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# GAMMA QUANTA EMISSION AT INTERACTION OF FAST NEUTRONS WITH $^{235}$U, $^{238}$U AND $^{232}$Th

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Abstract: The $\gamma$-rays spectra have been measured at interaction of neutrons with $^{235}$U, $^{238}$U and $^{232}$Th. The energies and excitation cross sections of several hundred $\gamma$-transitions have been determined at neutron energy 3 MeV. The $\gamma$-transitions of the (n, n'$\gamma$) reaction have been identified, as well as the transitions belonging to the prompt $\gamma$-radiation of fission fragments. The level excitation cross sections in the (n, n'$\gamma$) reaction have been obtained for $^{232}$Th and $^{238}$U. The total cross section of $\gamma$-ray production has been also determined. The experimental results have been compared with the results of the statistical model calculation. A good accordance is obtained for the total $\gamma$-spectra and, in general, a satisfactory agreement for the level excitation cross sections. Possible reasons are discussed of the discrepancy between the calculated and the measured values of some low-lying states population.

($\gamma$-rays spectra, $^{235}$U, $^{238}$U, $^{232}$Th, neutron energy 3 MeV, measuring, statistical model calculations)

## Introduction

Study of the $\gamma$-radiation arising at interaction of fast neutrons with deformed heavy nuclei enables to obtain information on both the level scheme of the target nucleus and the reaction's mechanism. Besides, there is a practical need for obtaining nuclear data for fissionable nuclei.

At present there are tens of works, in which inelastic interaction of fast neutrons with actinides have been investigated. Howewer, the complexity and incompleteness of the level schemes of these nuclei and a distorting effect of the fission do not allow yet to achieve the required accuracy of the results and their clear interpretation.

## Experiment

Most measurements of the spectra of the $\gamma$-rays emitted by the nuclides of $^{235}$U, $^{238}$U and $^{232}$Th, were carried out at neutron energy 3 MeV on accelerator NG-400 working in a pulse mode.

The $\gamma$-rays were registered with a Ge(Li)-detector placed at an angle 125° to the beam and surrounded with a shield made of lead and hydrogen- and boron-containing materials. The experimental information was accumulated in a microcomputer MERA-60 that also controlled the parameters of the setup and accelerator /1/. The $\gamma$-production cross sections were determined relative to the excitation cross section of the $\gamma$-transition 847 keV in $^{56}$Fe. The neutron pulsed beam's monitoring was done by means of a scintillation counter with the stilbene crystal.

Most part of the measurements were made with the metallic samples prepared of monoisotopes. They represented cylinders 15-22 mm in diameter and about 30 mm high. The corrections for distorsion of the neutron and gamma fields in the samples were calculated by the Monte-Carlo method /2/. To control the calculations' correctness, measurements were carried out with a thin plate 1.5 mm thick, the corrections of which are small and easy to calculate analytically.

The energies and intensities of the $\gamma$-transitions were determined by the SAMPO program. To unfold the total gamma spectrum, a response matrix was used, constructed by the method of interpolation and extrapolation of the experimentally measured response functions of the spectrometer to a monochromatic $\gamma$-radiation. The regularization method /3/ was used for unfolding. The setup and the measurement methods are described in more detail elsewhere /4, 5/.

## Results

Fragments of the measured spectra are shown in Fig. 1. Altogether over 300 $\gamma$-transitions were revealed for the three nuclides /5/. Among them in the $\gamma$-ray spectra of $^{235}$U and $^{238}$U, the gamma-transitions were identified of the fission fragments $^{84}$Se, $^{88, 90}$Kr, $^{92, 94, 96}$Sr, $^{98, 100}$Zr, $^{102}$Mo, $^{134}$Te, $^{138, 140}$Xe, $^{142}$Ba and some others /6/. the yields of the transitions $2^+$-$0^+$ terminating $\gamma$-cascades in the named even-even nuclei, measured as well as all the $\gamma$-spectra in the time interval 22 ns, are in most cases near to the independent yields of the said fragments at

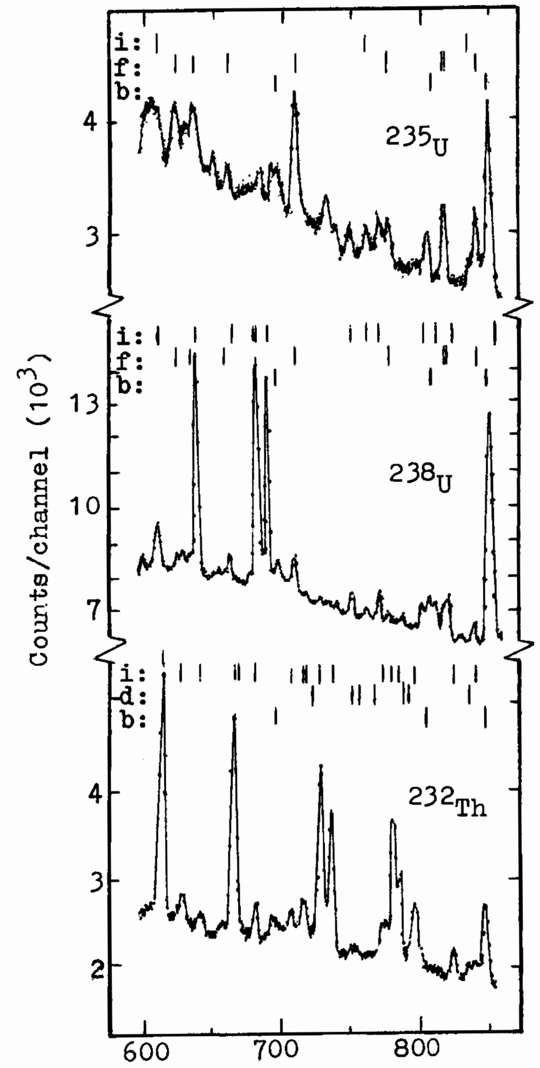

Fig. 1. Ge(Li) pulse-height distributions (only 0.6 - 0.85 MeV energy interval is shown). $\gamma$-peacks indicated by:

- i - from (n,n'$\gamma$)
- f - from fission fragments
- b - background from surrounded materials
- d - from isotope's natural radio-active decay.

$^{235}$U fission induced by thermal neutrons. $^{134}$Te is an exclusion, being formed with high probability at fission in an isomeric state. The analysis of the results allowed also somewhat to specify the level scheme of $^{238}$U /7/.

The calculations of the neutron-induced reactions' cross-sections and the spectra of the emitted $\gamma$-rays were done for $^{238}$U and $^{232}$Th by the program STAPRE /8/. The penetration coefficients from the coupled channels optical model /9/ were used in calculations. For parametrization of the fission barriers and level densities above and between them we used the data of paper /10/. The radiative strength functions were described by the Weisskopf form at normalizing of the absolute radiative widths to the data of /11/. The approximation of level density of the target nuclei above exciting energy 1.2 MeV was done according to the recommendation of work /12/. The calculation parameters were varied slightly to ensure good fit to the cross sections of the fission and the radiative capture, as well as the other known experimental data in the neutron energy range 1-4 MeV. The spectra of the fission $\gamma$-rays were not calculated in the program, therefore the spectra measured in /13/ at $^{235}$U thermal neutron fission were added to the calculation's results. Comparison of the measured and calculated total $\gamma$-spectra is shown in Fig. 2.

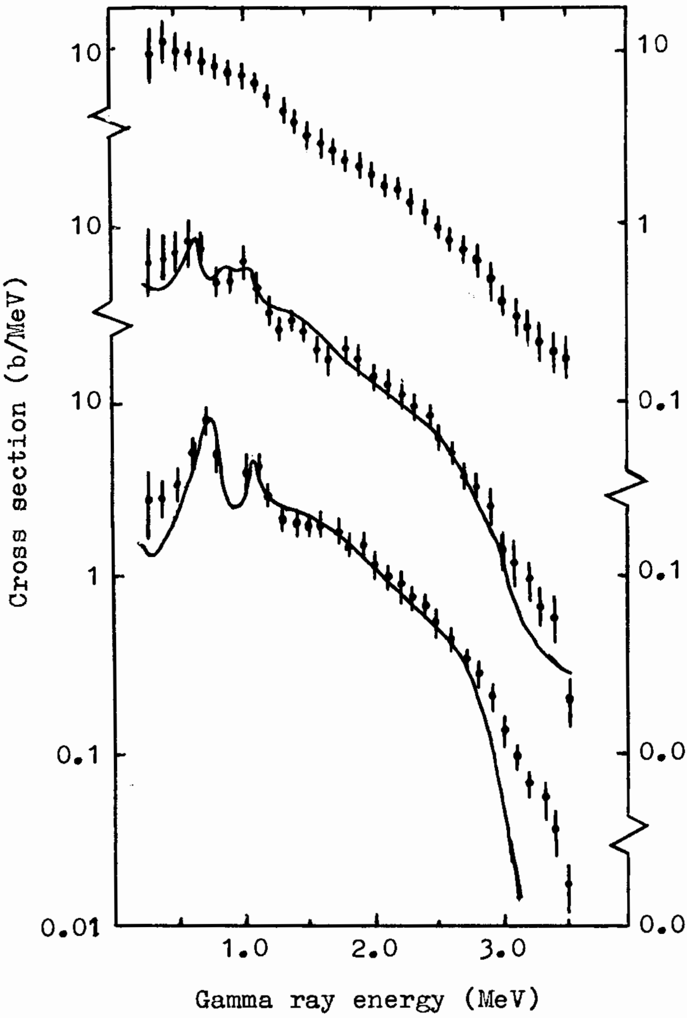

Fig. 2. Total gamma-ray production cross section induced by 3 MeV neutrons. Curve: those calculated by statistical model.

In tables 1 and 2 the experimentally determined cross sections of $^{238}$U and $^{232}$Th level excitation in the (n, n'$\gamma$) reaction are compared with the

Table 1. Population of the levels of $^{238}$U in (n, n'$\gamma$) reaction at neutron energy 3 MeV

| $E_{lev.}$ (keV) | $I^{\pi}K^{\pi}$ | Population (mb) | |
|---|---|---|---|
| | | Exper. | Theor. |
| 0 | $0^+0^+$ | | 2758 |
| 44.9 | $2^+0^+$ | | 2539 |
| 148.4 | $4^+0^+$ | | 1487 |
| 307.2 | $6^+0^+$ | 310(90) | 436 |
| 517.9 | $8^+0^+$ | 30(10) | 58 |
| 680.1 | $1^-0^-$ | 225(24) | 152 |
| 731.9 | $3^-0^-$ | 240(25) | 204 |
| 775.7 | $10^+0^+$ | | 2 |
| 826.8 | $5^-0^-$ | 100(15) | 115 |
| 927.0 | $0^+0^+$ | | 15 |
| 930.8 | $1^-1^-$ | 115(15) | 55 |
| 950.0 | $2^-1^-$ | 140(30) | 72 |
| 966.1 | $7^-0^-$ | 25(4) | 28 |
| 967.1 | $2^+0^+$ | 80(10) | 64 |
| 993 | $0^+0^+$ | | 13 |
| 997.5 | $3^-1^-$ | 105(20) | 80 |
| 1037.3 | $2^+0^+$ | 17(7) | 53 |
| 1057 | $4^+0^+$ | <15 | 59 |
| 1059.7 | $3^+3^+$ | 140(20) | 62 |
| 1060.6 | $2^+2^+$ | 100(15) | 50 |
| 1105.5 | $4^+3^+$ | 45(10) | 48 |
| 1106.2 | $3^+2^+$ | 80(15) | 55 |
| 1126.5 | $4^+0^+$ | <25 | 47 |
| 1128.7 | $2^-2^-$ | 140(15) | 45 |
| 1150.3 | $9^-0^-$ | | 1 |
| 1162.5 | $5^+3^+$ | 20(8) | 24 |
| 1167.9 | $4^+2^+$ | 47(9) | 42 |
| 1169.7 | $3^-2^-$ | 60(15) | 48 |
| 1223.9 | $2^+$ | 35(4) | 41 |
| 1239.4 | $5^+2^+$ | 27(7) | 23 |

Table 2. Population of the levels of $^{232}$Th in (n, n'$\gamma$) reaction at neutron energy 3 MeV

| $E_{lev.}$ | $I^{\pi}K^{\pi}$ | Population (mb) | |
|---|---|---|---|
| | | Exper. | Theor. |
| 0 | $0^+0^+$ | | 3095 |
| 49.4 | $2^+0^+$ | | 2824 |
| 162.1 | $4^+0^+$ | | 1563 |
| 333.2 | $6^+0^+$ | 320(70) | 468 |
| 556.9 | $8^+0^+$ | 27(9) | 66 |
| 714.2 | $1^-0^-$ | 186(13) | 133 |
| 730.4 | $0^+0^+$ | 23(4) | 32 |
| 774.1 | $2^+0^+$ | 225(15) | 329 |
| 774.4 | $3^-0^-$ | | |
| 785.4 | $2^+2^+$ | 170(15) | 136 |
| 829.6 | $3^+2^+$ | 131(9) | 154 |
| 873.0 | $4^+0^+$ | 22(2) | 124 |
| 883.6 | $5^-0^-$ | 100(10) | 113 |
| 890.1 | $4^+2^+$ | 110(20) | 120 |
| 960.4 | $5^+2^+$ | 65(9) | 78 |
| 1042.5 | $7^-0^-$ | 14(4) | 25 |
| 1072.9 | $2^+$ | 67(5) | 77 |
| 1077.3 | $1^-$ | 61(5) | 61 |
| 1078.7 | $0^+$ | 23(4) | 17 |
| 1105.7 | $3^-$ | 81(9) | 88 |
| 1122.8 | $2^+$ | 83(9) | 71 |
| 1143.3 | | 41(4) | |
| 1148.3 | | 9(2) | |
| 1182.5 | $3^-$ | 47(4) | 78 |

results of calculations. On the whole, the data are in a satisfactory agreement. In a detailed comparison, however, some discrepancies are found which are systematizable.

## Discussion

For example, the level 993 keV $0^+0^+$, 1037.3 keV $2^+0^+$ and 1126.5 keV $4^+0^+$ of $^{238}$U as well as the levels 730.4 keV $0^+0^+$, 774.1 keV $2^+0^+$ and 873.0 kev $4^+0^+$ of $^{232}$Th, exhibit themselves in the experiment weaker than it should be expected. All these states are members of the rotational bands constructed on $\beta$-vibrational states for which E0-transitions are probable /14/.

On the other hand, the bases of the other rotational bands and their first members ($I \approx K$) are populated stronger than the calculations predict. One of the probable explanations of this fact may be the following: by the calculations it was assumed that the probability of the $\gamma$-transitions populating low-lying states from the "continuum" ($E^* > 1.2$ MeV) depends only on the difference of the energy of the levels and their spins, and the structure of the states and, for instance, the quantum number K were not taken into consideration. It is clear that taking into account the K projection in the description of the level density and introducing a corresponding K-inhibition factor into probability of the $\gamma$-transition must improve the situation.

The observed excess of the yields of some $\gamma$-transitions over the calculated values may be attributed also to the direct mechanism of neutron inelastic scattering. The calculation of its contribution using the coupled channels model for the states of the octupole bands ($K^{\pi} = 0^-$) of $^{238}$U and $^{232}$Th and comparison with the results of the experiment at $E_n < 1.5$ MeV, showed that this contribution may be 10 - 15 mb /15/. This conclusion was also drawn by the autors of reference /16/. It seems that the cross sections of the direct excitation of the states calculated in /17, 18/, are somewhat overestimated, because such great values, in our opinion, could not fail to exhibit even in rough direct measurements of the inelastic scattered neutrons spectra.

A good agreement between the total spectra of $\gamma$-rays for $^{238}$U and $^{232}$Th nuclei measured at neutron energy 3 MeV and those calculated by the statistical model (Fig. 2) also evidence for general prevalence of the statistical mechanism of the population most of the exciting states. It may be noted here that introduction the dependence of the probability of $\gamma$-transitions on the K into the calculation must cause an increase of the soft component of the spectra, which would improve the agreement of the calculation results with the experiment.

## Conclusion

However, these arguments are not decisive due to a great error in measuring the total cross section of $\gamma$-quanta production (10-25%) and an insufficient definiteness of the calculation parameters. A more rigorous answer to the question about the role of direct reaction mechanism in excitation of individual states may be obtained by a direct measurement of the inelastic scattered neutrons spectra. As in this case very complex and prolong experiments are required in order to obtain the necessary accuracy, the measuring the $\gamma$-spectra of the (n, n'$\gamma$) reaction may be become quite competitive in this respect. But for this is necessary first to considerable improve the level schemes of transactinide nuclei.

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