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December 19, 1974

MASTER

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MAILED

MEASUREMENTS OF THE ENERGY DEPENDENCE OF THE EFFICIENCY OF FISSION CHAMBERS

Abstract

Pulse height distributions from ionization fission chambers containing ^{233}U , ^{234}U , ^{235}U , ^{236}U , ^{238}U , and mixtures of these isotopes were measured as functions of neutron energy over broad energy bands between 54 eV and higher than 30 MeV. We used this data to calculate fission chamber efficiencies as functions of energy range and pulse-height

bias level. We found the energy variation of the efficiencies to be $\pm 1.3 \pm 0.7\%$ for efficiencies near 90%. From this result we estimate the energy variation in the efficiency to be less than 0.5% for the present chambers operated at their maximum efficiency. When bias levels are used that give efficiencies less than 80% the efficiency decreases with increasing neutron energy.

Introduction

The variation with neutron energy of the efficiency of an ionization fission chamber for detecting neutron -induced fissions can be a major uncertainty in a fission cross section measurement. Energy dependence of the efficiency is expected because the angular distribution, energy distribution, and mass distribution of fission fragments are all known to change with incident neutron energy in the range 0-14 MeV. The linear momentum given to the fissioning nucleus also increases with neutron energy. Measurements of the energy dependence of the angular, energy, and mass distributions of fragments are incomplete. Also, the signal used to count events from a fission chamber has a complex dependence on the electronics used to amplify and process the signal before recording. These facts make it difficult to reliably calculate the effects of the energy dependence of the

fragments' properties. To circumvent these difficulties we use direct measurements of the energy dependence of the pulse height distributions from fission chambers.

In a series of cross section ratio experiments at the LLL 100-MeV-electron linear accelerator and time-of-flight facility we measured the pulse height distributions in parallel-plate ionization fission chambers as functions of incident neutron energy over a number of broad neutron energy ranges, as shown in Table 1. Relative efficiencies for detecting fission events were calculated from these pulse height distributions as functions of pulse-height "bias level." Relative efficiency is defined here to mean the fraction of total observed fission events with pulse heights above a given pulse-height channel bias level. The word "relative" is used to distinguish

Table 1. The fission chambers used in our measurements, their contents, and the energy ranges of their pulse height distributions. The energy ranges of chambers 1-5 differ slightly from the ranges for chambers 6-9.

Chamber number	Principal isotope(s)	Energy ranges						
		PH1	PH2	PH3	PH4	PH5	PH6	PH7
1	^{238}U							
2	^{235}U	54.6 eV	1013 eV	0.1101 MeV	1.028 MeV	2.06 MeV	5.33 MeV	Not used
3	$^{235}\text{U}, ^{238}\text{U}$	to	to	to	to	to	to	
4	^{233}U	1013 eV	0.1101 MeV	1.028 MeV	2.06 MeV	5.38 MeV	9.70 MeV	
5	$^{233}\text{U}, ^{238}\text{U}$							
6	^{234}U	54.4 eV	1009 eV	0.1005 MeV	1.018 MeV	2.04 MeV	5.20 MeV	9.47 MeV
7	$^{234}\text{U}, ^{235}\text{U}$	to	to	to	to	to	to	to
8	^{236}U	1009 eV	0.1005 MeV	1.018 MeV	2.04 MeV	5.28 MeV	9.47 MeV	87.1 MeV ^a
9	$^{236}\text{U}, ^{235}\text{U}$							

^aAlmost all of the neutrons in this energy range have energies less than 30 MeV.

these calculated efficiencies from the real efficiency of the fission chamber for detecting fission events. An estimated 3% of the fissions occurring in the fission chambers used here give no signal at all. These include fission events in which the fragments lost most of their energy in the deposit on the fission chamber plate rather than in the gas of the chamber. Thus the real efficiency of the chambers is the product of the relative efficiency and the probability that a fission event will give an observable signal.

We calculated relative efficiencies for the nine fission chambers listed in Table 1. We used the results to estimate an energy variation of less than 0.5% in the real efficiency of the fission chambers when all pulse heights above the reference level are accepted. The efficiency is found to decrease with increasing neutron energy when a bias level is used that rejects more than about 25% of the fission fragment signals. We will use these results to assess the accuracy of fission-cross-section ratio measurements made with the fission chambers studied here.¹

Experimental Details

To allow comparison of the present results with other experiments, we present here some details of the fission chamber construction and the electronics used to obtain pulse heights. The fission chambers were of modular design and were placed back-to-back in a pressure vessel. Each modular chamber

contained an odd number of fission foils - 3, 5, or 7. Table 2 gives the areal densities of fissionable material and a description of the contents of the nine fission chambers discussed in this report. The fission foils, made at LLL using a painting technique,² contained uranium isotopes applied to both sides

Table 2. Properties of the modular fission chambers.

Chamber number	Principal isotope(s)	Isotopic composition (%) by mass number					Total mass (g)	Number of foils	Plate spacing (mm)	Foil thickness (g/m ²)
		233	234	235	236	238				
1	²³⁸ U					99.99+	0.20	7	4.0	3.1
2	²³⁵ U		0.03	99.91	0.02	0.04	0.13	5	4.0	2.8
3	²³⁵ U, ²³⁸ U		0.01	25.35	0.01	74.63	0.24	7	4.0	3.8
4	²³³ U	99.99+					0.17	7	4.5	2.7
5	²³³ U, ²³⁸ U	12.69				87.31	0.17	5	4.5	3.8
6	²³⁴ U		99.84	0.10	0.05	0.01	0.08	3	4.0	3.0
7	²³⁵ U, ²³⁴ U		60.16	39.76	0.04	0.02	0.06	3	4.0	2.2
8	²³⁶ U				99.99+		0.05	3	4.0	1.9
9	²³⁵ U, ²³⁶ U		0.01	30.44	69.51	0.04	0.08	3	4.0	3.0

of each foil and confined to a 38-mm radius from the center of the 66-mm-radius aluminum substrates. The substrates were made of aluminum with an areal density of 30 g/m². The first pressure containments of the chambers were filled to a pressure of 127 kPa (18.5 psia) with a gas mixture of 90% argon and 10% carbon dioxide. Plate spacings are shown in Table 2. An operating voltage of 500 V was applied. Drift velocities of the electrons are typically 60 km/s (6 cm/ μ s) using an E/p ratio of 1.0 V/m per pascal (1.3 V/cm per mm Hg).³

The fission chambers were placed with their plates perpendicular to the neutron beam.

Figure 1 is a block diagram of the counting electronics. The current amplifier, shown in Fig. 2, was chosen because of its overall attractive properties, especially its ability to handle high alpha activity. With a gain of 1700, an rms noise of 13.5 μ V referred to the input, an input impedance of 50 Ω , and a risetime of 3.5 ns, this amplifier design provided good suppression of alpha-particle pileup when connected to the ²³³U fission cham-

ber. Typical fission-fragment pulses had risetimes of 12 ns, full-width-half-maximum values of 30 ns, and an average fission-fragment-pulse to amplifier noise ratio of about 5.

Signals from the current amplifiers travel along fast coaxial cables from the detector location to the experimental counting room. There, linear fanouts duplicate each signal; one is sent to a discriminator, the other to a linear gate and stretcher amplifier. The discriminator gates a 30-ns portion of the signal, which begins 5-10 ns before the rise of the pulse; this 30-ns portion is passed by the linear gate. These signals are integrated and shaped by the stretcher amplifier and sent on to the pulse-height analyzer. A separate output from the discriminator goes to the tag and stop box and then on to the time digitizer. After the time-of-flight, detector-tag, and pulse-height information for each event arrive at the computer interface they are recorded in a buffer area of the computer memory for further processing by the computer. A display scope and magnetic tape units are available for viewing data collection and data recording, respectively.

Further details of the experimental setup, which include a description

of the LINAC and time-of-flight facility, are given elsewhere.¹

Fig. 1. Diagram of counting electronics and data-acquisition system. (Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U. S. Atomic Energy Commission to the exclusion of others that may be suitable.)

Efficiency Calculations

Typical pulse-height distributions used in the efficiency calculations are shown in Figs. 3 and 4. The ^{235}U chamber has a clear separation between background and fission events, as shown in Fig. 3. The pulse heights of background and fissions overlap to some extent in the ^{233}U chamber, as shown in Fig. 4. The difference between the

chambers is that the background in the ^{235}U chamber is amplifier noise and single alpha-particle signals, whereas the background in the ^{233}U chamber has signals that are the result of several alpha particles being emitted within a short time interval (alpha pileup). Differences in the calculation of fission chamber efficiency for these two types

Fig. 3. Pulse-height distributions from fission chamber 2 (uranium-235). PH1 covers the neutron energy range 54.6 to 1013 eV; PH4 covers the range 1.028 to 2.06 MeV.

of distribution will be explained in the following discussion.

For each fission chamber there is a reference pulse-height channel that is defined as the first channel below the lowest channel containing fission counts. For example, in Fig. 3 the distribution labeled PH4 is essentially free from background and has no counts below channel 12; thus, channel 11 is the reference level. Likewise, channel 31 was

chosen as the reference level for the ^{233}U chamber shown in Fig. 4. The efficiency in each energy range is calculated for bias channels above the reference level as the sum of the real counts above the bias level divided by the total real counts above the reference level.

The real counts are determined by subtracting a background from the observed counts in the pulse-height distribution. The subtraction is based on the assumption

Fig. 4. Pulse-height distributions from fission chamber 4 (uranium-233). PH1 covers the neutron energy range 54.6 to 1013 eV; PH4 covers the range 1.028 to 2.06 MeV.

that the background pulse-height distribution in each energy range has the same shape and that the amplitude of the distribution is proportional to the time width corresponding to the energy range. For the fission chambers studied here, pulse-height-distribution 1 (PH1) has few fission events but many background events due to its long time width and low neutron flux. In contrast, pulse-height-distribution 4 (PH4) has a strong fission-fragment peak with few background events (see Fig. 3). Thus PH4, with its peak normalized to the fission fragment peak of PH1, can be subtracted from PH1 leaving a pure background distribution. This background distribution is then normalized to each time-of-flight interval and subtracted from the corresponding pulse-height distribution to produce a pure fission-fragment distribution.

In the fission chambers for which the tail of the background events in PH1 extends under the peak of the fission events (Fig. 4 illustrates this), the total events in the tail of PH4 is normalized to

the total events in the tail of PH1 beyond the background and then the subtraction proceeds as previously described.

Once pure fission-fragment distributions are obtained, the efficiencies for each energy range can be calculated relative to the reference channel. The errors in these efficiencies come from the uncertainty in the number of counts in each channel and the uncertainty in any corrections made to these counts during background subtraction. It should be noted that because the efficiencies for a given pulse-height distribution in a particular fission chamber are strongly correlated, the statistical error is not valid for comparison of efficiencies between different channels in the same pulse-height distribution. The errors are only valid in comparing the same bias channel for different pulse-height distributions.

The results for each fission chamber are shown in Tables 3-11. Some of the results have been omitted from the tables either because of large uncertainties

Table 3. Efficiency of fission chamber 1 (pure ^{238}U) as a function of neutron energy and bias level relative to a reference level at channel 23.

Channel number	Efficiency (%)			
	0.1101-1.028 MeV	1.028-2.06 MeV	2.06-5.38 MeV	5.38-9.70 MeV
31	98.4 $\pm$ 0.4	98.2 $\pm$ 0.1	98.2 $\pm$ 0.1	98.4 $\pm$ 0.1
34	95.1 $\pm$ 0.8	95.2 $\pm$ 0.1	95.0 $\pm$ 0.1	95.0 $\pm$ 0.1
36	90.5 $\pm$ 1.0	91.1 $\pm$ 0.2	91.0 $\pm$ 0.1	91.4 $\pm$ 0.2
39	80.9 $\pm$ 1.4	81.3 $\pm$ 0.2	80.9 $\pm$ 0.2	81.0 $\pm$ 0.3
41	71.9 $\pm$ 1.6	71.6 $\pm$ 0.3	71.5 $\pm$ 0.2	70.9 $\pm$ 0.3
43	60.5 $\pm$ 1.7	60.0 $\pm$ 0.3	60.2 $\pm$ 0.2	59.3 $\pm$ 0.3
45	49.2 $\pm$ 1.8	48.3 $\pm$ 0.3	48.6 $\pm$ 0.3	47.3 $\pm$ 0.3
47	39.1 $\pm$ 1.7	37.9 $\pm$ 0.3	38.1 $\pm$ 0.2	36.7 $\pm$ 0.3
52	20.3 $\pm$ 1.4	20.6 $\pm$ 0.2	21.1 $\pm$ 0.2	19.6 $\pm$ 0.3

from the background subtraction or because the background subtraction process caused a strong correlation between the

distribution used as the source of the background distribution (PH1) and the distribution used to subtract fission counts from PH1.

Table 4. Efficiency of fission chamber 2 (pure ^{235}U) as a function of neutron energy and bias level relative to a reference level at Channel 11.

Channel number	Efficiency (%)					
	54.6-1013 eV	1,013-110.1 keV	0,1101-1,028 MeV	1,028-2,06 MeV	2,06-5,38 MeV	5,38-9,70 MeV
23	98.0 ± 0.6	97.9 ± 0.1	97.9 ± 0.0	98.0 ± 0.0	98.0 ± 0.1	98.0 ± 0.1
28	95.5 ± 0.6	94.8 ± 0.1	94.9 ± 0.0	95.0 ± 0.1	94.9 ± 0.1	94.9 ± 0.1
32	91.0 ± 0.6	90.0 ± 0.1	90.0 ± 0.1	90.4 ± 0.1	90.1 ± 0.1	90.0 ± 0.2
36	80.2 ± 0.7	79.9 ± 0.2	79.7 ± 0.1	79.7 ± 0.1	79.6 ± 0.2	79.0 ± 0.3
38	72.0 ± 0.7	71.9 ± 0.2	71.4 ± 0.1	71.4 ± 0.1	71.2 ± 0.2	70.3 ± 0.3
40	61.8 ± 0.7	62.3 ± 0.2	61.3 ± 0.1	61.4 ± 0.1	61.4 ± 0.2	60.1 ± 0.3
42	52.0 ± 0.7	52.5 ± 0.2	51.7 ± 0.1	51.2 ± 0.2	51.2 ± 0.2	49.6 ± 0.3
44	42.9 ± 0.7	43.7 ± 0.2	42.6 ± 0.1	42.0 ± 0.2	42.1 ± 0.2	40.6 ± 0.3
52	19.5 ± 0.5	20.8 ± 0.2	20.0 ± 0.1	19.6 ± 0.1	19.7 ± 0.2	18.6 ± 0.2

Table 5. Efficiency of fission chamber 3 ($^{238}\text{U} + ^{235}\text{U}$ mixture) as a function of neutron energy and bias level relative to a reference level at channel 21.

Channel number	Efficiency (%)					
	59,6-1013 eV	1,013-110.1 keV	0,1101-1,028 MeV	1,028-2,06 MeV	2,06-5,38 MeV	5,38-9,70 MeV
29	98.3 ± 0.5	98.4 ± 0.1	98.4 ± 0.0	98.3 ± 0.0	98.3 ± 0.1	98.3 ± 0.1
32	94.8 ± 0.6	94.4 ± 0.2	94.2 ± 0.1	94.2 ± 0.1	94.1 ± 0.1	94.0 ± 0.1
34	90.1 ± 0.7	89.3 ± 0.2	89.0 ± 0.1	88.8 ± 0.1	88.8 ± 0.1	88.9 ± 0.2
36	82.4 ± 0.8	81.6 ± 0.3	81.3 ± 0.1	80.7 ± 0.1	80.8 ± 0.2	81.0 ± 0.2
38	72.3 ± 0.9	71.5 ± 0.3	71.0 ± 0.1	70.3 ± 0.2	70.3 ± 0.2	70.0 ± 0.2
40	60.9 ± 0.9	59.6 ± 0.3	59.0 ± 0.2	57.9 ± 0.2	57.9 ± 0.2	57.2 ± 0.3
41	54.5 ± 0.9	53.2 ± 0.3	52.8 ± 0.2	51.4 ± 0.2	51.5 ± 0.2	50.7 ± 0.3
43	42.6 ± 0.9	41.8 ± 0.3	41.0 ± 0.2	39.7 ± 0.2	39.8 ± 0.2	38.8 ± 0.3
48	23.2 ± 0.8	21.5 ± 0.3	20.9 ± 0.1	20.0 ± 0.1	20.1 ± 0.2	19.2 ± 0.2

Table 6. Efficiency of fission chamber 4 (pure ^{233}U) as a function of neutron energy and bias level relative to a reference level at channel 31.

Channel number	Efficiency (%)				
	1,013- 110.1 keV	0,1101- 1,028 MeV	1,028- 2,06 MeV	2,06- 5,38 MeV	5,38- 9,70 MeV
42	98,0 ± 0,2	97,9 ± 0,0	97,9 ± 0,0	98,0 ± 0,0	98,0 ± 0,1
44	95,2 ± 0,2	95,1 ± 0,0	95,0 ± 0,1	95,1 ± 0,1	95,1 ± 0,1
46	89,9 ± 0,2	89,8 ± 0,1	89,7 ± 0,1	89,8 ± 0,1	89,6 ± 0,2
48	81,9 ± 0,2	81,6 ± 0,1	81,5 ± 0,1	81,6 ± 0,1	81,1 ± 0,2
50	71,3 ± 0,2	71,1 ± 0,1	70,8 ± 0,1	70,8 ± 0,2	70,3 ± 0,2
52	59,9 ± 0,2	59,6 ± 0,1	59,2 ± 0,1	59,3 ± 0,2	58,7 ± 0,3
54	48,9 ± 0,2	48,6 ± 0,1	48,2 ± 0,1	48,1 ± 0,2	47,5 ± 0,3
56	39,2 ± 0,2	38,9 ± 0,1	38,4 ± 0,1	38,4 ± 0,2	38,0 ± 0,3
61	22,1 ± 0,2	21,6 ± 0,1	21,4 ± 0,1	21,1 ± 0,1	20,9 ± 0,2

Table 7. Efficiency of fission chamber 5 (^{233}U + ^{238}U) as a function of neutron energy and bias level relative to a reference level at channel 24.

Channel number	Efficiency (%)				
	1,013- 110.1 keV	0,1101- 1,028 MeV	1,028- 2,06 MeV	2,06- 5,38 MeV	5,38- 9,70 MeV
33	98,9 ± 0,9	98,0 ± 0,1	98,0 ± 0,1	98,0 ± 0,1	98,0 ± 0,1
36	95,0 ± 0,9	94,2 ± 0,1	94,2 ± 0,1	94,4 ± 0,1	94,5 ± 0,2
38	90,3 ± 0,9	89,3 ± 0,2	89,6 ± 0,2	89,5 ± 0,2	89,5 ± 0,2
40	82,5 ± 0,9	82,2 ± 0,2	82,4 ± 0,2	82,3 ± 0,2	81,8 ± 0,3
42	73,1 ± 0,9	72,5 ± 0,2	72,8 ± 0,2	72,7 ± 0,3	71,5 ± 0,4
44	62,8 ± 0,8	61,8 ± 0,3	61,8 ± 0,3	62,0 ± 0,3	60,2 ± 0,4
46	52,8 ± 0,8	51,4 ± 0,3	50,7 ± 0,3	51,3 ± 0,3	49,3 ± 0,4
48	43,0 ± 0,7	42,5 ± 0,3	41,9 ± 0,3	42,2 ± 0,3	40,2 ± 0,4
55	22,0 ± 0,6	22,5 ± 0,2	21,5 ± 0,2	21,4 ± 0,2	20,4 ± 0,3

Table 8. Efficiency of fission chamber 6 (^{234}U) as a function of neutron energy and bias level relative to a reference level at channel 26.

Channel number	Efficiency (%)				
	0.1005- 1.018 MeV	1.018- 2.04 MeV	2.04- 5.28 MeV	5.28- 9.47 MeV	9.47- 87.1 MeV ^a
35	98.2 ± 0.2	98.1 ± 0.1	98.3 ± 0.1	98.2 ± 0.2	98.1 ± 0.3
38	95.7 ± 0.2	95.5 ± 0.1	95.5 ± 0.2	95.7 ± 0.2	95.9 ± 0.4
41	90.0 ± 0.2	89.8 ± 0.2	89.7 ± 0.2	90.1 ± 0.3	89.9 ± 0.6
44	80.3 ± 0.3	80.1 ± 0.3	80.3 ± 0.3	80.3 ± 0.4	80.2 ± 0.7
46	71.5 ± 0.3	71.7 ± 0.3	71.6 ± 0.4	71.7 ± 0.5	72.2 ± 0.8
48	61.7 ± 0.3	62.1 ± 0.3	62.8 ± 0.4	62.1 ± 0.5	61.7 ± 0.8
51	48.1 ± 0.3	48.8 ± 0.3	49.2 ± 0.4	48.4 ± 0.6	47.6 ± 0.8
53	40.4 ± 0.3	40.7 ± 0.3	41.5 ± 0.4	40.5 ± 0.5	39.7 ± 0.8
61	20.3 ± 0.3	20.8 ± 0.3	21.0 ± 0.3	20.4 ± 0.4	19.5 ± 0.6

^aVery few neutrons in this range have energies greater than 30 MeV.

Table 9. Efficiency of fission chamber 7 ($^{234}\text{U} + ^{235}\text{U}$) as a function of neutron energy and bias level relative to a reference level at channel 22.

Channel number	Efficiency (%)				
	0.1005- 1.018 MeV	1.018- 2.04 MeV	2.04- 5.28 MeV	5.28- 9.47 MeV	9.47- 87.1 MeV ^a
33	98.2 ± 0.1	98.4 ± 0.1	98.0 ± 0.1	98.2 ± 0.1	98.5 ± 0.2
36	95.3 ± 0.1	95.1 ± 0.1	94.8 ± 0.2	94.8 ± 0.2	95.5 ± 0.3
38	90.5 ± 0.1	90.1 ± 0.2	90.0 ± 0.2	90.0 ± 0.3	90.4 ± 0.4
40	82.3 ± 0.2	82.0 ± 0.2	81.5 ± 0.3	81.7 ± 0.4	82.0 ± 0.5
42	70.8 ± 0.2	70.6 ± 0.2	70.2 ± 0.3	69.5 ± 0.4	70.5 ± 0.6
44	58.5 ± 0.2	58.4 ± 0.3	57.9 ± 0.3	57.0 ± 0.5	57.9 ± 0.7
45	52.7 ± 0.2	52.5 ± 0.3	51.9 ± 0.3	50.9 ± 0.5	51.8 ± 0.7
47	42.6 ± 0.2	42.1 ± 0.3	41.6 ± 0.3	40.6 ± 0.5	41.1 ± 0.7
54	20.4 ± 0.2	20.0 ± 0.3	19.7 ± 0.3	19.1 ± 0.4	18.5 ± 0.5

^aVery few neutrons in this range have energies greater than 30 MeV.

Table 10. Efficiency of fission chamber 8 (^{236}U) as a function of neutron energy and bias level relative to a reference level at channel 20.

Channel number	Efficiency (%)				
	0.1005- 1.018 MeV	1.018- 2.04 MeV	2.04- 5.28 MeV	5.28- 9.47 MeV	9.47- 87.1 MeV ^a
35	97.8 ± 0.3	97.8 ± 0.3	98.1 ± 0.1	98.0 ± 0.2	98.4 ± 0.2
41	93.9 ± 0.4	94.5 ± 0.2	94.3 ± 0.2	94.9 ± 0.2	95.0 ± 0.3
45	89.7 ± 0.5	90.4 ± 0.2	90.0 ± 0.2	90.2 ± 0.3	90.9 ± 0.4
50	79.4 ± 0.7	80.5 ± 0.3	80.0 ± 0.3	79.7 ± 0.4	80.5 ± 0.6
53	70.2 ± 0.7	70.6 ± 0.3	69.7 ± 0.4	68.6 ± 0.5	70.4 ± 0.7
56	60.2 ± 0.9	59.2 ± 0.4	58.3 ± 0.4	56.4 ± 0.5	58.8 ± 0.7
58	53.9 ± 0.8	51.4 ± 0.4	50.9 ± 0.4	48.9 ± 0.5	51.7 ± 0.7
62	42.3 ± 0.8	38.8 ± 0.4	38.6 ± 0.4	36.9 ± 0.5	39.1 ± 0.7
71	22.9 ± 0.7	21.0 ± 0.3	21.1 ± 0.3	19.7 ± 0.4	20.3 ± 0.6

^aVery few neutrons in this range have energies greater than 30 MeV.

Table 11. Efficiency of fission chamber 9 ($^{236}\text{U} + ^{235}\text{U}$) as a function of neutron energy and bias level relative to a reference level at channel 18.

Channel number	Efficiency (%)					
	1.009- 100.5 keV	0.1005- 1.018 MeV	1.018- 2.04 MeV	2.04- 5.28 MeV	5.28- 9.47 MeV	9.47- 87.1 MeV ^a
29	98.0 ± 0.3	97.9 ± 0.1	98.0 ± 0.1	98.1 ± 0.1	98.0 ± 0.1	97.9 ± 0.2
33	95.6 ± 0.4	95.3 ± 0.1	95.4 ± 0.1	95.3 ± 0.1	95.4 ± 0.2	95.0 ± 0.3
37	90.8 ± 0.5	90.4 ± 0.2	90.5 ± 0.2	90.6 ± 0.2	90.4 ± 0.3	90.2 ± 0.4
41	82.4 ± 0.6	81.4 ± 0.2	81.7 ± 0.2	81.6 ± 0.3	81.4 ± 0.3	81.5 ± 0.5
44	72.3 ± 0.6	71.1 ± 0.3	71.5 ± 0.3	71.2 ± 0.3	70.3 ± 0.4	70.4 ± 0.6
47	59.8 ± 0.7	58.7 ± 0.3	58.7 ± 0.3	58.4 ± 0.3	57.0 ± 0.4	57.1 ± 0.6
49	51.9 ± 0.7	50.7 ± 0.3	50.2 ± 0.3	50.1 ± 0.3	48.8 ± 0.4	48.0 ± 0.6
52	41.4 ± 0.7	40.3 ± 0.3	39.5 ± 0.3	39.5 ± 0.3	38.1 ± 0.4	37.6 ± 0.6
60	23.0 ± 0.6	21.7 ± 0.2	21.0 ± 0.2	21.0 ± 0.3	20.1 ± 0.4	19.6 ± 0.5

^aVery few neutrons in this range have energies greater than 30 MeV.

Conclusions

The measured relative efficiencies shown in Tables 3-11 have little energy dependence between 54 eV and 30 MeV for efficiencies of 90% and higher. The largest variation of efficiency with en-

ergy in the 90% efficiency region is $1.3 \pm 0.7\%$ in the $^{235}\text{U} + ^{236}\text{U}$ chamber (Table 5). Also, these high efficiencies show no significant effect in the energy band centered around 7 MeV, where the

(n, n'f) threshold occurs and measured angular anisotropies of fission fragments are large.⁴ The present data give no direct measure of the real efficiencies of the fission chambers at the reference levels, but they provide a base for estimating the energy variation of the real efficiencies. Such an estimate can be made if one assumes that the real efficiency is high (>95%) at the reference level and that the magnitude of any energy-dependent variation in efficiency varies linearly with one minus the efficiency. Given these assumptions, the variation in efficiency at the reference level is less than one-third the variation at the 90% level relative to the reference level. The assumptions used to obtain this estimate are consistent with simple models for the cause of inefficiency in a fission chamber such as loss of the fragments in the fissionable coatings of the foils in the chamber.⁵

For relative efficiencies less than 80% the general trend is for efficiency to decrease with increasing neutron energy. A possible explanation for this effect is that the energy variation of the efficiencies is dominated by the energy dependence of the fragment angular distribution, and the fragments being rejected at low ef-

ficiencies are mostly those that travel nearly perpendicular to the fission chamber plates (nearly parallel to the neutron direction). These perpendicular fragments produce less ionization in the chamber than the fragments that cross at large angles relative to the normal to the chamber plates. Thus, as neutron energy increases the angular distribution becomes more peaked parallel to the neutron direction or perpendicular to the chamber plates, and more fragments produce insufficient ionization to be accepted.

The present results and analysis indicate that the effect on fission-cross-section ratio measurements of the energy dependence in the efficiencies of the present fission chambers is probably less than 0.5% when the data include all pulse heights above the reference level. In contrast, ratio data taken with chambers like the present fission chambers operating at efficiencies less than 80% to avoid alpha pileup may have efficiencies decreasing by as much as 2-5% from low to high neutron energy. The present results lack sufficient energy resolution and precision to make corrections to cross-section ratio data, but they do provide a guide for estimating errors.

References

1. J. W. Behrens and G. W. Carlson, High Energy Measurements of Neutron-Induced Fission Cross Section Ratios Involving ^{233}U , ^{235}U , ^{238}U , and ^{239}Pu , Lawrence Livermore Laboratory Rept. UCID-16548 (1974).
2. J. W. Behrens, Preparation of Fission Foils for Fission Ionization Chambers Using a Painting Technique, Lawrence Livermore Laboratory Rept. UCRL-51476 (1973).
3. B. Rossi and H. H. Staub, "Ionization Chambers and Counters," Nat. Nucl. Energy Ser. Div. V2 (1949).
4. J. E. Simmons and R. L. Henkel, "The Angular Distribution of Fragments in Fission Induced by MeV Neutrons," Phys. Rev. **120**, 198 (1960).
5. G. W. Carlson, "The Effect of Fragment Anisotropy on Fission Chamber Efficiency," Nucl. Instr. Meth. **119**, 97 (1974).