diverging by its proper magnetic field. Let the state of the plasma in it be stationary, so that the condition $\rho = \gamma p / c_T^2$, where C_T is the sound velocity in the plasma, be fulfilled. Assuming $p \sim H^2 / 4\pi$ and taking into the account that for the absence of resistance we have $I \sim V\sqrt{m/L}$, we obtain, after a simple calculation, the following expression:

$$V = kc_T \sqrt{\Lambda},$$

Λ has been determined above [see Eq.(15)] and $k \sim 1$. The ejection velocity, therefore, is found to be of the order of the maximum velocity of sound in the jet during the acceleration stage. The formula is independent of the nature of the coupling with the current source (contact or induction) but since the flux Φ_0 in the ring is known and $V \sim \Phi_0 / \sqrt{Lm}$, the relation between m and c_T follows.

The author wishes to express his gratitude to Prof. A. A. Sokolov for the interest shown in the present work, and to G. M. Strakhovskii for the discussion of problems connected with it.

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Investigation of U^{235} Fission γ Rays in the Energy Region up to 250 kev

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A scintillation spectrometer with a NaI(Tl) crystal and a proportional counter connected in coincidence with a fission chamber was used to measure the U^{235} fission γ spectrum in the energy range up to 250 kev. Gamma rays with energies of 30 ± 1.5 and 210 ± 10 kev were detected, as well as a broad distribution in the 110 to 150 kev region, which apparently consists of several lines. It has been found that in the investigated energy region most of the fission γ rays are emitted by fission fragments with life times between 0.5×10^{-9} and 2.5×10^{-9} sec. The measurements made with the proportional counter showed that the line at 30 kev is not monochromatic and apparently corresponds to x radiation (K line) from heavy fission fragments with different Z.

1. INTRODUCTION

FISSION γ rays have thus far been the subject of very few investigations, and there have been only brief reports on the results of these. Rose and Wilson[1] have measured the angular distribution of fission γ rays relative to the direction in which the fission fragments emerge. Voitovetskii, Levin, and Marchenko[2] have discovered several monochromatic γ rays in the low energy region. Other papers[3-5] deal with measurements of either the average energy of fission γ rays or their spectrum.

The measurement of a fission γ ray spectrum by itself furnishes no basis for any conclusions as to the mechanism of the radiation. Theoretically one cannot rule out the possibility that some or all fission γ rays are connected with the proc-

esses that occur at the moment of fission. On the other hand they may be emitted by fission fragments in excited states.

In this investigation the geometric distribution method, consisting of making separate measurements of the γ rays emitted by fission fragments was used. This method has made it possible to establish that the principal part of fission γ rays in the energy region up to 250 kev is emitted by fission fragments.

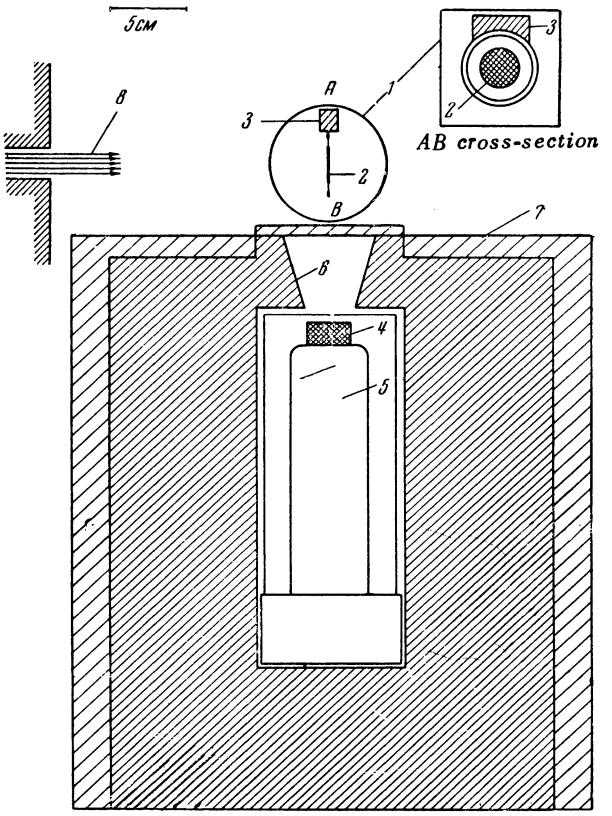

FIG. 1. Experimental Setup. *1* – fission chamber, *2* – layer of U^{235}, *3* – lead screen, *4* – NaI(Tl) crystal, *5* – photomultiplier, *6* – lead shield, *7* – boron, *8* – neutron beam.

2. EXPERIMENTAL APPARATUS

Figure 1 shows the experimental arrangement. The ionization chamber with a layer of U^{235} was located in a beam of thermal neutrons from the RFT reactor. The beam was 2.3 cm in diameter. The layer of U^{235} used had a density of about 1 mg/cm^2 and was spread on a nylon film*. This layer was covered by a thin conductive layer of silver which served as the collecting electrode for the chamber. The total pulse from both fragments was obtained from this electrode; furthermore, the high voltage was supplied to it. The chamber housing was the other electrode. The chamber was filled with a mixture of argon and methane (30%) to a pressure of 10 cm. At this pressure practically all the fission fragments emitted by the layer reached the walls of the chamber housing.

A scintillation spectrometer with a crystal of NaI(Tl) was used to measure the γ ray spectrum.

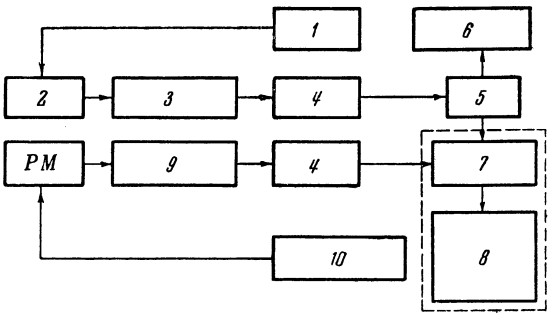

FIG. 2. Block diagram of the electronic apparatus. *1* – supply battery, *2* – fission chamber, *3* – pre-amplifier, *4* – linear amplifier, *5* – delay line, *6* – counter, to 10,000, *7* – coincidence circuit, *8* – channel amplitude analyzer, *9* – cathode follower, *10* – high-voltage rectifier.

The crystal was cylindrical in form and had a diameter of 3.0 cm and a height of 1.4 cm. A type "C" spectrometric photomultiplier was used. The crystal and photomultiplier were surrounded by a lead shield with a conical opening through which γ rays from the fission chamber irradiated the crystal. The distance between the center of the layer and the surface of the crystal was 11.5 cm. The scintillation spectrometer was calibrated by γ rays with energies of 661 kev (Cs^{137}), 102 and 41.7 kev (Gd^{153}). The resolution for photopeaks from these radiations was respectively 8, 20 and 30%.

Figure 2 is a block diagram of the electronic apparatus. Pulses from the photomultiplier were amplified by the linear amplifier and entered the coincidence circuit together with the amplified pulses from the fission chamber. Those pulses

* This layer was graciously presented by V. I. Mostov, to whom the author expresses his gratitude.

from the photomultiplier which coincide with the fission chamber pulses entered the 30-channel amplitude analyzer. In the fission chamber channel there was a variable delay, which made it possible to obtain the time resolution of the equipment. The resolving time used for the coincidence circuit was $2t = 0.4$ microseconds. Measurements of the resolution curve at different times showed that for $2t = 0.4$ microseconds, the counting efficiency for true coincidences was close to unity. The rate of counting fission fragments was $\sim 2 \times 10^4$ counts/sec.

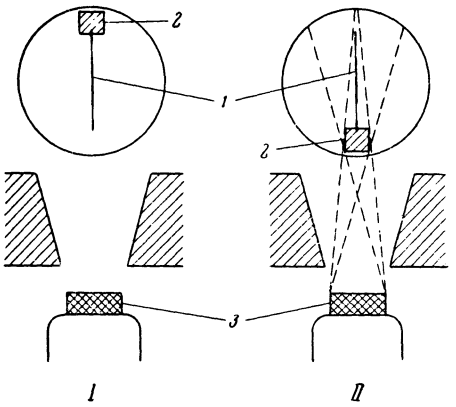

FIG. 3. Measurement geometry. *I* – measurement of the total intensity of the fission γ rays; *II* – measurement of γ rays emitted by fission fragments. *1* – layer of U^{235}, *2* – lead screen, *3* – NaI(Tl) crystal.

3. THE METHOD OF MEASUREMENT

The fission γ ray spectra were measured with the fission chamber in two different positions in relation to the crystal (positions I and II), as shown in Fig. 3. As is apparent from this figure, in position I the crystal records γ rays emitted by the layer of U^{235}, i.e., formed during the fission process, and γ rays emitted by fission fragments. In position II the layer and the area of space adjacent to it are closed off from the crystal by the lead screen, 1.5 cm thick. Such a screen absorbs practically all γ rays up to 250 kev. Therefore in position II the crystal records only γ rays emitted by fission fragments. In order to enter the chamber region "seen" by the crystal, the fission fragments must cover an average distance of $l = 1.5$ cm.

This method permits one to isolate the gamma radiation from fission fragments emitted after $t = l/v_{frag} \approx 1.3 \times 10^{-9}$ sec. after the act of fission. It is also possible to arrive at a quantitative evaluation of the life time of the excited states of the fission fragments which emit these γ rays.

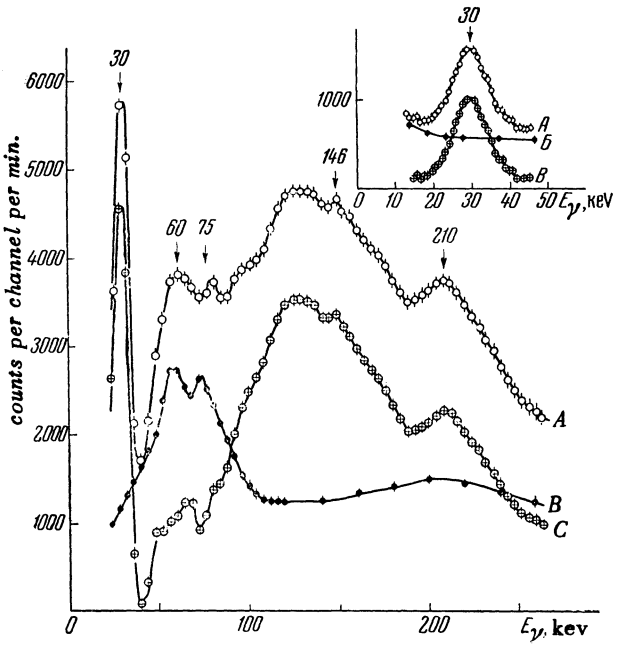

FIG. 4. Fission γ ray spectra obtained in position *I*.

4. RESULTS OF THE MEASUREMENTS

The results of the measurements made in position I are shown in Fig. 4, and the results of those made in position II are shown in Fig. 5. The A curves in these graphs represent the spectra of true coincidences, which were obtained by subtracting the spectra of random coincidences. The number of random coincidences for position I amounted to 2-4% and for position II, 6-10% of the total number of coincidences.

The B curves represent the spectra of true coincidences obtained when the chamber was separated from the crystal by a lead absorber whose thickness was sufficient for total absorption of the measured γ rays (0.16 mm for the 30 kev region and 2.5 mm for the rest of the spectrum). Thus, the B curves give the background of true coincidences created in the measured portion of the spectrum by hard fission γ rays and neutrons. The difference between the A and B curves (the C curve) gives the spectrum of pulses solely from fission γ rays in the measured energy region.

The fission chamber served as the monitor for all the measurements. The measurement time in

position I ($\sim$ 30 min) corresponded to $N_f = 3 \times 10^7$, total number of recorded fission fragments, and in position II ($\sim$ 60 min) to $N_f = 6 \times 10^7$.

As can be seen from Figs. 4 and 5, the radiation intensity at energy peaks of 60 and 75 kev is but slightly reduced by the lead absorber, which would have completely absorbed γ rays with these energies. Therefore, these peaks must be attributed mainly to secondary effects. Actually, the peak at 60 kev is produced by inelastic scattering of fission neutrons by the iodine nuclei in the crystal of NaI(Tl). The peak at 75 kev represents X radiation (K line) from the lead and is formed by fission γ rays and neutrons in the shield surrounding the crystal.

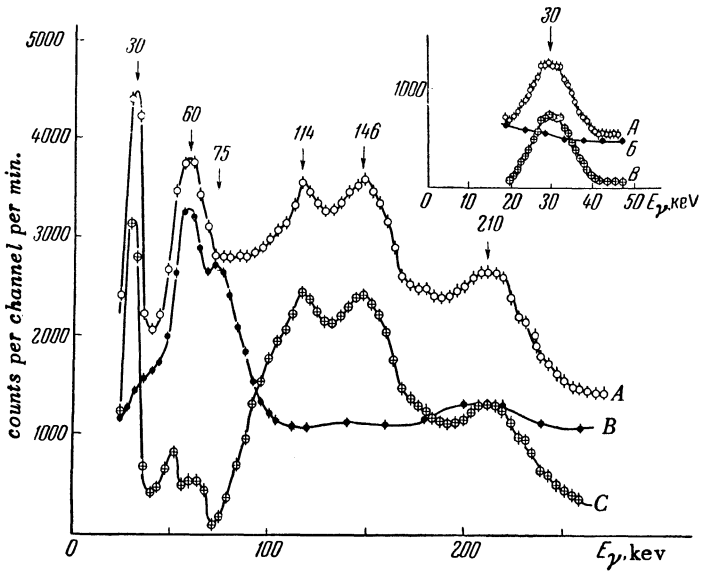

FIG. 5. Fission γ ray spectra obtained in position *II*.

The fission γ ray spectra measured in positions I and II (the C curves in Fig. 4 and 5) are plotted together in Fig. 6 for comparison, and they coincide at an energy of 114 kev. As can be seen

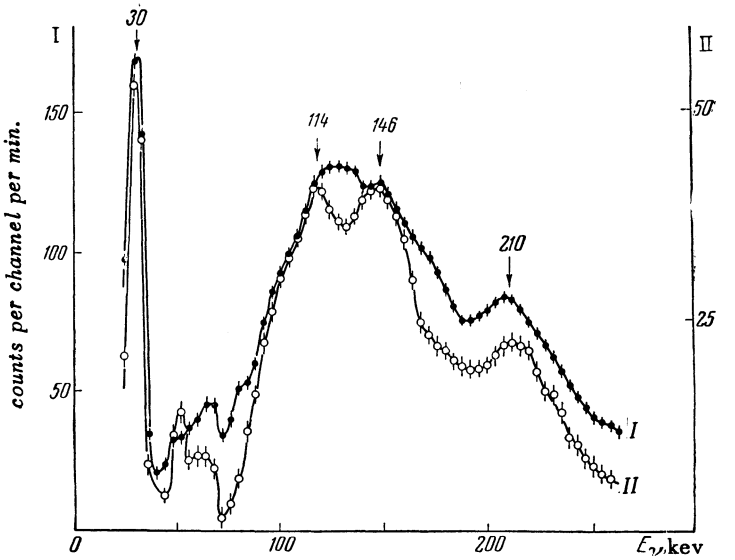

FIG. 6. Comparison of fission γ ray spectra obtained in positions *I* and *II*.

from Fig. 6, the spectra for I and II are almost identical in form, while the intensity of the spectrum for II is approximately 3 times less than that for I. In both spectra there are γ ray lines at 30 and 210 kev. Moreover, in the energy region 110-150 kev, there is an intense broad distribution whose form differs somewhat in the spectra for I and II. In the spectrum for II this distribution consists of two distinctly separate maxima at energies of 114 and 146 kev. Apparently the

γ ray energy	Number of γ quanta per fission, ν_I, measured in position *I*.	The ratio of the γ intensity measured in positions *I* and *II* ν_I/ν_{II}.
30 ± 1.5 kev	0.42±0.12	3.1±0.15
Group of lines in 110-150 kev region.	0.94±0.2	3.2±0.2
Single line or a group of lines in 210 kev region.	0.5±0.10	3.8±0.2

spectrum for I contains the greater number of unresolved lines. It should be remarked that this portion of the spectrum was investigated with special care, and the difference in the forms of the spectra for I and II was securely established for this region. The spectrum for I was also measured when screen 3 (see Fig. 1) was absent, and it was found that the screen does not distort the form of the spectrum.

Our results with regard to the spectrum for I are in agreement with the results described in Ref. 7. The first data on the presence of several lines in the fission γ ray spectrum are reported in Ref. 2.

The table presents the energies of the fission γ rays and their absolute intensities.

When ν_I was determined, allowance was made for γ ray absorption by all substances located between the chamber and crystal. The solid angle was determined from the control measurements on γ rays from a Am^{241} source (60 kev), which is an alpha emittor. These measurements were made in the same geometry and with the same apparatus as the measurements of the fission γ rays. The values for ν_I/ν_{II} were determined from the ratios of the areas of the spectra for I and II. Therefore, the error in determining ν_I/ν_{II} was less than the error in ν_I.

5. MEASUREMENTS WITH THE PROPORTIONAL COUNTER

The fission γ ray spectrum for the energy region up to 100 kev had already been measured by us[6] with a proportional counter filled with a mixture of krypton or xenon and methane (10%) under pressure of 800 mm of mercury. The measurements with the proportional counter were also made in two positions, one of which measured only γ rays from fission fragments and the other of which measured all fission γ rays. These measurements are in good agreement with the measurements made with the scintillation spectrometer, both as to the forms of the spectrum and its identity when measured in the two positions.

It is interesting that in the measurements made with the proportional counter the half-width of the 30 kev line ($\approx$ 30%) proved to be considerably greater than the half-width that should have characterized a monochromatic line of this energy (for example, the half-width for the 24 kev x-ray line from In^{114m} measured 15%). This may be explained by the fact that the 30 kev line represents x-radiation due to internal conversion of γ radiation from fission fragments with different Z. It is also noteworthy that a 30 kev line is likewise present in the spectra of U^{233} and Pu^{239} fission γ rays.

6. DISCUSSION OF THE RESULTS. AN EVALUATION OF THE LIFE TIME FOR FISSION γ RAY EMISSION

The results obtained can be summarized as follows: 1) the spectra measured in positions I and II have approximately the same form; 2) for the measured energy region ν_I/ν_{II} lies within the range 3.1-3.8. On the basis of these results it is possible to make alternate assumptions regarding

the origin of fission γ rays.

1. The γ rays measured in positions I and II are attributable to a single process – γ ray emission by fission fragments in excited states.

2. The γ rays measured in positions I and II were emitted as the result of different processes with different life times, one process consisting of γ ray emission during fission and the other of γ ray emission by fission fragments. In this case almost all the coincidence in the forms of the spectra in the two circumstances would be accidental.

The second assumption would be unnatural for the main portion of the measured γ ray spectrum. Using the first assumption, one can evaluate the lifetime of the excited states of the fission fragments that emit γ rays. Assuming that the γ rays measured in positions I and II were emitted with identical lifetime τ, we can easily derive (by elementary reasoning) the equation: $\tau = t/\ln(\nu_I/\nu_{II})$, where t is the average transit time of fragments through the region "unseen" in position II and is equal to $\sim 1.3 \times 10^{-9}$ sec, and ν_I/ν_{II} is the ratio of the intensity of γ rays with the given τ, emitted during the time from 0 to ∞, to the intensity of those γ rays emitted during the time from t to ∞. However, it must be noted that ν_{II} must be less than ν_I, not merely on account of disintegration but also because of the fact that some of the fission particles do not emerge at all beyond the limit of the "unseen" region in position II. Computation has shown that the contribution of these fission fragments is 20-25%, while the experimental value for ν_I/ν_{II} lies within the range 3.1-3.8. Therefore, the indicated correction can be neglected and then from $\nu_I/\nu_{II} = 3.1 - 3.8$ we obtain $\tau \approx (1.0\text{-}1.2) \times 10^{-9}$ sec. The true life time for the main portion of fission γ rays in the measured energy region can vary by no more than a factor two from this value, i.e., τ lies within the range $(0.5\text{-}2.5) \times 10^{-9}$ sec. The major error in the determination of τ is due to the indefiniteness in the value of t, which is caused both by inaccuracy in determining the distance crossed by the fragments in the "unseen" region and by the difference in the velocity of heavy and light fragments, $(0.9\text{-}1.4) \times 10^9$ cm/sec. To obtain more accurate results it would be necessary to collimate the fission fragments and sort them energy wise.

We should point out that some difference in the forms of the spectra for I and II, which appears especially clear near 120 kev, indicates the presence of γ rays either emitted by fission fragments, though with a life time far less than 10^{-9} sec, or directly released in the process of fission. The last possibility is especially interesting but requires more detailed investigation.

The results obtained can be explained in the following manner. The spectrum of fission γ rays in the energy region of 100-250 kev consists of many γ ray lines from emissions by various fission fragments in excited states. These states arise after the fission fragments emit neutrons and harder γ rays. The value of the life time of these states ($\sim 10^{-9}$ sec) appears to indicate that transitions from them are of a dipole nature. A quadrupole nuclear moment of the order of 2.5×10^{-24} cm^2 corresponds to a quadrupole transition with a life time of 10^{-9} sec. These quadrupole moments are possessed by greatly deformed nuclei in the rare earth region. However, fission fragments with $A > 145$, i.e., corresponding to these nuclei, have small yields, too small to explain the observed γ ray intensity.

The multichannel analyzer used in this investigation was operated by Engineer G. P. Mel'nikov to whom the authors are deeply grateful.

The authors express their obligation to Academician I. V. Kurchatov for his interest in the investigation and for his help in conducting it and also to L. V. Groshev and V. M. Strutinskii for reviewing the results.

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