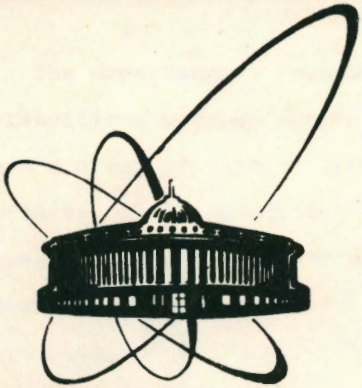

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AN ALGORITHM FOR THE CONSTRUCTION OF A COMPLEX GAMMA-DECAY SCHEME ON THE BASIS OF SPECTROSCOPIC DATA FROM (n, 2γ) AND (n, γ) RERACTIONS

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The experimental investigation of cascades from two-quanta transitions between compound states of complex nuclei ($A \geq 140$) and a group of their low-lying levels ("$(n,2\gamma)$ reaction") permits one to reveal the majority of intermediate levels of compound nuclei at an excitation energy up to 4 MeV and higher. However, in this way it is possible to reveal only part of the transitions. Experimental conditions for studying the $(n,2\gamma)$ reaction allow us to distinguish cascades and establish their intermediate levels only in the case, when :

a / Their intensity is higher than about unity per 10^4 decays;

b / An intermediate state E^* decays by exciting two or more low-lying states;

c / The excitation energy E_f of the final state of a cascade is not higher approximately than 1 MeV.

Nevertheless, within these limitations it is possible to determine positions of 40-50 levels of compound nuclei and their main decay modes. We think additional information could be obtained by analyzing spectroscopic data from (n,γ) and $(n,2\gamma)$ reactions.

The problem of the construction of a decay scheme on the basis of the spectra observed in the reaction of products belongs to a class of inverse and badly limited ones. The situation gets even worse due to the transformation of random analogue quantities (transition energy determination error) into discrete ones (either omission of a real level or an appearance of a false level in the scheme) in the procession of experimental data.

In general, the problem of the construction of a decay scheme on the basis of spectroscopic data from the (n,γ) and $(n,2\gamma)$ reactions accounting for the peculiarities of the latter could be divided into several stages:

1/ To improvement precision of energies of the cascade transitions observed in the $(n,2\gamma)$ reaction by comparing with sufficiently precise energy values of quanta from the (n,γ) reaction.

2/ To more precise determine the energies of intermediate levels, and if necessary, to identify doublets located close to this level and not resolved owing to a large mean error (σ=1÷1.5 keV) in energies of cascade transitions observed in the $(n,2\gamma)$ reaction.

3/ To place into the obtained level scheme all those transitions which were observed in the (n,γ) reaction and could not be observed in the $(n,2\gamma)$ reaction - the transitions between levels with an energy $E^* \geq 2$ MeV and $E_f \geq 1$ MeV.

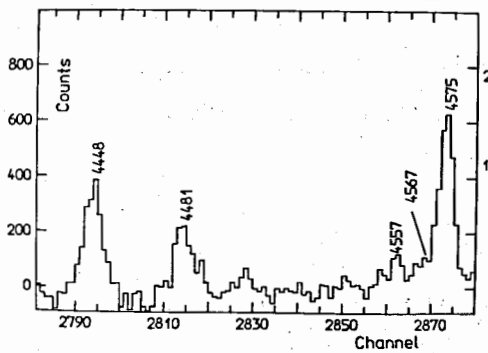

Fig.1. The total distribution of intensities of two-quanta cascades populating 5 low-lying levels of ^{187}W. Peaks are marked with energy values for hard primary transitions (keV).

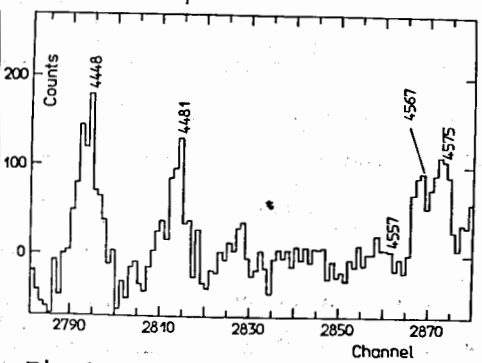

Fig.2. The total distribution of intensities of two-quanta cascades populating 2 low-lying levels of ^{187}W. Notations are the same as in Fig.1.

4/ To determine the transition order in the individual cascades observed in the $(n,2\gamma)$ reaction when one of possible transition orders is most probable.

5/ To exclude from the constructed decay scheme the transitions (random coincidences of the energy difference of levels with the energy of gamma-quanta), which clearly do not correspond to the relation between intensities of gamma-transitions populating and decaying the given level.

6/ To place on the basis of the Ritz combination principle all the remained transitions that could not be included in the decay scheme at states revealed in the $(n,2\gamma)$ reaction. To do this one may use the data on energies of levels observed in the (d,p) reaction, etc., in particular.

7/ To estimate the degree of validity of a decay scheme constructed for energy groups of transitions and excited states observed in the (n,γ) and $(n,2\gamma)$ reactions.

1. The first stage does not cause great difficulties. The only problem arising here is to our opinion, that the set of transitions observed in the (n,γ) reaction misses several transitions revealed in the $(n,2\gamma)$ reaction. In the first term it is true about hard primary transitions which excite very close components of a doublet, if transition intensities in the doublet differ by more than an order of magnitude while the energy differences in the doublet are about the same or smaller than the resolution of the spectrometer used in the investigation of the (n,γ) reaction. For illustration, in Fig.1 and Fig.2 fragments of spectra from the ^{186}W$(n,2\gamma)$ reaction for hard transitions with energy $E_\gamma \approx 4.56$ MeV are presented.

Fig.1 presents the total distribution of intensities of

cascades which populate 5 low-lying levels of ^{187}W observed in the $(n,2\gamma)$ reaction and Fig.2 - only cascades, which populate levels at 204 and 303 keV. Here one can clearly see that the $(n,2\gamma)$ reaction predominates, the primary transition with energy 4567 keV can be observed in the tail of the primary transition at 4575 keV (the ratio of their intensities is about 1:7). Therefore, it is very important to use the data received from the $(n,2\gamma)$ reaction in the analyses of spectra obtained from the (n,γ) reaction.

2. Possibly, a part of levels established in the $(n,2\gamma)$ reaction are doublets. The presence of a doublet can be assumed if the divergence of energies (after the improvement of energy precision) of intermediate levels as sums of energy values of different secondary transitions and final states excited by them is equal to several standard deviations. In practice, on the basis of data from the $(n,2\gamma)$ reaction obtained with germanium detectors, the energy values of transitions of cascades allow us to conclude about the presence of a doublet, if the intensity of a two-quanta cascade is greater than $3\text{-}5.10^{-4}$ and the difference of energies of components of the doublet is equal to or greater than 1 keV.

3. At present one can experimentally resolve cascades of transitions, if the excitation energy of the final state is less than 1 MeV . To increase this energy, it is necessary to use more effective detectors. Nevertheless, ways of decay unobserved in the $(n,2\gamma)$ reaction could be established by correspondence of level energy differences in the $(n,2\gamma)$ reaction with gamma-transition energies measured by means of an individual detector. Owing to random coincidences of energies of gamma-transitions and energy differences of levels, the

number of possible transitions in the decay scheme will be essentially overestimated. Within the present accuracy of experiment, on the average each transition observed in the (n,γ) reaction could be placed twice in the decay scheme established in the $(n,2\gamma)$ reaction.

4. The observed in the $(n,2\gamma)$ reaction cascades, which intensities are high enough (resolved experimentally in the form of two peaks in the distribution of intensities of cascades) are divided into two following groups :

a/ Cascades obtained in the decay of an intermediate level with two (or more) secondary transitions, which intensities are sufficient. As a rule in this case the position of the intermediate level in the cascade is determined unambiguously.

b/ Single cascades. They cannot be placed in the gamma-decay scheme immediately in the study of the $(n,2\gamma)$ reaction because of their transition order being not determined. Nevertheless, the possible presence of secondary transitions populating enough high-lying levels ($E_f \geq 1$ MeV) allows us to consider both possibilities of the cascade quanta placement. If one of these possible transition orders in the cascade is more probable, then the energy of an intermediate level may be fixed. The experience of processing together the results obtained from the $^{186}W(n,\gamma)$ [2] and $^{186}W(n,2\gamma)$ [3] reactions shows that the number of possible transitions from an intermediate level to the final level with $E_f \geq 303$ keV (not studied in work [3]) varies from 0 to 10. The upper value of this quantity is limited, for example, by condition that the transition from the data on the (n,γ) reaction must not occur in the decay scheme more than 2-3 times. Because of the fact that in the (n,γ) reaction only sufficiently intensive transitions are resolved,

they must be included in the proposed decay scheme at lowest possible excitation energies. The experience we have acguired by now shows that transitions with their energy difference of less than, for example, 2 keV (doublets in the (n,γ) reaction) usually appear in the decay scheme of the $(n,2\gamma)$ reaction not more than 2 and sometimes 3 times [1,4].

One of the possible ways to place single cascades in the decay scheme may be excluded by following rules :

a/ Most probable is the transition order in which several unplaced transitions could be introduced into the decay scheme to compare with that in which the only secondary transition is observed. This rule is based on the fact of the presence of a sufficiently great number of final levels with quantum characteristics, which allow one to excite them by dipole (quadrupole) transitions.

b/ The small difference between a sum of energies of secondary transitions and of levels excited by them in the case, when this difference is largely not the same for two possible variants of placing the cascade.

c/ A sum of intensities of secondary transitions in decay of an assumed level strongly exceeds the analogous value for neighbour levels revealed unambiguosly in the $(n,2\gamma)$ reaction.

In particular, this rule follows from the fact that at high enough excitation energies the presence of a resolved level is becoming much less probable than in the case of low excitation energies.

5.In most gamma-decay observed, a sum of intensities of secondary transitions detected in the experiment on decay of some given intermediate level must exceed that for transitions populating this level in result of decay of any higher-lying

levels. This rule comes directly from the fact that the level density of nuclei excitations decreases exponentially with decreasing its excitation energy. With this, the average intensity of the transition and the probability of its observation in the form of an isolated peak of sufficient intensity increases accordingly.

Part of transitions observed in the (n,γ) reaction, especially in deformed nuclei are doublets. One can determine these doublets by comparing intensities of cascades observed in the $(n,2\gamma)$ reaction with those of corresponding secondary transitions measured by a single detector. Owing to the fact that the way a level decays does not depend on the way it is excited, the ratio of intensities of cascades $i_{\gamma\gamma}$ and i_γ of corresponding secondary transitions must have a constant value. The accuracy of its observation is determined only by statistical errors of $i_{\gamma\gamma}$ and i_γ and does not depend on systematical errors of the determination of their absolute values .

The secondary transition (or its group), for which the ratio $Z = i_\gamma / i_{\gamma\gamma}$ is minimum (or within errors it is constant and minimum), must be considered as a singlet (singlets). It is obvious that in the case of a clear doublet, the relation of its components is also determined by Z value.

It is no less important that a sum of absolute intensities $\Sigma\, i_{\gamma\gamma}$ of cascades observed in the $(n,2\gamma)$ reaction must be some fraction of a sum of total absolute intensities i_p of primary transitions. One may see from the following expression for the cascade intensity :

$$i_{\gamma\gamma} = i_p \cdot i_s / \Sigma\, i_{se} \qquad (1)$$

that the ratio of sums of intensities $\Sigma\, i_{\gamma\gamma}$ of cascades

observed in the experiment to an intensity i_p may be expressed through the sum of intensities of secondary transitions $\Sigma\ i_{sz\gamma}$ observed in the $(n,2\gamma)$ reaction and the sum of intensities of secondary transitions $\Sigma\ i_{s\gamma}$ populating the final levels, not studied in the $(n,2\gamma)$ reaction :

$$R = \Sigma\ i_{\gamma\gamma} / i_p = \Sigma\ i_{sz\gamma} / (\Sigma\ i_{sz\gamma} + \Sigma\ i_{s\gamma}). \quad (2)$$

The value $\Sigma\ i_{s\gamma}$ determined unambiguosly from expression (2) limits not only the sum of intensities of secondary transitions not observed in the $(n,2\gamma)$ reaction, but also allows us to exclude from the decay scheme such secondary transitions, the intensities of which exceed $\Sigma\ i_{sz\gamma}.(1-R)/R$. Obviously, this part of intensity i_s of the secondary transition (measured in the (n,γ) reaction), which is connected with the doublets of transitions from other levels, should be excluded from the sum of intensities $\Sigma\ i_{sz\gamma}$.

As experience shows expression (2) helps effectively exclude the transitions wrongly placed into the decay scheme. For ^{187}W, the fraction of thus excluded transitions is about 20 % of the total number of (n,γ) listed.

6. The final conclusion about a possibly false placement of a gamma - transition into the decay scheme can be made from the comparision of the sum of intensities of transitions populating the level i and decaying it. If an analogue parameter q is introduced which satisfies the condition $0 \le q \le 1$, then the sum $\Sigma\ a_i q_{ij}$ of intensities of placed in the scheme levels populating a level j by decay of levels i, which are located above the j level, must be in principle smaller than the sum $\Sigma\ a_{ik} q_{ik}$ of intensities of transitions from level j to level k :

$$\Sigma\ a_{ij} q_{ij} < \Sigma\ a_{jk} q_{jk} . \quad (3)$$

To check on an obvious discrepancy between proposed decay

scheme and the process under study let us define the "current of intensity" as a sum :

$$P_k = \sum_{l \le k} a_{nl} q_{nl} , \quad (4)$$

where the level l is located lower than the k one, while the level n - higher than the k one. It is obvious that the value of $P_k > 100\%$ points to the fact that intensive transitions with energies randomly coinciding with the energy difference of two levels observed in the $(n,2\gamma)$ reaction are present in the decay scheme .

Possible solutions of a system of unequalities (2) were sought for, which would allow to exclude a random transition between two levels. System (3) is solved by the Monte-Carlo method.

The algorithm is as follows :

Values of q_{nl} in the sum $\Sigma\ q_{nl}=1$ for some given transition from the (n,γ) reaction data are redistributed in a random way for those two or three pairs of levels n and l, between which a transition could be placed. As a measure of the redistributed part of q, there was taken a random portion of the ratio of the excess of populating over decaying transition intensities, to the "population" of the level. In the first half from 60-70 iterations, only the "force" q_{nl} of the given transition was redistributed between different pairs of levels n and l for all the transitions included in the decay scheme. In the second half of the iteration process the "force" of transition will not be redistributed between levels but was excluded from the decay scheme.

The accuracy of solution by this method is better than 1%. A criterion of the optimum solution is as minimum as possible number of terms in expression (3).

7. The validity of the decay scheme found by the proposed procedure could be determined numerically. For this it is necessary to determine undistorted (i.e."exact")values of transition energies from the decay scheme found. There are added to them random errors having a normal distribution with mean 0 and dispersion being equal to square error of the determination of transition energy in the (n,γ) reaction. In result the decay scheme is again reconstructed from distorted values of transition energies.

Such a simulation is applied to the decay scheme of ^{187}W [2,3]. It is found that from about 520 secondary transitions included in the decay scheme of this nucleus following the proposed algorithm, about 420 of them are included in the decay scheme with any values of random errors which are added to "exact" values of transition energies (a mean error of transition energy obtained in the list of data from the (n,γ) reaction [2] is 0.196 keV). In this case from $\approx$ 520 transitions, about 270 are fixed in the decay scheme of ^{187}W either on the basis of investigation of $(n,2\gamma)$ reaction or on the basis of the data available in literature (a smaller portion).

The validity of the construction of the decay scheme from the $(n,2\gamma)$ reaction was investigated earlier [5]. The main conclusion of this work was that at the excitation energy $E^* \leq 4$ MeV, the probability of the presence of at least one false level in the decay scheme is not higher than 10% .

CONCLUSION

1. An effective algorithm is proposed to establish a decay scheme of states populated (depopulated) by intensive

gamma-transitions up to an excitation energy of about 3-4 MeV (and higher).

2. It is pointed out that the decay scheme of complex nuclei may be revealed at high confidence level in the range of excited states 2-3 times wider than that obtained by the traditional combination procedure .

3. The main portion of intensive gamma-transitions observed in the (n,γ) reaction by means of semiconductor detectors enters the synthesized decay scheme.

4. The probability of the presence of a false level at the excitation energy $E^* \leq 4$ MeV is small enough, while the portion of transitions definetely established is large enough.

5. The investigation of the $(n,2\gamma)$ reaction using more effective detectors and at different neutron energies will enable more full and reliable determination of decay-modes of complex nuclei in a wider range of their excitation energies.

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Бонева С.Т. и др. E3-90-307
Алгоритм построения сложных схем γ-распада
на основе спектроскопических данных
реакций (n, 2γ) и (n, γ)

Предложен эффективный алгоритм построения сложных схем γ-распада на основе спектроскопических данных реакций (n, γ) и (n, 2γ). Установлен набор действий, позволяющих установить с высоким уровнем достоверности схему распада сложного ядра в области возбуждений в 2-3 раза более широкой, чем это доступно традиционным способам. Алгоритм использует всю информацию о каскадах и γ-переходах из реакций (n, 2γ) и (n, γ).

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Препринт Объединенного института ядерных исследований. Дубна 1990

Boneva S.T. et al. E3-90-307
An Algorithm for the Construction
of a Complex Gamma-Decay Scheme on the Basis
of Spectroscopic Data from (n, 2γ) and
(n, γ) Reactions

An effective algorithm for the construction of a complex gamma-decay scheme on the basis of spectroscopic data obtained from the (n, 2γ) and (n, γ) reactions is proposed. A set of initial rules which allows establishment of a decay scheme at a high confidence level in the range of excited states 2-3 times wider than that obtained by the traditional procedure is formulated. This algorithm takes into account all the information about cascades and gamma-transitions obtained in the (n, 2γ) and (n, γ) reactions.

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

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