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A Measurement of the Fission Cross Sections of ^{239}Pu and ^{233}U Relative to ^{235}U

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A Measurement of the Fission Cross Sections of ^{239}Pu and ^{233}U Relative to ^{235}U

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The fission cross-section ratios $^{239}Pu:^{235}U$, $^{233}U:^{235}U$ have been measured as a function of neutron energy between 5 keV and 1 MeV with an accuracy between 1.5 and 3%. Fission events were detected in 4 π-geometry by means of argon-filled gas scintillation chambers. The neutron energy has been determined by the time-of-flight technique.

The results were compared with the evaluations of Davey. For the ratio $^{239}Pu:^{235}U$ there is fairly good agreement between the measured values and the evaluation of Davey, except in the energy region between 200 and 800 keV. There, our values are ~2 to 4% lower than those of Davey. The $^{233}U:^{235}U$ ratio agrees with Davey's curve for neutron energies <60 keV. Above this energy, our results are ~5% higher than the evaluated curve of Davey.

I. INTRODUCTION

The fission cross sections of ^{239}Pu, ^{235}U, and ^{233}U in the intermediate neutron-energy region are extremely important for fast-reactor calculations. The existing measurements, evaluated by Davey[1] and Schmidt,[2] only agree within ~10%, although the errors claimed for the individual measurements are smaller than this difference. For sufficiently accurate reactor calculations this uncertainty is too large. Therefore, a new effort was made to get new data by a different method to improve the accuracy of the fission cross sections mentioned above.

We measured the fission cross sections of ^{239}Pu and ^{233}U relative to that of ^{235}U, because the fission cross sections of ^{235}U are best known. By this method the difficulties of neutron flux determination and asymmetries in detector geometry could be avoided.

Our experiment was based on the gas-scintillation technique for detection of fission events. Over the whole energy range from 5 keV to 1 MeV, absolute measurements of the cross-section ratios were obtained without any renormalization in contrast to earlier work (see e.g., Refs. 3 and 4). The accuracy is better than 3% except below 10 keV.

II. PRINCIPLE OF MEASUREMENT

The technique adopted was to detect both fission fragments of neutron-induced fission events in two identical fission detectors, one of them containing ^{239}Pu or ^{233}U and the other containing ^{235}U as reference nuclide. Considerable effort was made to detect all fission events and to avoid any appreciable corrections. The two detectors were exposed in symmetrical positions to the neutron flux pro-

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[1]W. G. DAVEY, *Nucl. Sci. Eng.*, **32**, 35 (1968); also, W. G. DAVEY, *Nucl. Sci. Eng.*, **26**, 149 (1966).

[2]J. J. SCHMIDT, "Neutron Cross Sections for Fast Reactor Materials," KFK-120, Part I, Kernforschungszentrum Karlsruhe (1966).

[3]W. D. ALLEN and A. T. G. FERGUSON, *Proc. Phys. Soc.*, **70A**, 573 (1957).

[4]G. N. SMIRENKIN, V. G. NESTEROV, and I. I. BONDARENKO, *Atomnaya Energiya*, **13**, 366 (1962).

duced via the $^{7}Li(p,n)^{7}Be$ reaction with the Karlsruhe 3-MV pulsed Van de Graaff accelerator. Neutron-energy determination and background discrimination were accomplished by time-of-flight techniques.

III. EXPERIMENTAL DETAILS

Samples

The preparation and mass determination of the fissile samples were performed at the CBNM (Euratom) laboratory, Geel, Belgium. The samples consisted of a thin layer of uranium or plutonium acetate of 5-cm diameter. They were deposited by electro-spraying on 90 $\mu g/cm^2$ Vyns[a] foils metallized with 30 $\mu g/cm^2$ Al as described by Verdingh and Lauer.[5] Sample masses and isotopic composition are given in Table I. The quantitative measurements were based mainly on the samples marked by asterisks. The others were used to obtain data for corrections.

The sample masses were determined by several different methods. The 5.21 and 9.16 mg ^{235}U samples and the 2.10, 2.88, and 6.14 mg ^{233}U samples were dissolved separately. Each solution was then mixed with a solution of known mass and isotopic composition. Next, the isotopic composition of the mixture was measured with a mass spectrometer. From the measured isotopic compositions and the known mass one can calculate the unknown masses of the dissolved uranium samples with an accuracy of ± 0.4%. This method of isotope dilution is described by de Bièvre.[6] The other uranium sample masses were then determined by a comparison of their specific α-particle count rates with those of the samples with known masses. The uncertainties of these masses is ~ ± 0.8% for ^{235}U and ± 1.0% for ^{233}U.

The masses of the ^{239}Pu samples were calculated from the isotopic composition, the α-ray counting rate and the α-decay half-lives of the isotopes present. The half-lives were taken from several authors.[7-11] The uncertainty of the α-ray activities was ± 0.5% and the uncertainties of the half-lives were assumed as ± 0.2% for ^{239}Pu and ± 0.8% for ^{240}Pu. (Other isotopes do not give any noticeable contribution to the α-ray activity.) The resulting uncertainty of the plutonium masses is ± 1.0%.

Fission Detectors

The fission events were detected by gas-scintillation techniques with flowing argon as the scintillator. The scintillation chambers were made from bronze. Silver and aluminum were evaporated on the walls as reflector materials. The scintillation chamber (Fig. 1) is divided by the opaque, metallized sample in two optically

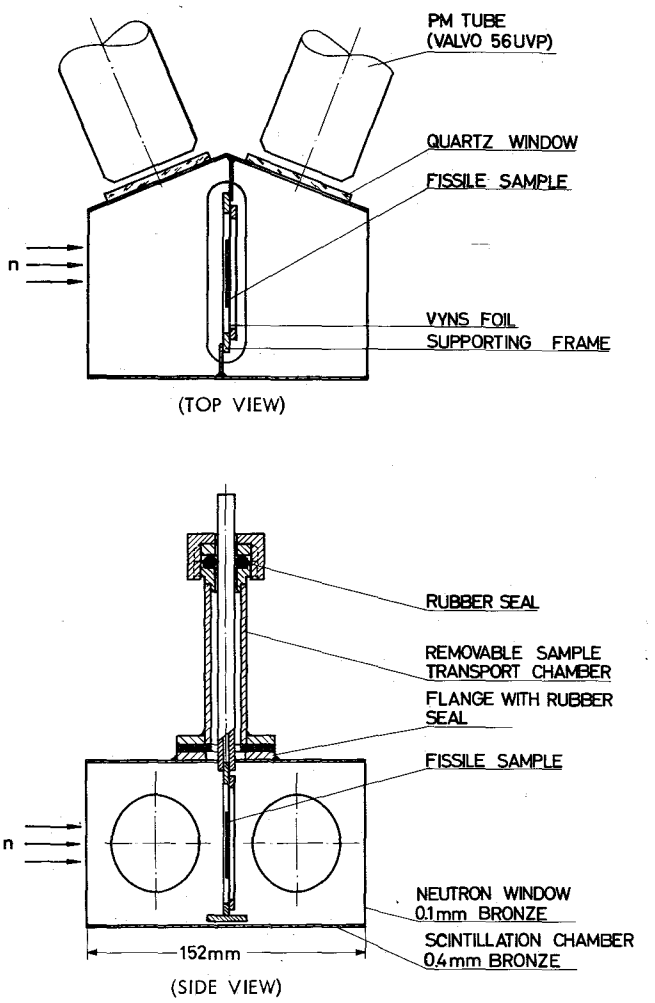

Fig. 1. Scintillation chamber. The arrangement is slightly simplified in top view.

[a]Vyns consists of 85% PVC and 15% Polyvinyl acetate. It was delivered by Union Carbide Europe, Brussels.

[5]V. VERDINGH and K. F. LAUER, *Nucl. Instr. Meth.*, **21**, 161 (1963).

[6]P. J. De BIÈVRE and G. H. DEBUS, *Nucl. Instr. Meth.*, **32**, 224 (1965).

[7]F. L. OETTING, in *Thermodynamics of Nuclear Materials*, 1967, p. 55, IAEA, Vienna (1968).

[8]H. R. IHLE, A. P. MURRENHOFF, and M. KARAYANNIS, in *Standardization of Radionnuclides*, p. 69, IAEA, Vienna (1967).

[9]M. G. INGHRAM, D. C. HESS, P. R. FIELDS, and G. L. PYLE, *Phys. Rev.*, **83**, 1250 (1951).

[10]J. P. BUTLER et al., *Phys. Rev.*, **103**, 634 (1956).

[11]Ya. P. DOKUCHAEV, *Atomnaya Energiya*, **6**, 74 (1959).

decoupled halves. Each half is viewed by a Valvo 56-UVP photomultiplier tube. The samples could be withdrawn from the scintillation chambers into removable transport chambers which could be interchanged between the scintillation chambers. In this manner it was possible to verify that there was no noticeable asymmetry in the neutron flux and in the electronics. This was confirmed by measuring the fission cross-section ratio $\sigma_f{}^{235}\text{U}:\sigma_f{}^{235}\text{U}$. The result agreed with the expected value of 1.0 within the statistical error. The response of the detectors to (n,γ)-processes could be tested when the fissile foils were withdrawn from the chambers.

Electronics

The electronics are shown schematically in Fig. 2. Each of the photomultipliers sees the scintillation caused by one fission fragment. For the registration of a fission event, each multiplier of one chamber must give a signal corresponding to a particle energy of $> \sim 15$ MeV coincident within 30 nsec. Time-of-flight spectra and pulse-height spectra were recorded simultaneously for both detectors. The pulse-height spectra were used to check the trigger levels and the high voltage supply for the photomultipliers. Each pulse-height spectrum was stored in 512 channels of a multichannel analyzer and each time-of-flight spectrum in 256 channels of a separate analyzer. The trigger, which was used for timing the fission events, was operated with a low threshold to minimize time jitter. Thus, the high ^{239}Pu and ^{233}U α-activity caused appreciable dead-time corrections. In order to minimize these corrections it was necessary to make a compromise between time resolution and dead-time correction. The consequence was a deterioration of time resolution from 3 to 4 nsec.

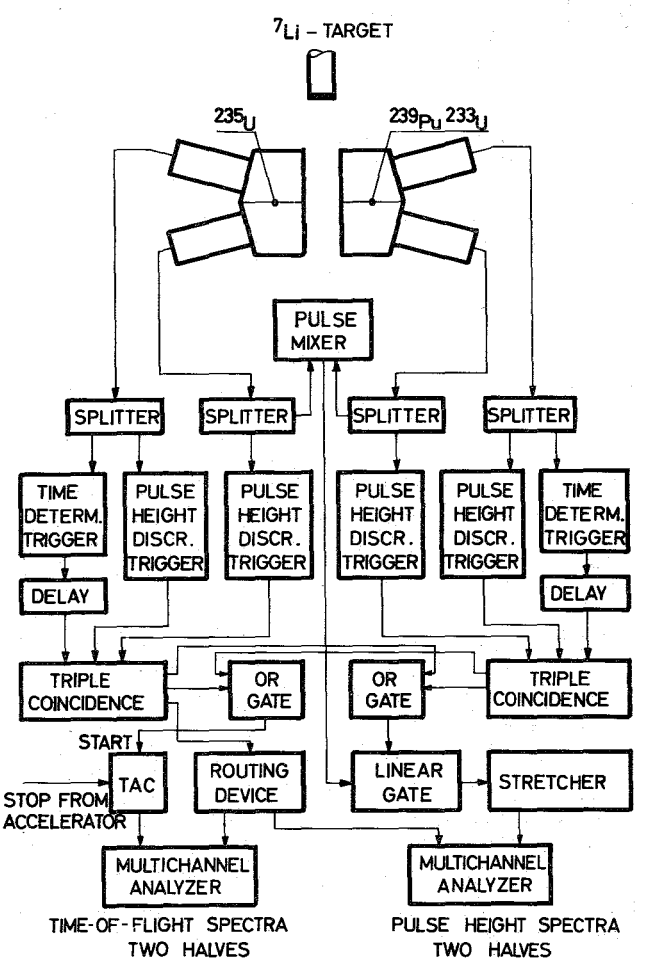

Fig. 2. Electronic equipment.

Pulse-Height Spectra

Pulse-height spectra from ^{235}U and ^{239}Pu recorded simultaneously with time-of-flight spectra are plotted in Fig. 3. For ^{235}U as well as for ^{239}Pu, it is possible to distinguish very clearly between real fission events and background. The dashed-dotted lines denote the results of the same measurement but with thermalized neutrons from a ^{241}Am-Be source. By means of these spectra it was possible to adjust the electronic thresholds without trouble from the background. In the case of neutrons from the $^{7}\text{Li}(p,n)^{7}\text{Be}$ reaction, the background is due to the γ flash of the accelerator.

The deviation of the pulse-height spectra from the real energy distribution of the fission fragments is due to geometric effects which do not influence the results in any way.

Time-of-Flight Techniques

The measurements were made with a flight path of 31.5 cm. The time resolution was 12 nsec/m. In the energy range up to 200 keV this was sufficient for the energy determination. In this energy range the measurements were performed with thick ^{7}Li targets which gave continuous neutron-energy spectra. At energies >150 keV, thin targets were used which gave sharply peaked neutron spectra with an energy spread of ~ 20 to 35 keV. The measurements were performed with these essentially monoenergetic neutrons point-by-point up to 1 MeV. Figure 4 shows the spectra of two runs, one with a thick and the other, at a higher energy, with a thin ^{7}Li target. Energies from measurements with thin ^{7}Li targets were determined with another fission detector and 1.50-m flight path, and a resolution of <2 nsec/m. The zero point of the time-of-flight spectra was calculated from the position of the γ peak produced

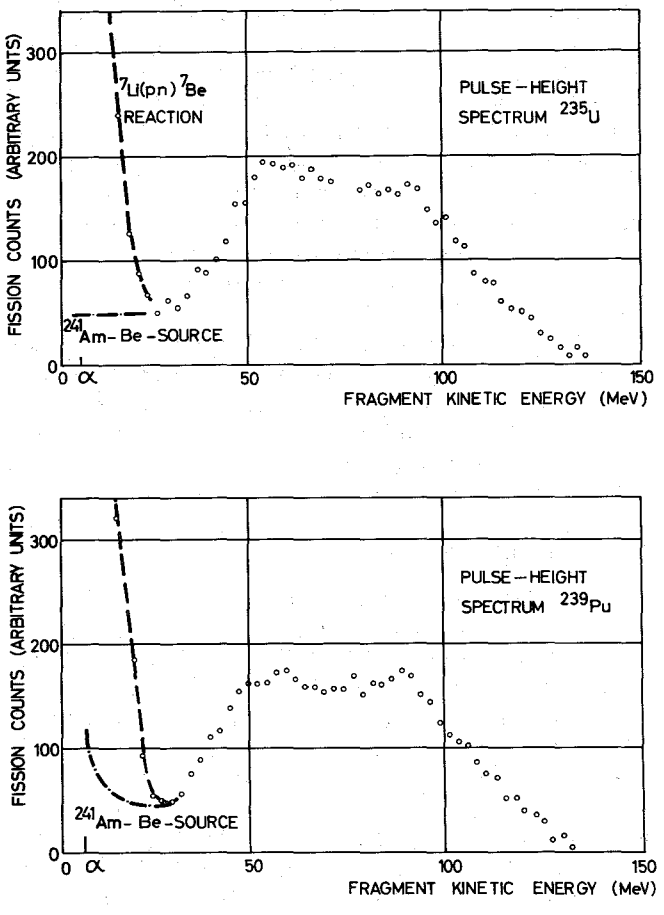

Fig. 3. Pulse-height distributions for ^{239}Pu and ^{235}U during the pulsed measurement (dotted line) and for thermalized neutrons from an ^{241}Am-Be source (dashed-dotted line).

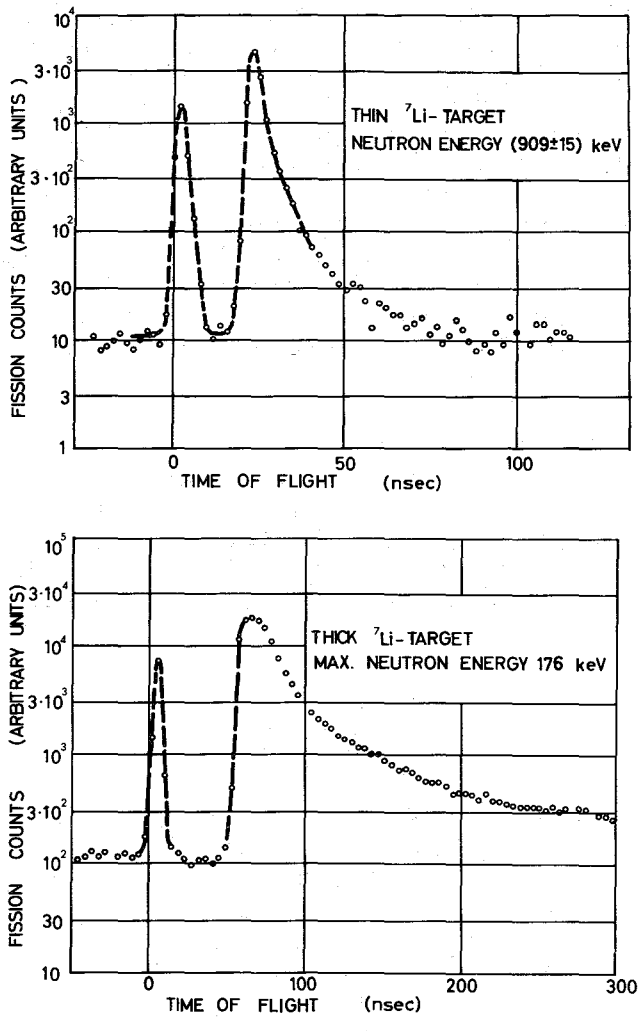

Fig. 4. Time-of-flight spectra from ^{235}U at various energies.

by the γ flash of the accelerator. The duration of the proton pulse generated by the accelerator was 1 nsec and the repetition frequency was 10^6 pulses/sec. A second neutron group corresponding to population of ^{7}Be at 470 keV could be distinguished from the main group in the time-of-flight spectra and did not distort the results.

IV. CORRECTIONS AND UNCERTAINTIES

Background

A time-independent background is produced by spontaneous-fission events, by accidental coincidences between α-particles which by geometric effects or pileup cause pulse heights greater than the thresholds, and by fission events due to back-scattered neutrons from the more distant surroundings. For the measurements with a thin ^{7}Li target, this time-independent background was $<0.5\%$. Even in the case of $>10^6$ α-disintegrations/sec, the background could easily be corrected for since there were many channels containing only background counts in the time-of-flight spectra. The corrections for the measurements with thick ^{7}Li targets increase with decreasing energy because of the longer data acquisition time and a smaller signal-to-background ratio. The uncertainty was calculated in every case and is included in the statistical error. The background correction uncertainty was found to be $<0.7\%$ except at energies <20 keV. Scattering from the nearby surroundings (mainly the detectors) produces a tail in the time-of-flight spectra. Since the amounts of material in the vicinity of the samples was very small this effect was not severe. Moreover, the tail was separated from the main peak by a small gap so that corrections were not necessary. In the continuous time-of-flight spectra, this background was not separated from the ordinary fission events. The

corrections due to this effect are of the order of 1% and cancel to a good approximation when the cross-section ratio is formed. Another type of time-correlated background stems from the response of the detectors to events other than fission, for example from (n,γ)-processes. These background events occur in the detector material at about the same time as fission events. They were measured separately by withdrawing the fissile samples from the detectors. The maximum correction for a time-of-flight spectrum was 5% and was measured separately for each run. The maximum error in the results due to this background correction is always $<0.5\%$.

Finite Foil and Backing Thickness

The greater the angle between the direction of a fragment pair and the incident neutron beam, the greater is the energy loss in the foil and in the backing. The fraction of fragments which leave the foil with energies >15 MeV was calculated by means of an approximation. This energy corresponds to the electronic thresholds which must be set to reduce α and γ background. The calculation of Rossi and Staub[12] for the energy loss of particles emitted from a foil in 2π geometry was modified for the case of emission of fragments from the sandwich uranium-acetate-evaporated aluminum-Vyns foil. The ranges and energy losses of fission fragments are known from various sources (Refs. 13 through 19). This calculation shows that 6.8% of the fragments from the ^{233}U sample and 6.7% from the ^{239}Pu sample could not be detected, while the undetected fraction of the thicker ^{235}U sample was 7.5%. Therefore, the correction for the cross-section ratios are 0.8% for $\sigma_f\,^{239}\text{Pu}:\sigma_f\,^{235}\text{U}$ and 0.7% for $\sigma_f\,^{233}\text{U}:\sigma_f\,^{235}\text{U}$. After this correction for the larger thickness of the ^{235}U sample, the undetected fraction of fission fragments with energies <15 MeV is practically equal in all samples. The reasons for this are the very similar energy spectrum of uranium and plutonium fragments and the fact that the same backing thickness was used in all cases. Strictly speaking, the thickness of the fission-foils differ somewhat, but their effect on energy loss and sample self-absorption is much smaller than that due to the backing.

Apart from mass uncertainties (see below) there are mainly two sources of errors in the undetected fraction of fission events. First, the calculation is approximate and the range-energy relations are not too well known. It is estimated that the calculation of the lost fraction of fission fragments is accurate to $\sim 20\%$. As the parameters, which enter into this calculation, are the same for all backings (thickness and stopping power of Vyns and aluminum) and quite similar for the fissile layers (stopping power of uranium acetate and plutonium acetate), the uncertainty of 20% goes in the same direction for both samples used in a measurement. Therefore, this uncertainty practically cancels, when the cross-section ratio is formed. Only a small change of 0.12% results in the cross-section ratio when the undetected fractions for both samples are increased by 20%. The second error source, namely thickness inhomogeneities, is more important. From low-geometry counting of the α activity of small parts of the samples (selected with a collimating mask) the thickness of the fission-foils is known to be homogeneous to $>1\%$.[5] This, together with inhomogeneities of the Vyns backing ($<10\%$), and with threshold variations ($<4\%$), results in an uncertainty of 11% in the undetected fraction. With respect to the total number of fission events this uncertainty is $\sim 0.8\%$ for every sample. This was verified by using different samples for the determination of the same cross-section ratio.

Electronic Corrections

The electronic dead time was changed within wide ranges during the measurements to detect its influence. The necessary correction in the final measurements was calculated to be 0.4% for ^{239}Pu with an uncertainty $<0.2\%$. Dead-time corrections were not required for ^{233}U and ^{235}U.

To prove the constancy of the electronic thresholds, the measurement of the cross-section ratio at 480 keV was repeated every few days during the experiment. All ratio values were equal within the statistical errors.

Sample Mass and Isotopic Composition

The errors in the sample masses were evaluated by CBNM, Geel. They are listed in Table I.

[12] B. B. ROSSI and H. H. STAUB, *Ionization Chambers and Counters*, p. 227, McGraw-Hill Book Company, Inc., New York (1949).

[13] F. NASYROV and S. V. LINEV, *Atomnaya Energiya*, **20**, 464 (1966).

[14] R. W. LAMPHERE, *Fast Neutron Physics*, p. 456, J. B. MARIAN and J. L. FOWLER, Eds., Interscience Publishers, New York (1960).

[15] G. KAHN and V. FORGUE, *Nucl. Sci. Eng.*, **23**, 8 (1965).

[16] J. B. CUMMING and V. P. CRESPO, *Phys. Rev.*, **161**, 287 (1967).

[17] E. K. HYDE, *The Nuclear Properties of the Heavy Elements III*, p. 195, Prentice-Hall, Englewood Cliffs, New Jersey (1964).

[18] J. NIDAY, *Phys. Rev.*, **121**, 1471 (1961).

[19] H. MÜNZEL, M. HOLLSTEIN, and T. ISHIMORI, in *Physics and Chemistry of Fission*, p. 573, IAEA, Vienna (1965).

TABLE I

Mass and Isotropic Composition of Samples

Mass (mg)				
^{235}U		^{233}U		^{239}Pu
1.39 ± 0.8%		2.10 ± 0.4%		[a]1.78 ± 1.0%
3.71 ± 0.8%		*2.88 ± 0.4%		4.27 ± 1.0%
*5.21 ± 0.4%		3.81 ± 1.0%		6.03 ± 1.0%
8.34 ± 0.8%		*6.14 ± 0.4%		7.49 ± 1.0%
9.16 ± 0.4%				8.69 ± 1.0%
Isotopic Composition (at.%)				
^{232}U		0.002	^{239}Pu	96.32 ± 0.06
^{233}U		87.803 ± 0.09	^{240}Pu	3.53 ± 0.04
^{234}U	0.169	0.846	^{241}Pu	0.15 ± 0.02
^{235}U	99.45 ± 0.05	0.099		
^{236}U	0.027	0.0005		
^{238}U	0.353	11.25		

[a]Samples which served for quantitative measurements.

The isotopic composition of the samples was known with an error $< 0.1\%$. The abundance of the main isotopes of the samples was 99.45% for ^{235}U, 96.32% for ^{239}Pu, and 87.80% for ^{233}U.

A correction to the cross-section ratios due to the isotopic composition of the samples was necessary for ^{239}Pu and ^{233}U. In the case of ^{239}Pu, there was a contribution to the fission rate from 3.53% ^{240}Pu. For ^{233}U, such a contribution comes from 11.25% ^{238}U, 0.85% ^{234}U, and 0.1% ^{235}U. Below 500 keV no correction was necessary; above, the corrections increased to a maximum of (2.0 ± 0.2)% for ^{239}Pu and (3.6 ± 0.5)% for ^{233}U.

The constant uncertainties are listed in Table II.

TABLE II

Uncertainties Other than Statistical Uncertainties

Source of Uncertainty	$\frac{\sigma_f^{233}U}{\sigma_f^{235}U}$	$\frac{\sigma_f^{239}Pu}{\sigma_f^{235}U}$
Correction for (n,γ)-background	^{233}U 0.5% ^{235}U 0.5%	^{239}Pu 0.5% ^{235}U 0.5%
Absorption losses in the samples	^{233}U 0.8% ^{235}U 0.8%	^{239}Pu 0.8% ^{235}U 0.8%
Dead Time		0.2%
Sample Mass	^{233}U 0.4% ^{235}U 0.4%	^{239}Pu 1.0% ^{235}U 0.4%
Correction for isotopic composition	0.5%	0.2%
Total constant uncertainty	1.55%	1.75%

The overall total uncertainty consists of the total constant uncertainty and the statistical uncertainty which is ~0.7 to 1.5% for most of the points.

TABLE III

Fission Cross Sections: $\frac{\sigma_f^{239}Pu}{\sigma_f^{235}U}$ and $\frac{\sigma_f^{233}U}{\sigma_f^{235}U}$

E_n(keV)	$\frac{\sigma_f^{239}Pu}{\sigma_f^{235}U}$	Overall Total Uncertainty (%)	E_n(keV)	$\frac{\sigma_f^{233}U}{\sigma_f^{235}U}$	Overall Total Uncertainty (%)
5.2	0.711	4.2	5.2	1.350	2.7
8.2	0.663	3.0	8.3	1.388	2.3
11.1	0.678	2.6	11.3	1.349	2.2
13.6	0.636	2.7	13.7	1.365	2.5
15.5	0.693	2.7	15.5	1.395	2.4
17.5	0.674	2.6	17.5	1.327	2.2
19.5	0.737	2.4	19.7	1.348	2.2
21.4	0.686	2.4	21.5	1.320	2.2
23.8	0.736	2.2	23.6	1.335	2.0
26.8	0.714	2.1	26.7	1.311	1.9
30.0	0.754	2.2	29.8	1.301	2.0
32.6	0.791	2.2	32.3	1.347	2.1
34.9	0.800	2.2	35.3	1.304	1.9
38.2	0.789	2.0	38.6	1.345	2.0
42.0	0.813	2.1	42.5	1.351	1.8
46.4	0.812	2.0	47.0	1.325	1.9
51.5	0.836	2.0	51.1	1.302	1.8
56.2	0.853	2.0	55.7	1.334	1.8
61.7	0.870	2.0	62.6	1.362	1.8
67.9	0.860	2.0	68.9	1.392	2.0
75.1	0.909	2.0	74.3	1.414	1.8
81.3	0.924	2.0	80.4	1.441	2.0
88.3	0.920	2.0	87.3	1.390	1.8
99.1	0.963	2.0	98.0	1.403	1.8
112.1	0.972	2.1	110.7	1.433	1.9
123.5	0.968	2.2	121.8	1.433	2.3
132.1	1.035	2.4	130.3	1.455	2.3
141.7	1.010	2.1	139.6	1.489	2.3
152.3	1.014	2.5	150.1	1.540	2.3
164.2	1.004	2.2	161.7	1.493	2.3
177.6	1.057	2.6	174.8	1.517	2.5
192.6	1.024	2.4			
226 ± 34	1.051	2.1	200 ± 20	1.626	2.0
284 ± 32	1.136	2.2	230 ± 21	1.615	1.7
330 ± 35	1.155	2.6	253 ± 16	1.701	1.8
389 ± 23	1.212	2.0	280 ± 15	1.730	2.0
445 ± 25	1.258	2.1	334 ± 18	1.711	1.9
483 ± 35	1.329	1.8	386 ± 15	1.692	2.2
			440 ± 18	1.696	1.7
			495 ± 26	1.710	1.6
557 ± 22	1.331	2.0	546 ± 25	1.661	1.7
608 ± 22	1.379	2.2	582 ± 22	1.681	1.7
645 ± 25	1.354	2.5	648 ± 28	1.687	1.6
706 ± 20	1.400	2.2	693 ± 30	1.684	1.9
750 ± 35	1.440	2.0	758 ± 28	1.631	1.9
811 ± 20	1.453	2.1	803 ± 25	1.624	1.9
850 ± 34	1.414	2.0	863 ± 28	1.589	1.8
905 ± 28	1.357	2.0	915 ± 33	1.522	1.8
950 ± 30	1.316	2.2	967 ± 28	1.564	1.9
1008 ± 36	1.359	2.1	1015 ± 20	1.472	1.8

Data available on request from the data bank of the ENEA Neutron Data Compilation Centre, 91 GIF-sur-YVETTE, B.P. 9, France.

V. DISCUSSION

The results of our measurements are listed in Table III. The neutron-energy spread at the points below 200 keV is ~ 10% of the neutron energy. Figures 5 and 6 give plots of the fission cross-section ratios together with the results of other measurements.

From Fig. 5, it can be seen that our ^{239}Pu:^{235}U ratios are in fair agreement with the values of Allen and Ferguson[3] and, except at 40 keV, with the data of White, Hodgkinson, and Wall.[20] Thus, our results confirm the evaluation of Davey. Only at neutron energies above 200 keV is there a small deviation toward lower values. White and Warner[21] and Nesterov and Smirenkin[22] measured the ^{239}Pu:^{235}U ratio at 1 MeV with a claimed accuracy of 2% but with a discrepancy of roughly 5%. Our results are in better agreement with those of Ref. 22.

The dip in the fission cross-section ratio at ~ 900 keV seems to be deeper than the renormalized data of Smirenkin et al.[4] We repeated our measurements in this energy region twice to confirm our result. Perhaps this difference may be due to a smaller neutron-energy spread in our experiment.

The curve which was evaluated by James and Patrick[23] at energies up to 100 keV seems to be too low when compared to our results. This is caused mainly by the Gilboy and Knoll[24] data

[20] P. H. WHITE, J. G. HODGKINSON, and G. J. WALL, in *Physics and Chemistry of Fission*, p. 219, IAEA, Vienna (1965).

[21] P. H. WHITE and G. P. WARNER, *J. Nucl. Energy*, **21**, 671 (1967).

[22] V. G. NESTEROV and G. N. SMIRENKIN, *Atomnaya Energiya*, **24**, 185 (1968).

[23] G. D. JAMES and B. H. PATRICK, "Evaluation of the ^{239}Pu Fission Cross Section in the Energy Range 1 keV to 100 keV," AERE-M 2065, Atomic Energy Research Establishment, Harwell (1968).

[24] W. B. GILBOY and G. KNOLL, "The Fission Cross Sections of Some Plutonium Isotopes in the Neutron Energy Range 5-150 keV," KFK-450, Kernforschungszentrum Karlsruhe (1966).

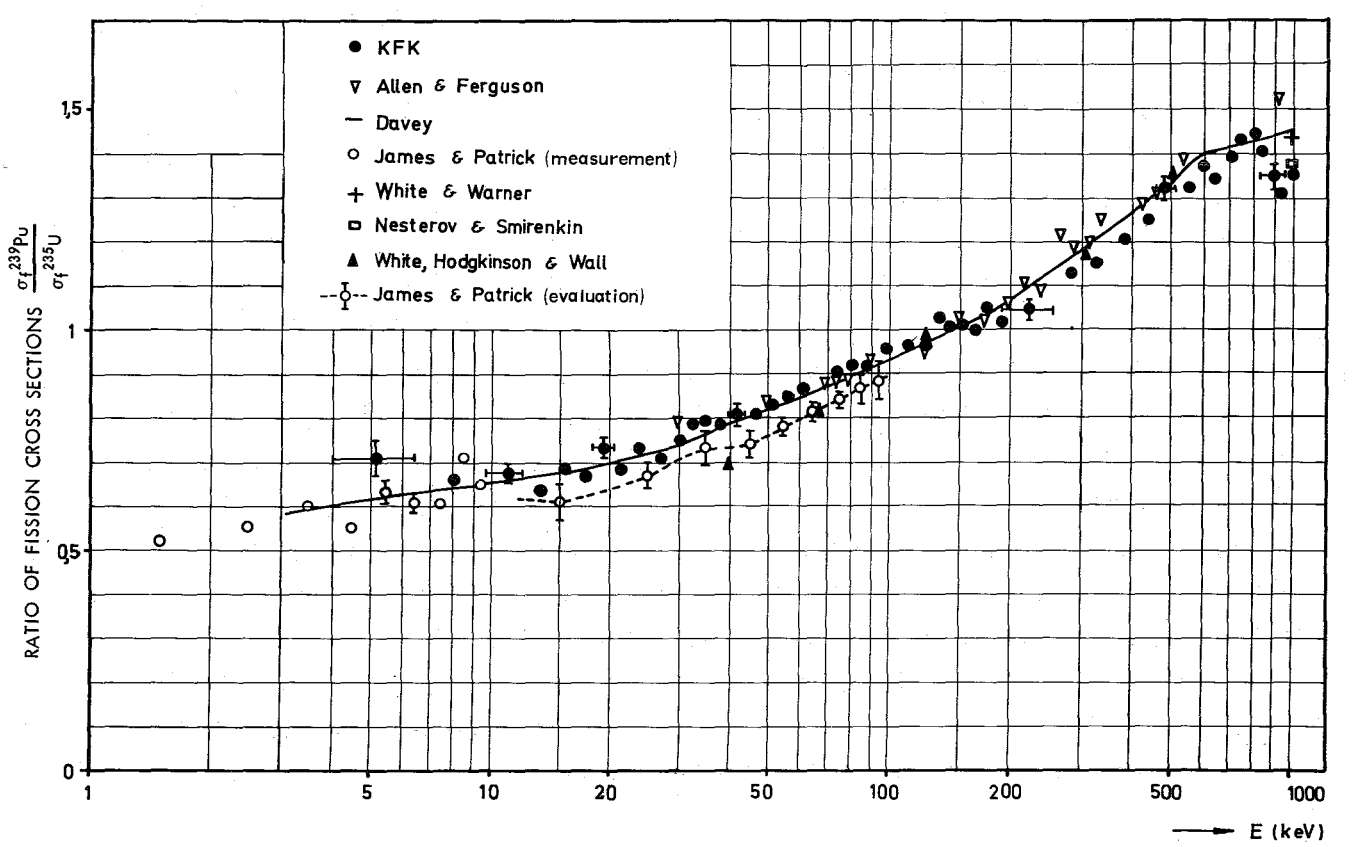

Fig. 5. Fission cross-section ratio ^{239}Pu:^{235}U;

full circles: present work,
solid line : Davey [2]

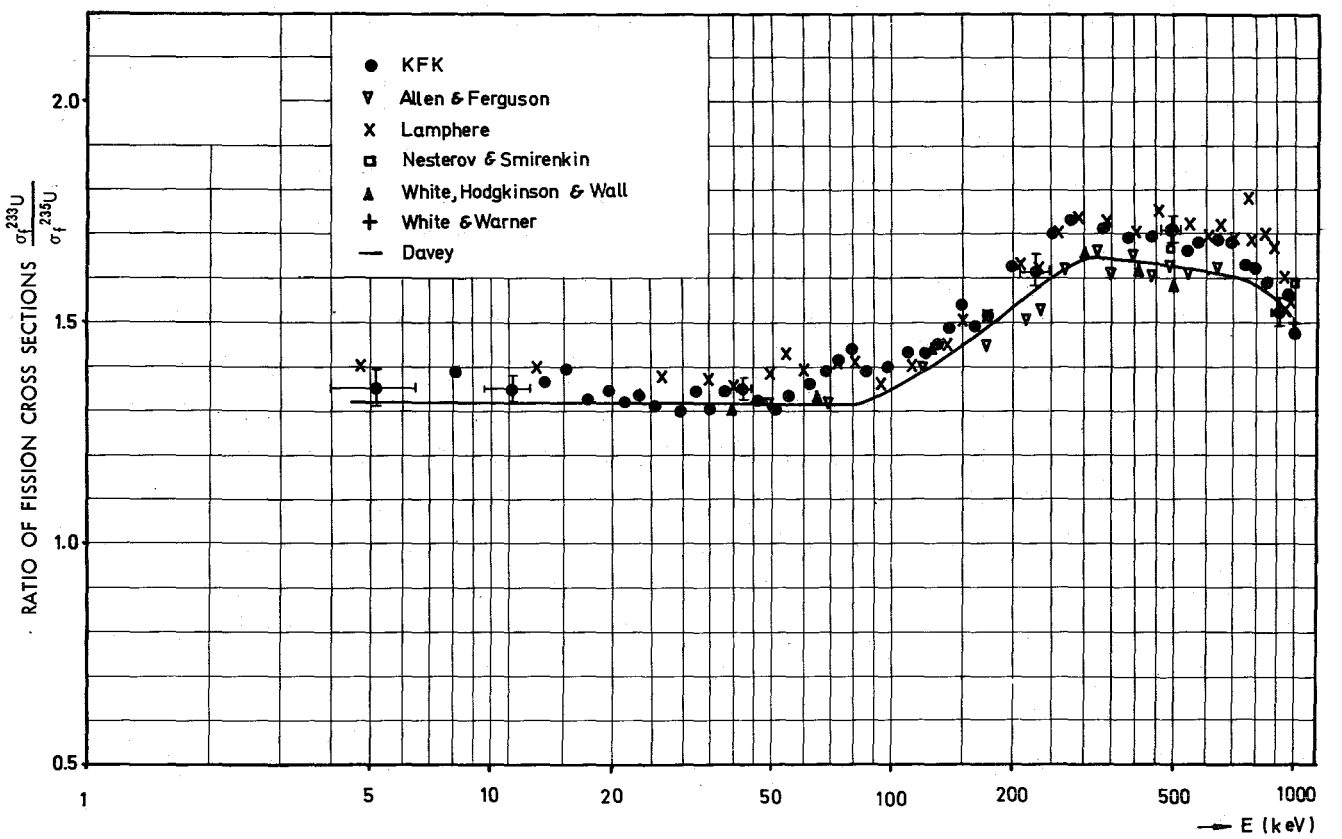

Fig. 6. Fission cross-section ratio $^{233}U:^{235}U$;

full circles: present work
solid line : Davey [2]

which, however, suffer from uncertainties in the determination of counter efficiencies.

The recent work of Lehto[25] supports our values in the energy region up to 25 keV within the given uncertainties.

Figure 6 shows the ratio $\sigma_f{}^{233}U:\sigma_f{}^{235}U$. Up to 700 keV there is good agreement between this measurement and that of Lamphere[26] and the renormalized data of Smirenkin et al.[4] Above 700 keV there is a discrepancy between Lamphere's data and ours, although there was no alteration in the technique of the measurement in either case throughout this part of the neutron-energy spectrum (500 keV to 1 MeV).

The data from White and Warner[21] and Nesterov and Smirenkin[22] at 500 keV and 1 MeV tend to support our values at these energies.

The results of Allen and Ferguson[3] and White et al.[20] are ~ 5% lower at energies above 100 keV. Because Davey's evaluation was based on these two measurements, his curve is also lower than our data.

At the lower end of the energy region, our values are in good agreement with the data of Lehto.[25]

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