tion energy. Assuming any of the appropriate forms of the level-density function, with values of level-density coefficient appropriate[12] to lead-206, it is estimated that the number of levels in the excitation interval 0 to 6 MeV is 10 times greater than in the interval 0 to 4 MeV. Assuming that the difference between experiment and calculation in Fig. 5 is due to compound-nucleus effect, we obtain a value for this effect of about 7 mb/sr at 4 MeV, diminishing to 0.7 mb/sr at 6 MeV due just to competition. The effect of direct interaction in the same energy interval is an increase from 3 mb/sr to about 7 mb/sr at 50 deg. It is clear at least semi-quantitatively, therefore, that the probabilities of the two reaction mechanisms for exciting a collective state shift in such a way in the interval from 4 to 6 MeV as to result in a marked shift from dominance of one mechanism to dominance of the other.

If noncollective states in the neighborhood of the collective state are not appreciably affected by direct interaction, they can be expected to diminish in prominence due to the effect of competition alone, as the bombarding energy is increased. Thus the sharply altered appearance of the spectra at 4 and 6 MeV can be qualitatively accounted for.

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U^{233} Fission Cross Section Measured Using a Nuclear Explosion in Space*

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A high-altitude nuclear explosion in 1962 was used as a neutron source in an experiment to measure the fission cross section of U^{233} relative to U^{235} in the 30-eV to 5-MeV energy region. Fission data were telemetered to the ground station at Kauai, Hawaii from sounding rockets carrying the fission counters which were near their apogee at the time the nuclear explosion occurred over Johnston Island. The flight path for the neutron time-of-flight experiment was 1280 km. The U^{233} fission-cross-section results indicated average values about 20% lower in the 2-MeV energy region and about 30–40% higher in the 30–500-eV energy region than the average of previously obtained values. The results also fill the gap in U^{233} fission-cross-section data which existed between previous high-energy Van de Graaff and low-energy time-of-flight measurements in the 1–20-keV region.

I. INTRODUCTION

IN 1962 the U. S. Atomic Energy Commission and Department of Defense conducted a series of high-altitude nuclear explosions over Johnston Island. The intensity of neutrons emitted during one of these events was enough to make neutron-cross-section measurements[1,2] at a distance of 1280 km from the explosion. The detectors (two fission counters and a BF_3 counter) were mounted in payloads which were launched from Kauai, Hawaii, by means of Nike-Apache sounding rockets. The rockets were near their apogee (about 150 km) at the time of the nuclear explosion.

Count-rate data as a function of time for the U^{233} and U^{235} fission detectors and the BF_3 neutron monitor counter were telemetered by means of a transmitter in the detector payload to the ground station at Kauai. Timing was referenced to the prompt gamma signal from the explosion. Data which were obtained for about 23 sec (duration of the experiment was limited by the length of recording tape used for signal playback) covered the energy region from 30 eV to 8 MeV.

The U^{233} fission cross section was selected for investigation in this experiment for the following reasons:

(1) Knowledge of the U^{233} fission cross section is fundamental to the economies of reactor technology based on the Th^{232}-U^{233} breeding chain. The economic feasibility of a thorium breeder reactor is of considerable importance since the total energy available from the world's thorium deposits is a significant fraction of the world's total energy resources.

(2) No fission-cross-section data for U^{233} in the energy region between 1 and 20 keV has been published, and data published in the energy region between 100 and 1000 eV is believed to have relatively low accuracy.

U^{235} was chosen for the other fission detector, since its fission cross section has been frequently measured and is often used as a reference standard in fission-cross-section experiments.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
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[1] R. D. Albert, Bull. Am. Phys. Soc. 8, 369 (1963).
[2] R. D. Albert, Bull. Am. Phys. Soc. 9, 76 (1964).

II. EXPERIMENTAL PROCEDURE

A. Fission-Counter Detectors

Each fission counter was constructed entirely of aluminum in the form of concentric cylinders on which uranium was chemically plated to a depth of about 200 $\mu g/cm^2$. This thickness is much less than one neutron mean free path at the peak of the largest fission resonance investigated.

The fission counters were 3 in. in diameter and 1.5 in. long. They were filled to a pressure of about 80 lb/in.^{2} with gas composed of 96% argon and 4% carbon dioxide, and had operating plateaus in the region of 500 V.

The electronic circuitry associated with the fission counters is illustrated in the schematic block diagram of Fig. 1. The amplifier for the fission counter was a four-stage, transistorized current type. The current signal from the amplifier triggered a tunnel-diode discriminator whose output was applied to a driver circuit. This signal drove a series of flip-flop circuits which formed a 10-element binary storage system. The discriminator level was set so as to prevent gamma-ray and electronic noise signals from appearing at the input to the binary stages. The fourth and seventh binary output signals were then applied to a summing network. The output signal of this summing network and the tenth binary output signal were then summed again by a second summing network. In this way, an 8-level voltage code was created at the second summer output, in which each voltage level could be related to a specific particle count. The output signal of the second summing network was then recorded on magnetic tape and telemetered to the ground receiving station.

Operation of the logic circuitry is illustrated by a section of the actual telemetry record shown in Fig. 2. This is a reproduction of a sample of raw data which was obtained from the U^{235} fission counter during the experiment and is a plot of the output summing voltage amplitude versus time, in msec.

The upper trace of this record represents data obtained at about 3.6 sec after zero time. The time interval between the largest voltage swings corresponds to an accumulation of 1024 counts. The other two time intervals correspond to accumulations of 128 counts and 16 counts. The average counting rate obtained from the data is about 10^4 counts/sec.

The lower record is a segment of the telemetry record which was received at about 7.2 sec after zero time. The largest voltage amplitude variation does not occur at this time, since the average count rate has fallen off by about a factor of 10 from its value at 3.6 sec after zero time.

B. BF_3 Detector

The BF_3 detector was manufactured by Reuter-Stokes and was constructed of aluminum with a diameter of $\frac{1}{2}$ in. and a length of 5 in. It was filled to 40-cm pressure and operated with a plateau in the region of 2300 V.

The BF_3 counter was potted in about $\frac{3}{4}$ in. of epoxy moderator which acted to smooth out any structure in the time-of-flight data obtained by the BF_3 detector which might be caused by resonances in the fluorine and boron (η,α) cross sections at higher energies. Because of the long time-of-flight path, broadening of resolution caused by the moderation time of this detector is negligible. The moderation time ($<100\,\mu$sec) is much smaller than the smallest time interval ($\sim 1000\,\mu$sec) used in reducing the data.

The electronic circuitry associated with the BF_3 detector is schematically illustrated in the block diagram of Fig. 3. The output signal from the BF_3 counter was amplified and applied to a tunnel-diode discriminator having a tripping level set high enough to eliminate electronic noise and gamma-ray pulses. The discriminator pulse was shaped so as to be independent of input-signal pulse amplitude and then integrated by means of a count-rate circuit which had a dynamic range of 3 decades. To increase the accuracy of the voltage cor-

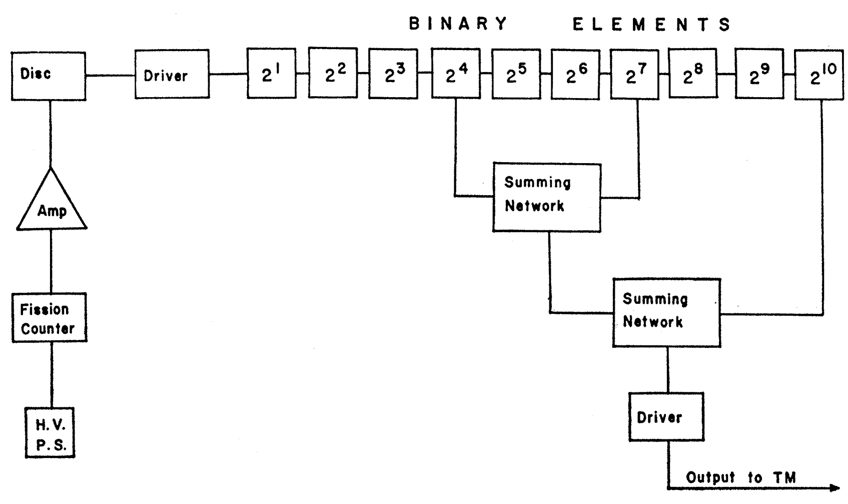

FIG. 1. Block diagram of electronics for fission counters.

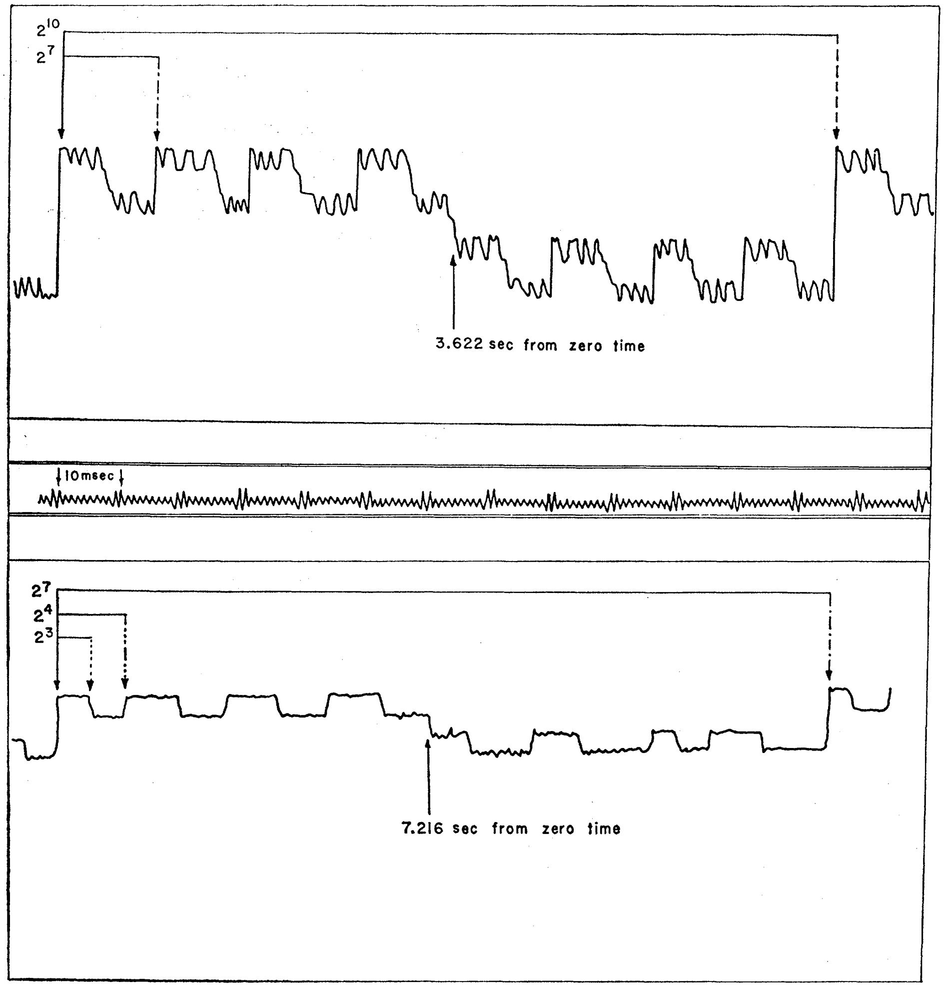

FIG. 2. Sample of telemetry record obtained during the experiment.

responding to a given count rate, a gating system was developed which provided a variable scale for the count-rate-meter output information. When the highest sensitivity count-rate meter (CRM1) started to read beyond scale, it was turned off by means of gate 1 and the next highest sensitivity count-rate meter (CRM 2) was read out to the telemetry system. The summing network output was also read out to the telemetry system to identify which of the three scales were being used.

The response time of the count-rate meter permitted identification of individual binary output pulses at slow counting rates, and this was the method used in analyzing the data in the energy region below 300 eV.

III. EXPERIMENTAL RESULTS

A. Count Rates

The average count rate for each detector was about 10^5 counts/sec for neutrons in the energy region above 20 keV. The count rate fell off rapidly below 10-keV energy because of the neutron spectrum of the source. However, a total of about one million counts was accumulated by all detectors in this experiment.

B. Neutron Spectrum

The neutron spectrum of the bomb source was measured over the energy region from 30 eV to 5 MeV. Unfortunately, time did not permit a complete preflight

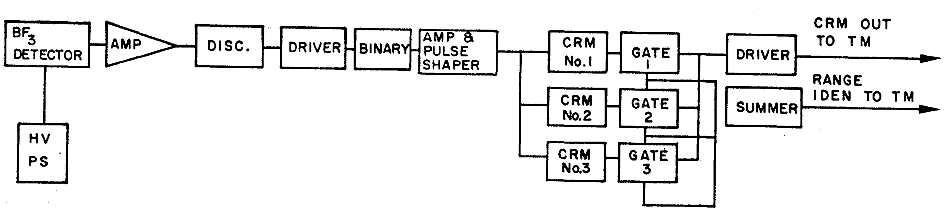

FIG. 3. Schematic diagram of electronic circuitry for the BF_3 detector.

calibration of the BF_3 flight package over this very large energy range. Consequently, its relative efficiency as a function of energy was determined, using the following relation:

$$\eta_R/N_B=\sigma_F{}^{235}/N_{235},$$

where η_R is the relative efficiency of the BF_3 counter, N_B is the count rate of the BF_3 counter, $\sigma_F{}^{235}$ is the U^{235} fission cross section,[3,4] and N_{235} is the count rate of the U^{235} fission counter.

The above relation is valid in the region where cross sections vary smoothly with energy. However, where resonance structure is present, the data must be averaged so as to give the smooth response characteristic of a moderated neutron detector.

The relative neutron spectrum of the nuclear device obtained in this manner is shown in Fig. 4. Above 5 keV the relative spectrum shows the $1/E$ behavior typically produced by a moderated fast-neutron source. In the energy region less than 5 keV, the variation of the spectrum may be reasonably approximated by a Maxwellian distribution having a temperature of about 1 keV.

Considerable fine structure is apparent in the spectrum, which may be interpreted as resulting from resonance scattering from various materials interposed between the source and the detector.

The large dip in the spectrum at 2.8 keV is caused by the scattering resonance in sodium due to the presence of a 3-mm-thick cylinder of sodium chloride which surrounded the BF_3 detector. The salt cylinder was added to make a crude investigation of the feasibility of a transmission experiment by this technique. However, no total-cross-section data were obtained from this measurement, since the geometry was poor and a thin target was not used.

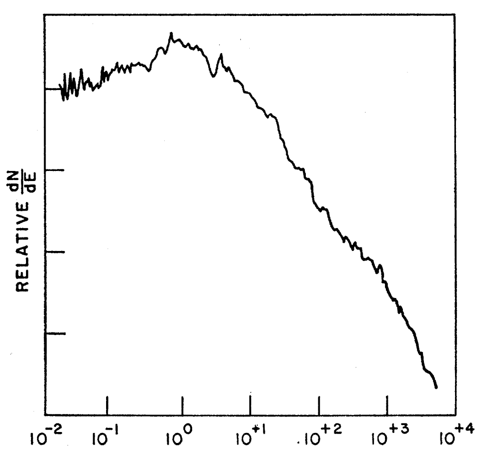

FIG. 4. Relative neutron-energy spectrum of the bomb source.

[3] A. Michaudon, R. Genin, and R. Joly, J. Phys. Radium **21**, 429 (1960); and CEA-1093, 1959 (unpublished).
[4] D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report No. BNL 325, 1958 (unpublished).

TABLE I. Isotopic analyses of U^{233} and U^{235} samples used in the experiment.

	Isotope	Purity (%)
U^{233} fission counter	U^{233}	97.28±0.05
	U^{234}	1.54±0.05
	U^{235}	<0.05
	U^{236}	<0.05
	U^{238}	1.16±0.05
U^{235} fission counter	U^{234}	0.415
	U^{235}	99.22
	U^{236}	0.044
	U^{238}	0.321

C. Fission Cross-Section Ratio of U^{233} Relative to U^{235}

The isotopic analysis of the uranium used in these chambers is given in Table I. The high purity shown in

TABLE II. Ratio of U^{233} to U^{235} fission cross sections, averaged over the indicated energy intervals.

E in keV	$\sigma_F{}^{233}/\sigma_F{}^{235}$	Error (%)
0.035– 0.1	1.47	3.08
0.1 – 0.2	1.38	2.57
0.2 – 0.3	1.30	2.54
0.3 – 0.4	1.32	2.77
0.4 – 0.5	1.20	2.62
0.5 – 0.6	1.19	2.76
0.6 – 0.7	1.27	2.75
0.7 – 0.8	1.23	2.87
0.8 – 0.9	1.45	2.92
0.9 – 1.0	1.39	3.06
1.0 – 1.2	1.30	2.21
1.2 – 1.4	1.33	2.26
1.4 – 1.6	1.36	2.39
1.6 – 1.8	1.29	2.44
1.8 – 2.0	1.38	2.57
2.0 – 2.5	1.35	1.75
2.5 – 3.0	1.35	1.85
3.0 – 3.5	1.35	2.01
3.5 – 4.0	1.36	2.17
4.0 – 5.0	1.39	1.69
5.0 – 7.0	1.38	1.44
7.0 – 8.0	1.37	2.44
8.0 – 10	1.41	1.84
10 – 11	1.35	2.88
11 – 12	1.41	3.09
12 – 14	1.39	2.40
14 – 16	1.36	2.60
16 – 18	1.42	2.78
18 – 20	1.33	2.94
20 – 22	1.41	3.12
22 – 25	1.42	2.75
25 – 27	1.39	3.64
27 – 30	1.36	3.73
30 – 35	1.41	3.18
35 – 40	1.44	3.95
40 – 45	1.45	4.43
45 – 50	1.44	4.60
50 – 55	1.50	4.86
55 – 60	1.42	4.88
60 – 70	1.44	3.68
70 – 90	1.46	3.34
90 – 130	1.55	3.27
130 – 200	1.60	3.30
200 – 300	1.56	3.54
300 – 600	1.61	2.59
600 -1000	1.54	3.16
1000 -3000	1.30	2.68
3000 -5000	1.19	5.62
5000 -8000	1.17	

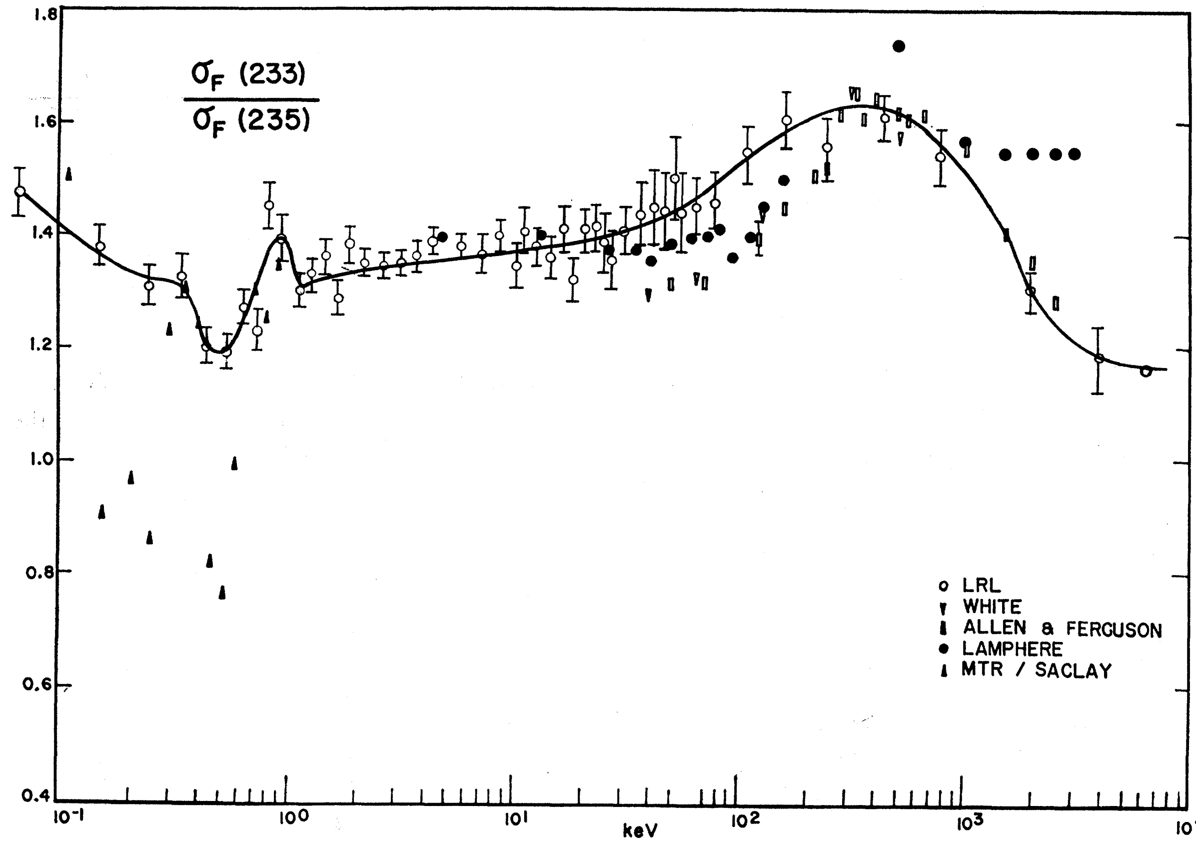

FIG. 5. Average ratio of U^{233} to U^{235} fission cross sections plotted as a function of energy.

the analyses, indicates that the fission-cross-section results obtained from these samples are not significantly affected by contributions from isotopic impurities.

The ratio of the U^{233} cross section relative to the U^{235} cross section was calculated from the ratio of the counting rates of the U^{233} and U^{235} fission chambers obtained from the experiment.

The data were averaged over large intervals of energy

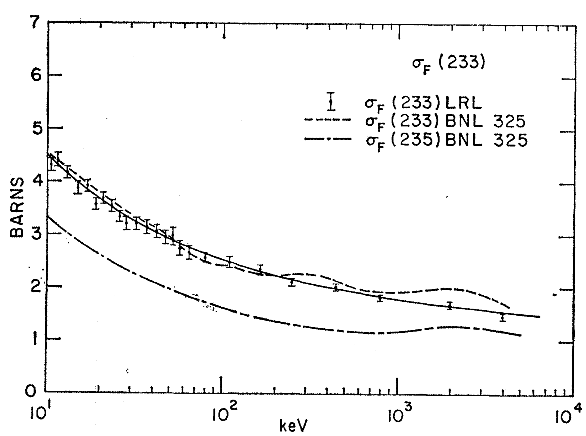

FIG. 6. The average U^{233} fission cross section plotted as a function of energy between 10 keV and 6.5 MeV.

to reduce statistical errors and facilitate comparison with previous comparable energy resolution data for the U^{233} relative to U^{235} fission-cross-section ratio. Figure 5 is a plot of our ratio in the MeV energy region compared with measurements of Allen and Ferguson,[5] White,[6] and Lamphere.[7] Our data have been normalized to the ratio of Allen and Ferguson which has a quoted accuracy of 3% in the 550-keV energy region. The shape of our curve is in satisfactory agreement with the curve of Allen and Ferguson in the energy region above 200 keV. However, it appears to be about 5% higher between 70 and 200 keV energy, although there are overlapping errors between many of the individual points of the two measurements in this energy region. Above 1 MeV our cross-section ratio is in good agreement with that obtained by Allen and Ferguson, but falls off below the ratio measured by Lamphere which is fairly constant in this region. The data are given in Table II.

Although there have been no direct measurements of the U^{233} to U^{235} fission-cross-section ratio reported below 5-keV energy, the cross sections have been measured

[5] W. D. Allen and A. T. G. Ferguson, Proc. Phys. Soc. (London) **A70**, 573 (1957).
[6] P. W. White, Atomic Weapons Research Establishment report, Harwell, United Kingdom (unpublished).
[7] R. W. Lamphere, Phys. Rev. **104**, 1654 (1956).

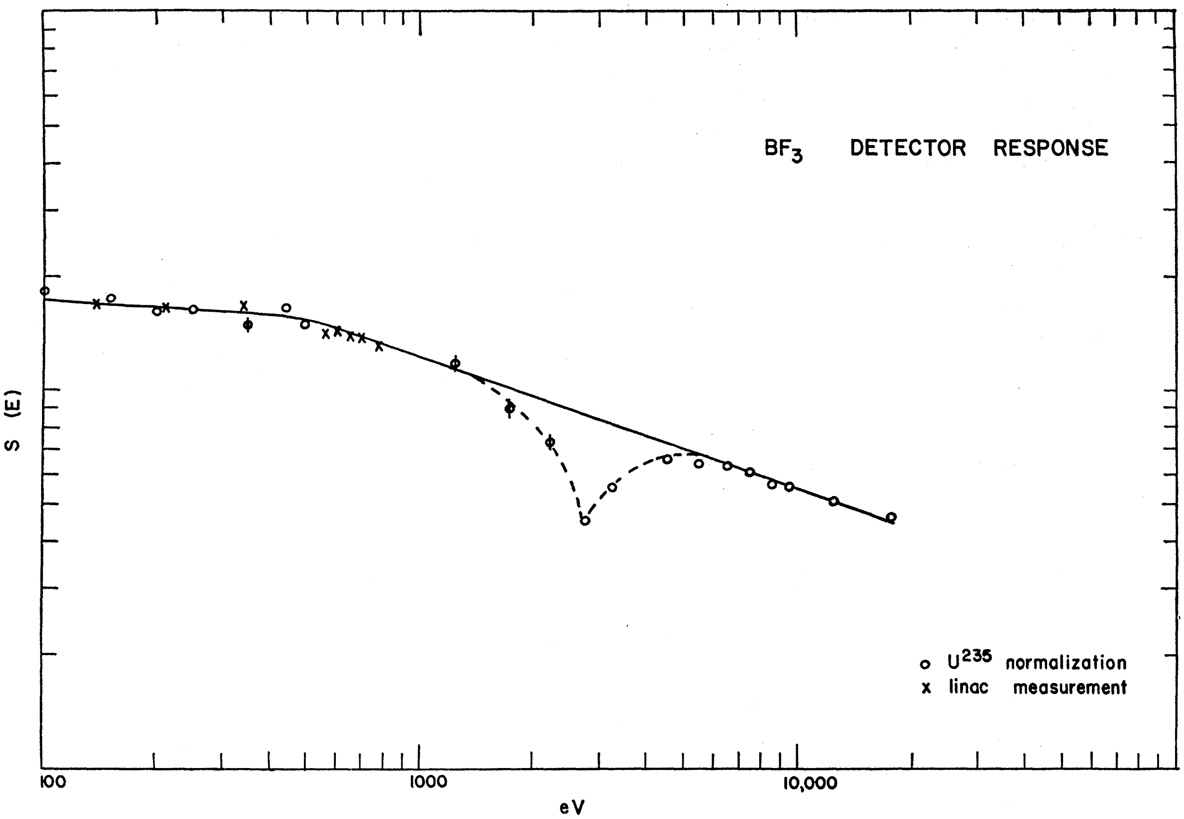

FIG. 7. Relative efficiency of the moderated BF_3 detector as a function of energy.

individually by Michaudon *et al.*[3] for U^{235} below 20 keV energy, and by Moore *et al.*[8] for U^{233} below 1 keV. A ratio was prepared from the two sets of data by averaging each set over an energy interval much larger than the resolution of either measurement. The ratio thus obtained is also plotted in Fig. 5. In general, it appears that the Moore *et al.* to Michaudon *et al.* fission-cross-section ratio values are considerably lower than our fission-cross-section ratio values with a discrepancy which appears to be well beyond the errors of the individual measurements.

D. U^{233} Fission Cross Section

The U^{233} cross section above 10-keV energy was obtained by multiplying the ratio of Table II by the U^{235} cross section[9] published in the latest Brookhaven compilation (BNL 325). The results are given in Table III. The U^{233} cross-section results are compared with the U^{233} cross section[9] of the latest (BNL 325) cross-section compilation in Fig. 6. Our cross section departs from the BNL 325 compilation curve at about 100-keV energy, and is about 20% lower in the 2-MeV

TABLE III. Average fission cross section of U^{233} over the energy range of 10–6500 keV.

E in keV	σ_F^{233} (barns)	% error
10.5	4.31	2.88
11.5	4.40	3.09
13.0	4.12	2.40
15.0	3.88	2.60
17.0	3.91	2.78
19.0	3.57	2.94
21.0	3.68	3.12
23.5	3.53	2.75
26.0	3.34	3.64
28.5	3.19	3.73
32.5	3.20	3.18
37.5	3.15	3.95
42.5	3.06	4.43
47.5	2.95	4.60
52.5	2.98	4.85
57.5	2.74	4.88
65.0	2.68	3.68
80.0	2.55	3.34
110	2.49	3.27
165	2.34	3.30
250	2.10	3.54
450	2.01	2.59
800	1.82	3.16
2000	1.68	2.68
4000	1.48	5.62
6500	1.58	

[8] M. S. Moore, L. G. Miller, and O. D. Simpson, Phys. Rev. **118**, 714 (1960).
[9] M. D. Goldberg (private communication, 1965).

energy region. The U^{235} cross section on which our U^{233} cross section is based is also included in Fig. 6.

To obtain the U^{233} cross section below 10 keV from our data relative to previous U^{235} cross-section measurements, it is necessary to consider the resonance structure that appears in the U^{235} cross section at lower energy. Since the observed structure is dependent on the resolution of the particular experiment which produced it, the resolution dependence may be considerably lessened by integrating the data over large energy intervals. The procedure used is as follows: We have the relationship

$$1/\eta_{235} dN_{235}/dE = \sigma_F{}^{235}(E)\phi(E)\,, \tag{1}$$

where (dN_{235}/dE) is the number of counts detected by the U^{235} fission counter in the energy interval between E and $(E+dE)$, $\sigma_F{}^{235}(E)$ is the differential fission cross section of U^{235}, $\phi(E)$ is the neutron flux (cm^{-2} keV^{-1}) between E and $(E+dE)$, and η_{235} is the probability of a fission event being detected by the chamber. We also have

$$dN_B/dE = S(E)\phi(E)\,, \tag{2}$$

where dN_B/dE is the number of counts detected by the moderated BF_3 detector in the energy interval between E and dE, and $S(E)$ is the probability that the BF_3 counter will detect one neutron in a unit flux of neutrons in the energy interval between E and dE. Dividing (2) into (1) we obtain an expression for $S(E)$ in terms of the measured ratio of the U^{235} fission counts to the BF_3 counts, $R(E)$, and the differential U^{235} fission cross section, which is

$$S(E) = \frac{\eta_{235}\sigma_F{}^{235}(E)}{R(E)}. \tag{3}$$

However, the experimental values of $\sigma_F{}^{235}(E)$ and $R(E)$ actually represent integrals of the true cross sections over energy intervals determined by the resolution of the experimental measuring apparatus. We can integrate $S(E)$ over an energy interval (ΔE) large compared to the experimental resolution to obtain

$$S(E) = \eta_{235}\int_E^{E+\Delta E} \sigma_F{}^{235}(E)\,dE \Big/ \int_E^{E+\Delta E} R(E)\,dE. \tag{4}$$

This response was compared with the efficiency of the moderated BF_3 detector which was experimentally obtained using the Livermore Linac facility as a pulsed-neutron source, and time-of-flight for the neutron energy determination. These measurements were made with respect to the known relative neutron cross section of a bare $B^{10}F_3$ detector in the 0.1- to 1-keV energy region. The detector response thus obtained is plotted in Fig. 7, along with the relative detector response obtained using expression (4) and the U^{235} fission cross section measured by Michaudon *et al.*[3] The dip in $S(E)$ at 2.8 keV, indicated by the dotted region, is due to the presence of the scattering resonance in sodium at that energy, as previously mentioned.

The U^{233} cross section between 0.1 and 10 keV was obtained by the following procedure:

$$\frac{1}{\eta_{233}}\frac{dN_{233}(E)}{dE} = \sigma_F{}^{233}(E)\phi(E).$$

Substituting (2) for $\phi(E)$ and (4) for $S(E)$ we obtain

$$\sigma_F{}^{233}(E) = \frac{\eta_{235}}{\eta_{233}}\frac{dN_{233}(E)}{dN_B(E)}\frac{\left[\int_E^{E+\Delta E}\sigma_F{}^{235}(E)\,dE\right]}{\left[\int_E^{E+\Delta E}R(E)\,dE\right]},$$

TABLE IV. Average fission cross section of U^{233} over the energy range of 0.1–10.0 keV.

E in keV	$\sigma_F{}^{233}$ (barns)	% error
0.112	30.0	5.96
0.137	27.0	6.04
0.162	28.9	6.03
0.187	26.9	6.01
0.212	29.6	5.94
0.237	28.3	6.04
0.262	26.6	6.09
0.287	32.8	6.09
0.312	28.2	6.48
0.337	22.7	6.74
0.362	24.5	6.05
0.387	25.9	6.03
0.412	23.5	5.83
0.437	15.6	5.51
0.462	15.3	5.77
0.487	20.6	5.66
0.950	9.44	2.86
1.050	10.7	3.03
1.150	10.6	3.18
1.260	11.2	2.89
1.380	10.5	3.05
1.500	10.8	3.07
1.630	9.28	2.92
1.775	9.01	2.91
1.925	8.51	2.96
2.075	8.81	3.16
2.675	7.72	1.37
3.300	6.09	3.28
3.500	6.35	3.25
3.700	6.15	3.45
3.900	6.20	3.52
4.125	6.14	3.21
4.375	6.02	3.29
4.625	6.71	3.40
4.875	6.48	3.46
5.175	5.78	3.07
5.525	5.70	3.19
5.875	5.85	3.44
6.275	5.84	3.03
6.750	5.33	2.97
7.250	4.91	3.18
7.800	4.92	3.13
8.450	5.11	3.00
9.200	4.85	2.90
10.000	4.56	3.00

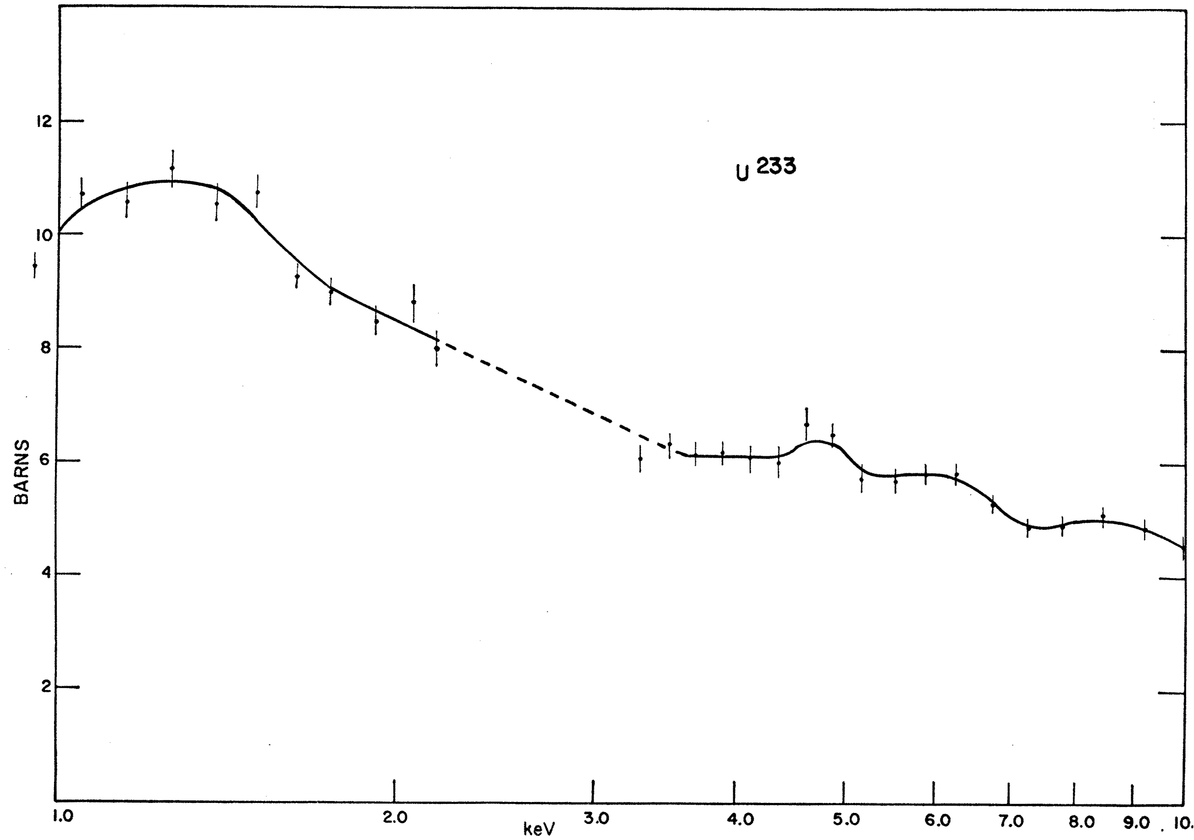

FIG. 8. The average U^{233} fission cross section plotted as a function of energy between 1 and 10 keV. Data in region of dotted line obscured by presence of a 2.8-keV scattering resonance in sodium (see text).

where the value of η_{235}/η_{233} is obtained using the relation

$$\frac{dN_{233}(E)}{dN_{235}(E)}=\frac{\eta_{233}\sigma_F^{233}(E)}{\eta_{235}\sigma_F^{235}(E)}$$

and the ratio $\sigma_F^{233}(E)/\sigma_F^{235}(E)$ measured by Allen and Ferguson is used for normalization at $E=550$-keV energy. Results thus obtained for the U^{233} fission cross section in the region 900-eV to 10-keV energy are tabulated in Table IV and the points are plotted as a function of energy in Fig. 8. No experimental data for the U^{233} cross section in this energy region are available at this time for comparison, since these results occupy a transition region between previously published low-energy and high-energy measurements.

U^{233} cross-section results at lower neutron energies were also obtained by means of the procedure described above. However, it is clear that the statistical significance of the data rapidly decreases as the neutron energy is reduced. Unfortunately, the signal from the BF_3 detector was unreliable in the 500–900-eV energy region and consequently this region has been omitted.[10]

The U^{233} cross section between 100 and 1000 eV is given in Table IV and plotted in Fig. 9. Also plotted for comparison are data of Moore *et al.*,[8] and Adamchuk *et al.*,[11] which are the only other data presently available for the U^{233} fission cross section in this energy region. To improve the statistical accuracy in this region, our data have been averaged over 25-eV energy intervals. The data of Moore *et al.* were similarly treated to facilitate the comparison. Our results indicate a considerably larger fission cross section (about 30%) for U^{233} in the 150–400-eV energy region. The statistical error in our cross-section values is approximately constant and is about $\pm 6\%$ at each point.

The U^{233} cross section in the region below 100-eV energy was obtained by multiplying the U^{235} cross-section data of Michaudon *et al.*[3] by our experimental U^{233} to U^{235} cross-section ratios. (The BF_3 count rate was low in this region.) To improve the statistical accuracy in this region, the ratio data were averaged over

[10] The average output voltage of count-rate meter CRM1 was near the saturation level of the telemetry system and thus on the edge of gating in the less sensitive count-rate meter CRM2. However, instantaneous variations in count rate caused by statistical fluctuations were frequently enough to alternately trigger the gates of count-rate meters CRM1 and CRM2. During this switching process (which was a large fraction of time for the 500–900-eV energy region) BF_3 count-rate data were lost.

[11] Adamchuk *et al.*, Proc. Intern. Conf. Peaceful Uses At. Energy 4, paper 641 (1956).

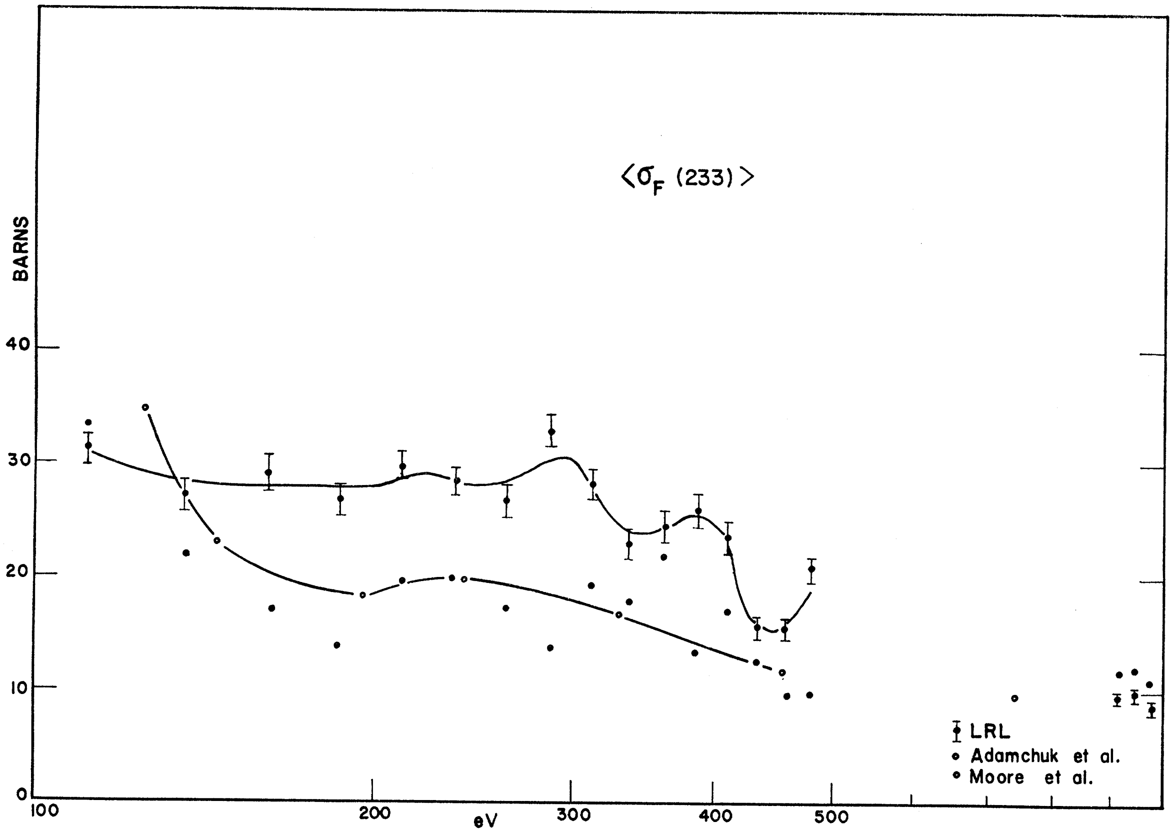

FIG. 9. The average U^{233} cross section plotted as a function of energy in the 100- to 1000-eV energy region.

5-eV energy intervals, yielding statistical errors of about 10–12% for each interval. The U^{235} data were averaged over the same energy intervals before multiplication. The averages were obtained by integrating the data points and dividing by the energy interval. Similarly treated for comparative purposes were data of Moore

TABLE V. Average fission cross sections of U^{233} and U^{235} in the 30- to 100-eV energy region.

	Average fission cross sections (barns)					
	U^{233}				U^{235}	
eV	LRL[a]	Moore *et al.*[b]	Nifenecker *et al.*[c]	Michaudon *et al.*[d]	KAPL[e]	Bowman *et al.*[f]
30–35	55.7	42.6	61.5	46.4	59.7	46.8
35–40	74.6	30.7	45.7	54.1	42.3	57.0
40–45	34.9	24.6	33.0	32.0	31.3	34.3
45–50	42.9	22.3	30.2	29.8	38.7	33.9
50–55	65.0	18.7	27.1	49.6	60.8	46.9
55–60	62.5	51.2	67.7	61.3	50.0	63.8
60–65	32.8	26.4		22.0	20.9	
65–70	14.5	20.9		10.2	26.7	
70–75	50.4	23.5		38.3	29.4	
75–80	36.6	40.8		20.1	21.9	
80–85	34.9	27.2		28.4	31.0	
85–90	37.6	17.8		22.8	27.1	
90–95	33.2	28.7		25.0	21.0	
95–100	43.8	27.9		19.4	17.7	
30–100	44.2±1.2	28.8		32.8	34.2	
30–60	55.9±2.6	31.7	44.2	45.5	47.1	47.1

[a] Present work.
[b] See Ref. 8.
[c] See Ref. 12.
[d] See Ref. 3.
[e] See Ref. 4.
[f] See Ref. 13.

et al.,[8] Nifenecker *et al.*,[12] Bowman *et al.*,[13] and some older Knolls Atomic Power Laboratory (KAPL) data.[4]

The results are shown in Table V. Although the fission integrals for the U^{235} data are generally in good agreement, large differences between the U^{233} results obtained from the three different measurements are apparent. In general, the results of Moore *et al.*, are lower than ours. The average of the U^{233} fission cross section between 30 and 100 eV is about 35% lower. The agreement between our data and that of Nifenecker *et al.*, which only goes to 60 eV is somewhat better, although the latter measurement is still about 20% lower than ours in this energy region.

It should be noted that the structure in our U^{233} averaged cross-section results depends on the detailed structure present in the average U^{235} cross-section values of Michaudon *et al.*, which differs from KAPL but agrees with Bowman *et al.* However, regardless of which set of data is used for normalization, the general nature of the disagreement in the U^{233} fission-cross-section measurements pointed out in the preceding paragraph is still valid.

IV. CONCLUSION

The experimental technique of measuring fission cross sections in space has a number of advantages as well as disadvantages. One of the disadvantages is the difficulty of repeating a measurement. Although there are no reasons to believe that the results previously presented are not correct, it is always reassuring when a measurement can be repeated and verified. Another disadvantage is that the cost of making a single measurement is prohibitive, unless it can be associated with a test series which is going to be conducted anyway. On the other hand, the economics improve considerably if a large number of measurements are simultaneously performed. The advantages of the technique may be listed as follows:

(1) Measurements are relatively easy for heavy elements whose high natural activities make their measurement in the laboratory difficult.

(2) Measurements are made in free space, thus avoiding neutron scattering from room walls, accelerator structure, and collimation material which may cause large errors in evaluating corrections to the data from this effect.

(3) In general, the amount of material required is less, which is important in the case of rare or valuable samples.

(4) The bomb spectrum peaks in the keV region, where laboratory measurements suffer from a lack of intensity. However, this results in a deficiency of resonance neutrons which may be overcome by special experimental considerations.

(5) The experimental data cover five decades of energy and thus may be normalized at either or both high- and low-energy regions wherever good previous data are available.

(6) High vacuums in space permit long flight paths which, at least in principle, should yield unsurpassed experimental resolution. (Limitations are caused, however, by counting statistics and telemetry bandwidth considerations.)

(7) The duration of the experiment is only a few seconds.

Results which have been presented here were averaged over large energy intervals to make it easier to compare them with previous measurements having different energy resolutions. This produced the desirable effect of reducing our statistical errors so that a more accurate quantitative evaluation could be made. Results which show more detailed fission-cross-section structure will be published in a separate report.

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[12] H. Nifenecker, D. Paya, and J. Fato, J. Phys. Radium **24**, 254 (1963).

[13] C. D. Bowman, G. F. Auchampaugh, and S. C. Fultz, Phys. Rev. **130**, 1482 (1963).