The Features of the Cascading Decay of ^{172}Yb Nucleus in the ^{171}Yb(n_{th},2γ) Reaction

Sukhovoj A.M.[1], Mitsyna L.V.[1], Hai N.X.[2], Anh N.N.[2], Khang P.D.[3], Thang H.H.[2], Vu D.C.[1, 4]

[1]*Joint Institute for Nuclear Research, Dubna, 141980, Russia*
[2]*Dalat Nuclear Research Institute, Vietnam Atomic Energy Institute, Hanoi, Vietnam*
[3]*Hanoi University of Science and Technology, 1 Dai Co Viet, Hanoi city, Vietnam*
[4]*Vietnam Academy of Science and Technology Institute of Physics, Hanoi, Vietnam*

Abstract. For the purpose of an enhancement of the experimental data set on the cascade intensities of two gamma quanta emitted step by step after radiative capture of thermal neutrons, the ^{171}Yb(n_{th},2γ)-reaction was investigated. In the analysis of the cascade intensities a structure change of the observed levels of the ^{172}Yb nucleus was discovered depending on the excitation energy, and the most probable breaking thresholds were obtained for four Cooper pairs of neutrons below the neutron binding energy.

1. INTRODUCTION

A nucleus with even number of neutrons (and protons) is, in the ground state, a system of pairing nucleons, and it becomes a system of excited fermions at its excitation in a process of pair breaking. An investigation of the dynamics of this process promotes obtaining the principally new information about fundamental interactions occurred in the nucleus.

In representation about the nuclear superfluidity, which is generally accepted among experimenters, an excited nucleus is considered as a statistic fermion system. And now as before, this representation is applied in the experimental analysis, even at using a state-of-the-art instrumentation and at a modern status of theory of the nucleus. Theorists exploit a representation about "pair correlations of superconductive type", at least, in an excitation region above the experimentally obtained energies of rotational and vibrational excitations.

Unfortunately, a multiple increase in errors of the extracted experimental parameters (level density ρ and widths Γ of emission of gamma-quanta), which exists due to large coefficients of transfer to them of errors of the measured spectra (or cross-sections), hamper the progress in understanding of the intranuclear processes.

In the realized in Dubna method [1] of measuring the intensities of two-step cascades at γ-decay of neutron resonances, the most probable values of both the level density ρ of intermediate levels in compound-nucleus and the partial widths Γ of emission of reaction products are determined simultaneously. It allows to study a change dynamics in behavior of superfluid phase of the nuclear matter at an increase in the excitation energy of the nucleus, since the energies of three cascade levels (initial, intermediate and final ones) as well as the probabilities of transmissions between them are determined in the investigated (n,2γ)-reaction with a high accuracy.

The correlation always exists between the obtained parameters ρ and Γ (or radiative strength functions $k = \Gamma/(A^{2/3}\cdot E_\gamma^{3}\cdot D_\lambda)$, where A is a mass of nucleus, D_λ is an average space between its levels, and E_γ is an energy of emitted γ-quantum). Nevertheless, at an existence of the total system of equations, which connect the ρ and Γ values in each point of the excitation energy E_{ex}, these two values could be calculated exactly. But because of a deficiency of experimental information, a simultaneous determination of ρ and Γ values from the experimental data is possible only with use of different appropriate model representations about $\rho(E_{ex})$ and $\Gamma(E_\gamma)$ functions. At that, an uncertainty, which exists due to a correlation between ρ and Γ values, is converted into systematical errors in the tested correlated models for $\rho(E_{ex})$ and $\Gamma(E_\gamma)$ functions.

At the analysis of the $I_{\gamma\gamma}(E_\gamma)$ intensities of the two-step cascades of γ-transitions, measured by now for 43 nuclei in the mass region $28 \leq A \leq 200$, it turned out, that the experimental information for each investigated nucleus is individual. It completely corresponds to the modern theories about dynamics of fragmentation of nuclear states (the wave functions of excited nuclear levels are formed in the fragmentation process of states of nuclear potential with different quantum numbers and various positions relative to Fermi surface) [2, 3].

The theoretical description of a structure change of the complex nuclei in the energy range from the ground state up to neutron resonances one can inquire for in [4], for example. Although there is no yet a comprehensive knowledge about an interaction between Fermi- and Bose-states in the nucleus, but on a base of the analysis of the cascades' intensities $I_{\gamma\gamma}(E_\gamma)$ measured for stable nuclei-targets with different *P*/*N* ratio (*P* is a number of protons, *N* is a number of neutrons) the quite realistic picture of nuclear changeover to fermion system at the excitation energy $E_{ex} < B_n$ (B_n is a neutron binding energy in the nucleus) already exists. In particular, the strength functions, obtained for pairs of nuclei with the same *P* and various *N* (^{156}Gd and ^{158}Gd, ^{188}Os and ^{190}Os), are essentially different, and the level densities for such pairs of nuclei differ to a lesser degree.

An existence of two phases of nuclear matter in the nucleus and their interaction indicate that the partial widths of gamma-transitions are determined by the wave functions with different contributions of vibrational and quasi-particle components, so regarding to them the Porter-Thomas hypothesis [5] cannot be applied, by a definition.

The investigations [6–10] resulted that both a number of breaking Cooper pairs of nucleons and a shape of excited nucleus [8] have an influence on the dynamics of superfluid phase of the nuclear matter. Widening of the region of investigated nuclei and, in that way, a numerical growth of experimental data will help to make clear the details of interaction between fermion and boson nuclear states.

2. EXPERIMENT

The experiment with the sample of ytterbium as a nucleus-target was carried out at the DDNR reactor (Dalat, Vietnam). The sample of 0.5 g mass contained 0.45 g of ^{171}Yb and was irradiated during 830 hours in "closed" [1] geometry with a distance between the target and the detector of about 5 cm. Cascades were recorded by HPGe-detectors with an efficiency of 35% relative to efficiency of NaI(Tl) crystal (with 72 mm in diameter and the same height). The recording threshold for a cascade gamma-transition was chosen 0.52 MeV.

An informative part of the spectrum of amplitudes' sums of coincided pulses for ^{171}Yb$(n_{th},2\gamma)^{172}$Yb reaction is presented in fig. 1. In figs. 2 and 3 the spectra of the cascades to the ground state and to the first excited level with the energy $E_f = 78$ кeV are shown. The algorithm is used for a digital improvement of resolution [11], according to which a deviation of the sum of γ-quanta energies from its average for any cascade is divided proportionally to widths of the cascade peaks and then subtracted from (or added to) the energies of primary E_1 and secondary E_2 transitions of each recorded event of the total absorption of the cascade energy by the detectors. The spectra of the intensities (figs. 2 and 3) are normalized by the recording efficiency of corresponding cascades with a storing of the total number of events. The energies and the relative intensities were determined for all experimentally resolved peaks for 386 cascades.

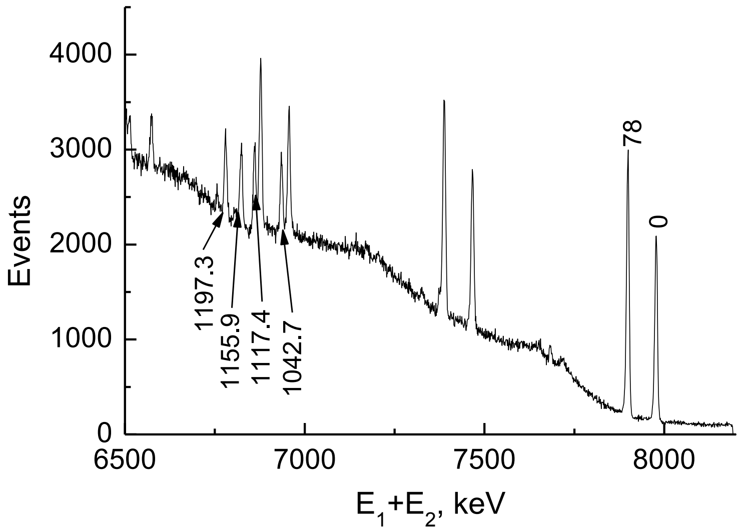

Fig. 1. Spectrum of the sums of amplitudes of coincident pulses for ^{171}Yb(n_{th},2γ)-reaction. Along X-axis: energy of the cascades, Y-axis: number of recorded events with the total energy $E_1+E_2 > 6500$ кeV. The energies of the final levels of the cascades (in keV) are pointed near the peaks of the total energy absorption.

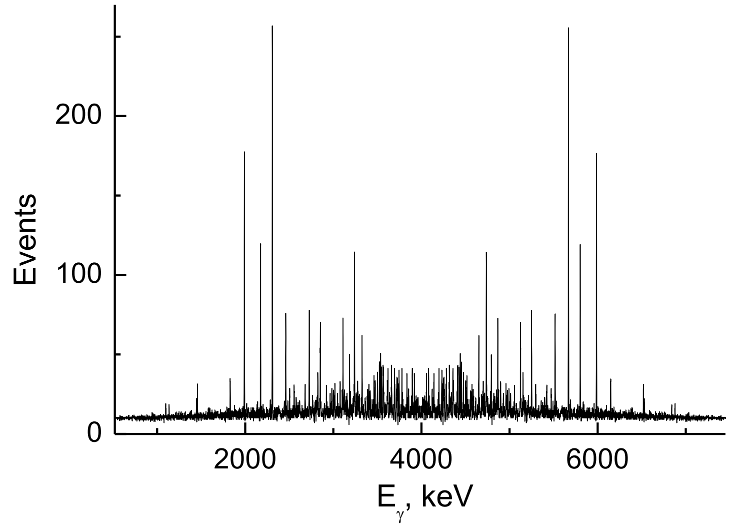

Fig. 2. Intensity distribution for the cascades to the ground state of the ^{172}Yb nucleus depending on the energies of the primary and the secondary quanta. An efficiency of the cascade recording is taken into account.

At the analysis the spectra of the experimental intensities of the cascades (figs. 2, 3), using the technique [1, 12] and the nuclear spectroscopy methods [13], are transformed [14] into two mirror-symmetrical distributions of intensities of primary $I_{\gamma\gamma}(E_1)$ and secondary $I_{\gamma\gamma}(E_2)$ transitions. The parameters p and q of the most probable functions $\rho=\varphi(p_1, p_2, ...)$ and

$\Gamma=\psi(q_1, q_2,...)$ were determined by fitting of a model description of the cascade intensity $I_{\gamma\gamma}(E_1)$ to the experimental one. The physical information about the nucleus is obtained from the experiment analysis at a comparison of some of the model representations. There are no other ways to obtain simultaneously the level density and the radiative strength functions from the gamma-spectra of the decay of high-excited levels. Any gamma-spectrum can be described, if only the energies, quanta numbers in the cascades and the total number of gamma-transitions are correctly determined.

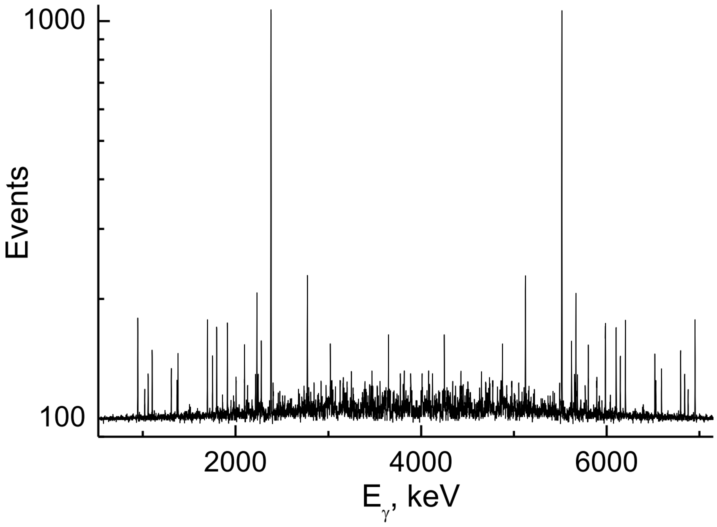

Fig. 3. Intensity distribution for the cascades to the level with the energy E_f=78 кeV of ^{172}Yb depending on the energy of the primary and the secondary quanta.

A cascade decay of a neutron resonance (or any compound-state) λ occurs through the intermediate levels i to the final levels f. Spins and parities of the intermediate levels of different cascades are determined by the selection rules on multipolarity. The part of primary transitions $I_{\gamma\gamma}(E_1)$ for any small energy interval ΔE_j of cascades may be presented by an equation:

$$I_{\gamma\gamma}(E_1)=\sum_{\lambda,f}\sum_{i}\frac{\Gamma_{\lambda i}}{\Gamma_{\lambda}}\frac{\Gamma_{if}}{\Gamma_{i}}=\sum_{\lambda,f}\sum_{j}\frac{\Gamma_{\lambda j}}{<\Gamma_{\lambda j}>M_{\lambda j}}n_j\frac{\Gamma_{jf}}{<\Gamma_{jf}>m_{jf}}. \qquad (1)$$

A sum of the partial widths of the primary transitions $\Sigma_j\Gamma_{\lambda j}$ to $M_{\lambda j}$ intermediate levels is $<\Gamma_{\lambda j}>M_{\lambda j}$, and a sum $\Sigma_j\Gamma_{jf}$ for the secondary transition to m_{jf} final levels is $<\Gamma_{jf}>m_{jf}$, inasmuch as $<\Gamma_{\lambda j}> = \Sigma_j\Gamma_{\lambda j}/M_{\lambda j}$ and $<\Gamma_{jf}> = \Sigma_j\Gamma_{jf}/m_{jf}$. In the small energy interval ΔE_j a number of intermediate levels of all types is $n_j = \rho\Delta E_j$.

As equipment possibilities to determine the parameters of all cascades are absent, the necessary information for the system (1) solving is extracted from the fits of model descriptions of the intensities for all observed γ-transitions to their experimental intensities. Any intensity distribution of two-step cascades (see figs. 2 and 3) contains only peaks of the full capture of the cascade energy and a noise background with a zero average [1]. A dispersion of a background line is effectively diminished at an increase in the number of events of recording the total energy of the cascade.

Taking into account a practical absence of a background, an equality of areas of the peaks of primary and secondary transitions (for each individual cascade) and a mirror-symmetry of their positions in relation to the spectrum center $0.5(E_1+E_2)$ of all cascades, we subtracted all peaks of intense low-energy secondary transitions from the energy interval of the intermediate levels $E_i \geq 0.5B_n$. The rest of intensity in this interval (a continuous distribution of intensity of large number of low-energy primary cascade gamma-quanta) in sum with intense resolved primary transitions from the energy interval $E_i \leq 0.5B_n$ is just the most probable distribution $I_{\gamma\gamma}(E_1)$.

Of course, if a part of peaks near the energy $0.5(E_1+E_2)$, where there is an mixture of inseparable the primary and the secondary transitions, is inaccurately identified, the obtained function $I_{\gamma\gamma} = f(E_1)$ distorts. But the part of the intensity of secondary transitions, which are mistakenly included into $I_{\gamma\gamma}(E_1)$, and the part of the intensity of primary transitions, mistakenly included into $I_{\gamma\gamma}(E_2)$, are equal to each other. At that, a possible distortion of a shape of $I_{\gamma\gamma}(E_1)$ distribution in a small energy region of the primary transitions near $0.5B_n$ decreases with an increase in statistics.

At the system (1) solving the average partial width of transitions of the same type and the level density in the branching coefficients ($\Gamma_{\lambda j}/(<\Gamma_{\lambda j}>M_{\lambda j})$ for the primary transitions and $\Gamma_{jf}/(<\Gamma_{jf}>m_{\lambda j})$ for the secondary transitions) were fitted in small energy intervals ΔE_j. A large statistics of events and a small background under peaks of full capture of the cascades' energies $E_1 + E_2 = 8020$ keV and $E_1 + E_2 = 7942$ keV allowed us to accept for ^{172}Yb the width of energy interval for summation of experimental intensity $\Delta E_j = 250$ keV (two times less than for all nuclei investigated before). So, a shape of $I_{\gamma\gamma}(E_1)$ function was obtained with a better accuracy for ^{172}Yb in comparison with the other 43 nuclei [8, 10].

The resolved peaks with the widths of ~ 2 – 4 keV for the cascades with $E_f = 0$ and $E_f = 78$ keV were 70% and 67% of the total area of the spectra, correspondingly (see figs. 2 and 3). According to [12], the primary quantum in two or more cascades with different E_f, as a rule, is the cascade transition of a bigger energy. This condition with use of the likelihood method allowed us to make an independent and correct scheme of the decay of initial cascade level, in addition to the data of the ENDSF file.

The absolute intensity of primary transitions of the investigated reaction was determined from the intensities of gamma-rays of ^{171}Yb+ ^{27}Al complex target. The obtained data for the cascade $E_1+E_2 = 5540+2402$ keV coincide with the data of [15] within some percents.

3. THE DECAY SCHEME FOR ^{172}Yb

Spectra of the sums of amplitudes of coincided pulses were obtained not only for the cascades to the ground state and to the first excited level of ^{172}Yb, but also for final levels of the cascades with the energies $E_f = 1042.7$; 1117.4; 1155.9 and 1197.3 кeV. Unfortunately, a large background under peaks of the cascades with $E_f > 78$ keV (because of events of recording of only a part of the cascade energy) did not allow to obtain for them such quality spectroscopic information as it was done for the cascades with $E_f = 0$ and $E_f = 78$ кeV.

In the presented experiment for the cascades of the biggest intensity the errors in the determination of $I_{\gamma\gamma}$ values were mainly much lower than 30% (at that error the cascade peak was assumed to be resolved). In a majority of cases, the procedure [12] shows that the primary transition triggers some (at least, two) secondary transitions, what (taken together with the data of [15]) allowed to identify the primary transitions with a strong probability.

In order to determine the parameters of the nuclear superfluidity in excited nucleus [16] the independent ρ values at two energy regions are needed: at $E_{ex} \approx 1$–3 MeV and at $E_{ex} \approx B_n$. The accuracy of ρ determination at these energies is bounded because of a loss of resonances with small neutron widths and an omission of low-lying levels, which are weakly excited in the nuclear reaction or have a big background. But it is worthy of being noted, that in the method of the two-step cascades' investigation there are no the main sources of background, which exist in the ordinary (one-step) experiments. So, background conditions in the case two-step cascades are practically not dependent on the excitation energy of the nucleus, what allows to determine the density of its "discrete" levels with a smaller (if to compare with other nuclear reactions [13]) threshold of gamma-quanta recording.

Radiative capture of thermal neutrons by the stable nucleus-target ^{172}Yb limits a number of spins of levels, which density is needed to determine, by the interval $0 \leq J \leq 3$. The obtained from different experiments densities of "discrete" levels of ^{172}Yb for all spins and parities are presented in fig. 4 in the energy region 2 – 4 MeV. Approximation of ρ and Γ values was done here for the cascades with the total energies 8020 and 7982 keV only. Up to excitation energy of E_{ex}=3 MeV the densities of low-lying intermediate levels of the cascades to the final levels with E_f = 0 and E_f = 78 keV from the presented experiment coincide quite good with the values predicted by the back shifted Fermi-gas model [17]. The same one could say about level densities from ENDSF file and from the experiment [15] with the neutron beam of 2 keV energy. But at a growth of the excitation energy a number of "discrete" levels descend faster than it is predicted by the Fermi-gas model.

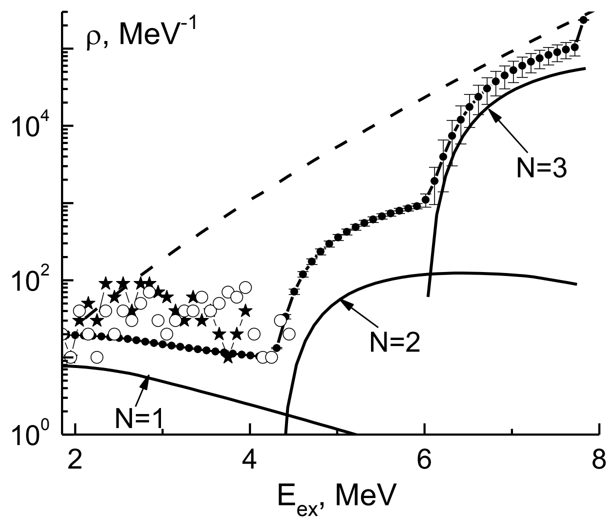

Fig.4. The dependences of the level density for ^{172}Yb on the excitation energy. Dased line – level density predicted by the model from [17]] for spins 0 ≤ J ≤ 3 and both parities. Open points – number of "discrete" levels obtained in the present experiment. Full points with errors – densities from the best fits to the experimental cascade intensities. Stars – calculation from the spectrum of resolved gamma-transitions after a capture of neutrons with the energy E_n= 2 keV [15]. Solid lines noted by numbers are density of vibrational levels above the breaking thresholds of three Cooper pairs, calculated according to (3) with fitted parameters.

In the framework of existing theoretical representations about deformed heavy nucleus the excitation energy of 2 – 2.5 MeV is approximately equal to the breaking energy of the first Cooper pair 2Δ (Δ is a pairing energy of the last nucleon in the nucleus). But a small level density at the energy about 2Δ prevents to notice the breaking threshold of the first Cooper pair, which is expected at this energy (according to a redistribution of the excitation energy). Nevertheless, for a quantitative description of the total cascade intensity, it is necessary to take into account in the fittings an existence of vibrational levels below the breaking threshold of the second Cooper pair.

4. THE EMPIRICAL MODEL OF THE GAMMA-DECAY

In order to extract reliable experimental information about a behavior of a superfluid phase of the nuclear matter it is necessary:

1) to measure an intensity of gamma-cascades to the low-lying levels of investigated nucleus (to the ground state and to a group of levels with small energies);
2) to ensure the best description of measured spectra at a simultaneous fitting of the parameters of both the level density and the partial radiative widths.

The principal problem for a study of superfluidity in the excited nucleus is a choice of model representations for reliable description of the investigated process. To obtain the level density and the partial widths of the products of the nuclear reaction, in a majority of the world's experiments, the models are used, which are based on the calculations of different spectra and cross-sections at the large excitation energies [17–19]. The analysis of the created by now experimental data on the intensities of the two-step cascades for 43 nuclei showed a worthlessness (for a valid description of the processes in the nucleus) of an obsolete representation, that the nucleus is a system of uninteractive Fermi-particles.

In the absence of correct theoretical models we used our empirical model, including the different realistic phenomenological representations into it. But it is illegal to use even generally accepted representations about the parameters of the investigated process without experimental testing. Otherwise, the principle errors will inevitably appear.

For the level density description in the present analysis the model of density of n-quasi-particle nuclear excitations [19, 20], which is commonly used in a study of the preequlibrium reactions, was parameterized. The density ρ_l of levels of fermion type above the expected breaking threshold of the l-th Cooper pair was written by an expression:

$$\rho_l = \frac{(2J+1)\cdot\exp(-(J+1/2)^2/2\sigma^2)}{2\sqrt{2\pi}\sigma^3}\Omega_n(E_{ex}), \qquad \Omega_n(E_{ex}) = \frac{g^n(E_{ex}-U_l)^{n-1}}{((n/2)!)^2(n-1)!}. \tag{2}$$

Here Ω_n is a density of n-quasi-particle states, σ is a factor of spin cutting, J is a spin of the compound-state of nucleus, g is a density of singe-particle states near Fermi-surface, and U_l – the breaking energy of the l-th Cooper pair (or the energy of an excitation of pair of quasi-particles).

For a description of the coefficient C_{coll} of an increase of a density of collective levels a phenomenological relation between entropies of phases of the nuclear matter was used [16] IGN] with taking into account a cyclical break of Cooper pairs:

$$C_{col} = A_l \exp(\sqrt{(E_{ex}-U_l)/E_u} - (E_{ex}-U_l)/E_u) + \beta. \tag{3}$$

Here A_l are fitting parameters of vibrational level density above the breaking point of each l-th Cooper pair, parameter $\beta \geq 0$ can differ from 0 for deformed nuclei. Parameter E_u (a rate of a change in densities of quasi-particle and phonon levels) is practically equal to the average pairing energy of the last nucleon in the majority of investigated nuclei [6–10].

As it was experimentally determined earlier [21], a correct description of the intensities of the two-step cascades is possible only if to add one or two peaks to the smooth energy dependence of the radiative strength functions of $E1$- and $M1$-transitions. The smooth parts of the energy dependences $k(E1,E_\gamma)$ and $k(M1,E_\gamma)$ were described as in the model [18] with addition fitted parameters of weight w_E (or w_M) and of a change of derivatives of the strength function κ_E (or κ_M) (indexes E and M refer to $E1$- or $M1$-transitions, correspondingly). And in order to take into account the local peaks one or two summands were added to the smooth parts of the strength function. In the presented analysis the asymmetric Lorentzian curve was used for description of the shape of each local peak. So, $k(E1,E_\gamma)$ and $k(M1,E_\gamma)$ strength functions were expressed similarly as:

$$k(E1,E_\gamma) = w_E \frac{\Gamma_{GE}^2(E_\gamma^2 + \kappa_E 4\pi^2 T_E^2)}{(E_\gamma^2 - E_{GE}^2)^2 + E_{GE}^2 \Gamma_{GE}^2} + \sum_i W_{Ei} \frac{(E_\gamma^2 + (\alpha_{Ei}(E_{Ei} - E_\gamma)/E_\gamma))\Gamma_{Ei}^2}{(E_\gamma^2 - E_{Ei}^2)^2 + E_\gamma^2 \Gamma_{Ei}^2}, \quad (4)$$

$$k(M1,E_\gamma) = w_M \frac{\Gamma_{GM}^2(E_\gamma^2 + \kappa_M 4\pi^2 T_M^2)}{(E_\gamma^2 - E_{GM}^2)^2 + E_{GM}^2 \Gamma_{GM}^2} + \sum_i W_{Mi} \frac{(E_\gamma^2 + (\alpha_{Mi}(E_{Mi} - E_\gamma)/E_\gamma))\Gamma_{Mi}^2}{(E_\gamma^2 - E_{Mi}^2)^2 + E_\gamma^2 \Gamma_{Mi}^2}, \quad (5)$$

where E_{GE} (or E_{GM}) and Γ_{GE} (or Γ_{GM}) are location of the center and width of the maximum of the giant dipole resonance, T_E (or T_M) is a varied nuclear thermodynamic temperature, for $E1$- (or $M1$-) transitions. And for each i-th peak ($i \leq 2$) of the strength functions of $E1$- (or $M1$-) transition: E_{Ei} (or E_{Mi}) is a center position, Γ_{Ei} (or Γ_{Mi}) – width, W_{Ei} (or W_{Mi}) – amplitude, and α_{Ei} (or α_{Mi}) ~ T^2 is an asymmetry parameter. A necessity of taking into account a peak asymmetry in the radiative strength function results both from the model [18] and from the theoretical analysis of features of the fragmentation of single-particle states in the nuclear potential [2]. At the fitting the functions (4) and (5) are appreciably varied.

The shell inhomogeneties of a single-partial spectrum were also taken into account in the presented analysis (as in [9]).

A comparison of the level density obtained from spectra of evaporated nucleons [22] with the data of analysis of the cascade intensities [23] shows their sizeable distortion in the energy points of the Cooper pairs' breaking. A phonon disappearance and an appearance of additional pair of quasi-particles must noticeably change the level density. From the existence of the smooth evaporated spectra results that a change in the level density (at breaks of the Cooper pairs in the nucleus) must be compensated by a change in the strength functions at the same excitation energies. And a resonance structure of the strength functions, experimentally discovered [24] near the point of the second Cooper pair breaking (at the excitation energy of about 3 – 4 MeV), which was interpreted by an existance of a "pygmy"-resonance in the nucleus, must be accompanied by a change in the level density. For a verification of this reasonable assumption we introduced into equations (4) and (5) the compensation coefficients M [6,25]:

$$M = \rho_{mod}/\rho_{exp}. \quad (6)$$

Here ρ_{mod} is the level density calculated using Fermi-gas model, ρ_{exp} – the level density obtained at the experimental intensity description. For the strength functions (4) and (5) coefficients M are fitted separately.

The compensation parameters M introduce some unaccounted anti-correlation between ρ and Γ, which was not completely included in used model representations for ρ and Γ. At a high enough quality of the experimental data on the two-step cascades on ^{172}Yb there is a real possibility to evaluate an influence of compensation parameters M on determination of the breaking thresholds of Cooper pairs.

5. RESULTS

5.1. On a stability of obtained parameters

The results of analysis of the cascade gamma-decay of ^{172}Yb using the empirical model describe with a high accuracy the intensity of the cascades with the total energies from $E_1 + E_2$

= 8020 keV to $E_1 + E_2 = 6823$ keV including the resolved local peaks above $E_{ex} \approx 5$ MeV (see fig. 5).

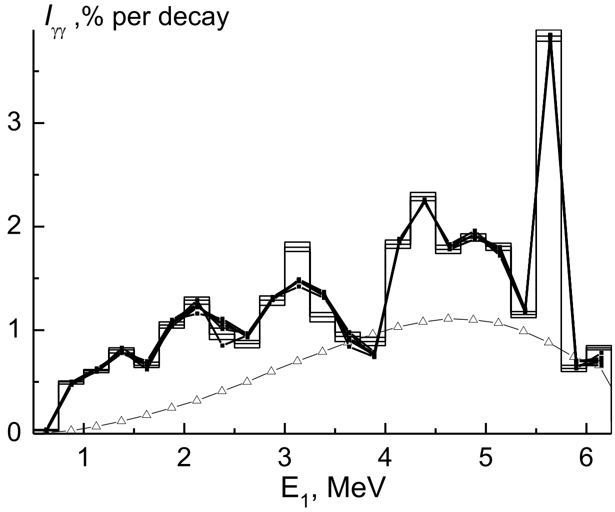

Fig. 5. The dependence of the total intensity of the cascades of ^{172}Yb to 6 final levels with $E_f \leq 1197$ keV on the energy of primary transition. Histogram is the experimental intensity with its errors obtained by the procedure [14]. Broken lines are the results of the best fits with different *M* coefficients. Triangles are intensity calculations using models [17] and [18].

In figs. 6 – 8 there are the best seven fits of the intensity of the cascades with different compensation parameters *M*. The initial *M* values were chosen in the interval $1 \leq M \leq 10$. The results of a description of the cascades' intensities with different initial *M* values showed that their fitted values are always bounded above (for *E*1-strength function $M \leq 5$, and for *M*1-strength function $M \leq 3$).

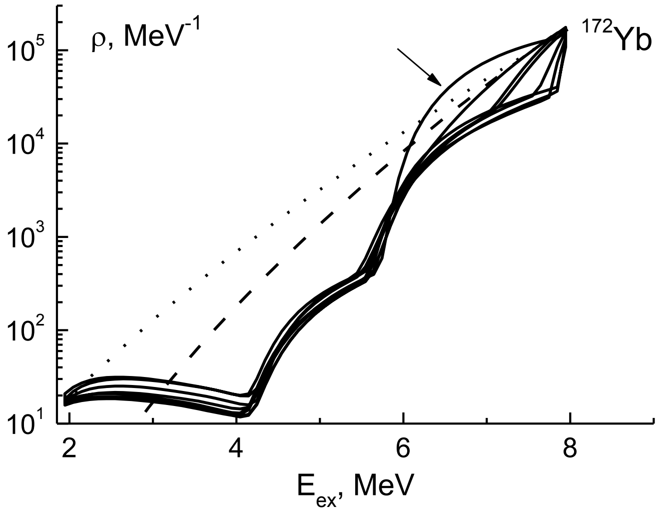

Fig. 6. The excitation energy dependences of the level densities for ^{172}Yb. Solid lines are the level densities obtained from approximations of the total intensity $I_{\gamma\gamma}$ of the cascades to 6 final levels with $E_f \leq 1197$ keV at varied *M* (6). Dashed and dotted lines are calculations of ρ value using the model [17] with and without taking into account the shell inhomogeneities of a single-particle spectrum [16], correspondingly. Fit without taking into account the parameter *M* is shown by a row.

For ^{172}Yb, as in [8, 10], the stepwise structure in the level density at a growth of the excitation energy was discovered (fig. 6), at a decrease of the density of the levels of vibrational type between the breaking thresholds of Cooper pairs. This result is in qualitative agreement with the model representations both from [16] about the behavior of the density of vibrational levels (see fig. 4), and from [20], where a rapid rise of density of the quasi-particle levels at each Cooper pairs' breaking threshold was predicted.

The probable values of *E*1- and *M*1-radiative strength functions for ^{172}Yb nucleus in dependence on the energies of primary transitions of the cascades (with taking into account a contribution of a negative (below neutron binding energy) resonance) are presented separately in fig. 7. In fig. 8 the sums of *E*1- and *M*1-radiative strength functions are shown. The results were obtained by a condition that a part of decays of the compound-state with the spin $J = 1$ is 60%.

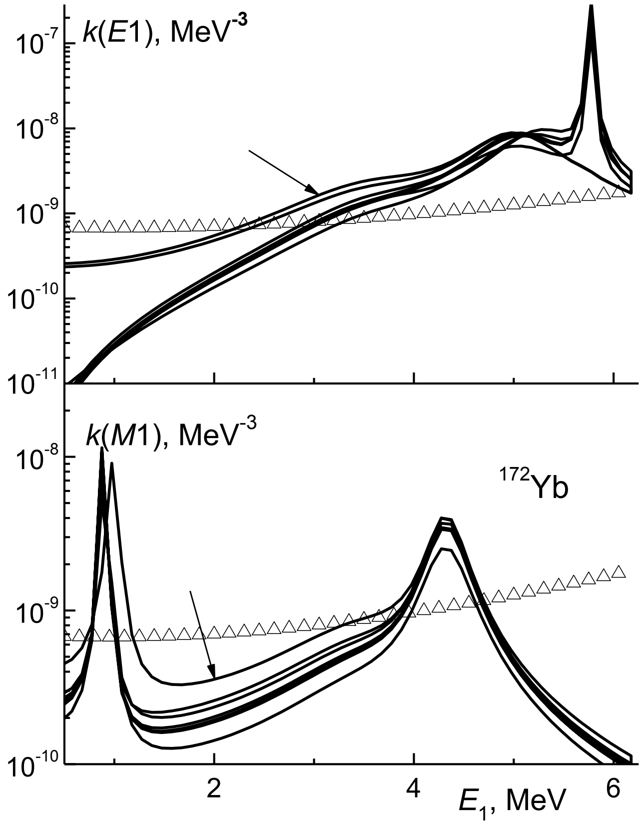

Fig. 7. The strength functions $k(E1)$ and $k(M1)$ of *E*1-transitions (upper picture) and *M*1-transitions (bottom picture) obtained for the energy of primary transition in the interval $0.52 < E_1 < 6$ MeV at varied parameter *M* (6). Triangles – calculation of the strength function of *E*1-transitions using the model [18] in a sum with c $k(M1)$= const. Two fits without taking into account the parameter *M* are shown by rows.

Figs. 5 and 6 results that the compensation coefficients *M* have almost no influence on the calculated cascade intensities and relatively weakly change the level density near the breaking thresholds of the first, the second and the third Cooper pairs. And figs.7 and 8 shows that the fittings with parameter *M* noticeably change the strength functions. More essential fact is that at $M > 2$ in the fitted spectra of radiative strength functions the local peak with the center at $E_1 \approx 1$ MeV appears (near excitation energy, where there is the breaking point for the fourth Cooper pair). An increment of the strength function in the point of breaking the 4-th

Cooper pair, as for ^{172}Yb, would be expected also for a number of nuclei with noticeable excess intensity of the cascades near $E_1 = 1 – 2$ MeV [8, 10].

At the fits with $M > 2$ the positions of both the peak of the electrical strength functions at the energy of primary transitions near 6 MeV and the peak of the magnet strength functions near E_1= 4 MeV (see fig.7) correspond to the breaking points of Cooper pairs of ^{172}Yb nuclear.

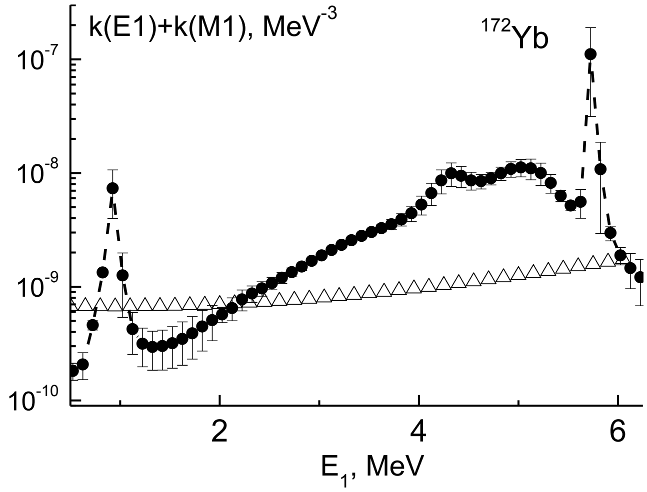

Fig. 8. Dependences of the sums of *E*1- and *M*1- radiative strength functions on the energy of primary transition. Points with errors connected by dashed line are the best 7 fits with varied *M* (6). Triangles – *E*1-strength function calculated using the model [18] in a sum with *k*(*M*1)=const.

At the fits with $M = 1$, in the energy dependence of the *E*1- radiative strength function, the peak of the strongest resolved cascade 5540+2402 keV near E_1= 6 MeV is not observed (according to [15], its relatively strong intensity is due to existing negative resonance). Nevertheless, such intense peak is not observed at a capture of 2 keV neutrons, so it would be a large random deviation.

5.2. On a connection between the parameters of the gamma decay and the compound-state spin

Cascading γ-decay of the neutron resonance of a target with odd number of neutrons (or/and protons) is happened through dipole *E*1- and *M*1-transitions practically in 100% of decays. Mixtures of dipole and quadrupole gamma-transitions are present at the γ-decay process and have an influence on the values of the strength functions, but their existence in the two-step cascades of all nuclei investigated earlier was not identified.

A high resolution of the detectors for the cascade recording allows to investigate a dependence of the parameters of the nuclear superfluidity on the spins of the excited levels and on their parities at varied excitation energy. At the fitting an unknown ratio of the densities of levels with different parities in the interval of excitation energy $E_d \le E_{ex} \le B_n$ (E_d is upper energy boundary of the area of discrete levels) was taken as $r = \rho(\pi-)/(\rho(\pi-)+\rho(\pi+))$, where $\rho(\pi-)$ and $\rho(\pi+)$ are the densities of levels with negative and positive parities, correspondingly. In all calculations for ^{172}Yb, at B_n =8 MeV $r = 0.5$ (it is generally accepted now hypothesis) and at $E_{ex} = E_d$ r varied from 0 to 1 (at $E_d < E_{ex} < B_n$ r value was taken from corresponding linear extrapolations).

A capture cross sections of thermal neutron by ^{171}Yb nucleus composed by known resonances to the compound states $J = 1$ и $J = 0$ are $\sigma_1 = 4$ b and $\sigma_0 = 1.8$ b, correspondingly.

And capture cross section from the negative resonance is 42.8 b [26]. An existence of the negative resonance with unknown spin influences on the fitting results (and on the calculated values of the breaking thresholds). Under selection rules on multipolarity, at the decay of compound-state with the spin $J = 0$ the two-step cascade excites the final levels with spins $I = 0, 1, 2$, and at the decay of the compound-state with $J = 1$ the final levels with $I = 0, 1, 2$ and 3 are excited.

It is possible to evaluate an influence of a spin of the compound-state on the fitted parameters, which describe the experimental intensities in the present experiment, from calculated dependences of intensities on a ratio $\sigma_1/(\sigma_1+\sigma_0)$. This ratio determines a contribution of a neutron capture by the compound states with spin $J = 1$ to the total capture cross section $\sigma_1+\sigma_0$. The calculated total intensities for a given ratios $\sigma_1/(\sigma_1+\sigma_0)$ (points connected by lines) are shown in fig. 9 for the cascades to 8 final levels of ^{172}Yb. Six of the final levels presented in fig. 9 have energy $E_f > 1$ MeV. The best fits for the level density and for the strength functions (figs. 6–8) are used in calculations of $I_{\gamma\gamma}$ for these cascades. The obtained from the experiment parts of intensities for the sums of two strongest cascades and of four cascades with the energies 1043; 1118; 1155 and 1198 keV are 0.203(11) and 0.078(11), correspondingly.

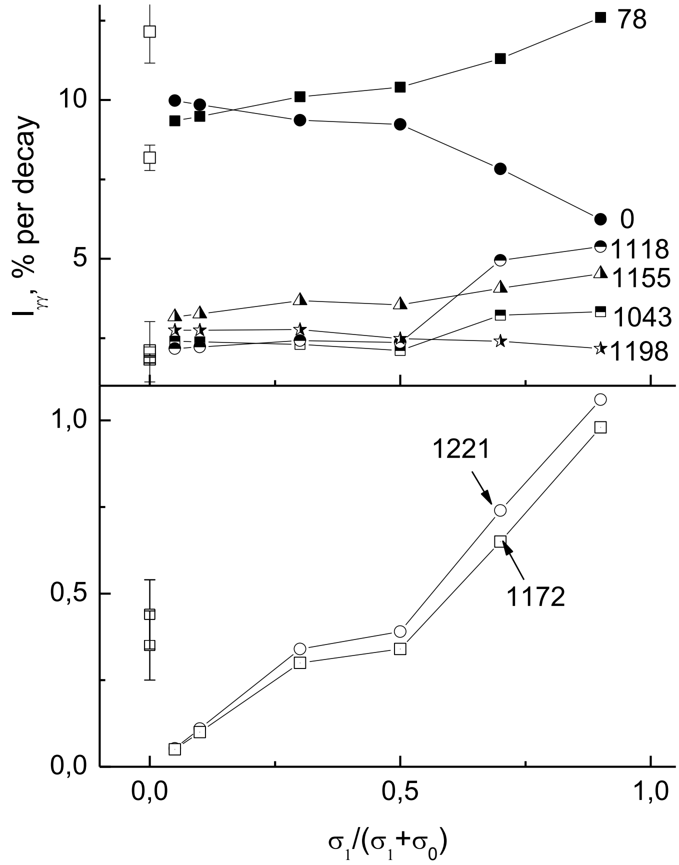

Fig. 9. The calculated total intensities of the cascades for a given ratios $\sigma_1/(\sigma_1+\sigma_0)$ of a capture cross section by the compound states with spin $J = 1$ to the total capture cross section (points connected by lines). The energies of the final levels are denoted by arrows (in keV). Points with errors are the experimental intensities of the explored cascades.

If the negative resonance have a spin $J = 0$, the calculations (fig. 9) show that the levels with $E_f = 1172$ keV ($I = 3^+$) and $E_f = 1221$ keV ($I = 3^-$) cannot be excited often than in

1 case per 1000 decays. If the negative resonance has a spin $J = 1$, these cascades have intensities up to 1 % per a decay. From a comparison of calculations, which are presented in fig. 9, the ratio $\sigma_1/(\sigma_1+\sigma_0)$ can be evaluated by a value 30 to 60 %.

In dependence on a spin of negative resonance the calculated sum of the intensities of the cascades to the ground and the first exciting states changes from 18.8 to 19.6% per decay.

The obtained intensities of the cascades with $E_f = 0$ ($I = 0$) and $E_f = 78$ keV ($I = 2$) clearly demonstrate an anti-correlation between calculated intensities of the cascades to these final levels, when the part of cross-section of a capture to the state with $J = 1$ changes.

6. CONCLUSION

In the present experiment the specific behavior of the gamma-decay, discovered by us earlier for 43 nuclei, was confirmed for ^{172}Yb nucleus. The intensities of the two-step cascades in the ^{172}Yb nucleus were determined with the best accuracy among all investigated even-even nuclei.

From the experimental distributions $I_{\gamma\gamma}(E_1)$ of the cascades to different final levels at a capture of thermal neutrons by ^{171}Yb nucleus the most probable value of the breaking threshold for the second Cooper pair was obtained with an uncertainty less than 0.5 MeV, and the breaking thresholds for the 3-rd and the 4-th Cooper pairs were determined with some bigger uncertainties. A demonstrable connection between the breaking thresholds and the spin of the neutron resonance was not discovered in the analysis. For ^{172}Yb (as for all investigated deformed nuclei) the obtained value of the breaking thresholds for 4-th Cooper pair satisfies the condition $U_4 \leq B_n$.

All obtained dependencies ($k(E1)$, $k(M1)$ and $\rho(E_{ex})$) for ^{172}Yb have the similar shapes if to compare with ones for ^{174}Yb [9, 10]. An existence of the stepwise structure in the $\rho(E_{ex})$ distribution with the closed for two ytterbium isotopes breaking thresholds of Cooper pairs can be considered as an observation of common pattern of the gamma-decay for these deformed nuclei. A comparison of the level density ρ obtained from approximation of the intensity of the cascades to two final levels (fig. 4) and analogous data for 6 cascades (fig. 6) showed a weak dependency of ρ on a structure of the wave functions of rotation and vibrational final levels of ^{172}Yb. An accuracy of the $I_{\gamma\gamma}(E_1)$ experimental distribution allows us to declare that the superfluid phase of the nuclear matter exists and we can observe its change with a growth of the excitation energy.

For ^{172}Yb the energy dependencies of $E1$- and $M1$-radiative strength functions are similar, on the whole, with ones obtained earlier for the other even-even deformed nuclei. Some difference can be explained by both errors of the experiment and imperfection of the model representations about ρ and Γ parameters of the investigated nucleus.

For a further research of the cascade gamma-decay of the compound-states the new models are needed, which would be able to describe the dipole radiative strength function and the level density at all excitation energies of investigated nucleus. First of all, it is necessary to change a phenomenological coefficient of vibrational enhancement of the level density by a modern appropriate model. The new models had to take into account a dependency of ρ and Γ on spin, parity, quantum number K etc., and, for an objectivity of obtained results at a study of the change dynamics of superfluid nuclear properties, the required models had to have a possibility the descriptions of the nucleus both as a pure fermion system and as a pure boson one, as special cases.

A heavy potential for investigation of the superfluidity of exited nuclei one can expect, if for the cascades' intensity recording the system of great number of HPGe-detectors would be used (for a separation of the cascades with different multiplicity of quanta and with the intensities up to 90% of the total intensity of primary transitions), and at a study of the decay of compound-states with emission of two divers reaction products.

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