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MAIN PARAMETERS OF THE ¹¹⁸Sn
COMPOUND-STATE CASCADE γ DECAY

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1 Introduction

The study of the two-step γ -cascades following thermal neutron capture in more than 50 nuclei of different types from ^{40}K to ^{200}Hg in Dubna, Riga and Řež allowed us to obtain unique information on properties of these nuclei in energy diapason from the ground state and, practically, to the neutron binding energy B_n . Analysis of this information provided the the following conclusions:

1. Experimental intensities of the cascades to the groups of low-lying levels E_f cannot be reproduced in the calculation with the precision achieved in the experiment if one uses conventional model ideas of a nucleus. This cannot be done not only within the simplest models like “non-interacting Fermi-gas” but also in the framework of modern enough generalized model of superfluid nucleus [1].

2. Reliable enough energy dependence of level density and radiative strength functions of dipole γ -transitions can be extracted only from the experimentally obtained dependencies of the cascade intensities on the energy of their primary transition E_1 (or energy of their intermediate level $E_i = B_n - E_1$).

Practical possibility to solve this problem is determined by the following factors:

(a) Cascade intensity distribution (Fig. 1) is extracted [2] from the mass of $\gamma - \gamma$ coincidences by means of the sum coincidence method. It contains some number of pairs of narrow enough [3] full-energy peaks corresponding to intense two-step cascades and a “noise line” with zero mean value formed by a number of low-intense cascades. The local specific deviations of the normal distribution of events in “noise line” can be partially or completely rejected numerically [4].

(b) main part (more than 95-99%) of intensity of cascades with $E_1 > 0.5B_n$ can be extracted from these spectra in form of energetically resolved pairs of peaks, quanta ordering in which is determined [5] with high reliability using the maximum likelihood method. But this requires modern enough [6] spectrometer for registration of coincidences.

Using only these data we determined (Fig. 2) most probable energy dependence of all two-step cascades terminating at the ground and first excited states of ^{118}Sn . This permits one to make according to method [7] quite unambiguous (in limits of existing notions and possibilities to study this process) conclusions about both density of the states excited at the thermal neutron capture and reduced probability of their population by γ -quanta.

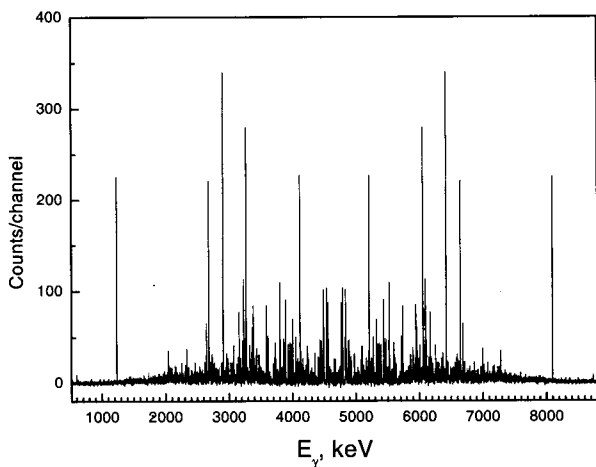


Fig. 1. The intensity distribution of two-step cascades with the total energy $E_1 + E_2 = 9326$ keV in ^{118}Sn (after background subtraction and correction for efficiency of registration of cascades).

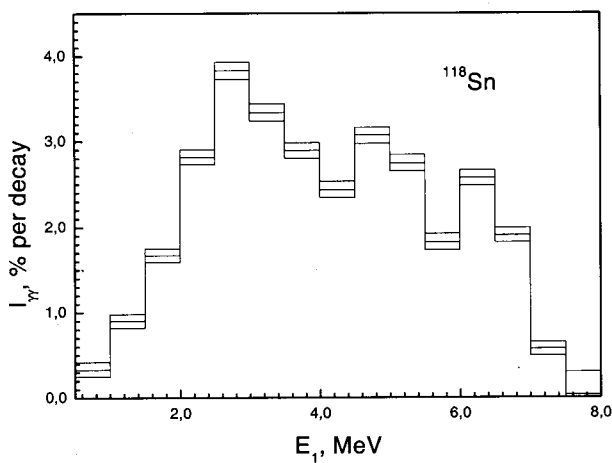


Fig. 2. Experimental distribution of the total intensity of the two-step cascades terminating at the ground and first excited states of ^{118}Sn in function of energy of their primary transitions E_1 . The ordinary statistical error is shown.

2 Estimation of probable density ρ of excited levels and radiative strength functions k of cascade transitions

Radiative strength function $k = \Gamma_{\lambda i} / (E_\gamma^3 \times A^{2/3} \times D_\lambda)$ (here $\Gamma_{\lambda i}$ is the partial width of γ -transition with the energy E_γ , A is the nucleus mass and D is the spacing between decaying levels λ) and level density ρ determine the total radiative width of the compound state Γ_λ and cascade intensity $I_{\gamma\gamma}$ [8] obtained in the following way:

$$\Gamma_\lambda = \langle \Gamma_{\lambda i} \rangle \times m_{\lambda i} \quad (1)$$

$$I_{\gamma\gamma} = \sum_{\lambda, f} \sum_i \frac{\Gamma_{\lambda i} \Gamma_{if}}{\Gamma_\lambda \Gamma_i} = \sum_{\lambda, f} \frac{\Gamma_{\lambda i}}{\langle \Gamma_{\lambda i} \rangle m_{\lambda i}} n_{\lambda i} \frac{\Gamma_{if}}{\langle \Gamma_{if} \rangle m_{if}}. \quad (2)$$

Here the values of the total and partial gamma-widths are set for the compound state λ and cascade intermediate level i , respectively; m is the total number of the excited levels, and n is the number of excited levels in the energy interval ΔE of averaging of cascade intensity.

These equations do not allow one to determine k and ρ unambiguously and independently. Some deviation of, for example, ρ from a real value is inevitably compensated by deviation of strength functions of the corresponding magnitude and sign. As it was shown in [7], however, possible value of these deviations is small enough. Nevertheless, the results obtained in analysis [7] can be used for the verification of nuclear models and, if necessary, for the determination of the direction of the further development of these models. The main argument in favour of this statement is relatively weak dependence of the final results on the initial values of k and ρ (even if they are absolutely unreal) in the iterative process [7]. The most serious supposition of the described in [7] method for determination of k and ρ is the equality in energy dependence of radiative strength functions for the primary and secondary transitions. If it is not true, then the obtained values of k and ρ can have unknown and, probably, significant systematic error. In dependence on the sign of this error, discrepancy between the model and experimental values of k and ρ can decrease or even increase.

Although calculation of the total γ -ray spectra with the use of level density [7] and different (but, in principle, possible) radiative strength functions showed [9] that the main properties of level density are extracted with the high confidence and probable error decreases discrepancy between the experimental and model [10,11] values of k and ρ , but independent complementary test of application of the method [7] for each concrete nucleus is required.

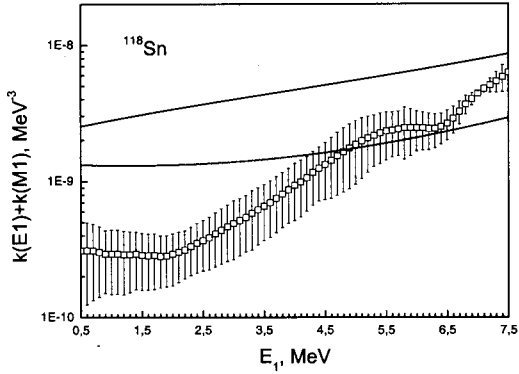


Fig. 3. The sum of the probable radiative strength functions of $E1$ and $M1$ transitions (with estimated errors). The upper and lower solid curves represent predictions of the models [13] and [10], respectively (the value $k(M1) = \text{const}$ normalized to the experiment at $E_\gamma \approx B_n$ is added).

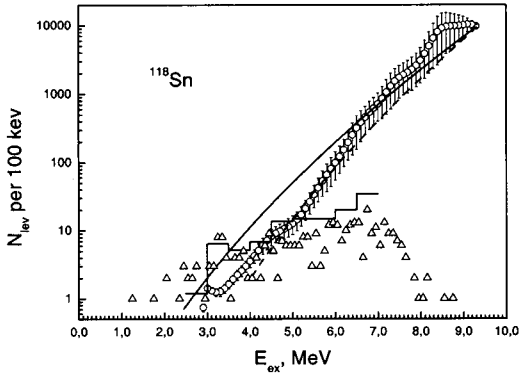


Fig. 4. The number of levels for $0^\pm \leq J^\pi \leq 2^\pm$ with their dispersion (circles with bars). The histogram represents the data of analysis [15], triangles show the observed in experiment number of intermediate levels of intense cascades. Solid and dashed lines represent predictions of the models [11] and [12], respectively.

Some grounds to consider the k and ρ values, shown in figures 3 and 4, as reflecting the most common regularities of their energy dependences can be get from the comparison of the experimental and calculated within different ideas of intensities of cascades terminating at higher-lying levels (see Table). Taking into account that the k and ρ values shown in figures 3 and 4 allow simultaneous reproduction of:

(a) the total radiative width Γ_λ of the compound state;

(b) the energy dependence of the intensity $I_{\gamma\gamma}$ of cascades to the ground and first excited states of ^{118}Sn ; and

(c) the total intensity of the cascades to different final levels with the energy up to 2.8 MeV

one can consider the strength functions and level density obtained for ^{118}Sn according to method [7] as the most probable. These data, of course, contain some systematic errors owing to errors in determination of $I_{\gamma\gamma}$ and incompleteness of the obtained information on the intensity of the two-step and larger multiplicity cascades.

Table. Energies $E_1 + E_2$ of cascades and their absolute intensities $I_{\gamma\gamma}$ (% per decay).
 E_f is the energy of the cascade final level

$E_1 + E_2$, keV	E_f , keV	$I_{\gamma\gamma}^{exp}$	$I_{\gamma\gamma}^{mod}$	$I_{\gamma\gamma}^{best}$
9326.30	0	16.0(34)	6.7	15.7
8096.63	1230	15.3(11)	7.2	15.5
7568.00	1758	2.4(7)	1.1	2.5
7283.42	2042	3.3(16)	2.4	5.5
7269.39	2057	2.8(9)	0.8	1.7
7000.36	2325+2328	5.6(9)	2.8	5.4
6923.08	2403	2.8(2)	1.5	3.0
6829.42	2497	[2]	0.5	0.7
6648.95	2677	[1.5]	1.0	2.0
6588.29	2738	[4]	1.7	5.5
sum		55.8(43)	25.7	57.5

Note: $I_{\gamma\gamma}^{best}$ is the calculated mean value for the ensembles of random parameters ρ and k (its mean value and dispersion is shown in Fig. 3,4 by points with bars) allowing reproduction [7] of the cascade intensity distribution (Fig. 2) with experimental precision. The mean-square scatter of each of these parameters for each final level of cascades equals 5 to 15%.

The results of the analysis are compared with predictions of the level density models [11,12] and models of radiative widths [10,13]. In the case of radiative strength functions, a comparison is performed in the following manner: the $k(E1)$ values calculated according to the models [13] and [10] (upper and lower curves in Fig. 3, respectively) are summed with $k(M1) = const$ which is normalized so that the ratio $\Gamma(M1)/\Gamma(E1)$ would be approximately equal to the experimental data at $E_\gamma \simeq B_n$.

A comparison of the results of the analysis with predictions of the models [10-13] (often used for this aim) shows that:

1. the energy dependence of $k(E1) + k(M1)$ for ^{118}Sn differs strongly from predictions of the models [10,13] as in the case of even-even compound nuclei from the region of the $4s$ -resonance of the neutron strength function;
2. the probable level density conforms to the picture obtained in previous experiments [11,12]: up to the excitation energy $\simeq 3.5$ MeV, our data do not contradict the exponential extrapolation of $\rho(E_{ex})$ predicted by the Fermi-gas back-shift model [11]. Level density for $E_{ex} > 3$ MeV is considerably less than that predicted by this model. Above $E_{ex} \approx 5$ MeV the level density, most probably, better corresponds to the predictions of the generalized model of the superfluid nucleus in its simplest form [12]. The values of ρ^{mod} predicted by the last model decrease parameter $\chi^2 = ((\rho^{mod} - \rho^{best})/\delta\rho^{best})^2$ by a factor of about 3 as compared with the predictions of model [11] for the interval $E_{ex} \geq 4$ MeV.

A very quick exponential increase in the level density above $\simeq 5$ MeV says [12] about the probable dominant influence of the inner, many-quasi-particle type of excitations of these states.

3 Discussion

This conclusion is true only to a precision determined by existing (and included in analysis [7]) notions of properties of the excited states and dynamics of development of the cascade γ -decay process of neutron resonance.

The main of these notions consist in the following:

- (a) the branching coefficients at depopulation of any level i do not depend on mode of its population;
- (b) all levels from a given excitation energy interval follow the sole statistic distribution. I.e., the mean reduced probability of their population by primary $E1$ and $M1$ transitions is equal for any level in the spin window determined by the selection rule and does not depend on the structure of wave functions of neutron resonance and intermediate cascade level E_i .

Therefore, according to the theorem on the average any sum of the widths is represented in calculation of $I_{\gamma\gamma}$ by product of their number by the mean partial width (determined through corresponding wave function).

- (c) energy dependence of k (but not its absolute value) is equal for the primary and secondary transitions of cascades.

It is not known how the notions (a) and (b) of the γ -decay process of heavy nucleus are close to reality. This should be found from the experiment. Analysis of the excitation spectra of intermediate levels of the most intense cascades testifies to possibility of their equidistancy. Besides, it shows that the population of levels in ^{118}Sn above $\simeq 3$ MeV cannot be described in model calculation. These allow an assumption about possible violation of, for example, notion (c). If interpretation of the results [14] as an existence of "vibrational bands" built on the states with complicated structure corresponds to reality, then the enhanced γ -transitions with the energy of some hundreds keV and higher inside these bands and between them are quite possible, as well. Discrepancy of the results obtained according [7] and shown in Fig. 4 to the estimation

[15] of the number of omitted levels admits as one of possible explanations the violation of notion (c).

4 Conclusion

The results of a comparison between the experimental and calculated cascade intensities in this nucleus (and like in the nuclei studied earlier) indicate a necessity to modify model notions of the properties of the excited states of the heavy nuclei. In the framework of the modern theoretical notions the qualitative explanation of the obtained discrepancy between the experiment and calculation can be removed only within the more detailed accounting by the nuclear models [1,12] for co-existence and interaction of fermion and boson excitations of nuclear matter. Otherwise, an achievement of complete correspondence between the observed and calculated parameters of nuclear reactions, for instance, neutron-induced reaction is impossible. This concerns, partially, the total radiative widths of neutron resonances, γ -spectrum, and cross-sections of neutron interactions.

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Гонзатко Я. и др.
Основные параметры каскадного гамма-распада
компаунд-состояния ядра ^{118}Sn

E3-2003-97

Изучены основные свойства возбужденных состояний ^{118}Sn , определяющие каскадный гамма-распад его компаунд-состояния. Как и в ранее изученных ядрах, качественная интерпретация основных свойств этого ядра невозможна без учета сосуществования и взаимодействия квазичастичных и фононных возбуждений ядра и их влияния на основные параметры изучаемого процесса.

Работа выполнена в Лаборатории нейтронной физики им. И. М. Франка ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2003

Honzátko J. et al.
Main Parameters of the ^{118}Sn Compound-State Cascade γ Decay

E3-2003-97

Main properties of the excited states of ^{118}Sn manifesting themselves in cascade γ decay of its compound state were studied. As in other heavier nuclei studied earlier, qualitative interpretation of the totality of the observed properties of this nucleus is impossible without accounting for coexistence and interaction of quasi-particle and collective nuclear excitations and their considerable influence on the main parameters of the process under study.

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

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