. 1. The scatter of random values $\rho_{\rm exp}$ and $K_{\rm exp}$ is large and brings to obvious shift of level

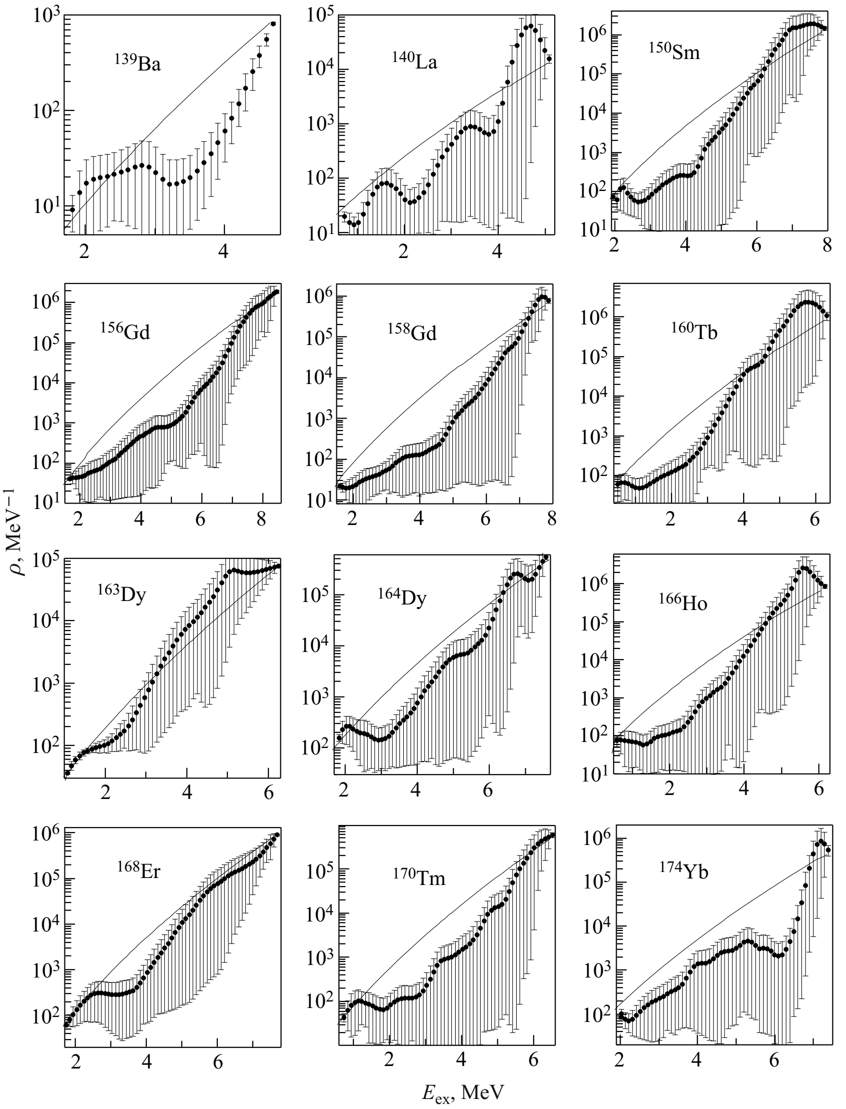

Fig. 3. The same as in Fig. 2, for ^{139}Ba, ^{140}La, ^{150}Sm, ^{156,158}Gd, ^{160}Tb, ^{163,164}Dy, ^{166}Ho, ^{168}Er, ^{170}Tm and ^{174}Yb

density in direction of maximal values at determination of their mean values as the average values of functions $\rho_{\rm exp} = \psi(E_{\rm ex})$ and $k_{\rm exp} = \phi(E_1)$. Therefore, in given variant of analysis, logarithms of the level density (practically — entropy

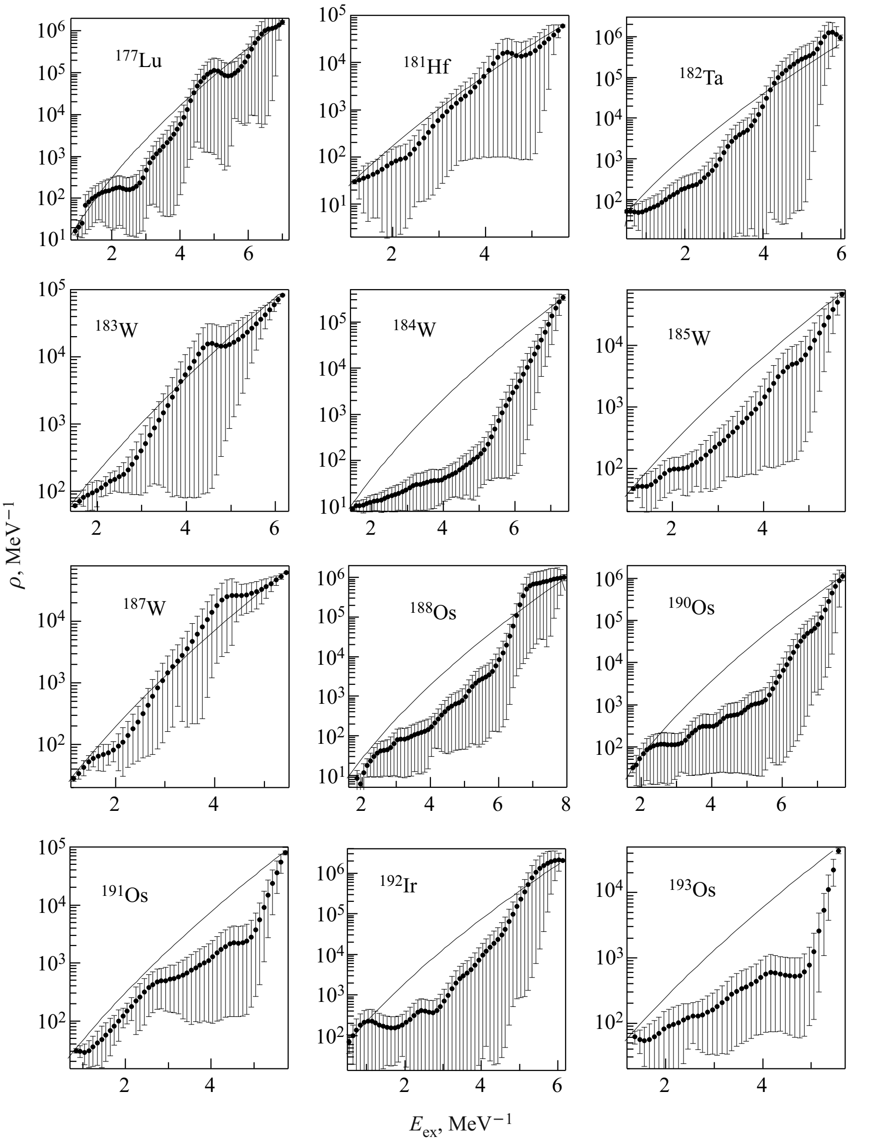

Fig. 4. The same as in Fig. 2, for ^{177}Lu, ^{181}Hf, ^{182}Ta, ^{183,184,185,187}W, ^{188,190,191,193}Os and ^{192}Ir

of nucleus) and strength functions were averaged. It is seen from Fig. 1 that the number of deviations from mean value is approximately equal at such an averaging. Besides, the difference between values of $\rho_{\rm exp}$ and $K_{\rm exp}$ obtained

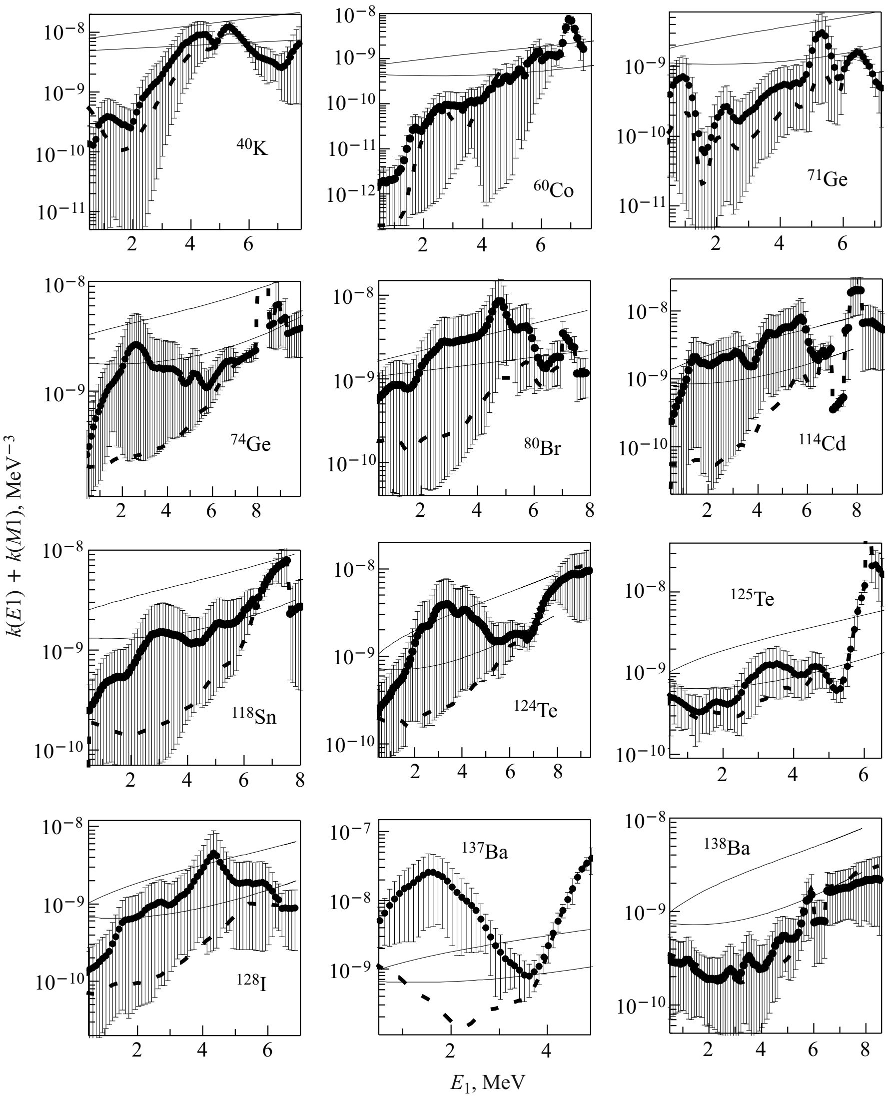

Fig. 5. Dark points — mean value of sum of radiative strength functions according to (6). Dashed lines — the same for determination (7) for ^{40}K, ^{60}Co, ^{71,74}Ge, ^{80}Br, ^{114}Cd, ^{118}Sn, ^{124,125}Te, ^{128}I and ^{137,138}Ba. Thin solid lines — model values according to [10, 11] in sum with $k(M1) = \mathrm{const}$

by such a variant of their determination with the one variant is minimal as well. Moreover, in region of neutron binding energy, for some nuclei above model value

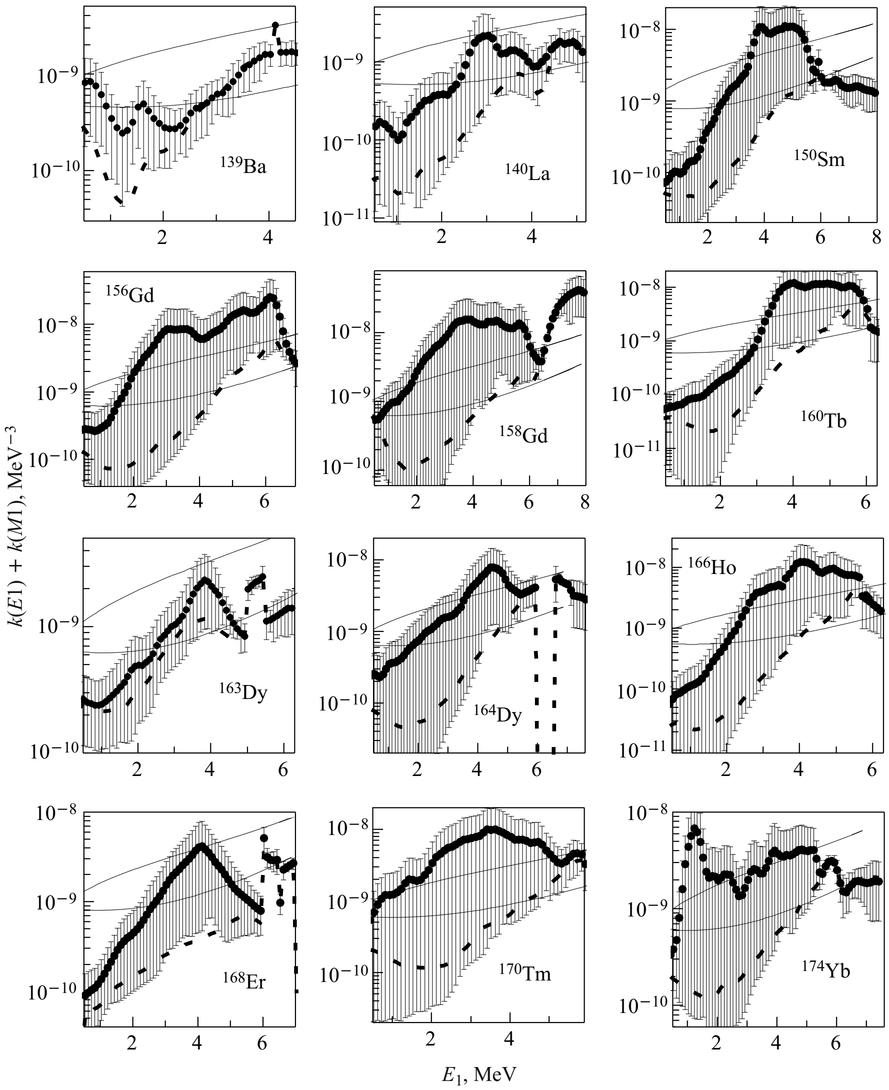

Fig. 6. The same as in Fig. 5, for ^{139}Ba, ^{140}La, ^{150}Sm, ^{156,158}Gd, ^{160}Tb, ^{163,164}Dy, ^{166}Ho, ^{168}Er, ^{170}Tm and ^{174}Yb. Upper lines are predictions of [10, 11], lower lines — [23]

$\rho_{\rm fg}$ is the very strong exceeding of $\rho_{\rm exp}$ disappeared or considerably decreased as compared with the data from [1, 2].

The appearance of disagreement between $\rho_{\rm exp}$ and $\rho_{\rm fg}$ below and near B_n for the same nucleus can be related also with difference in the process of energy

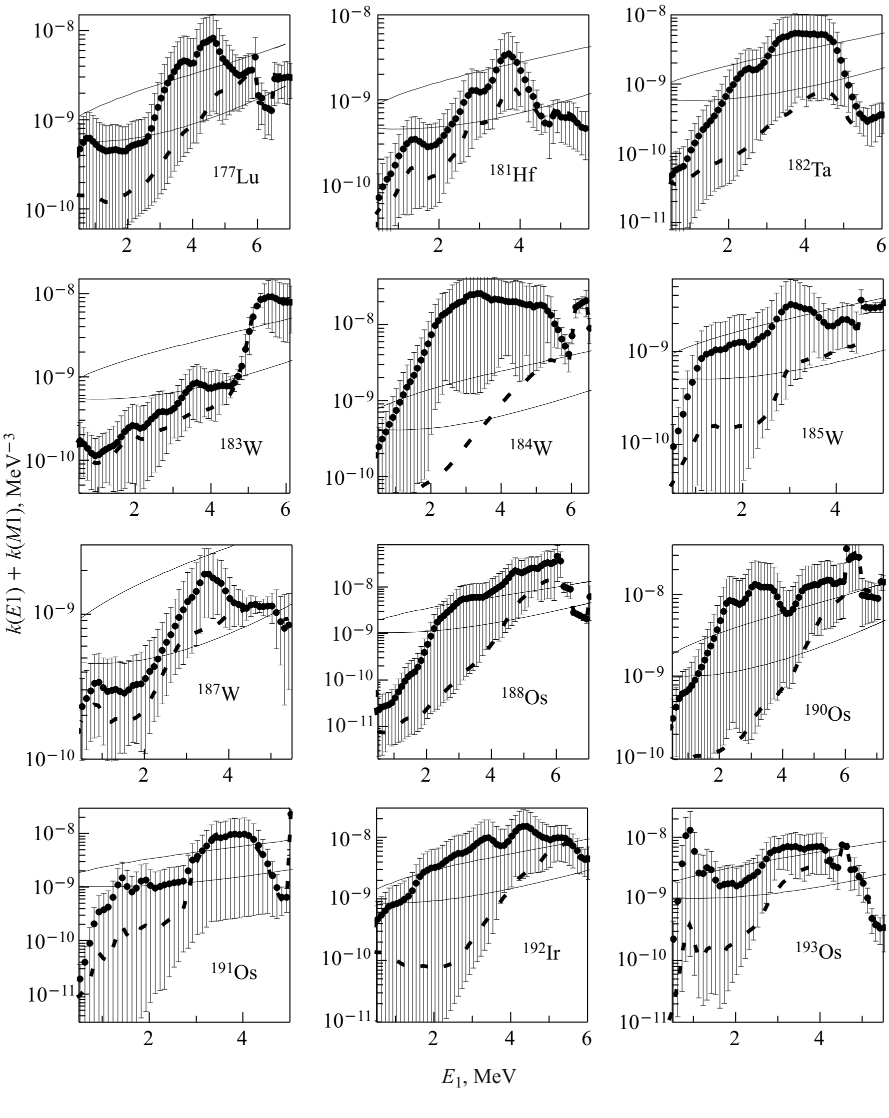

Fig. 7. The same as in Fig. 5, for ^{177}Lu, ^{181}Hf, ^{182}Ta, ^{183,184,185,187}W, ^{188,190,191,193}Os and ^{192}Ir

exchange between quasi-particles and phonons in different isotopes of the same element, or with close appearance probabilities in different variants of calculation of very strong step-like structures. In such an assumption — at different excitation

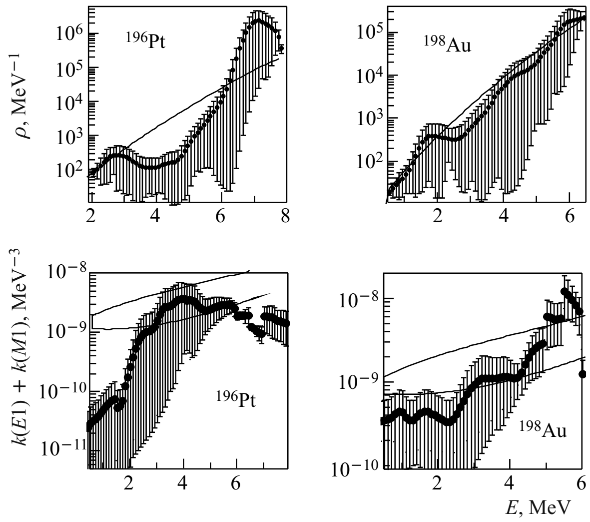

Fig. 8. The same as in Figs. 2 and 5, for ^{196}Pt and ^{198}Au

energies of a nucleus, or with omission of large amount of very small neutron resonances and corresponding potential ambiguity of estimation of spacing [23] of omitted resonances and so on.

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 a fact of obvious presence of sharp change in structure of nuclei levels of different type, which at present can be interpreted as break of the 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 followed 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 levels with large vibration components of wave functions. Respectively, such a 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.

The remaining unsolved problems require complex study of parameters of de-excitation process in two-step reactions with registration of evaporated nucleon at the first step, as well as in the experiments with registration of cascades with three and more gamma transitions. There are no technical obstacles for this [20, 24]. The expected maximally reliable data on the level density of nuclei in the range of excitation energy up to the neutron binding energy, is that they can give complete enough and reliable picture of dynamics of nucleus transition from superfluid to usual state.

REFERENCES

1. *Vasilieva E. V., Sukhovoj A. M., Khitrov V. A.* // Phys. At. Nucl. 2001. V. 64. P. 153.
2. *Sukhovoj A. M., Khitrov V. A.* // Phys. Part. Nucl. 2005. V. 36. P. 359.
3. *Khitrov V. A., Chol Li, Sukhovoj A. M.* // Proc. of the XI Intern. Seminar on Interaction of Neutrons with Nuclei, Dubna, May 2003. Dubna, 2004. P. 98; *V. A. Khitrov et al.* nucl-ex/0404028.
4. *Bohr A., Mottelson B. R.* Nuclear Structure. V. 1. N. Y., Amsterdam: W. A. Benjamin, 1969.
5. *Vonach H.* // Proc. of IAEA Advisory Group Meeting on Basic and Applied Problems of Nuclear Level Densities, N. Y., 1983; INDC(USA)-092/L, 1983. P. 247.
6. *Bartholomew G. A. et al.* // Adv. Nucl. Phys. 1973. V. 7. P. 229.
7. *Zhuravlev B. V.* // Bull. Rus. Acad. Sci. Phys. 1999. V. 63. P. 123.
8. *Schiller A. et al.* // Nucl. Instr. Meth. A. 2000. V. 447. P. 498.
9. *Sukhovoj A. M., Khitrov V. A.* // Proc. of the XVII Intern. Seminar on Interaction of Neutrons with Nuclei, Dubna, May 2009. Dubna, 2010. P. 268; nucl-ex/1009.4761.
10. *Axel P.* // Phys. Rev. 1962. V. 126. P. 671.
11. *Brink D. M.* Ph. D. Thesis. Oxford University, 1955.
12. *Soloviev V. G.* // Sov. Phys. Part. Nucl. 1972. V. 3. P. 390.
13. *Khitrov V. A., Sukhovoj A. M.* // Proc. of the XVIII Intern. Seminar on Interaction of Neutrons with Nuclei, Dubna, May 2010. Dubna, 2011. P. 180.
14. *Voinov A. V. et al.* // Phys. Rev. 2010. V. 81. P. 024319.
15. *Sukhovoj A. M., Khitrov V. A.* JINR Preprint E3-2005-196. Dubna, 2005.
16. *Sukhovoj A. M., Khitrov V. A.* // Phys. Part. Nucl. 2006. V. 37. P. 899.
17. *Sukhovoj A. M., Khitrov V. A.* // Phys. At. Nucl. 2010. V. 73. P. 1507.
18. *Strutinsky V. M.* // Proc. of the Intern. Congress on Nuclear Physics, Paris, 1958. P. 617.
19. *Sukhovoj A. M., Khitrov V. A.* // Phys. At. Nucl. 2009. V. 72. P. 1759.
20. *Pronyaev V. G. et al.* // Sov. J. Nuc. Phys. 1979. V. 30. P. 310.
21. *Dilg W. et al.* // Nucl. Phys. A. 1973. V. 217. P. 269.

22. *Kadmenskij S. G., Markushev V. P., Furman W. I.* // Sov. J. Nucl. Phys. 1983. V. 37. P. 165.
23. *Khitrov V. A., Sukhovoj A. M.* // Proc. of the XVIII Intern. Seminar on Interaction of Neutrons with Nuclei, Dubna, May 2010. Dubna, 2011. P. 216.
24. *Furutaka K. et al.* // Proc. of the Intern. Conference on Nuclear Data for Science and Technology 2007, Nice, France, 2007. P. 517.

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