REANALYSIS OF THE PROCESS OF THE CASCADE GAMMA DECAY OF $^{198}$Au COMPOUND STATE

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Abstract

To further study the "pygmy" resonance phenomena in the photon strength function, we reanalyzed the two-step cascade data for the target nucleus $^{197}$Au using the Dubna group approach. The range of obtained values allows for meaningful conclusions: the level density at low excitation energy shows a step-like behavior; the electric dipole photon strength function has a broad maximum around $E_\gamma = 5$ MeV and is not typical of a "pygmy" resonance; the level density below $B_n$ also demonstrates step-like behavior.

1 Introduction

The main task of an experiment in the low energy ($E_{ex} \lesssim 10$ MeV) physics is to study the influence of structure of excited levels of a nucleus on the parameters measured in the experiment, for example of the process of cascade gamma decay. After that – the extraction of dynamics of intranuclear interactions out of these experimental values and their theoretical interpretation with the development of theoretical models required in practice [1] for the nuclear parameters used in this case. This is necessary, in particular, in order to obtain the maximum realistic evaluation of cross sections of interactions of neutrons with nuclei necessary in practice. This is important especially for actinides where the existing models of level density can not [2] provide for the maximum reliable and accurate evaluation of cross sections with the absolute minimum of accepted hypotheses and assumptions.

In the stated analysis cycle the evident insufficiency of experiments sensitive to the structure of nucleus in the widest region of its excitations still remains the main problem. At present, the co-existence, interaction and defining influence of the nuclear excitations of qualitatively differing types, namely multiquasiparticle and vibration ones, on the structure of nuclei give no rise to doubt. This is the main conclusion of such fundamental models of nucleus as different variants of IBM and QPNM. Unfortunately, the majority of experiments carried out so far give direct and quite reliable information on the structure of nucleus only for too small energies of its excitation. In practice, for example, this region in the even-odd heavy nucleus [3] is still restricted to the interval of excitation energies of the order of 2 MeV. Therefore, there are no direct methods to determine level densities, first of all, at higher excitation energies. The mentioned parameter of a nucleus, like probability of the
gamma quantum emission in the whole region lower than the neutron binding energy or nucleon products of a reaction may only be determined from indirect experiments. Mainly, such analysis uses the spectra of products of a nuclear reaction measured by single detectors. Their amplitude depends both on the number of excited levels and on partial widths of the emission of nuclear reaction products according to the given decay channel of the initial state of an excited nucleus.

The situation is also complicated by the fact that the measured ordinary spectra of one-step reactions are mainly determined by the product of level density of a nucleus on the probability of emission of their products. As a result of strong correlation of these parameters, the transfer of inevitable errors in determination of the spectrum intensity to the unknown values increases abruptly their uncertainties. This circumstance completely excludes a possibility of simultaneous experimental determination, for example of reliable values of level density $\rho$ in a fixed interval of their spins or of radiative strength functions $f = \Gamma_{\lambda i}/(E_3^\gamma \times D_\lambda)$ of cascade gamma transitions, without attraction of any model notions: first of all, without the hypothesis [4], which is a basic one for the analysis of all the experiments carried out earlier, on the independence of cross section of the inverse reaction on the excitation energy of the final nucleus.

Potentially, the task of simultaneous determination of $\rho$ and $k$ could be solved for gamma decay of any excited level $\lambda$ of an arbitrary nucleus with the mass $A$ with any mean spacing $D_\lambda$ between them at the combining of experimental data of different experiments, for example of the cross sections of radiative neutron capture and spectra of gamma rays occurring simultaneously. However, there are no practical achievements in this direction so far.

A fundamentally new method to solve the problem under consideration was realized for the first time [5] in Dubna. The analysis of intensities of two-step cascades of radiative capture of thermal neutrons in the energy intervals $\Delta E$, fixed according to the method [6], of their intermediate levels $E_i = B_n - E_1$

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

made it possible for the first time to determine $\rho$ and $k$ simultaneously and without a model: in the initial variant - on assumption of the independence of partial radiative widths $\Gamma$ on the excitation energy of the studied nucleus (i.e. using the hypothesis [4]); in the modern one [7] - completely without using it. The indubitable advantage of such experiment is also the circumstance that for any interval of excitation energies $\Delta E$ the number $m = \rho \Delta E$ (or $n$) of levels is fixed by the spin window assigned by an experiment. At the same time systematic errors $\delta \rho$ and $\delta k$ of the determined parameters are restricted very much by the type of spectra measured in the experiment (in comparison with other methods of similar experiments) and have a quite acceptable value [8] for practically attainable systematic errors $\delta I_{\gamma\gamma}$.

Later, similar experiments were carried out in Riga, Řež, Los Alamos, Budapest [9,10,11,12] and started in Dalat. However, the conclusions of different groups on parameters of the cascade gamma-decay process differ fundamentally depending on the method of experimental data processing used by the authors. This difference is of purely technical character and may lead to the appearance of false conclusions about the process under investigation only if one does not take into account strong correlation in expression (1) of the
unknown parameters $\rho$ and $k$ in the analysis. Errors increase particularly in conclusions of
the analysis of experiment when anticorrelations of cascade intensities are neglected with
the energies of their primary and secondary gamma transitions located in one and the same
interval $\Delta E$ of each experimental spectrum.

2 Main tasks and problems of model-free determination of $\rho$ and $k$

Currently, the method [7] is the only source to obtain reliable data on $\rho$ and $k$ for any com-
pound nucleus if only the experimental conditions allow one to limit the energy spread of the
excited levels $\lambda$ to the interval of the order of 1-3 keV and less. However, in contrast to other
already existing methods, here a single-valued determination of the unknown parameters is
impossible in principle.

For example, for cascade gamma decay at the neutron capture in resonance the informa-
tion on experimental intensities of two-step cascades, their density and number of known
low-lying levels is available. However, it is impossible to obtain unambiguity in determination
of $\rho$ and $k$ even using [7] such additional information as the total (or only cascade)
population of levels in the low half of neutron binding energy.

A very essential limitation of the region of possible values of level densities and radiative
strength functions is provided by non-linearity of equation (1) relative to $\rho$ and $k$. The
non-linearity effect occurs only if its half is extracted [6] out of the experimental spectrum.
The half equals to the summarized intensity of two-step cascades, which excite intermediate
levels in each given interval of their energy. This very operation during the data processing
decreases the interval of values of $\rho$ and $k$, which accurately reproduce $I_{\gamma\gamma}$ from absolutely
non-informative ones [13] to practically accurate values of [8] $\rho$ and $k$ suitable for comparison
with the theory. That is why the analysis [7] makes it possible to obtain the maximum
realistic notions on the dynamics of the process of cascade gamma decay of any nucleus.
However, the existing quite serious discrepancies between the data on $\rho$ and $k$ from the
technique [7] and the technique, which is used for a long time, to extract level densities from
evaporative spectra point to the necessity of serious comprehensive analysis of both sources
of systematic errors in the compared experiments and search of factors, which may influence
essentially, in the first place, the determined values of level density.

At present, the problem of studying the influence of structure of wave functions of levels
connected by a cascade on its intensity takes on special significance in determination [7]
of $\rho$ and $k$. It is of special importance for heavy odd-odd compound nuclei where, due to
the insufficiency of experimental data on gamma ray spectra in the region $E_\gamma \sim 0.5B_n$, we
failed to estimate the degree of discrepancy of radiative strength functions of primary and
secondary gamma transitions of one and the same energy and multipolarity. It is also true for
the nuclei maximally close to the actinide region for preliminary evaluation of the conditions,
which may distinctly distort the values of $\rho$ and $k$ obtained with the help of method [7].

The models [1] of radiative strength functions surpass essentially with regard to the extent
of working over and account of structure of a nucleus of the level density models. The second
ones take into account in an explicit form the existence of two fundamentally different types of nuclear excitations, the first ones still use only excitations of the fermion type [1]. The accumulated data set for each of the nuclei studied in [14] points to the necessity, at least, of phenomenological inclusion of the contribution from excitations (or the corresponding components of wave functions) of vibration type into radiative strength function models.

Taking into account all these factors, the maximum complete data analysis for the compound nucleus $^{198}\text{Au}$ is of primary interest.

3 Properties of the cascade gamma decay of the $^{198}\text{Au}$ compound state

Experimental determination of the total gamma ray spectrum of the radiative neutron capture and its interpretation in the framework of the present-day notions made the authors [15] conclude that in this nucleus the gamma decay is “anomalous”: at the gamma transition energy of about 5 MeV the so-called “pygmy- resonance” [16] manifests itself in the radiative strength function. This interpretation of the observed increase of the strength function of emission of the corresponding gamma quanta still remains and it became a subject of investigation in [17]. Notions on the “anomaly” of gamma decay have been obtained and remain only in the framework of the condition that the level density has been determined by now and is described with the help of a model with a rather high accuracy in the whole region of neutron binding energy by a “smooth” function. From our point of view, no alternative has been considered here.

However, the present-day fully model-free method of simultaneous determination of $\rho$ and $k$ [7] gives another result. Its practical application for more than 20 nuclei from the mass region ($40 \leq A \leq 200$) points to the existence in a nucleus of, at the least, two excitation energies, in which abrupt and fundamentally important change of its structure occurs. Approximation [18] of the experimental data for $\rho$ by partial level densities of n-quasi-particle excitations shows that this effect with maximum probability may be caused by the breaking of Cooper pairs of nucleons in a heated nucleus with practically any mass. Unfortunately, the lack of data [19, 20] on the spectra of gamma rays of radiative capture of thermal neutrons in $^{197}\text{Au}$ has prevented from using the method [7] to determine $\rho$ and $k$ in this nucleus. Both level density and radiative strength functions in $^{198}\text{Au}$ have been determined [14] using only the hypothesis of independence of the radiative strength functions of primary and secondary gamma transitions of one and the same multipolarity and energy on the excitation energy. The use of this assumption must overestimate the $^{198}\text{Au}$ level density determined experimentally in the region of several MeV around $0.5B_n$ and underestimate the values of $k$ for the appropriate energies of primary gamma transitions. Estimation of the appropriate systematic error may be done on the basis of comparison of the data for $\rho$ from [7, 14] for the nuclei with a different parity of the number of neutrons and protons. Relative smallness of the obtained error indicates that if we take the value into account it will not lead to a fundamental distortion of conclusions of the analysis of the available data.

Nevertheless, it is necessary to perform all possible analysis of the earlier obtained experimental data [14] for this nucleus, in particular, to estimate the degree of possible difference
of radiative strength functions for primary and secondary gamma transitions for various final levels of $^{198}$Au, and also to estimate the degree of influence of other parameters of this nucleus on experimental cascade intensities and the form of their dependence on the intermediate level energy.

4 Analysis

It is very characteristic for the nuclei studied in accordance with the methods \cite{7, 14} that the change of sum $f(E1) + f(M1)$ at the change of levels excited by them is of alternating-sign character: a considerable increase of $k$ values in the region of “stepped” structure in the level density of relatively large energies excited by primary transitions of levels is accompanied by some decrease of $k$ for low-lying cascade levels. This effect in an odd-odd nucleus must lead to an overevaluation of calculated cascade intensities at the increase of energy of their final level.

Two-step cascade intensities to the levels of $^{198}$Au with the energy $E_f \leq 450$ keV required for comparison with the experiment \cite{21} have been calculated for the following variants of the level density:

a) the back-shifted Fermi gas model \cite{22},

b) combination of the Ignatiuk model \cite{23} higher than 2 MeV with the experimentally determined number of intermediate cascade levels at smaller excitation energies and

c) the experimental level density from method \cite{14}. In both variants of the method of simultaneous determination of $\rho$ and $k$ the level density of the positive and negative parity is varied independently. However, at the same time the conservation of the average spacing for levels corresponding to s-resonances and the summarized density of “discrete” levels is provided.

Radiative strength functions for E1-transitions are used from results \cite{14} and models \cite{24, 25}. The model presentation for $f(M1)$ for the last two variants is restricted by the case $f(M1) = const$. The corresponding data is given in Fig. 1.

The summarized level density of both parities for spin window $1 \leq J \leq 3$ is presented in Fig. 2.

All the variants of the values $\rho$, $f(E1)$ and $f(M1)$ obtained in accordance with \cite{14} and presented in Fig. 1 and 2 practically precisely reproduce the sum of cascade intensities to levels with the energy less than 514 keV \cite{21} (Fig. 3). The comparison of experimental intensities of two-step cascades to specific low-lying levels of $^{198}$Au for different variants of level densities and radiative strength functions of the gamma transitions is shown in Fig. 4a-c. The signs of random deviations of calculated intensities in different sets of data from \cite{14} anticorrelate with each other for different final cascade levels. The deviations of average values from the experimental intensities may be partially related to the systematic errors of determination of the sums of cascade intensities for the given final level. Here, there is no reason to exclude a possible dependence of $I_{\gamma\gamma}$ values on $J_f^\pi$, and the influence of details of the structure of wave functions of $E_f$ levels on the average value of $f(E1)$ and $f(M1)$ for secondary cascade transitions.
5 Discussion of results

In all the nuclei studied by now the final levels, the spin $J_f$ of which differs from the neutron resonance spin $J_\lambda$ no more than for 2 and has the maximum value at $\vert J_\lambda - J_f \vert = 0$, are excited along with the experimentally observed intensity. For the compound state of $^{198}$Au excited at the thermal neutron capture $J_\lambda^\pi = 2^+$ [26], therefore, the excess of cascade intensities calculated according to the data [14] to the final levels $E_f = 347$ and 406 keV with spins $J_f^\pi = 2^-$ [27] over the experimental values may be caused by the presence of unresolved doublets and/or the influence of structure of the enumerated levels on $f(E1)$ and $f(M1)$ of secondary transitions of the cascades. In any case this circumstance may not lead to changes of the obtained conclusions on the process of cascade gamma decay due to the relative smallness of excess of the calculated value in comparison with the value $\sum_f I_{\gamma\gamma}$ observed in the experiment.

If we take into account such possible explanation then the calculation using the data [14] gives a regular excess of intensity over the experiment for cascades on the levels with the energy $261 < E_f < 482$ keV. Due to the lack of other explanations it is possible to accept as the most probable hypothesis that the relation of radiative strength functions of secondary gamma transitions of cascades to the corresponding values for primary ones has the same [7] form as in even-even nuclei and in even-odd ones. In other words, the general dynamics of the process of cascade gamma decay of the neutron resonance is characterized by the regularities, which do not depend on the parity of nucleon number in the odd-odd compound nucleus, as well.

The presence of a local increase of radiative strength function in the region of the “stepped structure” in $\rho$ ($\approx 1.5 < E_{ex} \lesssim 3$ or for primary gamma transitions ($\approx 4 < E_\gamma \lesssim 5 - 5.5$ MeV) reflects, most likely [7], a considerable increase of the influence of vibration components of levels on its value in the region lower than the threshold of appearance of four-quasi-particle excitations. Radiative strength functions of primary gamma transitions decreased at the breaking of subsequent Cooper pairs of nucleons to the levels with four-, six-, etc. quasi-particle components.

In other words, new models of radiative strength functions must in an explicit form take into account the co-existence and interaction of excitations of quasi-particle and phonon types in the whole region under consideration of excitation energy of a nucleus. In the level density models this fact is explicitly taken into account, for example [1], by introducing the vibration enhancement factor of level density of quasi-particle type. Therefore, most likely, no new types of excitation of nucleus (of the “pygmy-resonance” type) should be proposed and included in the $k$ models.

Almost the same value of the calculated cascade intensity in the energy region $E_{ex} \approx 0.5B_n$ of their intermediate levels for all the tested variants of radiative strength functions and level density demonstrates that the conclusions made in [11], [12], [17] by now on the parameters of the process of cascade gamma decay must be in serious error, since they do not take into account a strong correlation of values $\rho$ and $k$, which are included in $I_{\gamma\gamma}$.

In the framework of the existing notions it is impossible to reach the conformity of the existing and possible models of $\rho$ and $k$ with the experiment by any parameter variation, if only they do not take into account quite realistically the influence of breaking of the nucleon
Cooper pairs on these parameters of the process of cascade gamma decay of the high-excited level.

6 Conclusion

Currently, there are no obstacles in obtaining the experimental data necessary for a rather detailed theoretical description of the properties of nucleus lower than $\approx B_n$. By analogy with the experience of study of two-step cascades at the thermal neutron capture one may assume that reliable data on $\rho$ and $k$ in other experiments may be obtained only at the study of two-step nuclear reactions in coincidences by high-resolution spectrometers.

Erroneous conclusions during the analysis of an experiment of such type may occur only if out-dated model notions on the level density or the probability of emission of nuclear reaction products are used.

The potential models of the level density of a nucleus and radiative strength functions of gamma transitions exciting them must in an explicit form take into account the co-existence and interaction of excitations of quasi-particle and phonon type at least lower than the neutron binding energy. Practical necessity in their development became apparent [2] at the evaluation of contemporary data on cross sections of the interaction of neutrons with fissionable nuclei.

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Fig. 1. Solid thick lines - $f(E1)$ from models [24, 25] and their sums with “pygmy-resonance” for its parameters from [17]. Open point with errors - region for set of random functions of $f(M1)$, solid points - $f(E1)$, reproducing $I_{\gamma\gamma}$ (Fig. 3) with practically the same values $\chi^2/f << 1$.

Fig. 2. The same as in Fig. 1 for the level density (solid points with errors). Solid line – model values [22], dotted line – [23] respectively. Open points – the density of intermediate cascade levels [14].
Fig. 3. Hystogram – summarized experimental intensity of two-step cascades in the intervals of 0.5 MeV in the function of energy of the primary gamma transition with statistical errors only [21]. Line 1 – calculation with level density from [22], line 2 – [23]. Points – the typical approximation for the data from [14], the examples of which are given in Fig. 1 and 2.
Fig. 4a. Histogram – experimental intensity of two-step cascades for the levels $E_{ex}$ (summed over the intervals of 250 keV), lines – different variants of the calculation. The first and third columns: combinations of models [22, 24, 25] – thin lines, [23, 24, 25] – dotted line. The second and fourth columns - the intensity is calculated for random sets of $\rho$ and $k$ from [14].
Fig. 4b. The same as in Fig. 4a for other final levels.
Fig. 4c. The same as in Fig.4a for other final levels.