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ON POSSIBILITIES OF STUDYING THE STRUCTURE OF HIGHLY EXCITED STATES (RESONANCES) BY NEUTRON SPECTROSCOPY METHODS

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S U M M A R Y

The characteristics of the highly excited states (resonances) are considered which are necessary for studying their structure. It is shown that the possibilities of the time-of-flight techniques in neutron spectroscopy as applied to the study of the highly excited state structure become essentially richer if unstable nuclei and isomers are used as the targets. The increase of the state density with excitation energy and the dependence of the density on the mass number are explained qualitatively. On the basis of the data on the reduced widths for the S -neutron capture and the E1 transitions to the low-lying states the contribution of few -quasiparticle components to the highly excited state wave functions is estimated. The problem of correlation between the reduced neutron and radiative widths is studied and some cases are indicated in which one can expect large correlations. The problem of correlations between ($n\gamma$) and (dp) reactions is also considered.

1. The structure of the ground and low-lying states of spherical and deformed nuclei is rather well described in the framework of the semi-microscopic approach by means of quasiparticles and phonons. The low-lying states of nearly magic nuclei are pure quasiparticle or one-phonon states. However, as we move still away from magic nuclei the admixtures of the highest configurations and the multiplet splitting energies increase and all the nuclear spectra become essentially more complicated. The nuclear states of transition regions are especially complex. In the case of strongly deformed nuclei the lowlying excitations are rather pure quasiparticle and one-phonon states.

In spherical and deformed nuclei a complication of the state structure with increasing excitation energy is observed. Fragmentation of the single-particle states proceeds over an ever-increasing number of levels[1,2]. In nearly magic nuclei the complication of the structure begins at an energy 1.5-2.5 MeV and proceeds far more slowly than in other nuclei. This concerns especially nuclei near ^{208}Pb. The general regularities of complication of the structure of states and of increase of their density have been observed up to an excitation energy 2-2.5 MeV.

To understand nuclear structure regularities it is necessary to know how proceeds the complication of the structure of states, increase of their density and fragmentation of single-particle states with increasing excitation energy and what is the nuclear level structure at various excitations.

The highly excited states (resonances), i.e. the nuclear states with excitation energies close to and larger than the neutron binding energy, are very complicated, their density is very large. Therefore they are usually treated by the nuclear statistical model.

Since there is no point of thinking about calculation of the energy and wave function for each resonance and about experimental determination of their quantum characteristics the problem arises as to what one should know about the structure of highly excited states. An attempt to answer this question is just being made in the present paper.

The paper is devoted to possibilities of studying the structure of highly excited states by neutron spectroscopy methods. The problem of finding some components of the wave functions of highly excited states by analysing experimental data on resonance neutron capture, resonance gamma and alpha decay and correlations between various processes is considered.

2. In ref. /3/ it was suggested to study the structure of highly excited states by means of the wave functions containing a large number of components with different number of quasiparticle and phonon operators. In ref. [2] it was demonstrated how effective this approach is for the study of the highly excited state structure. As an example, we consider the wave function of the highly excited state of an even-even

deformed nucleus:

$$\Psi_i(I^{\pi}) = {\sum_{\substack{q_1,q_2\\ \sigma_1,\sigma_2}}}' \sum_t b^{i2t}_{I^{\pi}}(q_1\sigma_1, q_2\sigma_2)\, \alpha^+_{q_1\sigma_1} \alpha^+_{q_2\sigma_2} \Psi_0 +$$

$$+ {\sum_{q_1 q_2 q_3 q_4}}' \sum_{t,t'} b^{i2t2t'}_{I^{\pi}}(q_1\sigma_1, q_2\sigma_2, q_3\sigma_3, q_4\sigma_4)\alpha^+_{q_1\sigma_1} \alpha^+_{q_2\sigma_2} \alpha^+_{q_3\sigma_3} \alpha^+_{q_4\sigma_4}\Psi_0 + \quad (1)$$

$$+ \cdots + {\sum_{\substack{q_1 q_2\\ \sigma_1,\sigma_2}}}' \sum_{t,t',\zeta} b^{i2t\Omega_\zeta(t')}_{I^{\pi}}(q_1\sigma_1, q_2\sigma_2)\alpha^+_{q_1\sigma_1}\alpha^+_{q_2\sigma_2}\, \Omega^+_\zeta(t'; q_1, q_2)\Psi_0 + \dots$$

In this formula only few-quasiparticle components are given, besides them there are many-quasiparticle components. The quasiparticle operators $\alpha^+_{q\sigma}$ are connected with the nucleon operators $a_{q\sigma}$ by the relation $\alpha^+_{q\sigma} = u_q a^+_{q-\sigma} + \sigma v_q a_{q\sigma}$, where u_q and v_q are the Bogolubov transformation coefficients. The coefficients $b^i_{I^{\pi}}$ define the contribution of the corresponding quasiparticle component, i being the number of the resonance with a given I^{π} . The set of the quantum numbers characterizing a single-particle state is denoted by $(q\sigma)$, $\sigma = \pm 1$ neutron states by $(s\sigma)$ and proton ones by (rs). The index $t = n$ implies the neutron system and $t=p$ the proton one. By Ψ_0 we denote the product of quasiparticle vacua for the neutron and proton systems. The products, like $\alpha^+_{q+} \alpha^+_{q-}$ in eq.(1) are replaced by the pairing vibration phonon operators $\Omega_\zeta(t)$. For the remaining notations see ref.[2,3]. The wave function of the highly excited state with

$I > max\ (I_1 + I_2)$ i.e. with large I, which cannot be formed by two quasiparticles contains no terms with $b_{I\pi}^{i2t}(q_1\sigma_1, q_2\sigma_2)$ and $b_{I\pi}^{i2t\Omega\lambda(t')}(q_1\sigma_1 q_2\sigma_2)$.

The wave function (1) has a very general form and is actually represented as a series in the senjority number. It can be applied to the description of low-lying, intermediate and highly excited states. It is reasonable to use the wave function (1) for the states up to excitation energies at which for the levels with a given I^π the following condition

$$\Gamma_i << D , \qquad (2)$$

is fulfilled, i.e. when the total resonance width Γ_i is much smaller than the average spacing D between the levels with given I^π.

The wave function (1) can be easily generalized as applied to description of the collective states or the states containing collective components. Then new terms containing the appropriate phonon and quasiparticle operators should be added to the wave function.

3. Let us attempt to answer the question as to what we should know about the structure of the excited states, in general and of the highly excited states, in particular.

We represent the excited state wave function in the form (1). To clarify the excited state structure we should be aware of the following characteristics of their wave functions:

1) values of few (one, two)-quasiparticle components and the region of their change in neighboring levels,

2) total contribution of few-quasiparticle components,

3) dependence of the contribution of individual few-quasiparticle components and of their total contribution on excitation energy $\mathcal{E}$ and spin I,

4) dependence of the contribution of individual few-quasiparticle components and the total contribution of them on the mass number A, i.e. how these values change as one moves away from magic nuclei to transition nuclei and further to strongly deformed ones,

5) the contribution of three- and four-quasiparticle components,

6) the role of many-quasiparticle components,

7) which collective excitation branches are essential,

8) distribution of the single-particle state strength over nuclear levels and its dependence on the single-particle energy (with respect to the Fermi surface energy), spin and the mass number A.

We should also answer the following questions:

1) What is the nuclear shape in highly excited states,

2) how is revealed the rotation of the nucleus as a whole in highly excited states and how good is the quantum number K,

3) do the wave functions of some highly excited states contain large components defined by some quantum numbers (for the exception of isobar-analog states),

4) are there else unknown branches of the collective excitations?

It is interesting to account for the large density of highly excited states and to investigate the density as a function of excitation energy, spin $\bar{I}$ and mass numbers A. We should also determine the total density of the states with all the values of spins $\bar{I}$.

The study of the excited state structure is tightly related to the establishment of the mechanism of the appropriate nuclear reaction. In the present paper attention is focused on the highly excited state structure whereas in most papers the consideration is made from the point of view of the nuclear reaction mechanism.

4. Integral characteristics like strength functions for s-neutrons or those in beta decay give an important evidence for the highly excited state structure. However, to answer the above questions it is also necessary to study characteristics of individual resonances.

The average spacing between levels with identical spins in medium - weight and heavy nuclei is from 1 ev to 10 keV at excitation energies close to B_n. Therefore the study of the structure of some highly excited states (resonances) needs experimental techniques with very high resolution. The use of the time-of-flight techniques, having a very high resolution for slow neutrons, allows one to determine energy, spin (not always unambiguously), neutron width and partial gamma and alpha widths for each resonance separately.

However, in neutron spectroscopy the time-of-flight techniques has the very high resolution up to neutron energy 0.1-10 keV.

Therefore, one may study the structure of resonances lying in a very narrow interval of excitation energies and spins. The energy interval is $\Delta\mathcal{E} = (0.1-10)$ keV and the excitation energies B_n to $B_n + \Delta\mathcal{E}$ are available. To make this interval wider great methodical difficulties should be overcome.

When the S -neutron is captured by the target-nucleus with spin I_0 it is possible to study highly excited states with spins $I_0 \pm 1/2$. The extension of the spin interval of the states under investigation, i.e. the study of the states with spins $I_0 \pm 3/2$, $I_0 \pm 5/2$ and so on is very difficult. This is explained by the fact that the p and d neutron capture cross sections are fairly small at low energies and with increasing neutron energy the resolution of the method becomes much worse.

In order to conceive more completely the highly exited state structure we should take into account the fact that the neutron binding energy B_n changes considerably in the transition from one nucleus to another. This just means that it is possible to study the resonance structure at different excitation energies. Table I gives the B_n values for odd-N isotopes of barium and ytterbium. It is seen that the B_n values change is going from ^{131}Ba to ^{139}Ba by 2913 keV and from ^{169}Yb to ^{177}Yb by

1260 keV. For medium-weight and heavy nuclei being near and inside the beta stability zone B_n runs the values 4–10 MeV.

If the S -neutron is captured by an even-even nucleus, compound states with $I^{\pi}=1/2^{+}$ are formed. If the S -neutron is captured by an odd-A nucleus then compound states with $I_0 \pm 1/2$ i.e. with spins 0 to 5 are formed since the maximum spin of the ground state of an odd nucleus is 9/2. Evidence on resonances with higher spins may be obtained from S -neutron capture by odd-odd nuclei. For example, when the S -neutron is captured by ^{176}Lu with $I^{\pi}=7^{-}$ and configuration $p\,404\downarrow + n\,514\downarrow$ compound states of ^{177}Lu with $I^{\pi}=15/2^{-}$ and $17/2^{-}$ are produced.

The possibility of using the time-of-flight techniques in neutron spectroscopy becomes essentially richer if as the targets one employs unstable nuclei and isomers. If one uses neutron-deficient isotopes for which the B_n values are large then one can obtain evidence for resonances at high excitation energies, and if one uses neutron-rich isotopes for which the B_n values are not large then one can study the state structure at somewhat lower excitation energies. If the S -neutrons are captured by an isomer of an energy $\mathcal{E}_e$ and spin I_e then one can obtain data on the structure of resonances with energies from $B_n + \mathcal{E}_e$ to $B_n + \mathcal{E}_e + \Delta\mathcal{E}$ and spins $I_e \pm 1/2$. In other words, there is an essential extension of the region of excitation energies and spins to be studied.

In table 2 we give the characteristics of the ground and isomeric states of a number of nuclei. It would be important to use these nuclei as the targets for studying elastic scattering of neutrons and the $(n\gamma)$ and $(n\alpha)$ reactions on resonances.

We discuss what evidence for the resonance structure may be obtained in studying the capture of s -neutrons by isomers. Table 3 considers four cases.

If the s -neutron is captured by an isomeric ^{174}Lu then compound states of ^{175}Lu of an energy B_n + 171 keV and $I^{\pi} = 11/2^-$ and $13/2^-$ are produced. The reduced s -neutron capture widths are

$$\Gamma_i^o = \Gamma_{s.p.} |2 \sum_{\substack{S_2 \sigma_2 \\ I_2^{\pi_2} = 1/2^+}} b_{I^{\pi}}^{ip2n} (\tau_0 \pm, s_o^+, S_2 \sigma_2) u_{S_2} | + \Gamma_i^{oo} , \quad (3)$$

where $\Gamma_{s.p.}^o = (m r_o^2 A^{2/3})^{-1}$ and the term Γ_i^{oo} is related to a more complex neutron capture mechanism than the direct one. If the direct neutron capture mechanism is predominant then the reduced neutron widths give information on the contribution of three-quasiparticle states of the type $p404\downarrow \pm n512\uparrow \pm n1/2^+$ ($n1/2^+$ are the neutron single-particle states with $I^{\pi} = 1/2^+$) to the wave functions of the resonances with $I^{\pi} = 1/2^-, 3/2^-,$ and $11/2^-, 13/2^-$ at energies differing by 171 keV.

When the s -neutron is captured by ^{179}Hf being in the ground and isomeric states, compound states of ^{180}Hf of an energy of 7330 keV and spins 4^+, 5^+ and of an energy of 8436 keV and spins 12^-, 13^- are produced. When the neutron is captured by ^{179}Hf being in the isomeric state there are produced highly excited states, the two-quasiparticle proton state with spin 8^- being, as if, superimposed on the states with spins 4^+ and 5^+. The reduced width for capture of the S -neutron by the isomer with $K^{\pi}=25/2^-$ and configuration $s_0+\tau_0+\tau_0' = n624\uparrow + p404\downarrow + p514\uparrow$ is of the form

$$\Gamma_i^{\circ} = \Gamma_{s.p.}^{\circ} \Big| 4 \sum_{\substack{S_2\sigma_2 \\ I_{S_2}^{\pi S_2}=1/2^+}} b_{I\pi}^{i2n2p}(S_2\sigma_2,\ s_0+,\tau_0+,\tau_0'+)\, u_{S_2}\Big|^2 + \Gamma_i^{\circ\circ}. \qquad (4)$$

If the direct neutron capture mechanism plays a predominant role then from the reduced neutron capture widths one can obtain information on the contribution of the four-quasiparticle components $p404\downarrow + p514\uparrow + n624\uparrow \pm n\,1/2^+$ to the wave function of the highly excited state with $I^{\pi} = 12^-$ and 13^-.

When the S -neutron is captured by the isomer ^{177}Lu with an energy 969 keV and $K^{\pi}=23/2^-$ the reduced width is

$$\Gamma_i^{\circ} = \Gamma_{s.p.}^{\circ} \Big| 6 \sum_{\substack{S_2\sigma_2 \\ I_2^{\pi_2}=1/2^+}} b_{I\pi}^{ip3n}(\tau_0+, S_0+, S_0'+, S_2\sigma_2)\, u_{S_2}\Big|^2 + \Gamma_i^{\circ\circ}. \qquad (5)$$

Then it is possible to obtain information on the contribution of the four-quasiparticle components $p404\downarrow + n624\uparrow + n514\downarrow \pm n\,1/2^+$ to the highly excited states of ^{178}Lu with spins 11^- and 12^-.

When the S -neutron is captured by an isomer ^{180}Hf of an energy of 1142 keV, $K^{\pi}=8^-$ and configuration $\tau_0+\tau_0' = p404\downarrow + p514\uparrow$, excited states with $I^{\pi} = 15/2^-$ and $17/2^-$ are produced the wave function of which with $I^{\pi}=1/2^+$ is, as if, superimposed by the two-quasiparticle proton components 8^-. Then the reduced width is of the form

$$\Gamma_i^{\circ} = \Gamma_{s.p.}^{\circ} \left| 2 \sum_{\substack{s_2\sigma_2 \\ I_2^{\pi_2}=1/2^+}} b_{I^{\pi}}^{in2p}(s_2\sigma_2, \tau_0+, \tau_0'+) u_{s_2} \right|^2 + \Gamma_i^{\circ\circ}. \qquad (6)$$

Evidence for the contribution of the three-quasiparticle components $p\,404\downarrow + p\,514\uparrow \pm n\,1/2^+$ to the highly excited states of ^{181}Hf with $I^{\pi} = 15/2^-$ and $17/2^-$ can also be obtained.

There are many examples of such a kind. However, it is clear without recourse to them that the use of unstable nuclei and isomers as the targets enlarges noticeably the neutron spectroscopy possibilities of studying the highly excited state structure.

5. Now let us discuss the problem of the density of states with definite spins near B_n and its dependence on the excitation energy and the mass number. The high density of these states is explained by the fact that due to the interaction of single-particle and collective degrees of freedom and, possibly to other forces fragmentation of the single-particle states proceeds over many nuclear levels. In ref.[2] a simple model is used to demonstrate how this fragmentations proceeds. With increasing excitation energy the fragmentation of the single-particle states becomes stronger and therefore the state density increases as well. Table I gives the average spacing between the $I^{\pi} = 1/2^+$ levels in the Ba and Yb isotopes. It is seen that it decreases with increasing excitation energy.

In ref.[4] the experimental data on the average spacing D between resonances with definite spins and excitation energies B_n are summarized. Qualitatively, D as a function of the mass number and spin may be explained on the basis of the fact that the density of highly excited states having non-zero few-quasiparticle components is mainly defined by the interaction of single-particle and collective degrees of freedom.

For example, the density of states in nuclei near the doubly magic nucleus ^{208}Pb decreases sharply. In nearly magic nuclei the lowlying states are practically pure single-particle states and the one-phonon states have a comparatively high energy. Therefore the fragmentation of single-particle states in these nuclei begins at higher energies than in non-magic nuclei and proceeds more slowly. Therefore the high density in nearly magic nuclei is reached at much higher energies than B_n.

Another example. In ref.[4] one gives the D -values for states with large spins which are approximately the same as for states with small spins. For example, in ^{177}Lu for states with $I^{\pi}=13/2^{-}$ and $15/2^{-}$ $D\approx 2.4$ eV at B_n = 6890 keV . Such a large density may be understood as follows: a neutron is absorbed by ^{176}Lu with $K^{\pi}=7^{-}$ and configuration $p\,404\downarrow + n\,514\downarrow$ then compound states of ^{177}Lu with $I^{\pi}=13/2^{-}$ and $15/2^{-}$ are formed for which the wave function of the $I=1/2^{+}$ states having a large density is as if superimposed by the two-quasiparticle components with $I^{\pi}=7^{-}$

6. In ref.[2,3] it is shown that the reduced neutron capture widths and the partial resonance alpha and gamma decay widths may give information on the integral contribution of some highly excited state wave functions.

We find the order of magnitude of the few-quasiparticle component ($\bar{b}^i_{I\pi}$) from the reduced neutron widths and the partial E1 transition widths and discuss some particular features of radiative decays of resonances.

The reduced width for the s -neutron capture by an odd deformed nucleus (with neutron in state S_0) is written in the form

$$\Gamma_i^\circ = \Gamma_{s.p.}^\circ \Big| \sum_{\substack{S_2\rho_2 \\ I_2\pi_2 = 1/2^+}} b^{i2n}_{I\pi} (S_0\sigma_0, S_2\sigma_2) u_{S_2} \Big|^2 + \Gamma_i^{\circ\circ}, \tag{7}$$

where $\Gamma_{s.p.}^\circ = \frac{\hbar}{m r_0^2 A^{2/3}} \approx \frac{20}{A^{2/3}}$ MeV. The quantity $\Gamma_i^{\circ\circ}$ is assumed to be small and is omitted. We estimate $\Gamma_i^\circ / \Gamma_{s.p.}^\circ$. For medium and heavy nuclei $\Gamma_i^\circ \approx 0{,}1 eV$, $\Gamma_{s.p.}^\circ \approx 10^6 eV$, $u^2_{S_2} \approx 1$, therefore

$$\frac{\Gamma_i^\circ}{\Gamma_{s.p.}^\circ} \approx 10^7 \approx \Big| \sum_{S_2\sigma_2} b^{i2n}_{I\pi} (S_0\sigma_0, S_2\sigma_2) u_{S_2} \Big|^2 \approx (\bar{b}^i_{I\pi})^2 \bar{n}^2,$$

where $\bar{n}$ is the average number of states with $I^\pi = 1/2^+$ for spherical nuclei $\bar{n} \approx 1$, for deformed $\bar{n} \approx$ 2-4. Hence it follows that

$$(\bar{b}^i)^2 \approx 10^{-7} - 10^{-8}. \tag{8}$$

We estimate $(\bar{b}^i_{I\pi})^2$ from resonance to low-lying states E1 transitions. The signle-particle width for E1 transition is

$$\Gamma_w(E1) = 0{,}1 A^{2/3} (E_\gamma(MeV))^3 eV \tag{9}$$

In ref.[5] one uses

$$K_{E1} = \frac{\Gamma_{\gamma if}(E1) eV}{(E_\gamma(MeV))^3 \; D(MeV)\cdot A^{2/3}} = \frac{0{,}1}{D(MeV)} \cdot \frac{\Gamma_{\gamma if}(E1)}{\Gamma_w(E1)}, \tag{9'}$$

$$\frac{\Gamma_{\gamma if}(E1)}{\Gamma_w(E1)} = 10 \, K_{E1} \, D(MeV).$$

According to refs.[5,6] for medium and heavy nuclei $k_{E1}=3.10^{-3}$, $D \approx 3.10^{-5}$ MeV, therefore $\frac{\Gamma_{\gamma if}(E1)}{\Gamma_{w}(E1)} \approx 10^{-6}$

The matrix element of $E\lambda$ transition from the highly excited state described with the wave function (1) to the ground state of an even-even deformed nucleus is

$$\mathcal{M}(E\lambda; I^{\pi}_{i} \to 0^{+}_{g}) = -\sum_{q_1,q_2,\sigma} \sum_{t} u^{(+)}_{q_1 q_2} \{\sigma \langle q_1+|\Gamma(E\lambda)|q_2+\rangle \cdot \tag{10}$$

$$\cdot\, b^{i2t}_{I^{\pi}}(q_1\sigma, q_2 -\sigma) + \langle q_1+|\Gamma(E\lambda)|q_2-\rangle b^{i2t}_{I^{\pi}}(q_1\sigma\, q_2\sigma),$$

here $\langle q\sigma|\Gamma(E\lambda)|q'\sigma'\rangle$ is the single-particle matrix element of the electric multipole λ, $u^{(\pm)}_{qq'} = u_q v_{q'} \pm u_{q'} v_q$.

The matrix elements for $E\lambda$ and $M\lambda$ transitions from resonances to single-quasiparticle, two-quasiparticle and one-phonon states are given in refs.[3,7]. Taking into account that $u^{(+)}_{s_0 s_2} \approx \frac{1}{\sqrt{2}}$, we write (10) for the $E1$ transition from resonance $I^{\pi} = 1^{-}$ approximately in the form

$$\mathcal{M}(E1; 1^{-}_{i} \to 0^{+}_{g}) \approx \frac{1}{\sqrt{2}} \langle s_0|\Gamma(E1)|s_2\rangle \sum_{s_2\sigma} b^{i2n}_{I^{\pi}}(s_0\sigma, s_2 \pm \sigma). \tag{10'}$$

Hence, it follows that

$$\frac{\Gamma_{\gamma if}(E1)}{\Gamma_{w}(E1)} \approx 10^{-6} = (\bar{b}^{i})^2\, \bar{n}^2_{\gamma},$$

therefore

$$(\bar{b}^{i})^2 \approx 10^{-6} - 10^{-8}, \tag{11}$$

i.e. $\bar{n}_\gamma = 1-5$, i.e. the number of terms in (10) must as a rule be larger than in the (7).

To obtain a more accurate estimate for the few-quasiparticle component $(\bar{b}^i_{I\pi})^2$ one should measure the partial widths for $E1$ transitions from $I^\pi=1^-$ resonances to the ground states of even-even nuclei. The $E1$ transition involves then the minimum number of the terms of wave function (1). As the tragets one may use ^{155}Gd, ^{157}Gd, ^{159}Dy, ^{169}Er, ^{171}Yb, ^{173}Hf, ^{181}Hf and other nuclei.

The ratio D/D_0 of the average spacing between levels with definite I^π at energies B_n to that near the Fermi energies in nonmagic nuclei is 10^{-5}-10^{-6}. This value is about two orders of magnitude larger than $(\bar{b}^i_{I\pi})^2$ obtained for few-quasiparticle components from the reduced neutron capture and $E1$ transition widths. Apparently this difference should not be taken into account since the main part the strength of single-particle may be concentrated at several levels at energies lower than B_n.

The study of $E1$ transitions from resonances to low-lying states in strongly deformed nuclei is interesting from the point of view whether the quantum number K (projection of the momentum on the nuclear symmetry axis) is good for highly excited states. If K is a good quantum number for highly excited states then there must exist K-forbidden $E1$ transitions from resonances to low-lying states. To answer the question whether the K-forbiddenness exists it is necessary to compare the reduced probabilities of $E1$ transitions from e.g. $I^\pi=5^-$

resonances to low-lying states with $I^{\pi}K=4^{+}4$ and $4^{+}0$. It is quite possible that the role of the quantum number K is not identical in different terms of (1). Therefore it would be interesting to investigate if there is K-forbiddenness in $E1$ and $M1$ transitions to two-quasiparticle proton states of even-even nuclei since these transitions are not correlated with the neutron capture probabilities. There are large possibilities of studying K -forbiddenness in odd-odd deformed nuclei.

There is experimental evidence for the fact that in a number of spherical nuclei $M1$ transitions from resonances to low-lying states are noticeably enhanced (see, e.g. refs.[8,9]). Therefore we consider $M1$ transitions in spherical nuclei. The wave function of the highly excited odd N spherical nucleus with $I^{\pi}=1/2^{+}$ is written in the form:

$$\Psi_i(1/2^+)=b^{in}_{1/2^+}\alpha^+_{jm}\Psi_0+\sum_{\substack{j_1 j_2 j_3\\ m_1 m_2 m_3}}\sum_t b^{in2t}_{1/2^+}(j_1m_1,j_2m_2,j_3m_3)\alpha^+_{j_1m_1}\alpha^+_{j_2m_2}\alpha^+_{j_3m_3}\Psi_0\ldots, \quad (12)$$

where jm is the total momentum and its projection. The matrix element of $M1$ transition from the highly excited state described by the wave function (12) to the single-quasiparticle state with wave function $\alpha^+_{j_f m_f}\Psi_0$ is of the form

$$\mathcal{M}(M1;1/2^+i\to j_f)=\frac{-(-1)^{j_f-m}}{\sqrt{3}}(j_f m_f j-m|1\mu)<j\|\Gamma(M1)\|j_f>$$

$$v^{1+}_{j_f j}b^{in}_{1/2^+}-\frac{1}{\sqrt{3}}\sum_{\substack{j_1 j_2\\ m_1 m_2}}(-1)^{j_1+j_2-\mu}(j_1m_1j_2m_2|1\mu)<j_2\|\Gamma(M1)\|j_1>$$

$$U^{(-1)}_{j_1 j_2} \{ b^{in2p}_{1/2^+} (j_f m_f j_1 m_1 j_2 m_2) + 3 b^{in2n}_{1/2^+} (j_f m_f j_1 m_1 j_2 m_2) \}, \quad (13)$$

where $\langle j_2 \| \Gamma(M1) \| j_1 \rangle$ is the single-particle matrix element, $v^{(\pm)} = u_j u_{j'} \pm v_j v_{j'}$. For transitions between states like $3S_{1/2} \rightleftarrows 4S_{1/2}$ the matrix element $\langle 3S_{1/2} \| \Gamma(M1) \| 4S_{1/2} \rangle$ is zero. Therefore the $M1$ transition proceeds due to the three-quasi-particle part of the wave function (12). Of most importance must be transitions of the type $\{j_f, j_1 = \ell - 1/2, j_2 = \ell + 1/2\} \to j_f$ the matrix elements of which $\langle \ell - 1/2 | M1 | \ell + 1/2 \rangle$ are large. The components like ($\ell - 1/2$, $\ell + 1/2$) form collective 1^+ states, which may lead to an enhancement of $M1$ transitions (see, e.g. ref.[10]).

7. Let consider the problem of correlations between processes proceeding through one and the same resonance. The reactions ($n\gamma$) and ($n\alpha$) are considered as two-stage reactions: the first stage-capture of a neutron and formation of a highly excited state, the second one - decay of the highly excied state.

The correlation of two processes going through the same state (e.g. through an i-th resonance) may exist if the main contribution to both processes come from one and the same components $b^i_{I\pi}$ of the wave function (1). Our approach to correlation studies differs in principle from the channel capture theory[II] in which correlations are due to non-zero $\gamma^2_{fc_i}$, which is the neutron width of the final state f for channel c_0 (see ref.[12]).

The highly excited state structure is very complicated, since the wave function (1) contains a large number of nonzero few- and many-quasiparticle components. Therefore the correlation of two processes proceeding through one and the same resonance occur rather rarely when the few-quasiparticle components play in these processes the most important role. Correlations are most strongly manifested in the region where the S -wave neutron strength functions are large.

It is hard to expect large correlations between neutron widths and radiative widths averaged over many resonances, especially if radiative widths are averaged over many final states.

The correlations between total reduced neutron widths Γ_i^{o} and reduced partial radiative widths $\Gamma^{o}_{\gamma i f}$ are analysed in ref.[13]. It is noted that these correlations are most clearly demonstrated in the case of $E1$ transitions from $I^{\pi}=1^{-}$ resonances to the ground states of even-even nuclei. The correlations between Γ_i^{o} and $\Gamma^{o}_{\gamma i f}$ occur in radiational transitions to two-quasiparticle states, like (q_0, q_2), where q_0 is related to the ground state of the odd nucleus which has captured the neutron. The large correlations between Γ_i^{o} and $\Gamma^{o}_{\gamma i f}$ in ^{164}Dy (ref./14/) and ^{170}Tm (ref.[15]) are accounted for in ref.[13].

Owing to the fact that the expressions for the highly excited state wave functions are very complicated it is worthwhile to speak about the most favourable case when large correlations occur between Γ_i^o and $\Gamma_{\gamma if}^o$. These correlations may show the role of some components of the wave functions (1).

It is not difficult to determine more clearly the cases when the correlations are absent at all. On the basis of the expressions for Γ_i^o and the matrix elements of $E\lambda$ and $M\lambda$ transitions (ref. [3,7]), one may conclude that there are no correlations between Γ_i^o and $\Gamma_{\gamma if}^o$ for the following gamma transitions: a) $M1$ transitions in spherical nuclei, b) $E\lambda$ and $M\lambda$ transitions to two-quasiparticle proton levels and two-quasiparticle neutron levels (s_1, s_2) which have $s_1 \neq s_0$, and $s_2 \neq s_0$ and $I^\pi \neq 1/2^+$, in even-even nuclei, c) $E\lambda$ and $M\lambda$ transitions to neutron-proton levels (τ, s) in odd-odd nuclei in which for the proton $\tau \neq \tau_0$ and for the neutron s has $I^\pi \neq 1/2^+$.

We show, for example, that there are no correlations between capture of an s-neutron by spherical nucleus and $M1$ transition to a single-quasiparticle state. The wave function of the highly excited state of an odd-N spherical nucleus is given in eq. (12). The reduced s-neutron capture width is

$$\Gamma_i^o = \Gamma_{s.p.}^o \, |b_{1/2^+}^{in}|^2 \, u_j^2 + \Gamma_i^{oo} . \tag{14}$$

The matrix element of an $M1$ transition to the single-quasiparticle state is presented in eq. (13) the first term in the right-hand side is zero. It is seen from eqs. (13) and (14) that the neutron capture is mainly defined by the single-quasiparticle component and the $M1$ transition by the three-quasiparticle component (12), therefore these processes are not correlated.

The correlations between the reduced neutron capture widths Γ_i^o and the reduced alpha widths $\gamma_{\alpha if}^2$, between $\gamma_{\alpha if}^2$ and

$\Gamma^{o}_{\gamma i f}$ for the same resonance i are considered in ref.[2]. It should be stressed that there is a necessity of simulataneous measuring alpha and gamma widths for the same resonances.

We consider the correlations between gamma widths in the transitions from resonances to different final states. The matrix element of $E\lambda$ transition from the highly excited state to the single-quasiparticle one of an odd N deformed nucleus described by the wave function $\alpha^{+}_{s_f \sigma_f} \Psi$ is

$$
\begin{aligned}
\mathcal{M}(E\lambda; I^{\pi_i}_i \to K^{\pi_f}_f) = & \sum_{s} b^{in}_{I\pi}(s) v^{(-)}_{s_f s_0} \{ \langle s_f + | \Gamma(E\lambda) | s + \rangle - \\
& - \sigma_f \langle s_f + | \Gamma(E\lambda) | s - \rangle \} + \sum_{q,q',\sigma} \sum_{t} (3\delta_{tn} + \delta_{tp}) \cdot u^{(+)}_{qq'} \{ b^{in2t}_{I\pi}(q - \sigma, q'\sigma, s_f \sigma_f) \sigma \cdot \\
& \langle q + | \Gamma(E\lambda) | q' + \rangle - b^{in2t}_{I\pi}(q\sigma, q'\sigma, s_f \sigma_f) \langle q + | \Gamma(E\lambda) | q' - \rangle - \\
& - \sum_{s} \sum_{\zeta} \tfrac{1}{\sqrt{2}} u^{(+)}_{s s_f} b^{in\Omega_\zeta(n)}_{I\pi}(s) \{ X^{\zeta}(s_f) + Y^{\zeta}(s) \} \{ \langle s + | \Gamma(E\lambda) | s_f + \rangle + \\
& + \sigma_f \langle s + | \Gamma(E\lambda) | s_f - \rangle \} ,
\end{aligned} \tag{15}
$$

where the functions $X^{\zeta}(s)$ and $Y^{\zeta}(s)$ characterize the pairing vibration phonons[2]. The correlations between the transitions from resonances to different single-quasiparticle state exists if the transition probabilities are defined by one and the same

$b^{i}_{I\Pi}(S)$ -values and the three-quasi-particle components are not important.

The matrix elements for $E\lambda$ and $M\lambda$ transitions to the two-quasi-particle states in even nuclei are given in refs.[3,7] These expressions contain the terms which are identical for transitions to two-quasiparticle states (q_1, q_2) differing by the position of only one quasiparticle, besides them there are other terms. The cases when gamma transitions from resonances to different two-quasiparticle states are mainly determined by one and the same components of the wave function (1) and when these transitions are correlated are not expected to be frequent. However, for example, in ^{170}Tm one observes correlations between gamma transitions to low-lying states[15].

We consider the correlation problem between the reactions ($n\gamma$) and (dp) which was widely discussed[8,16]. One may speak about them strictly if the reactions are treated as direct capture of the neutron to the final state. If the ($n\gamma$) reaction is considered as the two-stage one: the neutron capture and the formation of a compound state and then the decay of the latter, it is impossible to speak strictly about correlations between the ($n\gamma$) and (dp) reactions. However, if the neutron capture and the gamma decay are correlated with each other (i.e. they are defined by ones and the same $b^{i}_{I\Pi}$ -values) then the selection rules for population of the final states in even nuclei are identical for both ($n\gamma$) and (dp) reactions and can be displayed as correlations of the relative probabilities for population of the final states in ($n\gamma$)and (dp) reactions.

If there is no correlation between the neutron capture and radiational decay (i.e. the first and the second processes are connected with different $b^i_{JI\!I}$ values) then the (dp) and ($n\gamma$) reactions are not related to each other at all and no correlations are to be observed. For example, the (dp) reaction must not be correlated with the neutron capture and a subsequent $M1$ transition in spherical nuclei.

It is interesting to analyse the available experimental data on processes proceeding through resonances in medium-weight and heavy nuclei from the point of view of the suggestions made in the present paper.

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