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Yu.P.Popov

NUCLEAR STRUCTURE AND DECAY OF COMPOUND STATES

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1. Introduction

The results of the study of the structure of nuclear excited states up to an energy of about 20 MeV allow one in this energy range to identify several intervals differing in excited states nature. With increasing excitation energy simple states become more complicate upon transition to the Niels Bohr's compound states and then to the states with prevailing collective modes of excitation, i.e. to the various giant resonances (Fig.1).

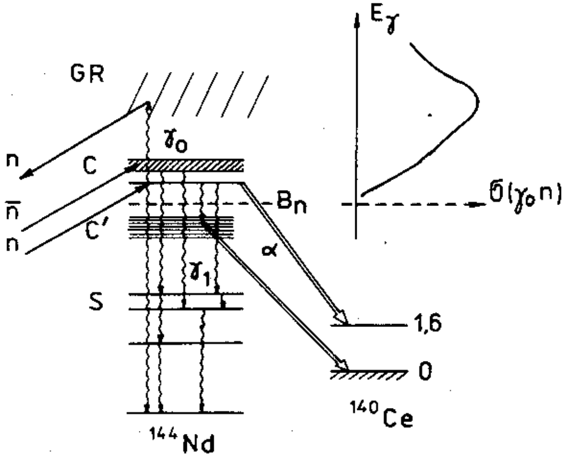

Fig. 1

For heavy nuclei the interval up to about 2 MeV is most studied nowadays. In this energy range nuclear spectroscopy has acquired most rich information both on the excitation scheme of states[1] and on their nature. From this information various theoretical models originate such as the model of interacting bosons[2], the quasi-particle phonon model[3] and others.

The studies by neutron spectroscopy methods that are now being carried out for half a century have already permitted scientists to obtain information on dozens (hundreds) of states in a narrow energy interval (< 10 keV)/4/ in the vicinity of the neutron binding energy ($B_n \sim 6 - 8$ MeV). These data are not badly described to the first approximation in the frame of the compound nucleus hypothesis and the statistical theory that operates on the parameters averaged over a large number of neutron resonances, but yielding no definite information on the nature of an individial compound state. Being not satisfied with the situation experimentalists often undertake wide-range and sometimes successful attempts to search for "nonstatistical effects" of various types in the characteristics of neutron resonances (see, for example, Proceedings of many conferences on neutron physics that took place during the last 20 years).

The area of giant resonances excited through various mechanism (E_{exc}~12–18 MeV) attracts more and more attention, however, a cardinal study on the nature of these states is yet far ahead. The indermediate intervals (see Fig. 1) between simple (S) and extremely complex compound states (C), pre-compound states, as well as between compound and giant resonances (GR) remain practically unstudied. Undoubtedly interesting is an attempt to follow the process of states' becoming complicated with increasing excitation energy, i.e. to follow a transition from "order" of an S state to "chaos" of a C state and further on to "order" (?) of a GR state.

But this presents a problem for a whole direction of nuclear physics, while here we would like just touch the results on compound and pre-compound states obtained by a group of scientists from the Laboratory of Neutron Physics, JINR, engaged in the studies of rare reactions.

2. Neutron Resonances in Heavy Nuclei as Compound States

According to modern notions of the statistical theory the wave function of a compound state of a heavy nucleus is a random set of various components each making a contribution of 10^{-6}, i.e. different excitation modes are fully fragmentated over compound states (the black nucleus model). But in a true nucleus it is not quite so. In the excitation energy range of the corresponding neutron resonances (6 – 8 MeV) a single-particle component of the wave function is not negligibly small, neutron strength functions systematically change from nucleus to nucleus thus forming peculiar giant resonances of size (Fig. 2).

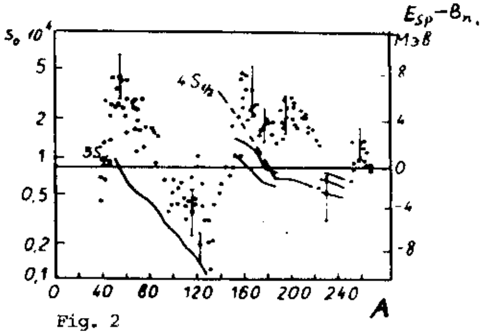

Fig. 2

The variations of neutron strength functions are in the scale of two orders of magnitude here. Besides the maxima and minima are well correlated with the positions of single-particle shells in the nucleus with respect to the neutron binding energy (see Fig. 2). So the nucleus appears semi-transparent for the neutron channel near the neutron binding energy and phenomenologically their interaction with neutrons is described with the optical model.

To estimate other components of excitation of neutron resonances let us try to make use of other decay channels in a compound nucleus. Information on more complex components of the wave function of the compound nucleus can be derived from the analysis of α-decay of neutron resonances. But the probability of such α -decay is essentially suppressed by the Coulomb barrier of the nucleus. This results in the fact that in heavy nuclei in most favourable cases the α -widths are by 6 - 12 orders of magnitude smaller than the radiation widths of resonances. This explains poor information on the alpha-particle strength functions of compound nuclei. Fig. 3/5/ shows the dependences on atomic weights of nuclei of ratios $\langle \Gamma_\alpha^{exp} \rangle / \langle \Gamma_\alpha^{cal} \rangle$, which correspond to α -particle strength functions multiplied by a constant. The errors of points are mainly due to the small number of the investigated resonances that the averaging was performed over. The satisfactory agreement between the experimental and theoretical data illustrated in Fig. 3 speaks in favour of the validity of the description of the average probabilities of α -decay of compound states in the frame of the statistical model ("black" nucleus). Consequently at the neutron binding energy the two-quasiparticle, four-quasiparticle and the "two-quasiparticle + + phonon" type wave functions (that determine α -decay of the compound state of the daughter nucleus/6/) are much stronger fragmentated than in the case of single-

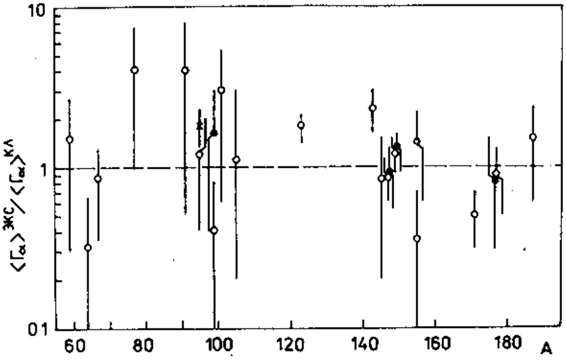

Fig. 3

particle neutron components (see Fig. 2). However one cannot exclude the possibility that greater accuracy of the data (by averaging over a larger number of resonances) will allow one to "get on the track" of the remains of the fragmentation of the above mentioned components. The possibility of this effect follows from the shown in Fig. 4 dependence on neutron energy of $\langle \Gamma_\alpha / D \rangle_J$ values measured for the presently most investigated nucleus ^{147}Sm. This dependence averaged over intervals of 100 eV

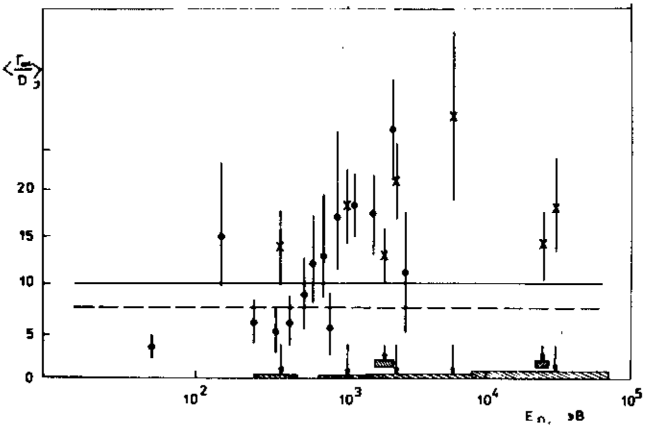

Fig. 4

(each containing 10-15 resonances) is shown by black points/7/ and averaged over shaded intervals indicated in the bottom of the picture/8/ by crosses. Rather obvious structure is observed in the energy dependence of $\langle \Gamma_\alpha / D \rangle$. According to the estimates obtained in the frame of the quasiparticle-phonon model of V.G.Soloviev, the average level distance between 4-quasiparticle $J = 4^-$ states in the ^{147}Sm nucleus is of the order of 2-3 keV. We do not know of course laws of fragmentation of such excitation modes on compound states, but the presence of not fully fragmentated few-quasiparticle states may seemingly lead to an enhancement of α-decay of the whole group of neighbour resonances via some definite channel.

3. The Nature of the Enhancement of γ-Transitions Following decay of 4S-Shell States

Usually the main regularities of the primary γ-transitions between compound states and low-lying levels in heavy nuclei ($140 < A < 190$) are successfully described in the frame of the statistical theory. However, in the study of fluctuations from resonance to resonance of the population of low-lying levels following the radiation decay of neutron resonances/9/ a certain doubt arises concerning the application of the statistical theory. The experimentally detected fluctuations appeared to systematically exceed the analogous values calculated within the statistical theory of γ-decay in the stated above mass region of 4S maximum of the neutron strength function. In the region of its minimum (see Fig. 2 for $90 < A < 140$) this exceeding is not observed. It was suggested/9/ that in γ-decay of nuclei from the 4S-shell the observed enhancement of fluctuations are due to the enhancement of certain cascades (γ-decay channels) reducing the effective number of intermediate states in the cascades and as a consequence leading to reducing average fluctuations.

We have succeeded in detecting this "channeling of γ-cascades by the investigation of the compound states decay via measuring two-quanta cascades following neutron capture (the $(n,2\gamma)$ reaction) with the help of two Ge(Li) detectors operating in the mode of summation over coinciding pulses/10/. This procedure does not only provide the most rich pure spectroscopic information on the states of energies up to ~ 4 MeV. For example, for the compound nucleus ^{179}Hf 239 cascades have been identified, 154 of them are located, the number of intermediate levels amounts to 48. So we have studied 67 ± 4 % of the total probability of γ-decay of the compound nucleus/11/. The original data on the mechanism of γ-decay have also been obtained.

An example of the amplitude spectrum of coinciding pulses (after background subtraction) obtained with one of the detectors in the measurement of the population via two-quanta cascades of an excited level at 375 keV in ^{179}Hf is shown in Fig.5a/11/. If one compares this spectrum with that expected from the statistical theory (Fig.5b), a number of essential qualitative differences can be outlined :

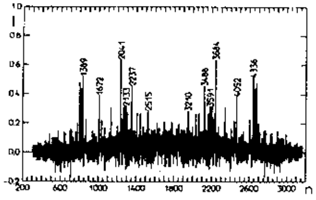

Fig. 5a

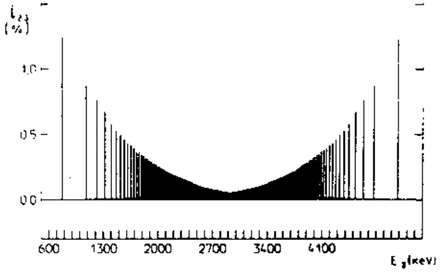

Fig. 5b

- in the experimental spectrum the enhanced gamma-cascades are distributed over the whole spectrum, while in the calculated one they concentrate on its edges;
- the high intensity cascades are often groouped;
- the two-quanta cascades from a state at $E_{\gamma 1} \simeq E_{\gamma 2} \simeq 0.5\ B_n$ appear rather probable.

Such "visual" conclusions obtain also the quantitative confirmation in the comparison of experimental values for the total intensity of all the two-quanta cascades populating a definite final state f – $I_{\gamma\gamma}^{exp}$ with a calculated from the statistical theory value of $I_{\gamma\gamma}^{cal}$. There the partial radiation widths of

E1 transitions were calculated within the model of the giant electric dipole resonance and for the M1 and E2-transitions within the Weisskopf model, the densities of states at energies below B_n being taken in accordance with the model of the Fermi gas with a Strutinsky correction/12/.

Table 1 presents as an example the data on ^{179}Hf including, besides $I_{\gamma\gamma}$ values there are also given the quantum characteistics of final states and a value of $R = I_{\gamma\gamma}^{exp}/I_{\gamma\gamma}^{cal}$ that qualitatively characterizes deviations from the statistical theory.

Table 1

Compound nucleus, I_0^{π}	E_f, keV	J_f^{π}	$K^{\pi}[Nn_z\Lambda]$	$I_{\gamma\gamma}^{exp}$ x)	$I_{\gamma\gamma}^{theor}$ xx)	R
^{179}Hf	214	$7/2^-$	$7/2^-$ [514]	2.1 ± 0.9	0.03	70 ± 30
	375	$1/2^-$	$1/2^-$ [510]	15.5 ± 1.6	6.3	2.5±0.3
$1/2^+$	421	$3/2^-$	"	16.5 ± 2.1	6.0	2.8±0.4
	476	$5/2^-$	"	7.6 ± 0.6	3.6	2.1±0.2
	518	$5/2^-$	$5/2^-$ [512]	4.0 ± 0.8	3.3	1.2±0.3
	614	$1/2^-$	$1/2^-$ [521]	9.5 ± 1.6	4.7	2.0±0.3
	679	$3/2^-$	"	3.8 ± 0.8	4.1	0.9±0.2
	701	$5/2^-$	"	2.6 ± 0.5	2.1	1.2±0.2
	721	$3/2^-$	$3/2^-$ [512]	3.1 ± 0.7	3.8	0.8±0.2
	788	$5/2^-$	"	2.7 ± 0.8	1.8	1.5±0.4
		Total		67.4 ± 3.7	36.0	1.9±0.1

x) $I_{\gamma\gamma}^{exp}$ in % per decay ; $I_{\gamma\gamma}^{exp}$ includes statistical uncertainties and random scaling errors.

xx) $I_{\gamma\gamma}^{theor}$ in % per decay.

From the analysis of the data summarized in Table 1 and of the analogous data obtained for ^{163,165}Dy, ^{167}Er, ^{175}Yb, ^{179}Hf and ^{183,187}W nuclei one can conclude that the enhancement of the cascades (R > 1) takes place, if final states reveal a certain structure, i.e. have a large single-particle components of the wave function (in particular the cascades populating the band $1/2^-$[510], for example).

The even-odd compound nuclei investigated lie in the mass region of 4S maximum of the neutron strength wave function.This maximum is explained by the fact that in this mass region near the neutron binding energy single quasiparticle states $1/2^+$[640] and $1/2^+$ [651] are located (see Fig.2). These states formed on neutron capture (being initial in gamma-cascades) may have essential single-particle components.

Unfortunately till now we could study only the cascades that follow the thermal neutron capture and not those from individial resonances which would allow one to investigate the dependence of the enhancement of the cascades ($R > 1$) on the neutron width for a given nucleus. Therefore, to clarify the role of single particle components of an initial compound state in the process of enhancement of gamma-cascades we have to use a relative reduced width of the resonance which determines the thermal cross section of a given isotope $\Gamma_n^0/\langle\Gamma_n^0\rangle$, or make use of a weighted average Γ_n^0, if several resonances make comparative contributions into the thermal cross section/4/.

Figure 6 presents the dependence of the value for the gamma-cascade enhancement R on the relative reduced neutron width of the initial state of the cascade for the investigated even-odd deformed nuclei. The positions of the experimental points qualitatively confirm the validity of this dependence. The quasiparticle-phonon model being developed by a group of V.G.Soloviev/13/ predicts correlation between Γ_n^0 and partial gamma-widths of K-allowed E1-transitions because both widths depend on the same single-particle components of the wave functions of neutron resonances. However, because of the fact that the reduced radiation width has also other components correlation between the neutron and radiation reduced widths may appear to be nonlinear. Then for R one may obtain the following expression/11/

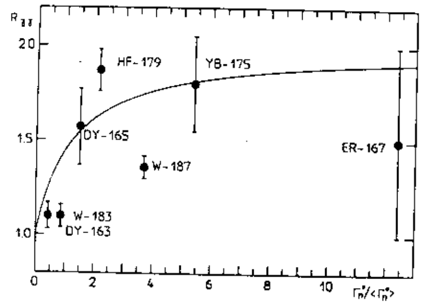

Fig. 6

$$R = \frac{1 + k\alpha\,\Gamma_n^0/\langle\Gamma_n^0\rangle}{1 + k\,\Gamma_n^0/\langle\Gamma_n^0\rangle}\,.$$

The possibility of the qualitative description of the experimental data with the dependence of this type is illustrated in Fig. 6. However, one should keep in mind that parameters k and α must be constant for a given nucleus, but may depend on A, since single-particle states change their positions with respect to B_n.

So we have demonstrated the connection of the enhancement effect observed for certain two-quanta cascades with quasiparticle components of initial and final states of the cascade. What intermediate states are selected by enhanced cascades?

In principle the method of summation over coinciding pulses used here does not allow determination of the order in time of emission of detected gamma-quanta. The shown in Fig. 5 amplitude spectrum from one of the detectors is compared with the calculated one that accounts for that and inverse order of emission of gamma-quanta with corresponding probabilities dependent on the energy of each quantum and its multipolarity. Some time ago in order to determine the sequence of gamma-quanta in a cascade we used the fact that, if a transition of given energy occurs in several cascades populating different final states of the nucleus investigated, then it is a primary transition/14/. This helped determine the positions of intermediate states in a majority of intensive gamma-cascades and as a consequence build for the main part of gamma cascades the dependence of the intensity of gamma-transitions on the energy of the primary transition and consequently on the excitation energy of the nucleus $E_{exc} = B_n - E_{\gamma 1}$.

An argument,in favour of the assumption that the structure of intermediate states excited in most strong cascades for even-odd nuclei with Γ_n^0 larger than $\langle \Gamma_n^0 \rangle$ contain a large number of single-particle components, is provided by the analysis made in Ref./15/. In this work in the frame of the quasiparticle-phonon model of the nucleus an attempt was made to compare the distribution of excited single-particle components with the experimentally obtained distributions of primary transition intensities summed over final states of cascades thus supposing that in the excitation energy range below 4 Mev more complex components can be neglected. This analysis should be considered as an initial step.

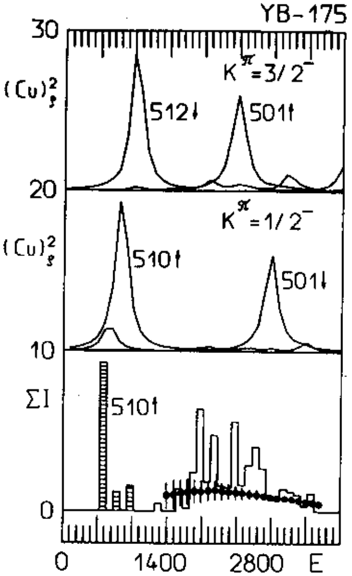

Fig. 7

Figure 7 presents an example of such comparison for ^{175}Yb. Here the hystogram means experiment (the data from single-quanta gamma-transitions are shaded),points reflect the data calculated from the statistical theory, "errors" illustrate the residual Porter-Thomas fluctuations, curves are the distributions of the $(Cu)^2_\rho$ strength of the fragmentated states ρ with quantum numbers $[N n_z \Lambda]$. It is seen that maxima in the distribution of the strength of single-particle states correspond to maxima in the distribution of sums of cascade intensities. (Let us take into account the fact that here we analyse primary gamma-transitions that make 50% of the total radiation width of a compound nucleus). This gives a possibility to assume that in the excitation energy range $E_{exc} \simeq 2 - 4$ MeV the single-particle neutron states $[501]\downarrow$, $[501]\uparrow$ and $[510]\uparrow$ contribute to the formation of enhanced partial widths of primary transitions. By the spherical basis extension these states are neutron shells $3P_{1/2}$ and $3P_{3/2}$. Note that the accuracy of the theoretical determination of the positions of maxima achieves several hundred keV.

So the reason for gamma-cascades "channeling" through certain intermediate states in the region of rare earth nuclei is most probably enhanced by several times gamma-transitions between neutron shells 4S – 3P.

Conclusions

This review of the results of the study of two channels of the compound states decay, i.e. followed by the emission of α-particles or gamma-quanta, shows novel possibilities of obtaining unique data on the structure of highly excited states of nuclei. Studies of a proton channel of decay have been initiated (see, for example, Refs./16,17/). Further progress in the study of decay through rare reactions (n,p) and (n,α) will apparently be connected with the development of the methods of high-intensity neutron spectroscopy and with the application of neutron-deficient nuclei as targets. The latter is especially favourable in the study of the proton channel of decay, since in stable nuclei the proton binding energy is close to that of the neutron.

The application of the method of summation over coinciding pulses to the analysis of gamma-decay of compound nuclei has not exhausted itself yet and not because of a small percent of nuclei that were investigated with it. For example, a more essential enhancement has been observed for the E2 gamma-transitions with an integral intensity by 1 - 2 orders of magnitude larger than that from the statistical theory/11/. The possibility has appeared to investigate soft gamma-transitions between the compound states near the neutron binding energy. Besides that the possibility appears to give for a wide range of nuclei a system of reliably determined states up to an excitation energy of 3 - 4 MeV that one may successfully use in the drawing of the schemes of highly excited states.

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