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M.A.Ali*, V.A.Khitrov, Yu.N.Kholnov,
Yu.P.Popov, A.M.Sukhovoj, A.V.Vojnov

POSSIBILITIES OF DETERMINING THE MAIN PECULIARITIES OF γ-DECAY CASCADES IN HEAVY NUCLEI

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*Permanent address: Physics Department, Atomic Research Center, Cairo, Egypt

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1. Introduction

The γ-radiation emitted after thermal neutron capture has been extensively studied in the past decades for the full Periodic Table. These experiments allowed one to either determine the peculiarities of the structure of low-lying states via measurements of level energies, spins and parities, and γ-ray branching ratios, or to investigate the properties of the primary γ-ray spectrum for capture state(s) decay(s). In fact, little is known about the properties of high excited states in heavy nuclei, for instance, for excitation energies from 2-3 MeV up to the neutron binding energy B_n. So, it is necessary to extend our experimental knowledge to the region $E_{ex} \simeq B_n$ in order to develop a model able to describe the properties of nuclei at intermediate excitation energies between the simple structure of low-lying states and the extremely complicated structure of compound states.

Nowadays, it is possible to measure and analyse in detail two-step γ-decay cascades between the compound state (neutron resonance) and a given low-lying state by the technique named "Summed Amplitudes of Coinciding Pulses" (SACP) [1]. The advantage of this technique is its ability to extract useful information even in cases where the spaces between decaying states are smaller than the γ-ray detector resolution.

A comprehensive idea about nuclear level properties in heavy nuclei ($A > 100$) below the neutron binding energy B_n, and their γ-decay modes, can be achieved if the following are known:
- the dependence of level density for a given spin on nuclear excitations;
- the dependence of excitation and decay probabilities (via a given channel) of a certain nuclear level upon its structure; and
- if there are, or are not, any other processes affecting the γ-decay modes, *e.g.* phase transitions.

Such information could be easily obtained if a set of high efficiency γ- ray detectors were used to measure the γ-decay cascades after thermal or resonance neutron capture in heavy nuclei.

In the present work the main information about, and properties of, high-lying states in some heavy nuclei in the mass region ($114 \leq A \leq 196$) are discussed. The experimental data of: nuclear level densities at excitation energies above 2 MeV; the peculiarities of the intermediate levels of two-step cascades; the corresponding experimental intensities of these cascades; the dependence of these intensities on the energy of the primary E1-transitions; and the experimental possibilities to observe phase transitions and their influence on γ-decay modes, for these heavy nuclei are presented and discussed in some detail. The data of these measurements are compared with the analogous ones predicted by different theoretical models.

2. Level density

The validity of any nuclear model may be tested only when its predictions are compared with experimental results. Evidently, discrepancies between experimental and calculated values from different theoretical models may occur and adjustments of these models are necessary to fit the experimental data.

Typical examples of experimental data concerning the number of excited states at an energy $E_{ex} > 1$ MeV for some even-even nuclei, ^{150}Sm, ^{156}Gd, and ^{164}Dy, are shown in figures 1-3. The number of levels which were measured that lie in the energy interval $\Delta E_{ex} = 100$ keV is compared with that predicted by two quite different nuclear models, namely:
- the Fermi-gas model with a back-shift [2];
- the Ignatyuk model [3], which makes use of the Strutinsky shell corrections approach and shell inhomogeneities for a single-particle scheme.

The common feature which can be obtained from all the studied nuclei is: that although these two models predict the same level density at the excitation energy B_n, they yield different predictions for other ranges of excitation energies. The first model, ref.[2], gives values close to the upper limits and the second model, ref.[3], determines the most likely lower limits of the nuclear level densities, see figures 1-3, for excitation energies up to $\simeq 3$ MeV. The figures clearly show that all nuclear states excited by primary dipole transitions could be observed up to excitation energies of 3 MeV, or higher, for cases where the peaks in the two-step cascade γ-ray spectrum were still well resolved. Our experience suggests that the Ignatyuk model describes the density of few-quasiparticle nuclear states rather than the total level density. The best level density description for levels excited by intense primary dipole transitions can be attained by a model in which the energy dependence of level density at low excitation energies is less strong than that actually considered in these two models. This conclusion will be confirmed again in the next section when comparison between the experimental and the calculated cascade intensity distributions, figures 4-7, is made.

Systematic measurements of the two-step cascade intensities for some heavy nuclei in the mass region ($114 \leq A \leq 196$) were carried out in the excitation energy range $0 \leq E_{ex} \leq B_n$. Table 1 shows a comparison between the number of intermediate cascade levels observed in these measurements in the energy range $2 \leq E_{ex} \leq 3$ MeV and the corresponding numbers predicted from the models mentioned in ref [2,3]. This comparison shows the differences and indicates the necessity for more experimental investigations of nuclear level density at excitation energies above 2 MeV, in particular for the mass region ($150 \leq A \leq 190$). Additional information about γ-decay cascades for many neutron resonances would create more convenient conditions for determining the density of nuclear levels excited by primary dipole transitions, especially in such cases where the partial radiative width fluctuation is at a minimum.

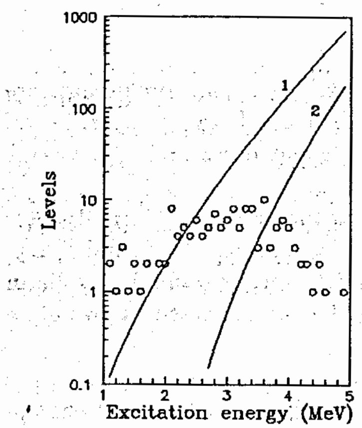

Fig.1. Number of observed levels with $J^\pi = 3^+, 4^+$ and 5^+ in ^{150}Sm for an excitation energy interval of100 keV (points). Curves 1 and 2 represent the BSFG (ref.[2]) and the Ignatyuk thermodynamical model (ref.[3]) predictions

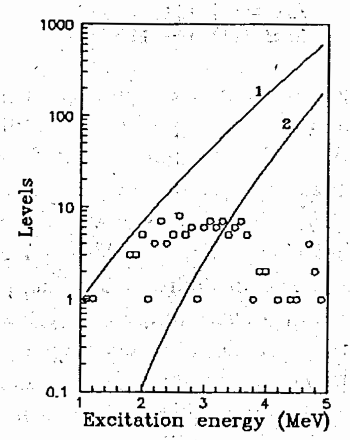

Fig.2. The same as in Fig.1 for levels with $J^\pi = 1^+, 2^+$ and 3^+ in ^{164}Dy.

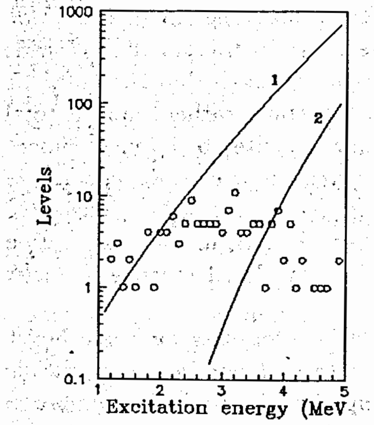

Fig.3. The same as in Fig.1 for levels with $J^\pi = 1^+, 2^+$ and 3^+ in ^{156}Gd.

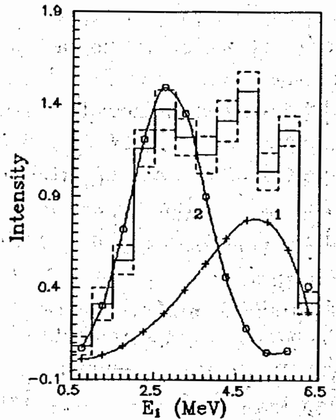

Fig.4. Sum intensity of cascades for the two low-lying levels in ^{150}Sm (% per decay) as a function of primary transition energy. Histograms represent the experimental data with ordinary statistical errors; curves 1 and 2 correspond to predictions according to models mentioned in ref.[2,3] respectively.

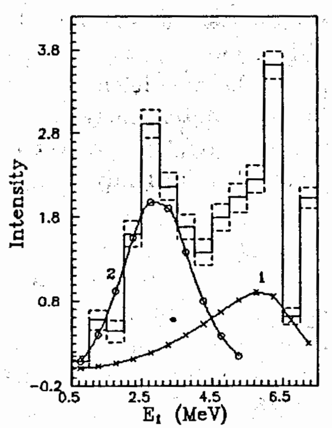

Fig.5. The same as in Fig.4 for cascades to the three low-lying levels in ^{156}Gd.

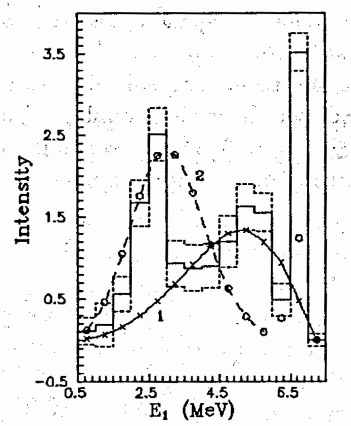

Fig.6. The same as in Fig.4 for cascades to the three low-lying levels in ^{158}Gd.

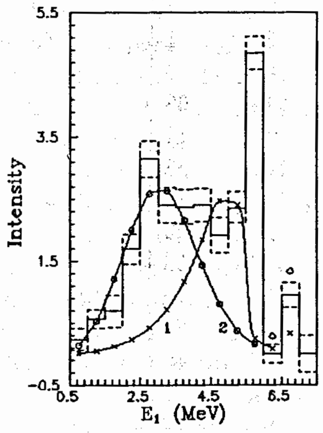

Fig.7. The same as in Fig.4 for cascades to the three low-lying levels in ^{164}Dy.

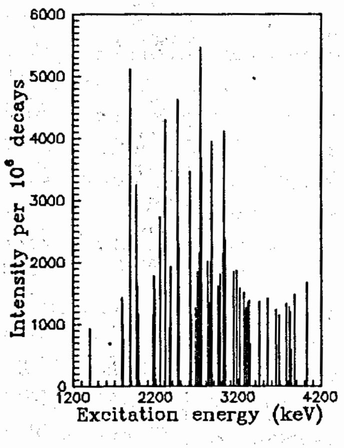

Fig.8. The intensity of two-step cascade transitions of the type $1^- \rightarrow J^\pi \rightarrow 0^+$ in ^{196}Pt versus the excitation energy of nucleus.

Table 1. Experimental sum intensities, $I_{\gamma\gamma}$, of two-step cascades (% per decay) to some low-lying excited levels. n_f is the number of these levels. n_c is the number of experimentally resolved cascades. n_i^{exp}, n_i^{th}[2], n_i^{th}[3] are the experimental and the predicted theoretical numbers of intermediate levels in the excitation energy interval $2 \leq E_{ex} \leq 3$ MeV according to the models mentioned in ref.[2,3], respectively. Parities for n_i^{exp} are unknown. n_i^{th} is calculated for positive parities only

Nucleus	$I_{\gamma\gamma}$	n_f	n_c	n_i^{exp}	n_i^{th}[2]	n_i^{th}[3]
^{114}Cd	12(1)	2	162	22	6	2
^{124}Te	14(1)	4	62	12	8	0.1
^{137}Ba	76(25)	3	23	10	15	13
^{138}Ba	26(1)	2	70	9	3	1
^{139}Ba	102(4)	4	23	10	14	15
^{143}Nd	30(2)	3	45	17	13	25
^{144}Nd	55(4)	5	39	13	5	2
^{146}Nd	34(1)	4	157	41	12	4
^{150}Sm	20(1)	6	188	54	82	1
^{156}Gd	26(1)	5	188	51	136	1
^{158}Gd	17(1)	3	139	44	102	6
^{163}Dy	28(2)	7	250	57	214	68
^{164}Dy	46(2)	6	198	47	211	11
^{165}Dy	55(7)	7	180	57	164	58
^{168}Er	27(2)	6	131	34	126	15
^{174}Yb	22(1)	3	157	44	73	23
^{175}Yb	69(9)	9	155	48	120	58
^{178}Hf	17(1)	6	176	44	160	16
^{179}Hf	67(4)	10	236	57	187	81
^{180}Hf	10(1)	7	172	49	103	16
^{181}Hf	52(4)	5	212	61	222	94
^{183}W	36(3)	5	180	50	202	71
^{187}W	43(2)	5	235	45	264	129
^{196}Pt	32(2)	3	139	40	22	2

3. Intensity of two-step cascades and the structure of intermediate levels

For all practical purposes, there are not enough data relevant to the structure of excited states, for instance, for even-even deformed nuclei above an excitation energy of $\simeq$2 MeV. However, an indirect conclusion about their nature can be obtained from an analysis of integral characteristics, such as the total intensity of two-step cascades between levels of known structure. For example, the intensities of two-step cascades exciting the final levels of a single-particle nature in ^{143}Nd, ^{163}Dy, and ^{183}W nuclei are compatible with theoretically predicted values [4]. Analogous intensities exceed, by at least a factor of 1.5, the values obtained from the statistical model calculations for nuclei such as ^{165}Dy, ^{175}Yb, $^{179,181}Hf$, and ^{187}W. Such divergence is due to different values of the reduced neutron width Γ_n^0, or to different structures of the neutron resonances. In the first case Γ_n^0 is about 10-20% of the average $< \Gamma_n^0 >$; in the second case it is either equal to or greater than $< \Gamma_n^0 >$.

Experiments show that cascades with large Γ_n^0 mainly excite few-quasiparticle low-lying final states. Those of small Γ_n^0 excite many-quasiparticle (collective) high-lying final states of rather complex structure. This result leads to a qualitative explanation [4] of cascade enhancements between compound states with large Γ_n^0 and states of a pure single-quasiparticle nature. Such an explanation assumes a system of intermediate levels with reasonable few-quasiparticle components in their wave functions to be excited in the case of a compound state with a relatively large single-particle component in its wave function (in the case of a sufficiently large Γ_n^0). It also assumes a system of a collective nature to be excited in cases of small single-particle components in the structure of the compound state. A test of the validity of this assumption requires more investigations of two-step cascades for different neutron resonances in the same nucleus.

Figures 4-7 show the dependence of cascade intensities on the energy of E_1 primary transitions for ^{150}Sm, $^{156,158}Gd$, and ^{164}Dy nuclei. It is clear that enhanced cascades for these transitions are observed in the region of $2 < E_1 < 3$ MeV. This enhancement can be attributed to the influence of single-particle primary transitions $4s \rightarrow 3p$, or to the increase of widths of secondary transitions due to the influence of the Giant Magnetic Dipole Resonances, GMDR.

Cascade intensities predicted from different model calculations depend mainly on the nuclear level density of high-lying states and the widths of γ-transitions which populate and depopulate the excited states of the nucleus. Consequently, discrepancies between such predictions may occur. Figures 4-7 demonstrate examples of such discrepancies. Neither the Fermi-gas model nor the Ignatyuk model describe the experimental results of two-step cascades intensities very well. The first model fails to describe the low energy part of cascade primary transitions while the second model is not able to describe the higher part. This can be explained qualitatively by assuming that different collective structure states are more weakly excited than those states of few-quasiparticle ones, at least for the region of the 4*s*-maximum of the neutron strength function. Again, as mentioned before, better agreement with experimental data could be achieved by a model which can predict the values for level density that lie between the estimated values from models mentioned in ref.[2,3].

The cascade intensity, $I_{\gamma\gamma} = (\Gamma_{\lambda i}/\Gamma_{\lambda}))(\Gamma_{if}/\Gamma_{i})$, depends on the partial widths of the primary $\lambda \rightarrow i$ and the secondary $i \rightarrow f$ transitions. That is why the intensities summed over all the final states for cascades exciting the same intermediate level, $\sum_f I_{\gamma\gamma} = \Gamma_{\lambda i}/\Gamma_{\lambda}$, permit the experimental determination of the sum over a given interval of values, $\Gamma_{\lambda i}$, irrespective of the excitation energy of level i. The values of $I_{\gamma\gamma}$ and $\sum_f I_{\gamma\gamma}$ for a large enough set of final levels f, *e.g.*, $n_f \simeq 10 - 50$ depending on the investigated nucleus, determine the ratio of the secondary transition partial width to the total radiative width of the decaying level, Γ_{if}/Γ_{i}, averaged over a given excitation energy interval. A direct and similar conclusion about the nature of the observed enhancement may be obtained when the γ-decay cascades of many neutron resonances in the same target nucleus are studied. Such investigations will allow a better understanding of different observed γ-decay structure effects.

The role of collective excitations in γ-decay of neutron resonance ("tails" of Giant Electric Dipole Resonance (GEDR) and GMDR) can be determined from an analysis of the ratios between the primary (or secondary) transition radiative widths to the total radiative widths of decaying levels. The GEDR "tail" determines the radiative strength function (RSF) of primary transitions. It may be noted here that the experimental data [5] can be described more precisely by the GEDR model [6], assuming that at low energy γ-transitions the GEDR width depends on the temperature of the nucleus and on the γ-quantum energy. Precisely, the experimental RSF data, obtained over all regions of the primary transition energies $E_1 > 0.5$ MeV, contain information about:

- shell effects,
- the general influences of the GEDR and GMDR "tails",
- the temperature of the excited nucleus, and
- the presence (or the absence) of phase transitions which may influence γ-decay processes.

Shell effects appear as local and sufficiently narrow maxima in the background corresponding to the smooth dependence of the RSF upon the γ- quantum energy. Such maxima were observed in the RSF data of $^{137,139}Ba$, and ^{181}Hf nuclei [4,7]. These shell effects are explained qualitatively by single-particle transitions between the 4*s* and 3*p* neutron subshells..

The influence of GEDR "tails" on RSF is, in general, clearly observed at high excitation energies in the investigated nuclei. But, little is known about the effect of GMDR states on neutron resonance γ-decay cascades at low excitation energies. The influence of GMDR can only be observed for compound states which populate the levels over which the strength of the GMDR is fragmented. It is impossible to differentiate the influence of either GEDR or GMDR on two-step cascade intensity without additional information. The nuclear resonance fluorescence (NRF) is one of the most efficient methods, up to now, for experimental investigations of GMDR in deformed nuclei [8]. This method observes the GMDR states which have a pure fixed quantum number K and have no interference with any other excited states with the same J^{π}. These states are referred as "Scissor modes".

Known GMDR states can, in principle, be excited by two-step cascades connecting the compound states of ($J^{\pi} = 1^-$, or 2^-) to the ground state of either even-even nuclei such as $^{156,158}Gd$, ^{164}Dy, ^{174}Yb, and ^{196}Pt, or even-odd nuclei such as ^{143}Nd and ^{163}Dy. A comparison of the measured [9-13] intensities, in the mentioned list of nuclei, for the cascades populating the ground state and the first excited levels with the data corresponding to NRF, ref.[8] for the even-even nuclei, and ref.[14,15] for ^{143}Nd and ^{163}Dy, shows that known states of GMDR, or multi-phonon-particle states, are usually not excited by primary E1-transitions. One can assume in such a case that the experimentally observed cascades [9-13] mainly excite intermediate levels of the few-quasiparticle structure and not the levels of vibrational states. Also, neutron radiative capture is selective for, at least, the excitation processes of Scissor modes in even-even deformed nuclei. It is fair to note here that this conclusion was obtained from a small set of compound states in the investigated nuclei for which Γ_n^0 is greater than $< \Gamma_n^0 >$.

The study of odd mass nuclei is particularly rich in structure information and experiments on neutron resonance cascades in even-odd nuclei, such as $^{155,157}Gd$, ^{163}Dy, ^{173}Yb, *etc.* may answer the following questions:

- whether the observation of GMDR states in γ-decay cascades, in particular for resonances of small Γ_n^0, is possible,
- whether the excitation probability of any collective state decreases with increasing Γ_n^0, and finally,
- whether the hypothesis of preferred excitation channels of collective (including vibrational) states for resonances of small Γ_n^0 holds true.

For the cases where cascades of neutron resonances with small Γ_n^0 could excite vibrational states it will be possible:

- to experimentally reveal all the levels related to GMDR, irrespective of the B(M1) values; and
- to study GMDR built on excited states in deformed nuclei.

The possibility (or impossibility) of selecting the GMDR state from a set of observed 1^+ states in even-even deformed nuclei depends on to what extent K is a good

Table 2. Sum intensities (in % per decay) for all possible two-step cascades of E1- and M1-transitions populating the ground and the first excited states in some heavy nuclei

Nucleus	Ground state		First excited state	
	$I_{\gamma\gamma}^{exp}$	$I_{\gamma\gamma}^{th}$	$I_{\gamma\gamma}^{exp}$	$I_{\gamma\gamma}^{th}$
^{156}Gd	2.8(1)	0.9	17.0(5)	3.0
^{158}Gd	4.6(2)	1.4	11.3(4)	4.6
^{164}Dy	3.6(2)	1.3	18.1(6)	5.1
^{174}Yb	3.4(3)	1.0	11.8(6)	6.5
^{196}Pt	12.2(9)	3.3	9.5(9)	7.3

These calculations were made using level densities of the Fermi-gas model, ref.[2], and RSF values according to ref.[6] for an actual mixture of neutron resonance spins after thermal neutron capture.

quantum number for the levels over which the GMDR strength is distributed and, accordingly, the Alaga rule [16] holds true.

Resonance built on states corresponding to γ-transitions from the compound state of ^{196}Pt to its ground-state has been revealed. Figure 8 shows the intensity of two-step γ-cascades $[1^- \to J^\pi \to 0^+]$ in ^{196}Pt versus the excitation energy of the nucleus. Resonance dependence is noticed in the vicinity of $E_0 \simeq 2.8$ MeV, with a width at half maximum of about 1 MeV. Such clear dependence has not been observed for cascade transitions to the first and the second excited states in ^{196}Pt. The specific character of two-step cascades to the ground state in this nucleus is distinguished by the unusually large ratio, see Table 2, between the total intensity of these cascades and the intensity of cascades populating the first excited state, relative to the corresponding ratio for all known data up to now. Table 2 lists the sum intensities (in % per decay) for all possible two-step cascades of E1- and M1-transitions populating the ground and the first excited states in some even-even heavy nuclei.

Investigation of γ-decay cascades to the ground state of neutron resonances in ^{196}Pt with $J^\pi = 0^-$ would allow one to obtain cascades of pure E1- and M1-transitions and exclude, for $J^\pi = 1^-$ resonances, all possible transitions of E2- or M2- nature. Table 1 shows that all the states in ^{196}Pt up to an excitation energy of 3 MeV, or even higher, can be observed experimentally. Figures 8-10 show the intensity of two-step cascades for transitions leading to the ground and first two low-lying excited states in ^{196}Pt as a function of nucleus excitation energy. A comparison of cascade intensities at excitation energies of $E_{ex} > 2$ MeV for several resonances where $J^\pi = 0^-$ and 1^- would give a reliable determination not only for the spin but also for the parity of the intermediate levels. It is assumed that the RSF of primary E1-transitions is greater by few times than the analogous values for M1-transitions.

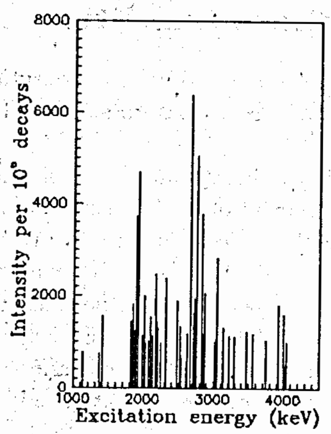

Fig.9. The same as in Fig.8 for cascades to the first excited state in ^{196}Pt.

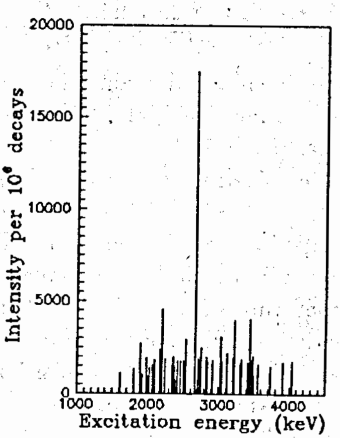

Fig.10. The same as in Fig.8 for cascades to the second excited state in ^{196}Pt.

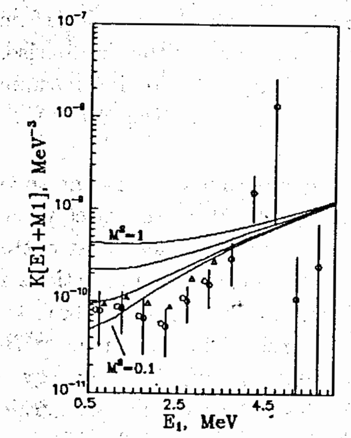

Fig.11. Experimental RSF (o) estimates for the primary γ-transition energies $E_1 \geq 0.52$ MeV in ^{137}Ba. Curves represent the recently developed GEDR model (ref. [7]) using different chosen values for the parameter M. The curves correspond to $M^2 = 0.1, 0.25, 0.5, 1$, respectively.

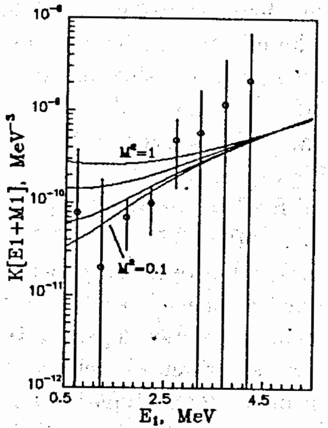

Fig.12. The same as in Fig.11 for the ^{139}Ba nucleus.

4. Nuclear temperature and phase transitions

One of the major domains of nuclear research is the behaviour of nuclei as excitation energy is increased, and the possibility that these nuclei reveal information on the nuclear properties.

The experimental data analysis [17] of level density in heavy nuclei at excitation energies $E_{ex} \simeq 4-5$ MeV shows that the energy dependence of level density changes in shape at a certain energy, E_s. Below this energy is the region where many nuclear properties can find their explanation in the superfluid-nucleus and the constant temperature models. Above this energy, the existence of transitions between the superfluid-liquid and the usual Fermi-gas states (referred to phase transitions) can be assumed [18]. Phase transitions determine the features of the nucleus and may manifest themselves not only as a change of the shape of the excitation energy dependence on level density, but also as a change of the partial widths of primary transitions, which excite levels whose energies lie arround E_s.

Radiative strength function deduced from measurements of two-step cascades in $^{137,139}Ba$ shows that these nuclei could have temperatures less than those estimated from the thermodynamical representation $T = \sqrt{u/a}$, which relates the nucleus temperature to the single-particle state density, a, near the Fermi-surface, and the effective excitation energy u of the nucleus. To improve the comparison between predicted theoretical values and experimental results a matching parameter, M has been introduced, and the previous relation can be rewritten in the form $T = M\sqrt{u/a}$, where $0 < M < 1$.

Figures 11 and 12, show a comparison between the experimental and the theoretical RSF values predicted by the model mentioned in ref. [7] for the cases where $M^2 = 1$, $M^2 = 0.5$, $M^2 = 0.25$, and $M^2 = 0.1$, respectively. It is clear that better agreement between the experimental estimates and the theoretical predictions is obtained as the nuclear temperature decreases. Also, the figures show that, the slopes of the energy dependence for $^{137,139}Ba$ nuclei (clearer in the case of the ^{137}Ba nucleus) are changed, relative to that of model calculations, when the energy of the primary transitions is at $E_1 \simeq 2$, and 1 MeV, respectively. These energies correspond to excitation energies of about 5, and 4 MeV in these nuclei. At such excitation energies the dependence of nuclear level density, for this range of mass, turns from constant temperature to Fermi-gas status. This is one of the main reasons that the two-step γ-decay cascades of compound states in heavy nuclei would allow, in principle, the study of possible phase transitions in heavy nuclei.

CONCLUSIONS

The comparison between the observed number of intermediate cascade levels over the 24 investigated compound states (in complex heavy nuclei in the mass region $(114 \leq A \leq 196)$, Table 1) and that predicted by two different theoretical models illustrates the necessity of additional experimental investigations on the nuclear level densities excited by primary dipole transitions at energies above 2 MeV. Such experiments are now feasable. A survey of available experimental data on level density and intensity of two-step cascades demonstrates the lack of information about the γ-decay cascades of many neutron resonances. The experimental analysis of cascade intensities of compound states for some heavy nuclei in this region clearly shows that it is impossible to describe the widths of primary and secondary transitions for heavy nuclei, in particular, in the region of the $4s$-maximum strength function, without taking into account the influence of level structures below the neutron binding energy. Experimental results show a low nuclear temperature relative to the thermodynamical estimates for, at least, spherical nuclei and illustrate that phase transitions are possible, and could be measured, at excitation energies $\simeq$5 MeV for mass $A \simeq 130$ nuclei. The non-observation of known 1^+ states in the Scissor mode for even-even deformed nuclei may indicate that the neutron radiative capture reaction is a selective one.

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М.А.Али и др. E3-93-434
Возможности определения основных особенностей
каскадного γ-распада тяжелых ядер

Приведены основные результаты анализа средних параметров каскадного γ-распада компаунд-состояний сложных ядер. Экспериментальные данные по плотности ядерных уровней для некоторых J^π для энергии возбуждения выше 2 МэВ сравниваются с предсказаниями двух различных теоретических моделей. Проводится также сопоставление с модельными расчетами экспериментальной интенсивности каскадов для интервала энергии возбуждения, равного энергии связи нейтрона. Приводится заключение об усилении парциальных ширин первичных переходов на высоколежащие уровни. Обсуждаются проблемы оценки реальной температуры возбужденного ядра и возможности обнаружения фазового перехода в ядре и его влияние на моды γ-распада.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

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M.A.Ali et al. E3-93-434
Possibilities of Determining the Main Peculiarities
of γ-Decay Cascades in Heavy Nuclei

The main results of an analysis of the average parameters for γ-decay cascades of compound states in complex nuclei are presented. The experimental data of nuclear level densities, for certain J^π, at excitation energies above 2 MeV are compared with that predicted by two different theoretical modes. Cascade intensities measured over the entire excitation energy range, from the ground state up to the neutron binding energy, are compared with different model predictions. Conclusion about the radiative partial width enhancements for transitions between the compound state and high-lying excited states are given. The problems of estimating the actual temperature of excited nuclei, and of the experimental possibilities to observe phase transitions and their influence on γ-decay modes are discussed.

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

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