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MEASUREMENT OF THE MULTIPLICITY AND TOTAL ENERGY OF GAMMA-QUANTA FROM THE FISSION OF U-235 INDUCED BY RESONANCE NEUTRONS[1])

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The spectrometry study of γ-radiation following the fission of U-235 by resonance neutrons has been carried out with the help of the pulse reactor IBR-30. The ionization chamber, containing 10 g of uranium, enriched to 90 % with the U-235 izotope, and the Ge(Li) detector, with a volume of about 30 cm^3 and energy resolution of about 2.8 keV at 1333 keV, were operating in coincidence. The multidimensional technique has been applied for the data analysis. The γ-spectrum in the (0.1—1.6) MeV interval has been obtained as a result of the reconstruction of the instrumental spectrum. The integral characteristics of γ-radiation from fission multiplicity, total and mean energy have been calculated for the neutron energy range from 0.7 eV to 36 eV.

ИЗМЕРЕНИЕ МНОЖЕСТВЕННОСТИ И ПОЛНОЙ ЭНЕРГИИ ГАММА-КВАНТОВ, ОБРАЗОВАННЫХ ПРИ ДЕЛЕНИИ УРАНА-235 ПОД ДЕЙСТВИЕМ РЕЗОНАНСНЫХ НЕЙТРОНОВ

В работе приводятся результаты спектроскопического изучения гамма-излучения, сопровождающего деление урана-235 под действием резонансных нейтронов, получаемых от импульзного реактора ИБР-30. Ионизационная камера, содержащая 10 г урана, обогащенного на 90 % изотопом урана-235, и германиевый (литиевый) детектор с объемом около 30 см^3 и энергетическим разрешением около 2.8 кэВ при энергии 1333 кэВ работали в режиме совпадения. Для анализа данных был применен многомерный метод. Гамма-спектр в области энергий 0.1 – 1.6 МэВ получен на основе восстановления спектра. Интегральных характеристики гамма-излучения рассчитаны на основе множественности деления и полной и средней энергии для области энергии нейтронов от 0.7 эВ до 36 еВ.

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I. INTRODUCTION

As known the fission of nuclei is followed by the emission of neutrons and γ-rays. Spectroscopic studies of radiation allow one to derive information about energy distribution in the fission process including the excitation energy of fission fragments.

Gamma-rays just after the compound nuclei have been formed, or just at the moment of the fragments scission, as well as gamma-ray from neutron-rich nuclei fragments after the evaporation of the last neutron are accepted to be considered prompt. A decay of isomeric states of fragments during $10^{-9}-10^{-3}$ sec causes the emission of γ-rays called delayed [1]. In the integral form the prompt and delayed γ-radiation is characterized by the total energy $\bar{E}_\gamma$, the total number of γ-quanta, i. e. the multiplicity $\bar{N}_\gamma$ per a fission event and by the everage energy per an emitted γ-quantum.

$$\bar{\varepsilon}_\gamma = \bar{E}_\gamma / \bar{N}_\gamma.$$

One has to know these integral characteristics to calculate the optimal parameters of nuclear installations, of their shielding, heating regime, etc.

The study of γ-emission following the fission of U-235 induced by thermal neutrons has been carried out since 1955 [2]. The results reported in a number of works are summarized in Table 1. It contains multiplicities and total mean energies for given energy intervals and time windows τ with an accuracy of $(4-10)$ %. The review [3] recommends to use the data found as an average of the results of three best measurements.

From the analysis of the above mentioned works it follows that in the energy interval 1.5 MeV—5 MeV the multiplicity and total mean energy were measured with an accuracy less than 2 %. For γ-quanta with energies from 0.1 MeV to 1.5 MeV where the intensity of the spectrum has a maximum as well as above 5 MeV the experimental errors are much greater and the experimental data accuracy leaves much to be desired. Absolutely no data exist on γ-rays following the fission of U-235 induced by resonance neutrons. An investigation of γ-rays following the fission of U^{235} by resonance neutrons was performed in the Laboratory of Neutron Physics of JINR Dubna. The spectrum of γ-rays was measured with the Ge(Li) detector and the integral characteristics were obtained in the energy range from 0.1 to 1.6 MeV.

II. EXPERIMENT

The study of γ-rays yield following the fission induced by resonance neutrons has been carried out at the pulsed reactor IBR-30. In the booster mode (the reactor operating with the linear electron accelerator) the neutron pulse duration was

4μsec at a repetition rate of 100 Hz. The neutron spectrum was measured in the energy interval from 0.7 eV to 36 eV with the time-of-flight method at a flight path of 60 m and a flux density of $2\times10^3\ E^{-0.9}\ cm^{-2}s^{-1}eV^{-1}$.

A collimated neutron beam went through an ionization chamber containing 10 g of U^{235} [8], the efficiency of registration of fragments being $\varepsilon_f \simeq 70$ %. For the spectroscopy analysis of γ-rays following the fission the authors used the spectrometer based on the Ge(Li) detector with a volume of $\sim 50\ cm^3$ and an energy resolution (FWHM) 2.8 keV for the ^{60}Co source.

For the absolute efficiency calibration of the Ge(Li) spectrometer there were used besides a standard γ-ray source (SGRS-OSGI (USSR)) the additional isotopes ^{181}Ta, ^{152}Eu, ^{133}Ba and ^{226}Ra.

The use of the lines soft γ-radiation of uranium contained in the chamber made possible a correct estimate of the account for the real geometry of the experiment and allowed to improve the calibration accuracy. The correction for γ-quanta, absorbed in the chamber walls and target layers, is calculated by the Monte-Carlo method using the known coefficients of absorption [9]. The correction factor and the energy dependence are illustrated in Fig. 1. The jump at an energy of 115 keV corresponds to the uranium K-absorption edge. Fig. 2 shows the absolute efficiency of the spectrometer with an account of the correction for absorption.

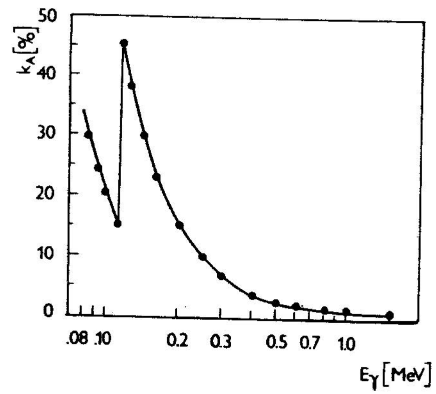


Fig. 1. Variation of the absorption in the fission chamber with the energy of gamma-rays.

During the measurements the γ-ray spectrometer was operating in coincidence with the fission chamber detecting the γ-rays with energies from 80 keV to 1.75 MeV. The time resolution of the whole system was ~ 15 ns. One had 60 coincidences per second, the level of the background of random coincidences being 0.9 %. The time window in the measurements was 33 ns.

The method of multidimensional analysis was applied in the experiment [10]. Three runs of measurements gave 1.5×10^9 fission events, 2×10^7 of them in coincidence with γ-quanta. Each event has two parameters: the time of flight of the neutron which induced the fission and the energy of γ-rays following the fission. The two dimensional data were recorded on magnetic tape with the help of the measuring module on the basis of the SM-3 computer. Data sorting and processing were off-line performed on the CDC-6500 and PDP 11/70 computers. The instrumental γ-spectrum obtained as a result is given in Fig. 4.

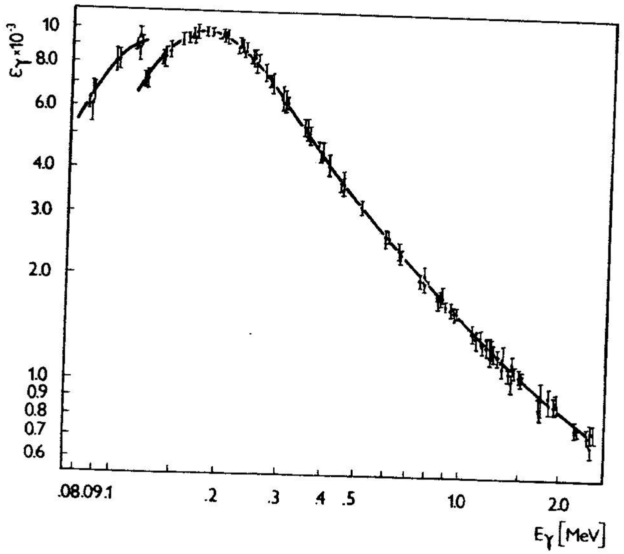


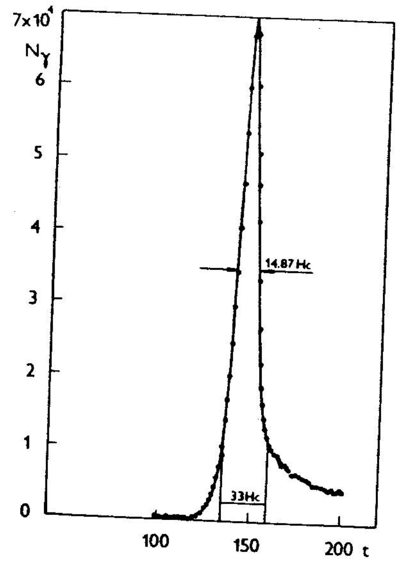
Fig. 2. Corrected absolute efficiency of the Ge(Li) detector in the experimental arrangement.

III. DATA PROCESSING

The instrumental spectrum has the peaks due to total absorption together with a continuum due to a not full absorption of γ-quanta in the detector or due to their loss of energy on scattering from construction materials. To restore the initial spectrum the method of amplitude weighting similar to that developed by Meier-Leibnitz [11] was used. The whole energy range was divided into 13 intervals: from 0.1 MeV to 0.2 MeV — 2 intervals, each 50 keV wide; from 0.2 MeV to 1 MeV – 8 intervals, each 100 keV wide; and from 1 MeV to 1.6 MeV — 3 intervals, each 200 keV wide.

The weighting coefficients g_N^i and g_E^i, respectively, for the multiplicity and total energy of each interval were found with the help of monoenergetic scaling sources and data on the absolute efficiency of the spectrometer in the frame of the matrix representation. The dependence of the coefficients on energy is shown in Fig. 5.

Fig. 3. The Ge(Li)-fission chamber coincidence spectrum. The applicable time window – 33 ns.

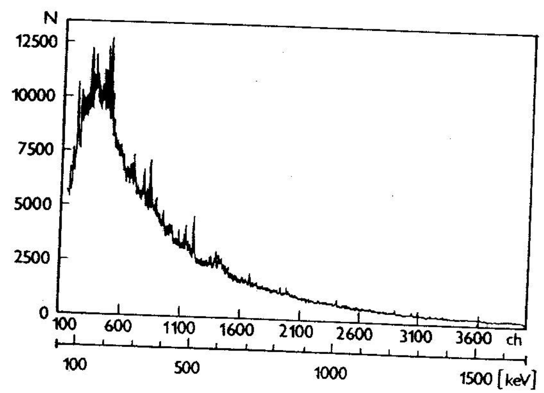


Group sums N_i were determined using the spectra. The multiplicity per event $\bar{N}_\gamma$, total energy per event $\bar{E}_\gamma$, and the mean energy per quantum were calculated as follows:

$$\bar{N}_\gamma = \sum_{i=1}^{13} N_i g_N^i / N_f$$

$$\bar{E}_\gamma = \sum_{i=1}^{13} N_i g_E^i / N_f$$

Fig. 4. Pulse-height distribution of prompt γ-rays from $^{235}U(n, f)$.



$$\bar{\varepsilon}_\gamma = \bar{E}_\gamma / \bar{N}_\gamma$$

Here N_i is the number of the events detected.

The multidimensional technique applied here has allowed the authors to single out the two groups of resonances with the spin 3^- and 4^-. Because of the impossibility of separate normalization these data were normalized to the total number of fission events N_f. The thus obtained multiplicity $\bar{N}_\gamma(J)$ and total energy $\bar{E}_\gamma(J)$, are not absolute. For the mean energy $\varepsilon_\gamma(J)$ there is no need for absolute normalization and it characterizes the hardness of the spectrum in each group of resonances.

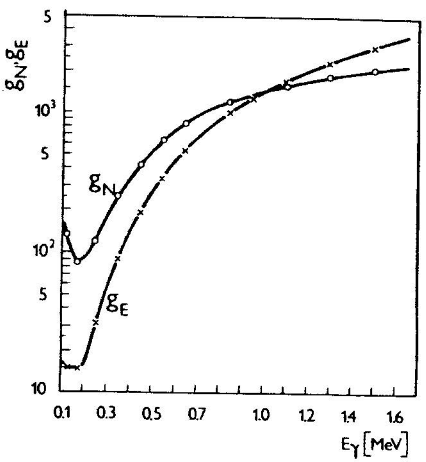


Fig. 5. Weighting factors g_N and g_E derived from the response matrix.

IV. ANALYSIS OF ERRORS

The statistical data processing and the analysis of errors were carried out by the maximum likelihood method.

The total error appearing in the calculation of the multiplicity besides the statistical error of group sums N_i includes also those of the determination of the weighting coefficients g^i_N, g^i_E and the number of fission events.

The statistical error in the determination of sums in several energy intervals does not exceed 0.3 % in all the three runs of measurements.

In the calculation of weighting coefficients most important is the probability of γ-quantum registration in the corresponding energy intervals of the spectrum. Therefore, their errors are mainly dependent on the error in the determination of the absolute efficiency of the spectrometer, averaged over each of the thirteen intervals, and amount to $\sim$0.3 %.

The statistical error of the fission events detected with the chamber is negligibly small. From the analysis of the dispersion of the ratio of the number of the fission events to the number of coincidences with γ-quanta at some moment, it followed that the systematical error of determination of the number of fission events was about 0.7 %.

The greatest part of the background of random coincidences, 0.75 % of 0.9 % is connected with the uranium natural activity. It was accounted for in data processing. contribution to the γ-spectrum of the inelastic scattering of fission neutrons from Ge and the construction materials made no essential addition to the summary error.

V. EXPERIMENTAL RESULTS

In the experiment carried out there has been measured the γ-spectrum of the radiation in the range from 0.1 MeV to 1.6 MeV following the fission of U-235 nuclei induced by neutrons with energies from 0.7 eV to 36 eV. In Fig. 6 one may see the histogram obtained after the reconstruction of the summary spectrum calculated for each of the three runs of measurements as well as the mean weighted values are given in Table 2. One may see from the comparison of these data with those summarized in Table 1 that the greatest part of γ-quanta and of the total energy correspond to the energy range $0.1 < E_\gamma \leq 1.6$ MeV. Since there are no reasons to expect big difference between γ-spectra of thermal and resonance neutrons, the measured spectrum has been extrapolated using the results of ref. [5] obtained for the thermal point. The integral characteristics in the energy range

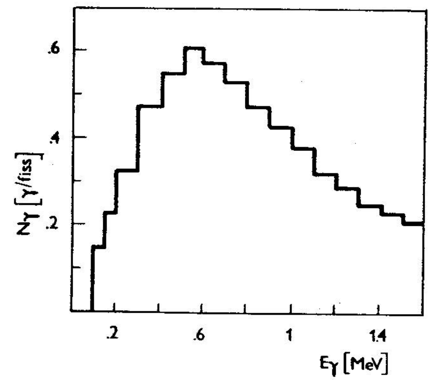


Fig. 6. Present experimental results. The variation of the multiplicity $\bar{N}_\gamma$ as a function of γ-energy.

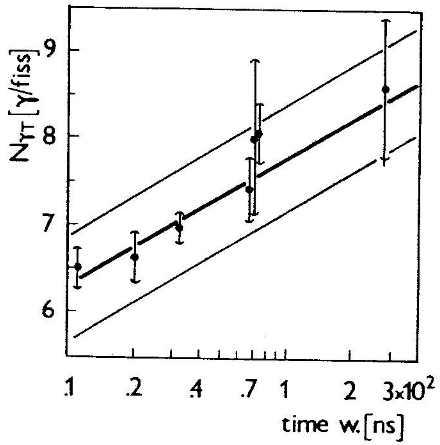


Fig. 7. Dependence of the multiplicity $\bar{N}_\gamma$ on the time window drawn for various experiments.

Table 1

Energy emitted per fission and the number of γ-rays per fission from various experiments

ΔE_γ [MeV]	τ [ns]	$\bar{N}_\gamma$ γ/fission	$\bar{E}_\gamma$ MeV/fission	$\bar{\varepsilon}$ MeV/γ	reference
0.09–10	10	6.51 ± 0.30	6.43 ± 0.30	0.99	[4]
0.14–10	20	6.69 ± 0.30	6.51 ± 0.30	0.97	[5]
0.14–10	69	7.45 ± 0.32	7.18 ± 0.26	0.96	[6]
0.01–10.5	69	8.13 ± 0.35	7.25 ± 0.26	0.89	[6]
0.03–10.4	70	8.10 ± 0.80	7.00 ± 0.70	0.90	[4]
0.10–2.5	220	7.90 ± 0.10	9.50 ± 0.20	1.20	[7]
0.30–10.4	275	8.60 ± 0.80	7.40 ± 0.70	0.86	[4]
recommended		6.89	6.71	0.97	[3]

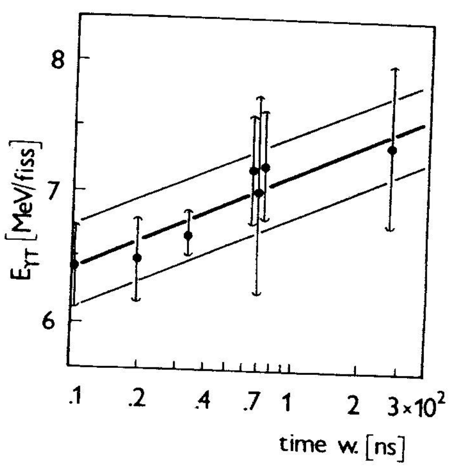


Fig. 8. Dependence of the total energy $\bar{E}_\gamma$ on the time window drawn for various experiments.

Table 2

Integral data on gamma-quanta emission from the three independent sets of data. In the lower part of the Table there are presented our data with the high energy part taken from [5].

$\Delta E_\gamma = 0.1-1.6$ MeV; $\Delta E_n = 0.7-36$ eV			
exp. run	$\bar{N}_\gamma$ γ/fission	$\bar{E}_\gamma$ MeV/fission	$\bar{\varepsilon}$ MeV/γ
1.	5.960 ± 0.057	4.587 ± 0.054	0.770 ± 0.016
2.	6.100 ± 0.060	4.620 ± 0.054	0.757 ± 0.011
3.	6.176 ± 0.061	4.726 ± 0.055	0.765 ± 0.012
mean value	6.039 ± 0.051	4.622 ± 0.048	0.765 ± 0.011
$\Delta E_\gamma = 0.1-10$ MeV; $\Delta E_n = 0.7-36$ eV			
$\bar{N}_\gamma = 6.890 \pm 0.100$; $\bar{E}_\gamma = 6.704 \pm 0.100$; $\bar{\varepsilon} = 0.973 \pm 0.015$			

Table 3

Multiplicity, total energy and the mean energy of the prompt gamma-emission for the two groups ($J^\pi = 3^-$ and 4^-) of fission resonances from the three sets of experimental data. Values for the $J^\pi = 3^-$ and $J^\pi = 4^-$ groups are presented as relative values without normalization over fission in separate groups of resonances.

$\Delta E_\gamma = 0.1-1.6$ MeV; $\Delta E_n = 0.7-36$ eV				
exp. run	J^π	$\bar{N}_\gamma(J^\pi)$ γ/fission	$\bar{E}_\gamma(J^\pi)$ MeV/fission	$\bar{\varepsilon}(J^\pi)$ MeV/γ
1.	3^-	1.821 ± 0.016	1.405 ± 0.018	0.771 ± 0.012
	4^-	4.239 ± 0.036	3.165 ± 0.041	0.747 ± 0.012
2.	3^-	1.800 ± 0.016	1.418 ± 0.019	0.788 ± 0.012
	4^-	4.174 ± 0.075	3.200 ± 0.041	0.767 ± 0.017
3.	3^-	1.903 ± 0.017	1.460 ± 0.019	0.767 ± 0.012
	4^-	4.281 ± 0.038	3.270 ± 0.025	0.764 ± 0.009
mean value	3^-	1.852 ± 0.009	1.421 ± 0.009	0.775 ± 0.007
	4^-	4.203 ± 0.025	3.233 ± 0.019	0.759 ± 0.007

$0.1 < E_\gamma < 10$ MeV have been calculated. Their values given in Table 2 correspond to those recommended in Ref. [3].

Figs. 7 and 8 presenting in diagram form the obtained results and integral data from Table 1, show that the dependence of multiplicity and total energy on the time window duration used in the experiment is similar. The analysis of the dependence has allowed to find the multiplicity and total energy of γ-quanta emitted after the decay of the isomeric states of nuclei fragments in the time interval from 10 ns to 300 ns.

$$\overline{N}_\gamma = 2.2 \pm 0.2$$

$$\overline{E}_\gamma = 1.1 \pm 0.1.$$

Table 3 shows data on two types of rexonance for each run, separately, and their mean weighted values. The gamma-quantum energy of resonance wsith spin $J = 3^-$ was a little higher than that of resonances with spin $J = 4^-$ in all three runs. The mean weighted values differed by $\Delta\bar{\varepsilon}_\gamma(J) = (16 \pm 10)$ keV. On the basis of the result obtained one may assume that $\Delta\bar{E}_\gamma$ cannot exceed 100 ± 60 keV. Under assumption that the total energy E does not change and equals

$$E = \overline{E}_K + \overline{E}_\gamma + \overline{E}_{neut}$$

where E_K is the mean kinetic energy of fission fragments one cannot expect either a change in the kinetic energy of fission fragments to be more than 100 keV.

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REFERENCES

[1] Gorbachev, B. M., Zamiatnin, Yu. S., Lbov, A. A.: *Vzaimodejsívie izluchenij s jadrami tjazhelykh elementov i delenije jader.* Atomizdat, Moscow 1976.
[2] Francis, V. E., Gramble, R. L.: Report ORNL — 1879 (1955).
[3] Hoffman, D. C., Hoffman, M. M.: Annual Rev. of Nucl. Sci. *24*(1974), 151.
[4] Pleasonton, F., Ferguson, R. L., Schmitt, H. W.: Phys. Rev. C *6*(1972), 1023.
[5] Verbinski, V. V., Weber, H., Sund, R. E.: Phys. Rev. C *7*(1973), 1173.
[6] Peelle, R. W., Maienschein, F. C.: Phys. Rev. C *3*(1971), 373.
[7] Rau, V. F. E. W.: Ann. Phys. *10*(1963), 252.
[8] Bogdzel, A. A., Duka-Zolyomi, A., Kliman, S., Presperin, V., Avdeev, S. P., Kuznetsov, V. D., Dlouhý, Z.: Nucl. Instr. and Meth. *200*(1982), 407.
[9] *Nuclear Data Tables,* A7 No. 6 (1970), 565.
[10] Antonov, S. A., Bogdzel, A. A., Gundorin, N. A., Duka-Zolyomi, A., Kliman, J., Kristek, D., Ostrovnoj, A. I., Ostrovnaja, T. M., Popov, A. B., Presperin, V., Tishin, V. G., Shirikova, N. Yu.: JINR prepr. 11-85-701, Dubna 1985.
[11] Meier-Leibnitz H., Schmit, H. W., Ambruster, P.: *Proc. of the Symp. on Phys. and Chem. of Physics,* Salzburg 1965. IAEA Vienna 1965, vol. II, 143.

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