объединенный
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ядерных
исследований
дубна

E3-90-45

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INTENSITIES OF TWO-QUANTA CASCADES AT DIFFERENT EXCITATION ENERGIES OF COMPOUND NUCLEI ^{146}Nd, ^{174}Yb AND ^{183}W

Submitted to "Zeitschrift für Physik A:
Atomic Nuclei".

1990

INTRODUCTION

The population of high-lying levels ($E_M \geq 3$ MeV) in compound-state gamma-decay of complex (i.e.,deformed) nuclei has not been systematically studied as yet. Some information about this phenomenon was obtained from a comparison of measured and calculated (by different models) values of total radiative widths of resonances. Radiative strength functions of soft primary transitions were searched for in a direct manner only in reactions $(n,\gamma\alpha)$ and just for few nuclei.

The possibility to perform systematic study of excited states in the whole region of their energies below the neutron binding energy (Bn) appeared as a result of the application of a method of amplitude summation of coinciding pulses (SACP) with two Ge(Li)-detectors to analyze the compound-state γ-decay process.

In the study of two-quanta cascades following thermal neutron capture in heavy nuclei some effects were observed:

a) The comparison of the total experimental intensities of these cascades with the partial radiative widths and the level density below Bn calculated in the frame of γ-decay statistical theory by different models reveals a set of models, which provide the least difference between the experimentally obtained parameters and their predicted values for a large number of nuclei. b) At present it is impossible to reach sufficient (within experimental errors) agreement between the predicted and obtained values of the cascade transition intensities for a considerable number of nuclei under study at different excitation energies of a compound nucleus.

Therefore, one is urged to further detailed investigation of the properties of compound-state γ-decay leading to the population of high-excited levels of the compound nucleus.

THE EXPERIMENTAL DATA ANALYSIS

Intensity distributions of two-quanta cascades with a fixed total energy between the compound-state and a group of low-lying levels of the compound nucleus are measured in the experiment (see, for example, /2/) as a function of the energy of one of transitions. In such a spectrum every two-quanta cascade is represented as a pair of very narrow peaks of equal widths (photopeaks) /3/ at practically full exclusion of background events of any type /1/.

It is important, that in rather wide intervals of the cascade transition energy the measured spectra are a superposition of:

a) few very intensive cascades, which form strong well resolved peaks in the experimental spectra and

b) the continuum formed by a large number of low intensity cascades.

The experience in the procession of such distributions with the following construction of compound-nucleus decay schemes shows, that the largest part of intensive cascades may be located in the excitation energy interval $1 \leq E_M \leq 4$ MeV. In the case of well studied nuclei, it is rather unlikely that an intensive cascade is located at an exitation energy below 2-3 MeV with a wrong order of cascade transitions /5/. In practice this means that the order of γ-transitions of intensive cascades is known. The continuous distribution of low-intensive cascades is mainly due to intermediate levels in the upper (E_M>0.5 Bn) half of the excited states interval of the compound nucleus.

The primary and secondary transition energies are approximately equal in the vicinity of half neutron binding energy (i.e. in the region of half total cascade energy).

The experimentally measured two-quanta cascades can be naturally divided into three types:

a) the cascades with strong primary transitions,

b) the cascades with soft primary transitions represented by a continuous rather smooth distribution;

c) the cascades with aproximately equal transition energies for which the uncertainty in the determination of the intermediate level energy value is noticeably less than the cascade energy.

The largest part of the cascades of the third type is not placed in the γ-decay scheme and the order of their transitions is not determined. Because of that half their total intensity is included into the final intensity distribution of primary transitions (figs. 1-7) without specifying the order of their transitions.

Generally, it is possible to divide two-quanta cascades into primary and secondary transitions provided several conditions are met:

1. the spectra to be analysed have sufficiently high statistics of events,

2. the peak to background ratio in the SACP spectrum is sufficienly high,

3. the decay-scheme (at least the excited states positions of the nucleus) in the excitation energy region up to E_M =2-3 MeV is known.

The study of even-even and even-odd compound nuclei with A =140-190 requires in the first turn the use of the Ge(Li)-detectors, able to register a cascade from a ^{60}Co isotope with an absolute efficiency $\varepsilon > 5.10^{-5}$ (events per decay) in a summary peak 2505 KeV in the condition /1/ that the radiation transfer between the detectors is suppressed by means of heavy metal filters.

The time required for the accumulation of γ-γ -coincidences in this case must be at least 400 hours.

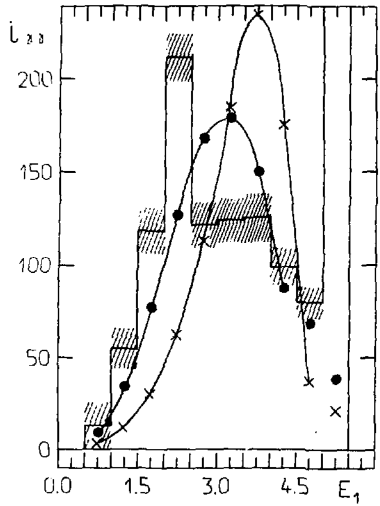

Fig.1. The distribution of intensities $i_{\gamma\gamma}$ of two-quanta cascades to the ground state of ^{183}W (normalized to 10^4 neutron capture events as a function of the primary transition energy E_1 (MeV). The histogram shows the experimental data. Statistical errors are shaded; O-calculated in the frame of the level density model /9/, X-in the model reported in /10/.

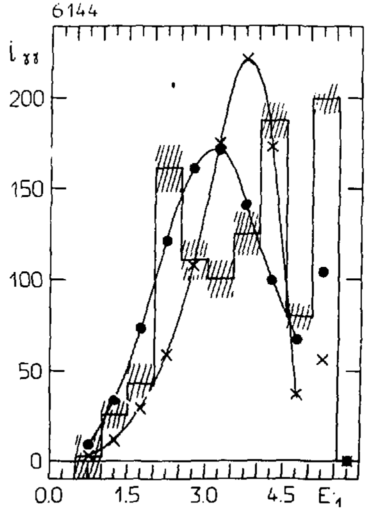

Fig.2. The intensity of cascades to the first excited state of ^{183}W. The notations are analogous to those in Fig.1.

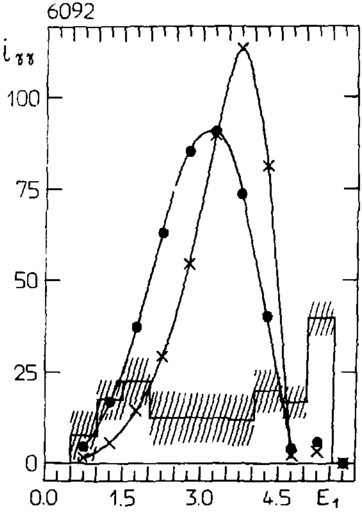

Fig.3. The intensity of cascades to the second excited state of ^{183}W. The notations are analogous to Fig.1.

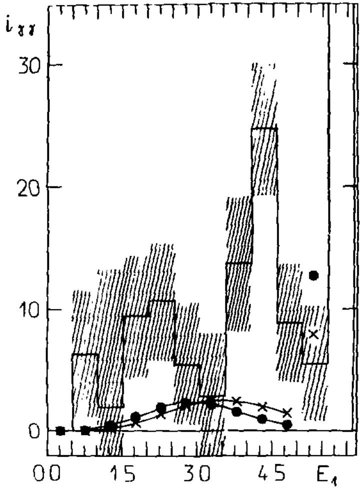

Fig.4. The intensity of cascades to the ground state of ^{146}Nd. The notations are analogous to Fig.1.

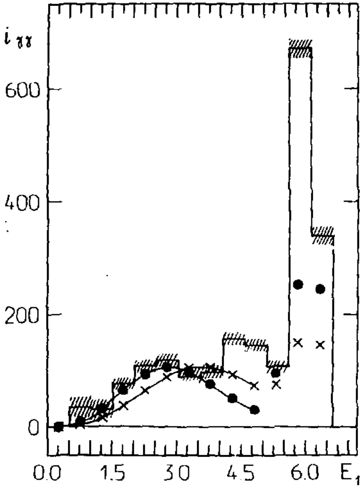

Fig.5. The intensity of cascades to the first excited state of ^{146}Nd. The notations are analogous to Fig.1.

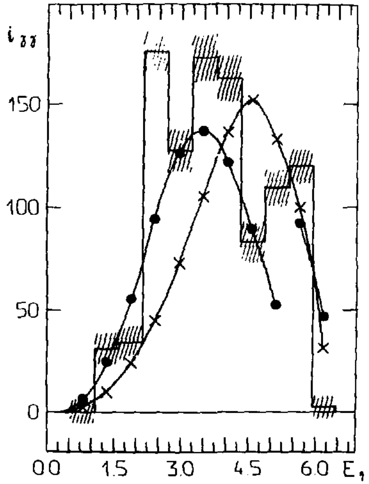

Fig.6. The distribution of cascade intensity to the first excited state of ^{174}Yb. The notations are analogous to Fig.1.

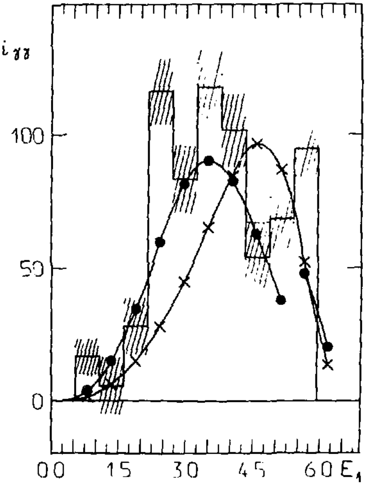

Fig.7. The distribution of cascade intensity to the second excited state of ^{174}Yb. The notations are analogous to Fig.1.

The background under the peaks in the SACP spectrum is due to several components:

a) For cascades with greater sum energy ,only part of its energy is registered because of the Compton scattering (or the pair formation process). This background predominates in the spectrum at registration of the cascades which energies are at least 0.5 MeV less than the neutron binding energy .

b) The radiative capture of scattered neutrons by the detector material. This background becomes essential in the study of nuclei with low ($\sigma_c \leq$ 1-10 b) neutron radiative capture cross sections, if measures are not taken for its suppression.

c) The pile-up of pulses in a slow part of the fast-slow coincidence scheme. This type background causes at least half of background coincidences for the cascades of maximum summary energies (two γ-transitions from the compound-state trough any intermediate level to the ground or one of the lowest lying levels of the compound nucleus).

The investigation of the reactions ^{145}Nd(n,2γ)^{146}Nd /6/, ^{173}Yb(n,2γ)^{174}Yb /7/ and ^{182}W(n,2γ)^{183}W /8/ was performed with due regard for these conditions. In the dividing of two-quanta cascade intensity distributions into components corresponding to different primary transition energies it was assumed that the decay-scheme for ^{183}W is exactly and completely determined up to the excitation energy E^*=2.5 MeV (0,5Bn=3.1), for ^{174}Yb up to 3 MeV (0.5Bn =3.7), and for ^{146}Nd up to E^*=3.15MeV (0.5Bn = 3.8) Virtually it means that the order of transitions was completely determined for the cascades with E_M being outside the interval ΔE_M=0.5 Bn $\pm$0.7 MeV. It is achieved that practically all the cascades with the intensity $i_{\gamma\gamma}>3\text{-}5.10^{-4}$ per decay were determined from two-quanta cascade intensity distributions as experimentally resolved peak pairs outside the third part of each spectrum.

One can determine the order of transitions of not placed cascades so that the intermediate level energy shoud be higher than E^*, i.e. $E_1 \leq E^*-E_f$. Here E_f is the energy of the final level excited by the cascades with the total energy $E_1+E_2= B_n-E_f$.

The part of the cascades determined as experimentally resolved peak pairs decreases with increasing excitation energy up to E^* and higher. The decay-scheme becomes accordingly more complete and reliable. For this reason in this work we do not divide the cascade intensities into the components connected with the registration of primary or secondary transitions with energies in the interval $E^*-E_f \leq E_1 \leq Bn-E^*$. This circumstance is not absolute, since the experimentally achievable improvement of the resolution of the SACP spectrum by a factor of 2-3 and the increase of events statistics by several times by using Ge(HP)-detectors will permit the enlargement of the value of E^* up to 4 MeV and higher that is above half Bn. Thus the uncertainty in the determination of the order of defined quanta in the cascade near $E_M \cong 0.5$ Bn will be eliminated.

The useful to background events statistics relationship for the $^{145}Nd(n,2\gamma)$, $^{173}Yb(n,2\gamma)$ and $^{182}W(n,2\gamma)$ reactions permits the determination within acceptable error of the energy dependence of intensities in cascades from compound- to the 2rd or 3rd low-lying states. Figures 1-7 present sums of cascade intensities (histogrames with a step ΔE = 500 keV) as a function of primary transition energies. For comparison these figures present cascade intensities predicted by different models of level density.

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In figures 1-3 there are compared experimental sums of cascade intensities with given primary transition energies with those calculated by the following two versions of the level density model below neutron binding energy Bn:

a) the Fermi-gas model including the Strutinsky's shell correction approach method /9/;

b) the Fermi-gas model /10/.

Both versions use the same set of models of partial radiative widths that was used earlier /11/: the partial widths of M1- and E2- transitions are proportional to E_γ^3 and E_γ^5, respectively, and E1-transitions are determined in the frame of the giant electric dipole resonance model (GEDR). Other details are analogous to those described earlier /2,11/.

As is seen from figures 1-3 it is impossible to fully describe the energy dependence of cascade intensities for the ^{182}W(n,2γ)-reaction in the frame of simple models /2,11/.

One should only note the following circumstances:

1) For primary transitions in any energy intervals the best agreement between the experiment and the calculation is achieved, if the Fermi-gas model is used, as it takes into account shell inhomogeneities in the one-particle spectrum by Strutinsky's shell correction method /9/.

2) An essential deficiency of intensity is observed for cascades to the state $5/2^{-}$ ^{183}W (fig.3) /6/ with primary transition energies lying in the interval $1.5<E_\gamma<4.5$ MeV. In the same but somewhat narrower region of primary transition energies a deficiency of intensities is also observed for the cascades to the states $1/2^-$ (fig.1) and $3/2^-$(fig.2). The similarity of all the three spectra points to the possibility of a mutual cause of discrepancy between the calculated and the experimental spectra.

3) As was demonstrated in /2,11/ and explained in /12/ the exceeding of the experimental intensities above the calculated

ones in decay of compound-states with a relatively larger one-quasiparticle component of their wave function (the region of the 4S-maximum neutron strength function plus the exceeding of Γn° above it mean value) must be attributed to the structural peculiarities of the intermediate level of the cascade.

As is seen from figures 1-3, the dependence of the cascade intensities on the intermediate level energy is observed also for the compound-state, which thermal neutron capture cross section is determined by a resonance of ^{182}W /13/ with Γn° somewhat smaller than the mean width $<\Gamma n^{\circ}>$.

NEODIMIUM-146

The statistics of the events accumulated in the peaks of the spectrum SACP for ^{146}Nd and in the background under them (even by the use of the pile-up rejection method) permits the expansion into components only of measured intensity distributions of the cascades populating the ground (fig.4) and the first excited state (fig.5)

The known decay-scheme of this nucleus allows one to replace in the calculation the model values of transition widths and of the level density by the experimental values obtained at excitation energy $E_M \leq 2.302$ MeV.

Such an algorithm leads to considerable variations of calculated cascade intensities at primary transition energies above 5.31 MeV.

The comparison of experimental with calculated data on the cascades to the first excited state $2^+(E_f=454$ keV) shows, that the level density model /9/ well predicts the experimental cascade intensities, if their primary transition energy is lower than $E_\gamma=4$ MeV. For the transition energies above this value the cascade intensities obviously exceed those calculated with this model and with the Fermi-gas model wich a backshift. In accordance with ref

/14/, for example, the single-particle states of the spherical potential $3P_{3/2}$ and $3P_{1/2}$ are (for A=146) by 4 or 3 MeV lower than the neutron binding energy. The nucleus ^{146}Nd belongs to the region of the 4S-maximum of the neutron strength function. It is possible that the observed enhancement of the experimental intensities of the cascade transitions is due to single- particle transitions between 4S and 3P shells, as the early analysis of the peculiarities of cascade decay of nuclei ^{165}Dy, ^{175}Yb and ^{179}Hf /12/ have revealed.

It should be noted, that the width of the resonance of ^{146}Nd responsible for the main part of the thermal neutron capture cross section is $2g\Gamma_n^{\circ}=180$ meV and the mean width $<2g\Gamma n^{\circ}>$ = 10 meV. According to ref./2,12/ this circumstance facilitates the observation of intensified two-quanta cascades connected with the 3P-shell. It should be added, that the Fermi-gas model which takes into account shell inhomogeneities in a one-particle spectrum /9/ is connected with experimental level density above the neutron binding energy. Because of its simple functional dependence this model gives an essentially smaller level density just over the Fermi surface, than it follows from the experiment. The model /11/ was chosen to calculate γ-decay as it enables the transition from the theoretical description of the nucleus to its real decay sheme at energies $E_{lim} \leq 2$ MeV and explains the inversion of calculated values $i_{\gamma\gamma}$ at $E_1 > 5$ MeV observed for different level density models (fig.5). The statistical error of experimental data on the cascades to the ground state $\Sigma E = 7565$ keV is too large to make any simple conclusion about the relation between the experimental and calculated intensities in this case. Nevertheless, as experimental values systematically exceed the calculated ones, one may preliminarily conclude that in cascades with a spin difference of initial and final states equal to 3 a systematic enhancement of their intensities is observed in a wide range of excitation energies of the compound nucleus. The relation between the transition widths of the three taken into account multipolarities was adopted to be equal to $\Gamma(E1):\Gamma(M1):\Gamma(E2)=1:0.15:0.02$ at a primary transition energy $E_1=6.8$ MeV. This relation is deduced on the basis of the primary transitions /15/ observed for even-even nuclei from approximately the same region of mass numbers A.

The systematical intensification of the intensities of the cascades in which one of the transitions must be a pure E2-transition, was noted earlier /2,11/ on the basis of the comparison drawn between the calculated and experimental intensities of all the possible two-quanta cascades of this type in even-odd compound nuclei.

YTTERBIUM-174

Figures 6 and 7 present the dependence of the intensities of two-quanta cascades to the states 2^+ and 4^+ of this nucleus as a function of excitation energy.

It is again obvious, that the level density predicted within the Fermi-gas model with a backshift gives worse agreement with the experiment than that predicted by model /9/.

The deviation of cascade intensities from their mean value could be due to fluctuations of the widths of primary and secondary transitions. If these widths fluctuate within the Porter-Thomas distribution, then the expected dispersion can be related to the cascade number ν as follows $\sigma=8/\nu$. Deviations of cascade intensities could be observed if, for example, $\sigma\leq$ 20%. This value will be exceeded if ν were smaller than 200.

The calculation shows that for the compound-states with $I^{\pi}=2^{-}$ the dipole electric transitions excite less than 200 levels in the interval $\Delta E=500$ keV in this nucleus at the energy of primary transitions E_1=4.2 MeV. Therefore one can speak about significant intensification of cascade intensities only in the region E_1=3.7 MeV, where intensities maxima are observed, but σ_{PT} is below 20%. These maxima must be also connected with some structural peculiarities of the given nucleus. Good reproduction of the peculiarities of the distributions of cascade intensities to final levels 2^+ and 4^+ (figures 6 and 7), evidences in favor of this assumption.

Conclusion.

The intensity of a cascade with the energy of the primary transition in the interval ΔE_M is determined by the following relation

$$i_{\gamma\gamma}=(\Gamma_{\lambda g}/\Gamma_\lambda)(\Gamma_{gf}/\Gamma_g)\cdot\langle\rho_g\rangle\Delta E_M \ . \qquad (1)$$

Here $\Gamma_{\lambda g}$ and Γ_{gf} are the partial widths of transitions in cascades which connect levels λ,g and f; Γ_λ and Γ_g ,the full γ-widths of decaying states; $\langle\rho_g\rangle$,the mean density of levels ρ in the interval ΔE_M.

It follows from (1), that the intensification (weakening) of the cascade intensities can be due to deviation of both the level density value ρ and the partial widths values $\Gamma_{\lambda g}$ and Γ_{gf} from the expected value (predicted by the model).

Therefore; the above conclusion that the Fermi-gas model together with the Strutinsky shell correction approach give better agreement with the experiment in comparison with the Fermi-gas model with a backshift is preliminary.

So it is necessary both to perform the further study by the reported here method and continue development of the model description of the compound-state decay.

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Received by Publishing Department
on January 25, 1990.

Бонева С.Т. и др. E3-90-45

Интенсивность двухквантовых каскадов при различных энергиях возбуждения составных ядер ^{146}Nd, ^{174}Yb и ^{183}W

Интенсивности двухквантовых каскадов определены для 2-3 конечных низколежащих уровней ядер ^{146}Nd, ^{174}Yb и ^{183}W. Измеренные интенсивности сопоставляются с расчетами в рамках различных моделей для энергий первичных переходов от 0.5 МэВ до энергии связи нейтрона. Выделены некоторые интервалы энергий возбуждения, где эксперимент не совпадает с модельными расчетами.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1990

Boneva S.T. et al. E3-90-45

Intensities of Two-Quanta Cascades at Different Excitation Energies of Compound Nuclei ^{146}Nd, ^{174}Yb and ^{183}W

Intensities of two-quanta cascades are obtained for 2-3 final low-lying levels of the following nuclei ^{146}Nd, ^{174}Yb and ^{183}W. These measured intensities are compared with the intensities calculated in the frame of various models at primary transition energies ranging from about 0.5 MeV to the neutron binding energy. Some excitation energy intervals are revealed, experimentally obtained intensities of cascade are inconsistent with model calculations.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1990

15 коп.

Редактор Э.В.Ивашкевич. **Макет** Н.А.Киселевой.

Подписано в печать 6.02.90.
Формат 60х90/16. Офсетная печать. Уч.-изд.листов 0,99.
Тираж 385. **Заказ** 43100.

Издательский отдел Объединенного института ядерных исследований.
Дубна Московской области.