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PARTIAL LEVEL DENSITY OF THE
n-QUASIPARTICLE EXCITATIONS
IN THE NUCLEI OF THE $40 \leq A \leq 200$ REGION

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Парциальные плотности уровней n -квазичастичных возбуждений ядер в области $40 \leq A \leq 200$

Из анализа интенсивностей двухквантовых каскадов, возбуждаемых при захвате тепловых нейтронов, получены значения плотности уровней и сумм радиационных силовых функций каскадных гамма-переходов. Полученные значения плотностей уровней аппроксимированы суммой парциальных плотностей уровней, соответствующих возбуждению n -квазичастиц. Найдены наиболее вероятные значения коэффициента коллективного увеличения плотности уровней и порогов разрыва очередной куперовской пары нуклонов. Полученные данные позволяют просто и максимально точно рассчитать плотность уровней практически любого ядра в заданном спиновом окне в рамках модельных представлений, учитывающих все три известных типа ядерных возбуждений.

Наличие заметного несоответствия результатов аппроксимации с теоретическими представлениями указывает на необходимость довольно существенной модификации моделей плотности уровней. Оно указывает также на возможности прямого получения из эксперимента принципиально новой информации о корреляционных функциях нуклонов возбужденного ядра.

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Partial Level Density of the n -Quasiparticle Excitations in the Nuclei of the $40 \leq A \leq 200$ Region

Level density and radiative strength functions are obtained from the analysis of two-step cascades intensities following the thermal neutron capture. The data on level density are approximated by the sum of the partial level densities corresponding to n -quasiparticle excitations. The most probable values of the collective enhancement factor of the level density are found together with the thresholds of the next Cooper nucleons pair breaking. These data allow one to calculate the level density of practically any nucleus in given spin window in the framework of model concepts, taking into account all known nuclear excitation types. The presence of an approximation results discrepancy with theoretical statements specifies the necessity of rather essentially developing the level density models. It also indicates the possibilities to obtain the essentially new information on nucleon correlation functions of the excited nucleus from the experiment.

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

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INTRODUCTION

First of all, obtaining data on the level density ρ and radiative strength functions k emission of nuclear reaction products is a way to universally test nuclear models. Their accuracy is quite unequivocally limited by the experimental data quality used for both creation of new modeling representation and for its parameterization. Naturally, the experimental data used for this purpose should be the most reliable. At present, for evaluating of neutron cross sections it is required that there is a high reliability of modeling representations on the level density in a wide nucleus excitation energy interval [1]. It is also important for describing their fission process [2]. It means they are needed for quite practical applications of nuclear physics. Thus, materials' and nuclear power cycle fuel's profitability and safety directly depend on the accuracy of their cross-section evaluation.

The history of developing the techniques for experimental determination of ρ covers several decades, but the significant part of the experimental data obtained up to now has too large systematical error, which is essentially unavoidable within the framework of existing experimental analysis algorithms. It is connected to extraction peculiarity of the level density and radiative strength functions from experimentally measured spectra. This regards the situation, when the insufficient resolution of nuclear reaction products, provided by the existing spectrometers, does not allow one to resolve the individual levels of a nucleus. In wide energy intervals, where the nuclear reaction products are registered, the intensity of spectra simultaneously depends on both ρ and k . Errors transfer results in a large increase of systematical errors in the found values. It always occurs when there are systematical experimental errors of the measured spectra and the strong correlation of parameters.

Currently, there is a set of various advanced modeling representations [3] for predicting both the level density and the radiative strength functions of the primary gamma transitions following compound-state decay. However, the accuracy of k values, calculated with their help, is unknown for the low-energy primary gamma transitions following neutron resonance decay. Therefore, contemporary techniques, in which parameters of a nucleus are extracted from the measured spectra of the nuclear reactions gamma rays, can provide no high accuracy for

either level density or the radiative strength functions. It is impossible if the modeling representations on one of these values are used to determine the other.

These circumstances demand an obligatory revealing of all of the most essential systematical errors of ρ and k certain values by comparing any model representation with the experiment.

1. SYSTEMATICAL ERRORS OF THE LEVEL DENSITY AND RADIATIVE STRENGTH FUNCTIONS IN THE EXPERIMENTS OF VARIOUS TYPES

By present time four different techniques to determine functional dependence of the level density are realized. They are based on the following experimental data:

- 1) Nuclear evaporation spectra in reactions of various types;
- 2) Full spectra of gamma transitions for various energies of the decaying levels;
- 3) Intensities of the two-step cascades appearing at the thermal neutrons capture;
- 4) Distribution of the random intensity values of individual energetically resolved two-step cascades with the energy of their intermediate level $E_i < 0.5B_n$.

Here, it is necessary to add a completely independent technique of [4] to determine the deviation sign of the experimental level density from any model prediction. The corresponding analysis uses the data on random fluctuations of the intensity ratios of secondary gamma transitions at the resonance neutron capture. Its results obviously contradict the conclusions of the 1st and 2nd techniques and qualitatively confirm the basic of the 3rd and 4th methods that the level density is smaller than that given by the present standard models.

As is stated above, all specified techniques always result in ρ and k values having unknown systematical errors. The most exact of their estimation can be obtained only by comparing their values, determined in various and complementary independent experiments. The comparison quite uniquely shows that the level density in the region of the half of neutron binding energy, found within the framework of the first two techniques is $\sim 3 - 5$ times (in a number of nuclei and more) larger than that determined according to the 3rd and 4th algorithms. At lower and higher excitation energies this discrepancy decreases because densities of resolved low-lying levels and of neutron resonances are always normalized to the same values in techniques 1–3.

Thus, during development and parameterization of ρ models, results of application of the level density, obtained by using of the listed above techniques, may bring to rather fallacious ideas about this parameter of a nucleus.

1. Practically, all theoretical models of level density [3] are completely developed on the base of the experimental data on ρ , obtained similarly to [5] from evaporation spectra of nucleons or light nuclei in various nuclear reactions. In order to determine the experimental level density, the model-set values of transmission coefficient T of a nucleus surface have been used for the emitted nucleons or light nuclei. Up to present the analytical method of an optical model of a nucleus is used for its determination, providing that there is no determinate choice of nuclear potential used for calculation. It is necessary to take into account, that 283 various parameterizations of optical potential were developed to describe the neutron–nucleus interaction process; 101 — for proton, correspondingly [3]. Such a quantity of entrance factors needed for calculation of the transmission coefficient in reaction (n, p) [5] serves as a serious reason for assuming that there are very big errors in extraction of level density by means of the first technique. Naturally, determination of level density with the minimal error requires one to calculate T values within the framework of nuclear models with the guaranteed accuracy which exceeds that needed for ρ determination. The latter, by magnitude scale, may be equaled to the modern accuracy of observation of the spectrum intensity. In the worst case it makes some tens of percents. Currently, such an accuracy of T calculation is most likely unattainable, even if not only the optical model of a nucleus, but also more modern nuclear models are used. As a bright example, it is possible to indicate the comparison of calculated and experimental values of strength functions of (d, p) - or (d, t) -type reactions. Now it is fulfilled for many nuclei in experiments with high resolution at the Tandem Accelerator of the University and Technical University of Munich up to the approximately half of neutron binding energy. In all cases, the significant information on the excited level structure, which allowed one to make a comparison of the nuclear theory with the excitation energy of up to several MeV, is obtained in these experiments. Such techniques as in Ref. [5] do not take this fact into account.

The comparison of (see, for example, [6]) the results obtained in Munich with calculations within modern nuclear models shows that details of a fragmentation process of any states of nuclear potential over real levels with excitation energy up to several MeV can be reproduced only with a significant error. First of all, this circumstance is caused by an insufficient accuracy of the notions incorporated in the modern model on the nature of the nucleons interaction in a nucleus, as well as by the inevitable approximations of its account in anyone of them. The uncertainty of parameterization of the concrete nuclear models (optical, quasiparticle-phonon, models of interacting bosons and fermions, etc.) always brings an additional error to the process of determining [5] ρ with the help of calculated T values. First of all, it is pointed out by the unavoidable and rather significant discrepancy between the experimental and model-calculated values of energies even for the most low-lying levels of the simplest structure. Moreover, it is also emphasized

by the essentially greater one at the calculation of the nucleus parameters in case when excitation energy is higher than 1–3 MeV.

Discrepancy between the notions of the level density extraction from the nuclear evaporation spectra and the technique of determining the excited level structure by the level excitation probability in nuclear reactions is a principal one. Basic thesis of a technique [6] follows from the experiment and cannot cause doubts. Reasoning from this, the existence of big systematical errors in T calculation is expected in case of using the theoretical models for the experimental determination of the level density from the evaporation spectra [5].

One should not exclude a possibility of another explanation of a discrepancy of ρ values determined by the first and the third techniques. For example, it may occur if a discrepancy of model notions and the experiment for spin dependence of the level density is not taken into account at energies lower than several MeV. Particularly, as there is a possible, but theoretically unconsidered, strong dependence of collective enhancement factor in level density on a level's spin [3]. If such an appreciable effect exists, it is displayed for spins J exceeding ~ 6 . It follows from maximal spin values of neutron resonances in ^{150}Sm , ^{177}Lu and from ρ value obtained for these and other nuclei.

2. Very serious and, probably, unsolvable problems arise at determination [7, 8] of ρ and k parameters of the cascade gamma-decay process of the nucleus from the gamma-ray spectra S of any nuclear reactions, in which the nucleus product is excited up to the energy of 5–8 MeV and higher.

Rather simple modeling [9] of process of transferring errors δS of the determination of the total gamma-spectra intensity into that of primary gamma transitions [7], subsequently extracting the values of the level density and radiative strength functions has shown that the value of $\delta\rho/\rho \leq 40 - 50\%$ can be obtained within the framework of type procedure [8]. But it is possible only under the condition of all relative systematical errors of the measured gamma spectra belonging to the region $\delta S/S < 0.001 - 0.003$ for all energies of emitted gamma transitions and depopulated levels. This conclusion is just, at least, for the case of monotonous increasing or decreasing of the systematical errors δS as the nucleus excitation energy changes. Such an accuracy of measuring the intensity of total gamma spectra by means of scintillation detectors is most likely unattainable at present. It appears so, both because of the instability of their work, and of the impossibility of such an exact subtraction of Compton background from the instrumental spectra. Besides, in case when there is a nucleus with the high level density, the subtraction errors are the greatest.

Additional and very essential systematical errors in the data for ρ and k , obtained by means of a technique of the primary gamma-transition spectra determination [7] in corresponding experiments, are conditioned by its authors applying their own [8] algorithm for searching the maximum of likelihood function. It is used instead of the updates of Gauss method developed for completely similar

cases and well tested by mathematicians. It is impossible to estimate the systematic errors related to it, as the method [8] can provide no information on position and value of its false maxima unlike the modern variants of Gauss method.

The assumption stated in [8] deals with the equality of radiative strength functions of gamma transitions of equal multipolarity and energy for depopulating levels with different energies. It contradicts the basic ideas of modern nuclear models (see, for example, [10]) and results in the unknown systematic errors occurring both in ρ and k .

Therefore, there is a necessity to develop the essentially new techniques for ρ and k determination. These should provide their extremely possible reliability. As mentioned above, such techniques cannot be created on the basis of any of the model notions for obtaining the experimental values of level density and radiative strength functions used both separately and combined. That is why any of the newly developed techniques should be both model-independent, and determine the level density and radiative strength functions of the reaction emission products. It should be simultaneously accompanied with providing the data accuracy of the modern experiment for the whole of the excitation energies range of the studied nucleus from the most suitable, for this purpose, reaction product spectra. This operation should be realized within the framework of the insufficient opportunities (for the guaranteed problem solution) and of essential limitations of a mathematical statistics algorithm developed for such purposes. Exactly at this stage of determination of the investigated phenomenon parameters from strong correlating experimental data there appear the most serious systematic errors for both level density and radiative strength functions. It should be noted that in the mathematical expressions, describing the experimental spectra, the nonlinearity of the sought parameter connection is exactly responsible for the significant reduction of the area of pair parameter values with a hundred-percent correlation concerning a case of the linear equation systems. On this account, the degenerate systems of the nonlinear equations can have infinite number of solutions, all of which are in the limited intervals of their values.

2. THE POTENTIAL OF MODERN EXPERIMENT TO PRECISELY DETERMINE THE MAIN PARAMETERS OF A NUCLEUS

On one hand, proceeding from the basic principles of mathematical statistics, the extraction of a number of unknown parameters from the data of an experiment demands a superfluous number of values to be determined in its course. On the other hand, the system of the sought parameter functional connections with the measured values has to provide both unambiguity of determination and minimum of errors of the sought values. Most likely, these two conditions cannot be satisfied in cases of obtaining the level density ρ from evaporation spectra [5] of

any nuclear reactions or the radiative strength functions k both from total spectra [7] of gamma-rays following neutron radiative capture and from nuclear reactions at the charged particle beams [8].

Therefore, the experimental data of other type are necessary in order to get main nuclear parameters with higher accuracy than achieved at present. The analysis [11] of the experimental data on cascade gamma decay of one (or several) of the highly excited levels (compound states), fixed at energy B_n , satisfies the listed above requirements to the maximal degree. First of all, these are the two-step cascade intensities

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

following the thermal neutron radiative capture, connecting a compound state λ and a group of low-lying levels f , in function [12] of energies E_1 of their primary gamma transition. Nucleus excitation energy (energy of the intermediate level of the cascade E_i) is unambiguously determined by energy E_1 : $E_i = B_n - E_1$. Cases of full absorption of the two-step cascade gamma-transition energy, necessary for the experimental definition of $I_{\gamma\gamma}$, are concentrated in the narrow peaks of the sum coincidence spectrum (Fig. 1) obtained with the help of ordinary HPGe-detectors.

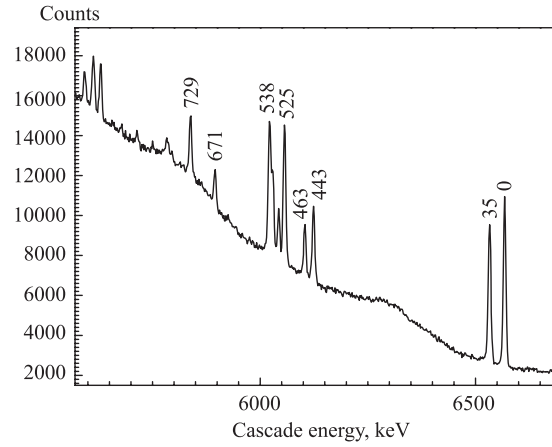


Fig. 1. The main part of the sum coincidence spectrum for the target enriched in ^{124}Te is presented. Full energy peaks are labeled with the energy (in keV) of final cascade levels

In the same experiment an inevitable background is measured with the maximal possible accuracy.

Functional (1) depends both on ratio of partial and total radiative widths Γ of primary E_1 and secondary E_2 gamma transitions of cascades between levels λ , i and f and on number of levels $n(m) = \rho \times \Delta E$ excited in different energy

intervals ΔE . A degree of detailed elaboration of finding the form of energy dependence the level density and radiative strength functions is determined by the optimum interval width of an averaging-out of cascades intensities. Technically, its limiting value equals the HPGe-detector resolution. However, combined with the inevitable partial width fluctuations, real capabilities of the modern detector and computer facilities limit ΔE interval width, over which nucleus excitation energy of 50 keV value (or a little larger) is distributed.

Cascade transition type (dipole electric or magnetic) and an excited intermediate level i spins and parity are unequivocally determined by known J^π values of λ and f levels. Practical absence of cascades between levels with $|J_\lambda - J_f| > 2$ excludes the necessity of accounting for transitions with higher multipolarities in analysis like [11]. For convenience of direct comparison of the obtained radiative strength functions with $E1$, and $M1$ transitions in nuclei with different mass A , it is appropriate to determine them in the following form:

$$k = \Gamma_{\lambda i} / (E_\gamma^3 \cdot A^{2/3} \cdot D_\lambda) \quad (2)$$

and to use their ratios $k(M1)/k(E1)$ for mutual normalization of data, experimentally measured near B_n .

Intensity of cascades in expression (1) is proportional to a derivative dk/dE and, as a first approximation, it is inversely proportional to ρ . It provides the maximal sensitivity of the experiment in the range of ρ lowest values. So, in the field of excitation energy, the influence of the nuclear structure on parameters of studied nuclear reaction should be maximal. The essentially new connection type between the sought parameters, compared with the ordinary evaporation and gamma spectra, provides smaller influence of correlation parameters on their real error.

The specified experiment has two sources of the ordinary, but potentially rather significant, systematical errors. They are connected to a possibility:

a) Full compensation of a divergence between the experimental and calculated intensity values of the cascades with primary transitions E_1 by a divergence of an intensity opposite sign of cascades with secondary transitions from the same energy intervals and

b) Presence of an excessive systematical error at the normalization of $I_{\gamma\gamma}$ intensities.

The first type error is related to the impossibility of instrument determination of the quanta ordering in the bulk of observed cascades. To full extent it is visible in analysis [13], using for extraction of the information on ρ and/or k the fact that the intensities directly observed in the experiment and calculated for different tested functional dependences of parameters are equal to their values for all cascade quanta energies. According to [9] this error leads to that the experimental spectra can be precisely reproduced by the level density and the

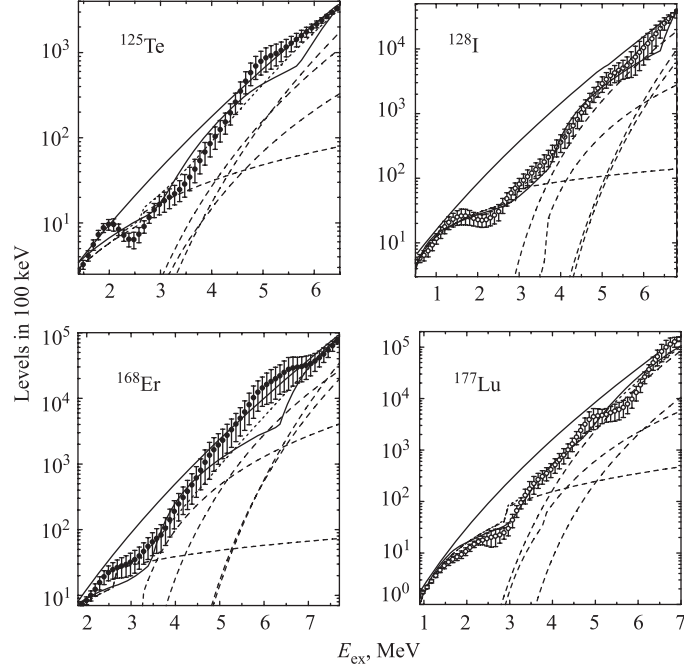


Fig. 2. Examples are shown of the experimental data on approximation for nuclei ^{125}Te , ^{128}I , ^{168}Er and ^{177}Lu by the partial level density in the first variant of the analysis. Full points with error bars represent the experimental data of [20], open points show the data of [11]. A thin dotted line indicates partial density, points display their sum. A solid line presents the sum of the partial level density from the second variant of the analysis. Thin line stands for the level density calculated within the model of [29]

radiation strength functions distinguished from the sought ones by several tens of times. The indicated error is practically reduced to zero only in the case, when the intensity of cascades in function of their primary transition energy is determined from the experimental spectra [12]. The corresponding algorithm uses the experimentally proved fact: even in nuclei with the maximal level density there are pairs of energetically resolved peaks, corresponding to the cascades with $E_i < 3 - 5$ MeV, which concentrate the main part of sum cascades intensity. A threshold of their intensity registration is much less than the average value even when rather ordinary detectors are used. Cascades with primary gamma transitions from the same energy interval are registered mainly in the form of continuous distribution of small amplitude. Total background in any experimental spectra of two-step cascade intensities is equal to a determination error of a substrate under peaks of full capture of the cascade energy by the HPGe-detectors (Fig. 1).

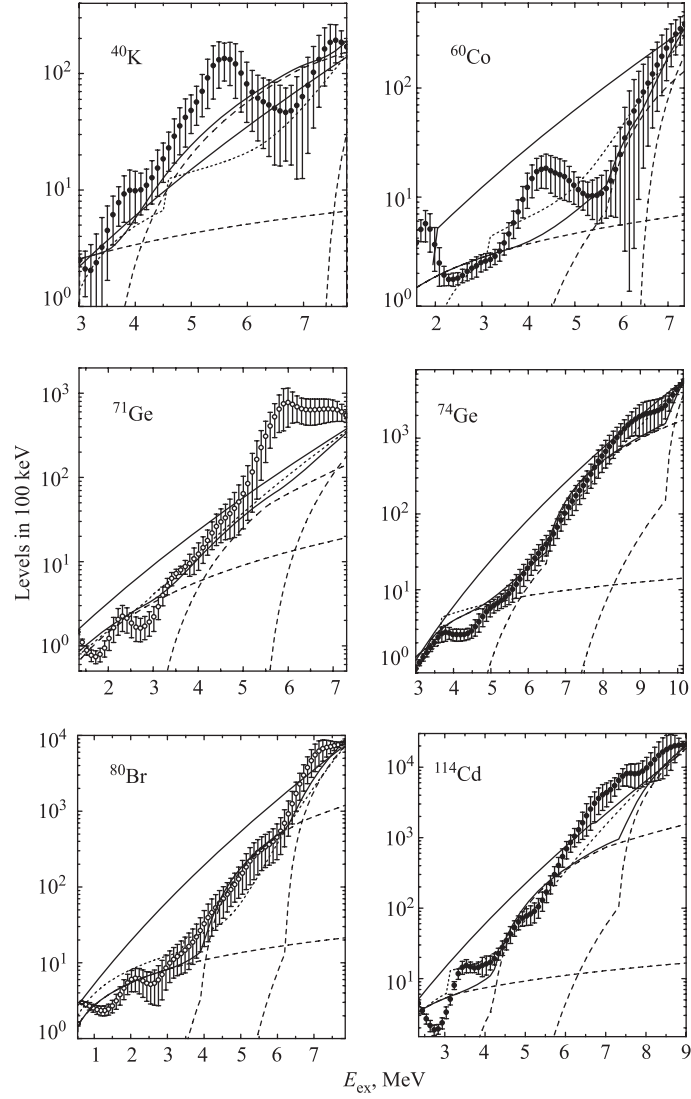


Fig. 3. The same as in Fig. 2, for nuclei: ^{40}K , ^{60}Co , $^{71,74}\text{Ge}$, ^{80}Br , ^{114}Cd . Here, the partial level densities obtained from the second variant of the analysis are shown

Practically, very exact algorithm, realized in [14] in combination with the results obtained by nuclear spectroscopy, allows one to determine the quanta ordering with high accuracy. Consequently, it makes possible for one to find the form of

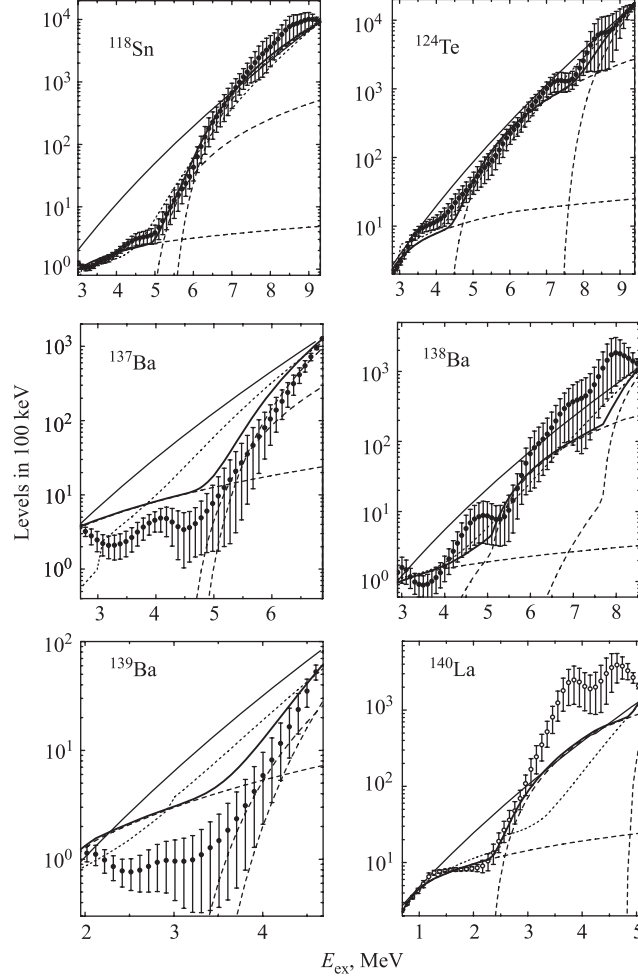


Fig. 4. The same as in Fig. 2, for nuclei: ^{118}Sn , ^{124}Te , $^{137,138,139}\text{Ba}$, ^{140}La

energy dependences of experimental values $I_{\gamma\gamma}(E_1)$ with a relative systematical error less than 0.01–0.05 [15].

The approximation of distribution of the resolved cascades intensity random values in small energy intervals of their intermediate levels allows (see [15]) both determination of the corresponding error $\delta I_{\gamma\gamma}$ and direct estimation of the most possible level density at any energy interval of cascade intermediate levels below $\approx 0.5B_n$. It happens within the framework of a hypothesis by Porter–Thomas law on fluctuations of the primary transition intensities with the subsequent ex-

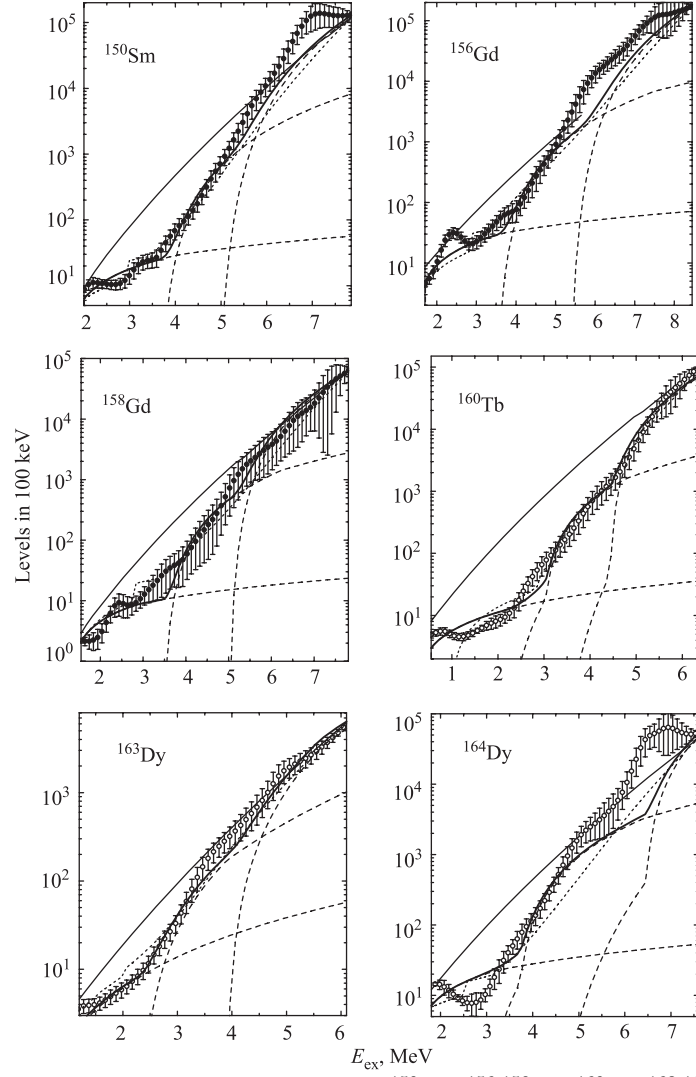


Fig. 5. The same as in Fig. 2, for nuclei: ^{150}Sm , $^{156,158}\text{Gd}$, ^{160}Tb , $^{163,164}\text{Dy}$

trapolation of the approximated distribution below gamma-quantum registration threshold. In all of the analyzed nuclei the level density either practically coincides with the data from [11], or differs from the latter much less, than that measured with techniques from [5] and [8].

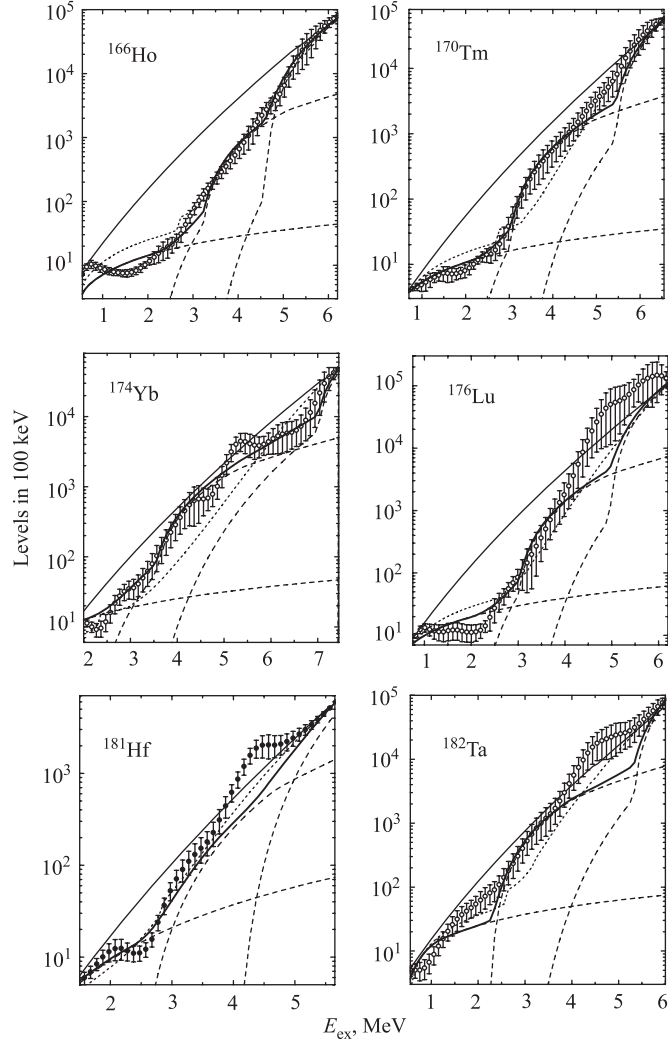


Fig. 6. The same as in Fig.2, for nuclei: ^{166}Ho , ^{170}Tm , ^{174}Yb , ^{176}Lu , ^{181}Hf , ^{182}Ta

Practically, expected systematical error $\delta I_{\gamma\gamma}$ of the intensity cascades used in a technique of Ref. [11] is almost fully determined by an error of measuring of the most intense primary gamma transitions of cascades with low-lying intermediate levels. Comparison of the corresponding data from [16] and [17] shows that its value can be estimated as $\approx 10 - 20\%$. Coefficients of an error $\delta I_{\gamma\gamma}$ transfer onto

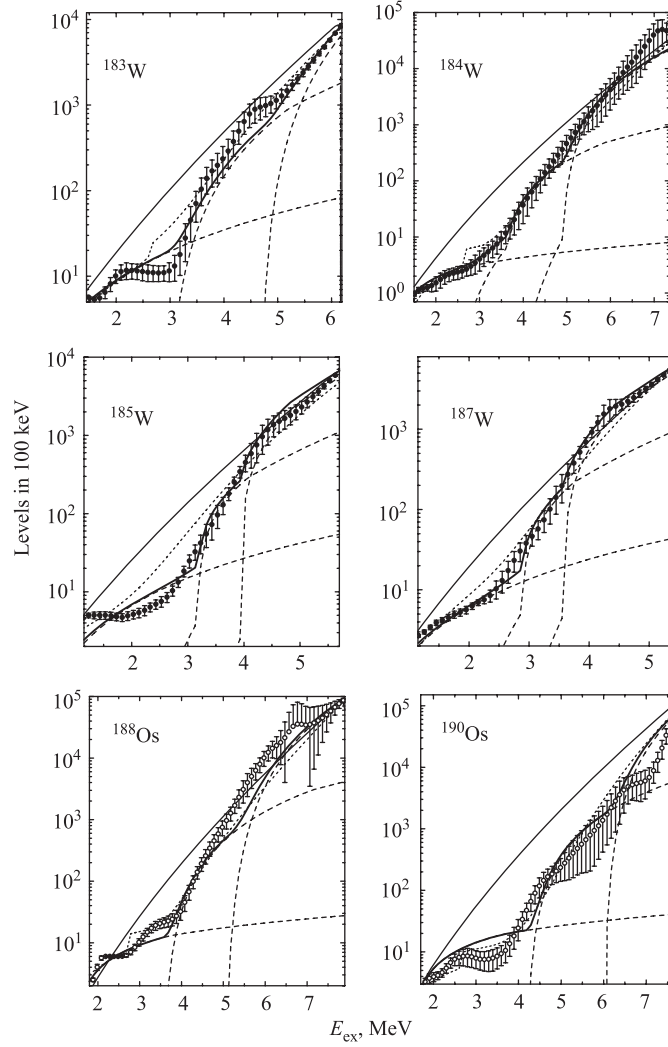


Fig. 7. The same as in Fig. 2, for nuclei: $^{183,184,185,187}\text{W}$, $^{188,190}\text{Os}$

the values $\delta\rho$ and δk are estimated in [18] for even-odd isotopes of tungsten and osmium. It was made for all of their excitation energy values. An error variation in an interval of $-25\% \leq \delta I_{\gamma\gamma}/I_{\gamma\gamma} \leq 25\%$ changes values, found for the level density below $0.5B_n$, less than by 2 times, and for radiative strength functions — less than by 3 times.

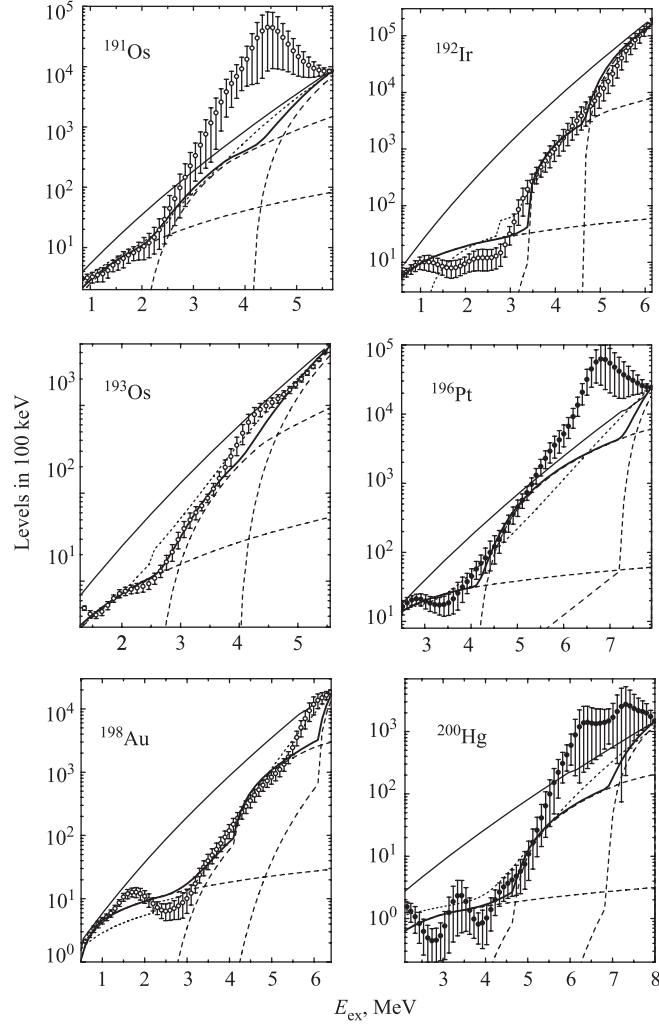


Fig. 8. The same as in Fig. 2, for nuclei: ^{191}Os , ^{192}Ir , ^{193}Os , ^{196}Pt , ^{198}Au , ^{200}Hg

It should be noted that the error in determining of $I_{\gamma\gamma}$ can be larger than $\pm 25\%$ in the nuclei where the thermal neutron capture cross section was measured with the big relative uncertainty. In these cases, the amplitude of the expected relative errors of level density and radiative strength functions can significantly increase as compared with the results obtained in [18]. For some nuclei [6], this problem can be completely removed by comparison of the measured gamma-

transition intensities with the known absolute intensities of gamma rays related to the following β decay of the compound nucleus. One can only assume, however, that the relative errors of the measured capture cross sections for the most nuclei represented below are, in average, close to zero and have different signs.

The third systematical error, by decreasing of the importance, is introduced into the results of technique from Ref. [11] by using the notions of the identical form of energy dependences of radiation widths of the primary and secondary gamma transitions of given multipolarity and energy. For the first time, the problem was formulated in the obvious terms and partly solved at the experimental ρ and k determination from intensities $I_{\gamma\gamma}$ of the two-step cascades [19]. Its partial solution is achieved by using the experimental information on a full cascade population of the maximal number of levels in the bottom part of the investigated excitation energy regions. The main result of the joint analysis [20] states that the level density decreases at the account of radiative strength function dependence on the energy of depopulating level as compared with the data from [11]. It regards the two-step cascade intensities distribution onto low-lying levels and the data on population the high-lying ones for two tens of nuclei.

In technique [11] the examined systematical error displays itself to much smaller degree than in [8]. Due to that the revealed in radiative strength functions of secondary gamma-transition changes have a different signs for various excitation energies, they are summarized in Γ_i with a multiplier E_γ^3 (2) and, consequently, are relatively less in changing the total radiative width of cascade intermediate levels. This conclusion is just only for the obtained by the present time data on intensities of two-step cascades to final levels with energy $E_f < 0.5 - 1$ MeV.

As in any other experiment, at the extraction [11, 20] of the cascade gamma-decay parameters, the existing ideas are used as well as constants and earlier established concrete nucleus parameters. First of all, it concerns:

- the number of low-lying levels determined by nuclear spectroscopy [21],
- an average spacing D_λ between the neutron resonances, Γ_λ total radiative width of a decaying compound state [22].

The corresponding data bring also additional, but correlating for various techniques, errors into the found ρ and k values. They can be significant only if the existing ideas of a nucleus contain essential errors. For example, it is so when the probability of excitation by a neutron of a level with a given J^π higher than neutron binding energy, strongly depends on its structure. In such a hypothetical case, value of D_λ can be essentially overestimated. It may be also possible that the branching coefficients at the decay of even rather long-living levels noticeably depend on their excitation way.

If not to take into account such exotic opportunities, the information on cascades of gamma-quanta allows one to determine ρ and k without using the model-calculated values with the smallest possible systematical error for any

stable target nucleus at any neutron beam. It is also needed to carry out [23] an independent check of the found values of the level density and strength functions by comparing the calculated and experimental total gamma spectra. It can be fulfilled at capture of both thermal and, in principle, resonance neutrons.

Thus, comparison of possible systematical errors of ρ and k values in experiments of various types shows a basic advantage of techniques [11, 20] over the known ways of determining only the level density [5] or of simultaneous determining the same value together with absolute ones of radiation strength functions [8]. It is caused by the following:

a) due to the instrument selecting only cases of full capture of the cascade energy, high resolution and stability of semiconductor detectors the two-step cascade spectra are measured with a smaller systematical error as compared with the gamma spectra, used by technique of [8];

b) the value $I_{\gamma\gamma}$ depends on absolute value of the level density (used by the alternative techniques in their existing [5, 8] variants, spectra do not depend on the absolute ρ and k values);

c) the transfer coefficients of a spectrum error onto the $\delta\rho$ and δk values in method from [11, 20] are ~ 2 orders smaller than in [8];

d) owing to the condition (b) there is a physically determined and essential limitation of the interval of possible ρ and k values, precisely reproducing both the intensity of cascades in energy functions of their primary transition, and other functionals of cascade gamma-decay process of any compound nucleus.

e) especially, it is necessary to emphasize that fixing of spins levels, for which the level density is determined, is practically unequivocal in expression (1), and there were no similar experimental results on this parameter till now.

It should be noted that there is an essentially unavoidable error of ρ and k extraction from cascade intensities. It is caused by an excess of the unknown parameters number in (1) over the number of the experimentally measured values $I_{\gamma\gamma}$. Accordingly, the concrete values $I_{\gamma\gamma}$ can be reproduced with an equal χ^2 by infinite set of parameters determining them. But the region of possible ρ and k values is always limited, providing that the relation of strength functions of primary and secondary transitions of equal energy and multipolarity is unequivocally fixed for any energies of decaying levels. Their widths are minimal in the case of using all of the available experimental information on the investigated nucleus for determining the cascade gamma-decay parameters. Due to these conditions, an interval of the most probable ρ and k variations do not in reality exceed several tens of percents if the value $I_{\gamma\gamma}$, used in [11, 20], is function of energy of the only primary cascade transition [12].

Potentially, obtained ρ and k values can be distorted because of the influence of all three cascade level structure on their intensity. The structure of a decaying compound state can influence $I_{\gamma\gamma}$ in a wide excitation energy interval, intermediate — locally. The influence degree of the structure of two-step cascade final

level on its intensity is evidently shown in [19, 20]. Corresponding effects for primary gamma transitions of cascades can be estimated and reduced only at their study in many neutron resonances. At present, a variation of the level density in concrete nucleus with respect to its average general trend (Figs. 2–8) can be accepted as the top value of an influence effect of resonance structure on the determined ρ and k values.

3. ON A BASIC POSSIBILITY OF THE PRECISE MODEL DESCRIPTION OF THE MODERN DATA ON THE EXPERIMENTAL LEVEL DENSITY

The general form of dependence of the most reliable modern values of the level density on the investigated nucleus excitation energy points at [11, 20] the presence of at least two «step-like» structures below neutron binding energy with its faster increase in between than it is predicted by a notion of a nucleus, as a system of noninteracting Fermi particles. It means that, at least, at two excitation energies the abrupt change in the excited levels wave functions structure occurs in a nucleus. The unique factor, known at present to be capable of providing such a change is the breaking of nucleons Cooper pairs with addition of two quasiparticles to the existing ones, as well as fast increasing the level density at increasing excitation energy.

In modern theoretical notions [3], the level density at a given nuclear excitation energy U , spin J and parity π is expressed through the density ρ_{qp} only of the quasiparticle excitations and its vibrational and rotational (for the deformed nuclei) enhancement coefficients K_{vibr} and K_{rot} , respectively:

$$\rho(U, J, \pi) = \rho_{qp}(U, J, \pi)K_{\text{vibr}}(U, J, \pi)K_{\text{rot}}(U, J, \pi) = \rho_{qp}(U, J, \pi)K_{\text{coll}}(U, J, \pi). \quad (3)$$

For the further analysis of the experimental data it is expedient to unite coefficients of vibrational and rotational increase in the level density in the general coefficient of its collective enhancement K_{coll} . In the level density from the analysis the basic contribution to its value is brought by the effect of vibration [11, 20]. In the examined case the effect of rotational enhancement of the level density for the deformed compound even–odd nucleus is less than the experimental data error. Probably, it is a little more for nuclei with neutron resonance spins of $J \geq 2$. By the order of magnitude in a neutron binding energy range, it is expected that K_{coll} value for the complete level density is in the interval: $10 < K_{\text{coll}} < 100$ [3]. There is no experimental information on dependence of K_{vibr} on U , J , and π . Modern theoretical ideas of this account admit a significant change in K_{vibr} when changes U up to the change of [24] its functional forms dependences on nucleus excitation energy. The presence [11, 20] of rather reliable experimental data for the sums of radiation strength

functions of dipole cascade transitions allows, basically, to solve this problem by creation of precise models of strength functions. This opportunity is caused (see, for example, [10]) by known distinctions in values of partial radiation width from a ratio of quasiparticle and vibrational components in the structure of excited (decaying) levels. However, currently, there are no theoretical models of such a level [3].

Therefore, the further analysis of the level density is possible to be carried out only within the framework of zero assumptions of K_{coll} independence on the nucleus excitation energy in the interval from $\sim 0.5 - 3$ MeV up to B_n . For the first time, it allows one to receive direct experimental information on partial density of quasiparticle excitations with various numbers of quasiparticles in the specified excitation energy intervals for some nuclei with their masses of $40 \leq A \leq 200$.

The possibility of determining the partial level density ρ_n with a given number n of the excited quasiparticles for U nucleus energy excitation

$$\rho_n = \frac{(J+1)\exp(-(j+1/2)^2/(2\sigma^2))}{2\sqrt{(2\pi)\sigma^3}} \frac{g^n(U-E_n)^{n-1}}{((n/2)!)^2(n-1)!} \quad (4)$$

has been found by Strutinsky [25]. For the first time, he has obtained simple functional dependence of the nucleus excited states density (the second coefficient in (4)). In more general form than expression (4), the model takes into account the existence of proton and neutron Cooper pairs (for the first time considered in [2] — for fissile nuclei). All kinds of its modern notions are included in [3], being quoted from original publications. Modern state of methods of partial density calculation is analyzed by Běťák and Hodgson in [26].

Practically, for comparison with the experiment [11, 20] within the framework of existing theoretical notions of a nucleus [3], it is necessary to choose value of the spin cutoff factor $\sigma = f(n, U)$ for the given Cooper pair and excitation energy, together with the energy $U - E_n$ of the excited quasiparticles. Density of single-particle levels g for the presented here nuclei is known from the data on neutron resonances. The parameter g can take into account shell inhomogeneities of single-particle spectrum and depends on U . These rather theoretical opportunities have not been taken into account in the analysis because of the inevitable increase in its conclusions uncertainty.

3.1. Fitting Conditions. In first of the tested by us variants, the $E_n = 0.25g(\Delta_0^2 - \Delta_n^2) + \delta e_n$, functional dependence suggested by A. V. Ignatjuk and Yu. V. Sokolov (see [24]) has been used. It is based on the idea of existence of $0.25g\Delta_0^2$ condensation energy in a nucleus at its transition from normal to superfluid state. The maximal number of decayed pairs in this variant is limited to value $N = 5$, basically, by possibilities of used fitting algorithm. The essential increase in N could reduce χ_f^2 value at least up to equaling it to χ_s^2 value of the

second variant. But it may be necessary to insignificantly change the obtained conclusions. At present the parameter δe_n for next decayed pair is determined only in modeling [2]. However, for comparison of (4) with the experiment it was selected so that to provide the best ρ fitting for the experimental values [20] (when they are absent the data on level density from [11] are used). Correlation function Δ_0 of the ground state of the even–even nuclei is accepted as equal to the experimental (determined from atomic masses) pairing energy of last neutron; whereas in odd-neutron nuclei $\Delta_0 = 12.8/\sqrt{A}$ approximation was used. Energy dependence of correlation function Δ_n for the Cooper pair of number N at nucleus excitation energy U was set within the framework of its theoretically determined and presented in approximation of Ref. [2]. It assumes that n -quasiparticle ($n = 2N$) excitations can exist above the threshold energy U_{th} . It may be defined by the following expressions:

$$\frac{U_{\text{th}}}{C} = 3.144(n/n_c) - 1.234(n/n_c)^2 \quad \text{for } n/n_c \leq 0.424, \quad (5)$$

$$\frac{U_{\text{th}}}{C} = 1 + 0.617(n/n_c)^2 \quad \text{for } n/n_c > 0.424. \quad (6)$$

Here, $C = 0.25g\Delta_0^2$ is the condensation energy, and $n_c = 0.791g\Delta_0$ is the number of excited quasiparticles in the vicinity of the phase-transition point from the superfluid to normal state.

The energy dependence of the pairing-gap parameter Δ_n , that is required for calculations of the level density (4), can be parameterized in the form:

$$\frac{\Delta_n}{\Delta_0} = 0.996 - 2.36(n/n_c)^{1.57} / (U/C)^{0.76} \quad \text{for } U/C \geq 1.03 + 2.07(n/n_c)^{2.91}, \quad (7)$$

$$\frac{\Delta_n}{\Delta_0} = 0, \quad \text{otherwise.} \quad (8)$$

To correctly account the spin dependence of the level density is a serious problem because of the ambiguity of model notions of the spin cutoff factor [3]. In both described here variants, the functional dependence suggested by Fu [27], has been used. The corresponding function, written in FORTRAN77, is taken from file RIPL-2 [3] with necessary parameters. As the breaking threshold for number N pair was selected only by comparing values of expression (4) with the experimental density of levels, so its value, suggested in [27], has been replaced with the best one obtained by us. Values used in calculation of constants g and the best fitting parameters E_n (for $E_n = U_{\text{th}}$) of expression (4), found in the first variant, are presented in Tables 1 and 2.

First of all, it is found out that in this representation the experimental level density requires accounting for not less than 5 partial densities for its reproduction. According to the notions [25], the effect of pairing takes a share of nucleus

excitation energy, which is equal to $2\Delta_0$. For five breaking nucleon pairs the total energy of pairing is equal approximately to 10 MeV for the heaviest of the nuclei that are included in the analysis. This energy is more than the neutron binding energy and, consequently, notions together with the data such as obtained in [5] seriously disagree with our experimental data [24, 28].

The substantial problem is also presented by discrepancy of energy thresholds of various pairs breaking. As a rule, for the investigated nuclei this threshold for the 5th pair is significantly less than for the 4th one. Sometimes inversion is observed for other pairs as well. In some of the nuclei still more inversion of disintegrated pairs thresholds is observed. The trivial explanation can consist of a divergence of model notions [2] and the experiment in close vicinity to the quasiparticles pair-production thresholds. If it is so, results of the executed approximation of the experimental level density in the first variant analysis show that with the error of about 1 MeV of breaking energy of 3rd, 4th and 5th nucleon pairs practically coincide. Within the framework of notions [2] about the form of Cooper pair correlation functions energy dependence of excited nucleus, a conclusion, corresponding to the basic statement [28], is observable. This

Table 1. The best values of the collective enhancement factor K_{coll} for analyzed nuclei, E_N is the value of breaking thresholds of pair number N , MeV

Nucleus	g, MeV^{-1}	K_{coll}	E_1	E_2	E_3	E_4	E_5
⁴⁰ K	4.04	15.0	0.20	5.43	5.42	3.33	2.13
⁶⁰ Co	4.04	11.6	-1.88	0.14	4.38	4.32	2.09
⁸⁰ Br	6.18	14.0	-2.10	4.05	4.83	2.56	1.46
¹²⁸ I	7.79	33.0	-1.75	2.15	1.95	3.05	2.45
¹⁴⁰ La	7.79	17	-1.10	2.37	1.98	2.29	1.79
¹⁶⁰ Tb	10.7	22.6	-1.11	2.12	1.78	2.46	1.86
¹⁶⁶ Ho	10.3	21	-1.71	1.95	1.83	2.62	1.80
¹⁷⁰ Tm	10.7	27.3	-1.69	2.04	2.19	2.65	2.05
¹⁷⁶ Lu	11.0	23.8	-1.62	1.95	1.90	2.63	2.04
¹⁸² Ta	10.9	32.8	-1.40	1.84	1.67	2.87	2.27
¹⁹² Ir	12.3	27.8	-0.97	1.79	2.07	2.80	1.90
¹⁹⁸ Au	9.88	6.9	-1.64	1.82	2.03	2.37	1.48
		21(8)					
⁷⁴ Ge	6.05	5.5	-0.14	3.59	4.27	4.24	5.04
¹¹⁴ Cd	7.90	17.8	-0.51	2.49	3.14	3.52	4.10
¹¹⁸ Sn	8.08	1.5	-0.58	3.17	2.96	2.75	2.41
¹²⁴ Te	8.27	8.8	-0.13	2.42	3.16	3.91	4.31
¹³⁸ Ba	6.98	1.5	-0.72	2.48	3.27	3.56	2.56
¹⁵⁰ Sm	10.3	10.0	-1.12	2.04	2.79	3.29	2.80
¹⁵⁶ Gd	10.2	19.6	-0.87	1.66	3.02	3.60	3.21
¹⁵⁸ Gd	10.1	13.	-0.82	1.96	3.06	3.32	2.92
¹⁶⁴ Dy	9.26	9.4	-1.43	1.76	2.51	2.81	2.31
¹⁶⁸ Er	10.1	14.	-0.82	1.67	2.48	3.45	3.04

Table 1 (continue)

¹⁷⁴ Yb	9.70	9.5	-1.32	1.74	2.56	2.78	2.28
¹⁸⁴ W	11.0	7.0	-0.69	1.97	2.15	3.02	2.51
¹⁸⁸ Os	11.7	13.	-0.91	2.18	2.31	3.59	3.19
¹⁹⁰ Os	11.4	5.9	-1.04	2.44	3.12	3.18	2.54
¹⁹⁶ Pt	9.30	25.	-0.85	2.04	3.11	3.22	3.26
²⁰⁰ Hg	7.30	3.3	-1.34	3.13	2.69	2.16	3.46
		10(6)					
¹⁷⁷ Lu	11.2	11.7	-1.04	1.59	2.58	1.46	
⁷¹ Ge	5.06	6.2	-1.49	1.17	0.18	-0.49	
¹²⁵ Te	8.45	12.4	-1.14	1.38	1.08	0.78	
¹³⁷ Ba	8.42	6.5	0.69	2.44	2.47	1.17	
¹³⁹ Ba	8.70	0.9	-1.89	1.98	1.12	-0.28	
¹⁶³ Dy	9.47	11.	-1.23	2.04	0.84	0.11	
¹⁶⁵ Dy	9.37	2.	-1.59	1.58	0.00	-0.80	
¹⁸¹ Hf	10.7	9.9	-1.48	1.35	0.96	0.36	
¹⁸³ W	10.2	10.9	-1.62	1.95	1.50	0.32	
¹⁸⁵ W	10.3	4.1	-1.44	1.79	0.74	-0.49	
¹⁸⁷ W	11.3	15.5	0.17	1.63	0.94	0.86	
¹⁹¹ Os	10.4	13.0	-1.62	1.09	0.74	0.14	
¹⁹³ Os	10.2	11.8	-1.23	1.61	0.84	0.17	
		8.4(45)					

Table 2. ΔJ is the interval of spins for which the experimental value ρ is determined, parameter p of expressions (9) and the best values of the collective enhancement factor K_{coll} for analyzed nuclei in the second variant of the analysis. E_N , MeV is the value of breaking thresholds of pair number N . $R = \chi_s^2/\chi_f^2$ — relations of criteria of fitting quality of the second (s) and the first (f) variants of the analysis

Nucleus	ΔJ	p	K_{coll}	E_1	E_2	E_3	R
⁴⁰ K	1-3	2.2	3.9	-1.45	2.5	7.1	0.6
⁶⁰ Co	2-5	2.2	5.6	-2.10	5.17	6.2	0.4
⁸⁰ Br	0-3	2.2	8.8	-2.50	3.45	6.0	0.5
¹²⁸ I	1-4	2.2	26.	-1.24	1.95	4.8	3.3
¹⁴⁰ La	3-5	2.2	11.7	-1.24	1.95	4.8	0.5
¹⁶⁰ Tb	0-3	2.0	10.6	-1.40	2.73	4.3	0.6
¹⁶⁶ Ho	2-5	2.2	11.0	-1.50	2.90	4.5	0.5
¹⁷⁰ Tm	0-2	2.2	16.4	-1.46	2.70	5.3	0.2
¹⁷⁶ Lu	2-5	2.3	13.8	-1.51	2.68	4.9	0.4
¹⁸² Ta	2-5	2.2	18.5	-1.00	2.00	5.2	0.9
¹⁹² Ir	0-3	2.2	16.0	-1.80	3.15	4.6	0.6
¹⁹⁸ Au	1-3	2.2	12.0	-0.96	3.81	6.1	0.5

Table 2 (continue)

		2.19	13(6)	-1.3(3)	2.6(8)	4.7(8)	
⁷⁴ Ge	3-6	2.2	5.1	1.80	6.00	9.5	0.5
¹¹⁴ Cd	0-2	2.2	7.6	0.09	3.72	7.2	0.8
¹¹⁸ Sn	0-2	2.2	2.0	-0.20	4.10	4.7	0.4
¹²⁴ Te	0-2	2.4	10.5	-0.20	2.90	6.9	0.5
¹³⁸ Ba	1-3	2.2	1.6	0.10	4.60	7.5	0.9
¹⁵⁰ Sm	3-5	2.4	10.4	-1.03	2.63	4.4	0.7
¹⁵⁶ Gd	1-3	2.3	17.0	-1.33	2.42	4.8	0.6
¹⁵⁸ Gd	1-3	2.0	6.0	-0.30	3.10	4.8	0.6
¹⁶⁴ Dy	1-4	2.3	14.	0.15	3.33	6.5	0.9
¹⁶⁸ Er	2-5	2.3	8.5	-0.24	3.02	6.2	1.6
¹⁷⁴ Yb	1-4	2.2	12.	-0.43	3.23	6.9	0.2
¹⁸⁴ W	0-2	2.3	3.4	-0.07	3.25	4.8	0.4
¹⁸⁸ Os	0-2	2.3	10.	-0.26	3.76	5.8	0.7
¹⁹⁰ Os	0-3	2.2	10.3	-0.26	3.76	5.8	1.4
¹⁹⁶ Pt	0-2	2.3	36.	-0.11	3.67	7.0	0.6
²⁰⁰ Hg	0-1	2.2	3.6	0.16	4.44	6.8	1.0
		2.25	10(8)	0.1(9)	3.5(7)	5.7(17)	
¹⁷⁷ Lu	11/2-15/2	2.2	7.1	-0.90	2.48	4.4	1.0
⁷¹ Ge	1/2-3/2	2.3	9.1	-2.46	2.07	5.2	1.2
¹²⁵ Te	1/2-3/2	2.3	14.5	-1.52	2.56	5.6	1.1
¹³⁷ Ba	1/2-3/2	2.2	5.0	-2.71	3.83	4.0	0.1
¹³⁹ Ba	1/2-3/2	2.3	2.7	-2.86	1.63	1.8	0.6
¹⁶³ Dy	1/2-3/2	2.3	13.	-0.82	2.08	3.9	2.0
¹⁶⁵ Dy	1/2-3/2	2.3	5.6	-1.06	2.49	3.6	0.5
¹⁸¹ Hf	1/2-3/2	2.3	14.8	-1.60	1.70	3.8	1.2
¹⁸³ W	1/2-3/2	2.2	16.3	-1.49	2.58	4.6	0.2
¹⁸⁵ W	1/2-3/2	2.2	12.2	-1.87	3.19	4.0	0.2
¹⁸⁷ W	1/2-3/2	2.2	8.4	-1.27	2.81	3.6	0.3
¹⁹¹ Os	1/2-3/2	2.3	18.7	-1.30	1.53	4.0	2.0
¹⁹³ Os	1/2-3/2	2.3	14.0	-0.94	2.31	3.9	0.3
		2.27	11(5)	-1.6(5)	2.4(7)	3.9(8)	

statement deals with the generalized model of a superfluid nucleus – its phase transition between superfluid and normal states (but at the essentially smaller energy of such transitions).

Model approximation of correlation function Δ_n , presented in [2], is obtained on the basis of the experimental data such as in [5]. Their basic distinctive feature is that the speed of increase in the level density is smaller as compared to data of [11, 20]. It is true at least for excitation energy higher than $0.5B_n$. In this variant of model notions, at the increase in excitation energy the smooth enough change in Δ_n can provide the greater $d\rho/dU$ value only when expression (4)

accounts for five and more breaking pairs. An alternative opportunity consists in using other ideas of nucleon correlation functions of Cooper pairs in the excited nucleus.

The smaller values of n can be obtained only with the more rapid decrease in Δ_n , than it is predicted by Eq. (7) at increasing of the excitation energy U . And Eq. (4) cannot present any other opportunity. The number of variants of the functional dependences satisfying this condition is great. In the second variant of the analysis for E_n the following functional dependence has been used:

$$U - E_n = U - \Delta_0 \ln[(U - U_{\text{th}})/(p\Delta_0)]. \quad (9)$$

The only reason for using function (9) for this purpose is a logarithmic dependence of macrosystem thermal capacity in a point of second-order phase transition on its temperature. But such a dependence is valid only in an ideal case. In case of a mixture of helium isotopes, for example, the maximal thermal capacity decreases, whereas the degree of change increases at the increase of ^3He concentration. Therefore, dependence (9) can be accepted as the utmost possible Δ_n estimation for pair number N at the energy U with an additional condition [25] that maximum U_{th} value is in $U_{\text{th}} \leq n\Delta_0/2$. Probably, following this condition for the majority of nuclei gives overestimated E_n values. Only for ^{74}Ge , ^{185}W , ^{192}Ir and ^{196}Pt , it is required to increase the maximal value of E_n in (9) by 1.1–1.5 times in order to obtain the minimum possible χ_s^2 . Such a correction is essential only for the second breaking Cooper pair. If presence of systematical errors in ρ is taken into account, the specified E_n increase does not indicate its excessive divergence in various nuclei. It is also true for the known significant fluctuations of pairing energy of last nucleons pair.

The best value of parameter p for all tested nuclei is about 2.2–2.3. Therefore, in the second of the investigated variants, the pairing influences the level density $\rho_{qp}(U, J, \pi)$ for next breaking Cooper pair only in essentially limited, as compared to (7), energy interval $U_{\text{th}} < U \leq U_{\text{th}} + p\Delta_0$, i. e., it is practically equal to the known value of gap width in the low-lying states spectrum of an even–even nucleus.

In the carried out variants of the analysis, the coefficient K_{coll} has been accepted as independent on excitation energy U , spin and parity of levels and unchanging at the increase of nucleus excitation energy. Its absolute value is almost completely determined by the ratio of the experimental level density and the density of two or three quasiparticle excitations. In case, when this value for any number $N > 1$ Cooper pairs differs by several times, such discrepancy is easily compensated by changes in U_{th} within the limits of several hundreds keV maximally.

At the analysis of the experimental data in even–odd compound nucleus some ambiguity arises at a choice of threshold of three-quasiparticle level excitation

energy. If the threshold of their production is accepted as sufficiently high (about several MeV), in such nuclei, the required collective enhancement factor of one-quasiparticle level density will exceed similar value for even–even and odd–odd nuclei by a factor of several tens. Therefore, it has been postulated, that in the excitation energy interval of about 2–3 MeV above the ground state of even–odd nucleus, the base density is the one of three-quasiparticle excitations instead of the density of one-quasiparticle ones.

In odd–odd compound nuclei the density of two-quasiparticle excitations assumes that there is an excitation both of neutron and proton quasiparticles. The type of quasiparticles for four and more quasiparticle excitations in these nuclei, as well as in even–even ones cannot be established by the analysis carried out here.

3.2. Results and Their Discussion. Examples of the best approximation of the experimental data [11, 20] for four nuclei with various parity of neutrons and protons are displayed in Fig. 2. It also shows the partial level density obtained in the first variant of the analysis. In Figs. 3–8 the similar data are presented for the most of the analyzed nuclei with partial densities obtained in the second variant of analysis. In Table 2 the parameters of the approximated partial level density for the second variant of accounting for nucleon pairing interactions in nucleus are presented. Thresholds of excitation energy U_{th} , necessary for calculation by expressions (4) and (9), are averaged in it after division of E_N onto the approximated value of correlation function $\Delta_0 = 12.8/\sqrt{A}$ for nuclei with different neutron and proton parity, separately.

From these data quite unequivocally follows, that:

1) The first step-like structure in level density [11, 20] is caused by existence of, at least, two quasiparticles in nucleus of any type.

2) For the precise reproduction of the level density (comparable with an experimental data error) it is required to postulate the breaking from three up to five and more such pairs.

3) Two, three and more nucleon Cooper pairs can have practically equal breaking threshold if only the effect of nucleons pairing of any pair demonstrates itself in a wide interval of nucleus excitation energy [2]. If not to take into account the circumstance that the approximation of experimental data on ρ both from [11] and [20] necessarily inverts thresholds of breaking at least of the fourth and fifth pairs, the proximity of their values allows one to speak about practically observable simultaneous breaking of several Cooper pairs. That is, according to [28] a nucleus phase transition from superfluid to the normal state.

4) The coefficient K_{coll} , taken from the data of [20], has practically equal value in both even–even and even–odd compound nuclei and is significantly higher in odd–odd ones (for the level density from a variant of the analysis [11]). This difference is qualitatively explained by value and error distinction sign of the level density given by [11] as regard to [20].

5) From the data of approximation, presented in Figs.3–8, it is obvious, that in the second variant of the analysis the experimental level density can be well reproduced at the account of only six or seven-quasiparticle excitations. Moreover, representation of correlation functions (9) allows one to obtain small enough value of the level density of n -quasiparticle excitations, having lower energy than U_{th} . So, the known from nuclear spectroscopy fact of the two-quasiparticle excited levels presence within the limits of nucleus excitation energy somewhat lower than $2\Delta_0$ is thus explained.

6) In Tables 1 and 2 data of comparison of average values of collective enhancement factor of the level density are collected and show smaller scatter in the second variant of the analysis. In this variant differences $\langle E_2/\Delta_0 \rangle - \langle E_1/\Delta_0 \rangle \approx 4$ and $\langle E_3/\Delta_0 \rangle - \langle E_2/\Delta_0 \rangle \approx 2$ coincide in nuclei of various types within the limits of an error.

7) In [25] it is predicted that the level density of odd A nucleus corresponds to that of even nucleus with excitation energy $U + \Delta_0$, accordingly. Results of the first variant of the analysis (Table 1) do not prove this prediction to be true. However, in the second one it is carried out within the limits of E_n energies determination error.

8) The shell effects demonstrate the maximum extent in near magic nuclei being close to $N = 82$ and 126 . Their exhaustive reproduction is impossible within the framework of expression (4). More exact approximation can demand to revise the basic assumption [25] about equidistant character of single-particle spectrum of near magic nucleus and to account for shell inhomogeneities of single-particle spectrum [24]. It may also be required to account for change in K_{coll} value for different nuclei and excitation energies, not taken into account by performed analysis.

Therefore, it is undoubtedly required to obtain better experimental data on gamma–gamma coincidences and further development of algorithms of their analysis. First of all, it concerns the determination of E_n energy values, connected with collective type excitations near a breaking threshold of pair number N . The problem of K_{coll} value determination at a given excitation energy U is directly connected to this circumstance. For even–even nuclei it is visible from the given tables and figures. Approximation of ρ is done in its starting with $U \approx 2$ MeV. Just this is the explanation of the discrepancy of E_1 energy value with $2\Delta_0$. As long as in even–even nuclei of Δ_0 region there are only levels of vibrational type, so far it is necessary to accept $K_{\text{coll}} \approx \infty$ in this excitation region. The available experimental data, unfortunately, do not give an opportunity to estimate this problem near to values E_2 and E_3 basically because of the lack of theoretical representations on this account and mathematical methods of the analysis of the experimental data.

Despite of the specified ambiguity, volume and quality of the obtained [11, 20] experimental data presents extremely favorable possibilities for the greatest

possible development of modern models of the level density. The obtained values of the most probable parameters of the experimental data approximations can be used for ρ calculation in nuclei that are relatively far from the magic ones. It may be done either directly or at interpolation of the data given by Tables 1 and 2, or by using the corresponding average values. It is certainly necessary to develop new model ideas of the nucleon correlation functions energy dependence for near magic nuclei in the whole region of $E_{ex} < B_n$ and about ρ vibration enhancement factor.

It is also necessary to reveal the degree with which the initial levels λ structure influences the two-step cascade intensity and to estimate the ρ and k systematical errors connected to this circumstance.

CONCLUSION

There is an urgent need for both the experimental and theoretical determinations of the excited level density in a given nuclear reaction, as well as the probability of its products emission for all possible excitation energies with a guaranteed systematical error not exceeding several tens of percents. It is to be accomplished with the same accuracy of measuring various spectra of nuclear reactions and their cross sections, as carried out, presently. Only such a reduction of available systematical errors of the experimental ρ and k determinations allows one to observe dynamics of nucleus structure change at its excitation energy variation and to reveal factors causing it. There is no other possibility to develop new nucleus model and to specify the existing ones. Known techniques [5, 7, 8] of ρ and k determination are incapable of solving this problem. It is true either because of the impossibility of getting accuracy-specified model-designed transmission coefficient for nuclear reaction's nucleon products, or because of practical inaccessibility of the required measurement accuracy of gamma-rays spectra, accompanying nuclear reactions with the charged particles emission.

Specific feature of the model-free simultaneous extraction [8, 11, 20] of both the level density and strength functions of emission of the nuclear reaction's registered products is necessary to determine the intervals of their values, reproducing experimental spectra with the required accuracy. Essentially, it is provided for the irremovable ambiguity of such problem's solution both for [8] and [11, 20] techniques. The marked circumstance is connected with degeneracy of the equation systems, connecting values of the sought parameters with the measured spectra intensities. Model notions and hypotheses (first of all, on independence of strength functions on a nucleus excited levels structure) reduce or fully eliminate the equation systems degeneracy [5]. But they necessarily lead to an unknown systematical errors of ρ and k . Therefore, reliable results for ρ and k can be only obtained by using a mathematically correct technique of the experimental data processing. The data should most precisely reflect this circumstance.

The accumulated, up to present, data file on two-step cascades following thermal neutron radiative capture, points to the existence of systematical discrepancy in experimentally obtained data for ρ and k and their model-calculated values. These data also specify excessive idealization of notions about a nucleus, used by techniques of [5, 7, 8] for the extraction of its major parameters. Presence of significant systematical discrepancy between the experiment and theory allows one to hope on the possibility of a substantial improvement in model notions about properties of a nucleus at its excitation being lower than nucleon binding energy.

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REFERENCES

1. Maslov V. M., Maslov V. M., Porodzinskij Yu. V., Baba M., Hasegawa A. // Nucl. Sci. Eng. 2003. V. 143. P. 1.
2. Rejmund F., Ignatyuk A. V., Junghans A. R., Schmidt K.-H. // Nucl. Phys. A. 2000. V. 678. P. 215.
3. Reference Input Parameter Library RIPL-2. Handbook for calculations of nuclear reaction data. IAEA-TECDOC, 2002, <http://www-nds.iaea.or.at/ripl2/>; Handbook for Calculation of Nuclear Reactions Data, Vienna: IAEA. TECDOC-1034, 1998.
4. Khitrov V. A., Popov Yu. P., Sukhovej A. M., Yazvitsky Yu. S. // Proc. of the III International Symposium on Neutron Capture Gamma-Ray Spectroscopy // Ed. R. E. Chrien, W. R. Kane. N. Y.; London: Plenum Press, 1979. P. 665.
5. Grudzevich O. T. et al. // Sov. J. Nucl. Phys. 1991. V. 53. P. 92;
Zhuravlev B. V. // Bull. Rus. Acad. Sci. Phys. 1999. V. 63. P. 123.
6. Bondarenko V., Honzatko J., Tomandi I. et al. // Nucl. Phys. A. 2005. V. 762. P. 167;
Honzátko J. et al. // Nucl. Phys. 1999. V. 645. P. 331.
7. Bartholomew G. A. et al. // Adv. Nucl. Phys. 1973. V. 7. P. 229.
8. Schiller A. et al. // Nucl. Instr. Meth. Phys. Res. A. 2000. V. 447. P. 498.

9. *Sukhovej A.M., Khitrov V.A., Chol Li* // Proc. of the XII International Seminar on Interaction of Neutrons with Nuclei. E3-2004-169. Dubna, 2004. P.438; nucl-ex/0409016.
10. *Soloviev V.G. et al.* // J. Phys. G. 1994. V.20. P.113;
Soloviev V.G. et al. // Part. Nucl. 1997. V.27(6). P.1643;
Soloviev V.G. Theory of Atomic Nuclei: Quasiparticles and Phonons. Bristol; Philadelphia: Institute of Physics Publishing, 1992;
Soloviev V.G. Theory of Complex Nuclei. Oxford: Pergamon Press, 1976.
11. *Vasilieva E.V., Sukhovej A.M., Khitrov V.A.* // Phys. At. Nucl. 2001. V.64(2). P.153; nucl-ex/0110017.
12. *Boneva S.T., Khitrov V.A., Sukhovej A.M.* // Nucl. Phys. A. 1995. V.589. P.293.
13. *Voinov A. et al.* // Nucl. Instr. Meth. Phys. Res. A. 2003. V.497. P.350;
Voinov A. et al. // Yad. Fiz. 2004. V.67(10). P.1891;
Bečvář F. et al. // Phys. Rev. C. 1995. V.52. P.1278.
14. *Popov Yu.P., Sukhovej A.M., Khitrov V.A., Yazvitsky Yu.S.* // Izv. AN SSSR, Ser. Fiz. 1984. V.48. P.830.
15. *Sukhovej A.M., Khitrov V.A.* // Phys. At. Nucl. 1999. V.62(1). P.19.
16. *Lone M.A., Leavitt R.A., Harrison D.A.* // Nucl. Data Tables. 1981. V.26(6). P.511.
17. <http://www-nds.iaea.org/pgaa/egaf.html>
18. *Khitrov V.A., Chol Li, Sukhovej A.M.* // Proc. of the XI International Seminar on Interaction of Neutrons with Nuclei, Dubna, 22–25 May 2003. E3-2004-9. Dubna, 2004. P.98; nucl-ex/0404028.
19. *Bondarenko V.A. et al.* // Proc. of the XII International Seminar on Interaction of Neutrons with Nuclei. E3-2004-169. Dubna, 2004. P.38; nucl-ex/0406030, nucl-ex/0511017.
20. *Sukhovej A.M., Khitrov V.A.* // Phys. Elem. Part. At. Nucl. 2005. V.36(4). P.697 (in Russian).
21. <http://www.nndc.bnl.gov/nndc/ensdf>.
22. *Mughabghab S.F.* Neutron Cross Sections. BNL-325. V. 1. Parts A, B. N. Y.: Academic Press, 1984.
23. *Sukhovej A.M., Khitrov V.A., Grigoriev E.P.* // Report INDC(CCP). 2002. V.432. P.115; nucl-ex/0508007, nucl-ex/00508008.
24. *Ignatyuk A.V.* Report INDC-233(L). Vienna: IAEA, 1985.

25. *Strutinsky V. M.* // Proc. of the Int. Conf. Nucl. Phys. Paris, 1958. P. 617.
26. *Běťák E., Hodgson P.* // Rep. Progr. Phys. 1998. V. 61. P. 483.
27. *Fu C. Y.* // Nucl. Sci. Eng. 1986. V. 92. P. 440.
28. *Rastopchin E. M., Svirin M. I., Smirenkin G. N.* // Yad. Fiz. 1990. V. 52. P. 1258.
29. *Dilg W., Schantl W., Vonach H., Uhl M.* // Nucl. Phys. A. 1973. V. 217. P. 269.

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