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Contents

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Abstract

The ratio of the neutron-induced fission cross section of ^{241}Pu relative to that of ^{235}U was measured with fission ionization chambers at the LLL 100-MeV electron linear accelerator. The time-of-flight technique was used to measure the cross-section ratio as a function of neutron energy from 0.001 to 30 MeV. The continuous energy spectrum of the neutron source allowed us to cover the entire energy range in one measurement. Pulse height distributions were also measured as functions of energy over broad energy bands. These data were used to estimate the energy variation in the efficiency to be less than 0.75%. The threshold cross-section method normalized the ratio independent of other cross-section measurements to 1.268 ± 0.022 in the interval 1.75 to 4.00 MeV. The ratio was also taken to thermal neutron energy where it was normalized to evaluated thermal fission cross sections and the resulting ratio in the 1.75- to 4.00-MeV interval was 1.242 ± 0.021. Corrected for the impurities in the ^{241}Pu sample, the average of these two values resulted in a ^{241}Pu:^{235}U fission cross-section ratio of 1.251 ± 0.016 for the normalization interval. Typical energy resolution is 5% at 20.0, 1.0, and 0.1 MeV. Most of the data have counting uncertainties smaller than 4%, expressed as a standard deviation. Systematic errors are discussed, and current results are compared with previous measurements. Tables of our data are included.

Introduction

The neutron-induced fission cross section of ^{241}Pu is of importance in designing fast breeder reactors since in some instances ^{241}Pu constitutes about 5% of the plutonium content in the fuel. A common way to measure a fission cross section is to measure it with respect to the fission cross section of another isotope, e.g., ^{235}U. A recent measurement has been reported that gives the fission cross-section ratio $^{241}Pu:^{235}U$ in the neutron energy range 0.01 to 1 MeV.[1] Other measurements of the fission cross section of ^{241}Pu and its ratio with respect to that of ^{235}U are also available.[2-7] The present work represents a continuation of the fission-cross-section-ratio measurements in progress at LLL and reports the $^{241}Pu:^{235}U$ fission cross-section ratio from 0.001 to 30 MeV. The continuous energy spectrum of the neutron source allowed us to cover the entire energy range in one measurement.

To normalize our fission cross section ratio we used two independent methods. In the MeV energy range, the ratio was normalized using the threshold cross-section method. The ratio was also taken to thermal neutron energy where it was normalized to the ratio of the thermal fission cross sections.

Most of our experimental procedures have been documented.[8-10] This report summarizes most of these procedures; however, those not previously discussed, e.g., normalization at thermal neutron energy, are treated in more detail.

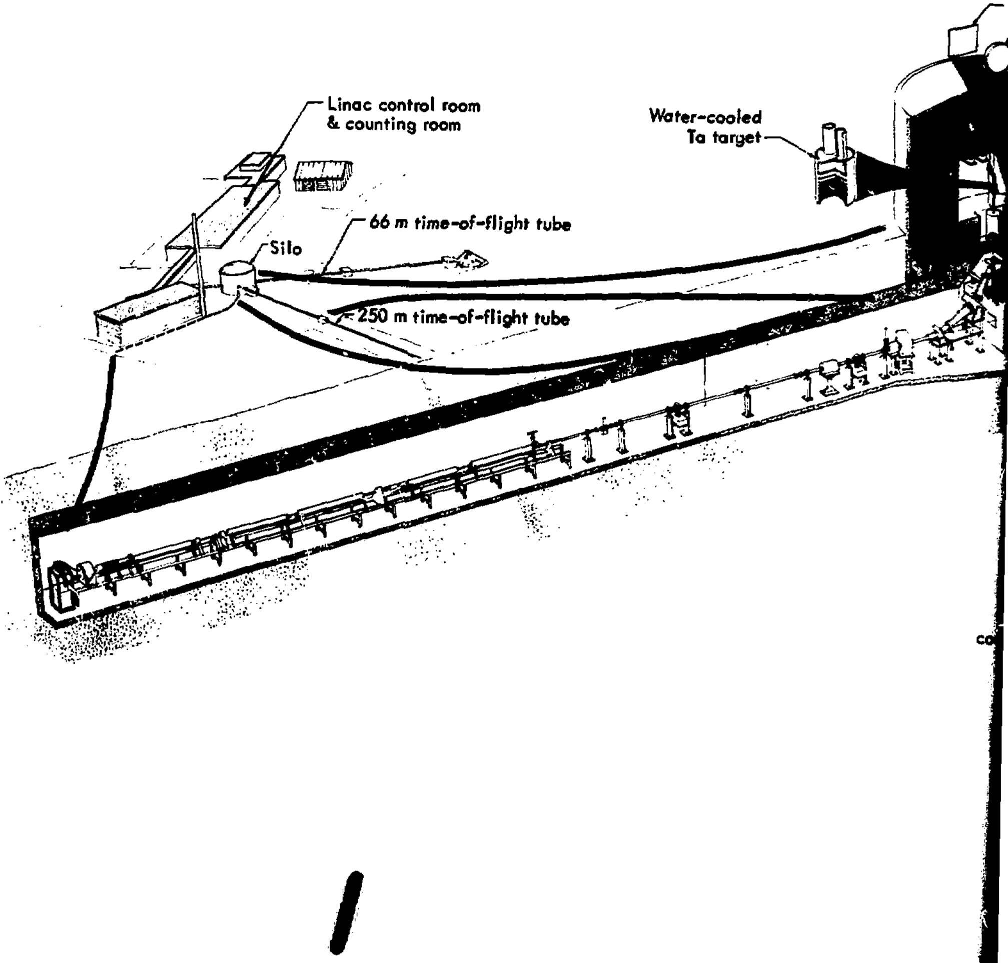
The Experiment

NEUTRON SOURCE AND DETECTORS

The ratio measurements were made with fission chambers at the 34.3-m station of the 250-m time-of-flight tube at the LLL 100-MeV linac (Fig. 1). For the high-energy measurement, (0.001 to 30 MeV), the linac was operated at 1440 Hz with an electron pulse width of 10 ns to produce neutrons in a water-cooled-tantalum target. For purposes of thermal normalization, a low-energy measurement (0.015 to 30 keV), was taken with the linac operated at 15 Hz, an electron pulse width of 2 μs, and a water moderator surrounding the target.

Our fission detectors are parallel-plate ionization chambers of modular design placed back-to-back in a pressure vessel with the foils oriented perpendicular to the incident neutron beam. Tables 1 and 2 give the isotopic compositions and areal densities of the fissionable materials and a description of the contents of the modular fission chambers.

Time-of-flight and pulse-height information were processed for each event in our data acquisition system.


Linac control room
& counting room
Water-cooled
Ta target
66 m time-of-flight tube
Silo
250 m time-of-flight tube

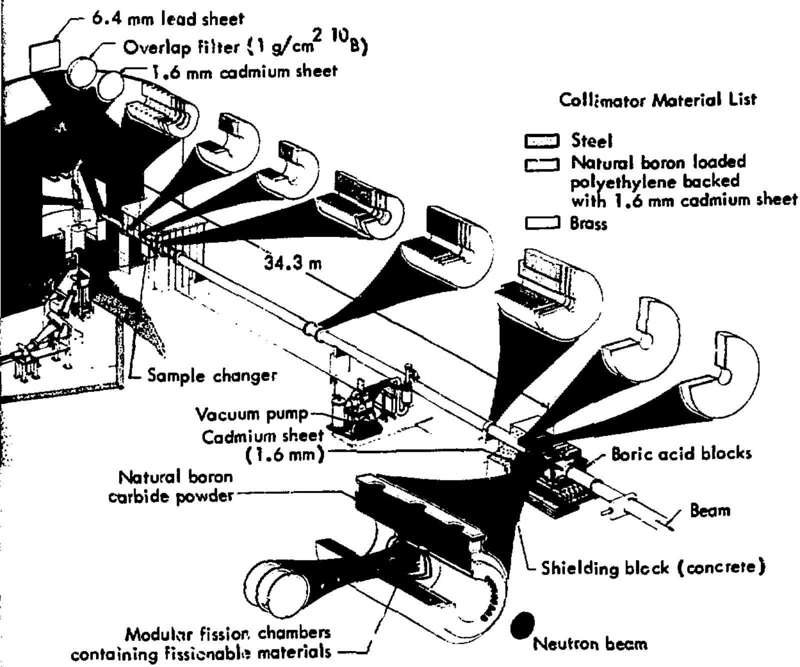


Fig. 1. The 100-MeV electron linear accelerator (linac) and experimental setup.

2

Table 1. Isotopic analyses of high-purity isotopes using mass spectrometry.

Isotope[a]	Isotopic composition mass number (at.%)								
	234	235	236	238	239	240	241	242	244
^{235}U	0.03	99.91	0.02	0.04					
^{238}U[b]		0.0006		99.99+					
^{241}Pu[c]				<0.0004	1.372	0.234	98.30	0.088	<0.0004

[a]These high-purity isotopes were obtained by our Special Materials Department from Oak Ridge National Laboratory and were separated using the Oak Ridge calutrons.

[b]Used in the ^{241}Pu, ^{238}U mixture for modular fission chamber 4.

[c]The ^{241}Pu sample was separated from ^{241}Am using an ion exchange column. The isotopic composition was then determined using mass spectrometry. At the midtime of the experiment, the sample was 97.30 at.% ^{241}Pu and 1.00 at.% ^{241}Am, assuming a beta-decay half life of 14.4 yr.

Table 2. Description of modular fission chambers.

Modular fission chamber No.	Description[a]	Total fissionable material (mg)	Areal density per coated surface (g/m^2)
1	5 foils of ^{235}U	135	3.0
2	2 foils of ^{241}Pu	35	1.9
3	2 foils of ^{241}Pu	35	1.9
4	4 foils of ^{241}Pu, ^{238}U	75	2.1

[a]Each foil was coated on both sides with fissionable material. Foil coating was restricted to a 76-mm diameter.

Typical pulse-height distributions for the ^{235}U and ^{241}Pu fission chambers are shown in Figs. 2 and 3. These distributions were measured as functions of neutron energy over broad energy bands. The real efficiency for detecting fission fragment was estimated to be 96 ± 2% for the ^{235}U chamber and 86 ± 5% for the ^{241}Pu and ^{241}Pu, ^{238}U chambers. Measurements of the energy dependence of the efficiency of the modular fission chambers were used to estimate the energy variation in the efficiency to be less than 0.75% for the present chambers operated at their maximum efficiencies.

Details of the fission chambers, electronics, and data acquisition system have been reported.[9,10]

TIMING, RESOLUTION, AND BACKGROUNDS

The gamma flash from the tantalum target was our main timing reference for the high-energy measurement. In earlier experiments,[8] we verified the gamma flash timing to within about 10 ns by measuring the location of the 6.295 ± 0.016- and 2.079 ± 0.003-MeV resonances of carbon[11] and the 0.525 ± 0.002-MeV resonance of lead.[12] In the present measurement,

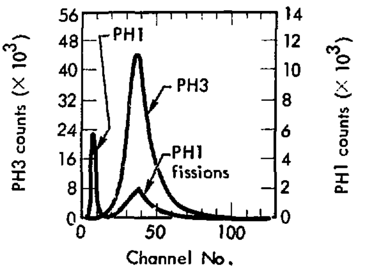


Fig. 2. Pulse-height distributions from modular fission chamber 1 (^{235}U). PH1 covers the neutron energy range 13.0 to 1012 eV; PH3 covers the range 0.0962 to 1.01 MeV.

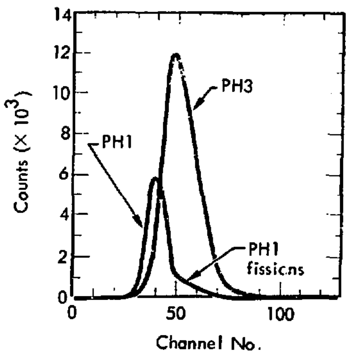


Fig. 3. Pulse-height distributions from modular fission chamber 2 (^{241}Pu). PH1 covers the neutron energy range 13.0 to 1012 eV; PH3 covers the range 0.0962 to 1.01 MeV.

the lead resonance was used to confirm the gamma flash timing. Our time-to-energy conversion includes the relativistic correction.

The resolution of the high-energy measurement was about 0.38 ns per meter. The data are reported with a minimum time per channel of 16 ns, which corresponds to 5.9% energy resolution at 20 MeV at the 34.3-m time-of-flight station. Below 5 MeV, the data were compressed to give about 5% energy resolution at 1.0 and 0.1 MeV.

Out-of-time neutron backgrounds were measured earlier[8] using the black-resonance absorber technique and found to contribute an error of <0.1%. This was confirmed in the present experiment by looking at the 2.85-keV sodium resonance during a portion of the high-energy measurement.

The relative timing of fission chambers was not affected when the electron pulse width was changed from 10 ns to 2 μs; however, the absolute timing, used to determine the energy scale, was changed by about 1 μs. Timing for our low-energy measurement was verified to within about 0.1 μs by measuring the location of the 34.70 ± 0.10-keV aluminum, the 1.098 ± 0.002-keV manganese, and the 60.3 ± 0.1-eV gold resonances.[12]

Out-of-time neutron backgrounds were measured using the black resonance absorber technique and found to contribute an error of <0.1%. The use of sodium and gold absorbers and a Pyrex glass overlap filter, containing about 4 wt% boron, allowed us to measure these backgrounds at 2.850 keV, 4.906 eV, and <0.002 eV, respectively.

Time-independent backgrounds due to amplifier noise, alpha- and beta-particle pileup, and spontaneous fission were subtracted from both measurements.

NORMALIZATION METHODS

Our data were normalized in the interval 1.75 to 4.00 MeV using a method which we call the threshold cross-section method.[8,9] This method was applied in the present experiment by measuring the ratio of counts in the fission chamber containing the mixture of ^{238}U and ^{241}Pu to the counts in the ^{241}Pu chambers. Below the threshold of ^{238}U, the measured ratio of counts in these chambers gave the ratio of their "effective" masses of ^{241}Pu. This information together with the atom ratio of plutonium to uranium, η, in the mixed chamber allowed us to obtain a normalized ^{238}U:^{241}Pu fission cross

Table 3. Normalization values obtained using the method of threshold cross sections.

Ratio	Energy range (MeV)	Threshold method ratio	Breakdown of uncertainties[a]		
			η	Q	R
$^{238}U:^{241}Pu$[b]	1.75-4.00	0.3473 ± 0.0048	0.0007	0.0033	0.0034
$^{238}U:^{235}U$[c]	1.75-4.00	0.4405 ± 0.0040	0.0010	0.0022	0.0032
$^{241}Pu:^{235}U$[b]	1.75-4.00	1.268 ± 0.022[d]			

[a]As defined in the equation $\frac{\sigma_t(E)}{\sigma_{nt}(E)} = \eta\left(\frac{R(E)}{Q} - 1\right)$.

See Ref. 9 for more details about the threshold cross-section method.

[b]*Not corrected* for impurities in ^{241}Pu sample.

[c]As reported in Ref. 9.

[d]Total error, expressed as a standard deviation, is 0.022, consisting of a statistical error of 0.021 and an estimated systematic error of 0.006.

section ratio. Results for the normalization of our data are shown in Table 3 together with a previously reported value for the fission cross-section ratio $^{238}U:^{235}U$ over this same energy interval.[8] A $^{241}Pu:^{235}U$ fission cross-section ratio of 1.268 ± 0.022 was obtained for the normalization interval.

The data were also normalized by extending the ratio to thermal neutron energy where it was normalized to evaluated fission cross sections.[13] A correction was made for the change in neutron flux across the ^{235}U and ^{241}Pu fission chambers at thermal neutron energy. Normalized in a narrow band about thermal, i.e., 0.0233 to 0.0273 eV, the ratio was then determined in broad energy bands from 1-2, 4-7, 7-10, and 10-20 keV.*

*The energy average of R(E) over the interval E_1 to E_2 is

$$\overline{R} = \frac{1}{E_2-E_1} \int_{E_1}^{E_2} R(E)dE.$$

Table 4. Values obtained by normalization at thermal neutron energy.

Energy range (MeV)	^{241}Pu:^{235}U Fission cross-section ratio[a]			
	Low-energy ratio data	Statistical uncertainty (%)	High-energy ratio data	Statistical uncertainty (%)
2.33E-8 to 2.73E-8	1.7084[b]	0.899		
1.0E-3 to 2.0E-3	1.353	1.44	1.366	1.44
4.0E-3 to 7.0E-3	1.349	1.93	1.342	1.31
7.0E-3 to 1.0E-2	1.321	2.45	1.304	1.57
1.0E-2 to 2.0E-2	1.275	1.77	1.286	1.05
1.75 to 4.00			1.242[c]	0.356

[a]Not corrected for impurities in ^{241}Pu sample.

[b]Fission cross sections used at thermal for ^{235}U, ^{239}Pu, and ^{241}Pu are 580.2±1.8, 741.6±3.1, and 1007.3±7.2 barns, respectively.[13]

[c]Total error, expressed as a standard deviation, is 0.021, consisting of an error due to normalization of 0.010, based on quoted errors in Ref. 13, and a combined counting error of 0.018.

These values normalized the high-energy data. See Table 4 for the results of the thermal normalization. A ^{241}Pu:^{235}U ratio of 1.242 ± 0.021 was determined from 1.75 to 4.00 MeV.

To normalize our data we used a value 1.255 ± 0.015, for the interval 1.75 to 4.00 MeV, which represents an average of the two values. Corrected for the ^{239}Pu, ^{240}Pu, and ^{241}Am impurities in the ^{241}Pu sample, this value was 1.251 ± 0.016.

DETERMINATION OF η

An accurate determination of η is essential for the successful application of the threshold cross-section method. Unlike the cases where two isotopes of the same element were mixed,[8] the present experiment involved a mixture of different elements. Controlled-potential coulometry and isotope-dilution mass spectrometry were used to determine η.

Measurements of η are reported in Table 5 along with their total uncertainties, expressed as a standard deviation, as determined by groups at Lawrence Livermore Laboratory and Los Alamos Scientific Laboratory. A value of 0.2904 ± 0.0006 was used for η in the data analysis. This value was determined using isotope-dilution mass spectrometry by a group at LASL, which analyzed the fission foils from modular fission chamber 4 at the conclusion of our experiment.*

At various intermediate steps other assays were performed as shown in Table 5. Since they were not done on the actual foils used in the experiment, they are not included in the determination of η used in the data analysis. However, these intermediate assays do indicate that gross errors were not present in the preparation technique and lend additional confidence to the Las Alamos assay.

*The following is quoted from the LASL assay report.

"The uncertainty of 0.21 relative percent is expressed as the standard deviation. This uncertainty includes systematic errors (standard deviation) of 0.15% for the ^{233}U 'spike' standardization, 0.09% for the ^{242}Pu 'spike' standardization, and a random standard deviation of 0.11% computed from the duplicate analyses. The standardizations of the ^{233}U and ^{242}Pu were done by isotope dilution mass spectrometry using NBS standards SRM 949 (Pu metal) and SRM 960 (natural U metal) as well as LASL-prepared highly pure ^{235}U metal."[14]

Table 5. Measurements of η, the Pu/U atom ratio.

Method	LLL	LASL
Controlled-potential coulometry	0.2790 ± 0.0024[a]	
Isotope-dilution mass spectrometry	0.2882 ± 0.0013[b]	0.2904 ± 0.0006[c]

[a]Analyzed by J. E. Harrar at LLL. Assay performed on ^{241}Pu and ^{238}U solutions from which known volumes were mixed and used to form the fissionable coating for modular fission chamber 4. Quoted total error based on error analysis of method.[15,16]

[b]Analyzed by R. S. Newbury at LLL. Assay performed on ^{241}Pu, ^{238}U mixture from which the fissionable coating was prepared.

[c]Analyzed by J. E. Rein at LASL. Assay performed on foils after experiment concluded.

Corrections and Errors

Most of our data have statistical counting errors, expressed as a standard deviation, of less than 4%. The $^{241}Pu:^{235}U$ fission cross-section ratio was normalized to a value 1.255 over the energy interval from 1.75 to 4.00 MeV after which corrections were made for the ^{239}Pu, ^{240}Pu, and ^{241}Am impurities in the ^{241}Pu sample. The corrected $^{241}Pu:^{235}U$ ratio was obtained using the expression

$$\begin{aligned}\text{Corrected } {}^{241}Pu:{}^{235}U &= 1.0277({}^{241}Pu:{}^{235}U)\\ &- 0.0141({}^{239}Pu:{}^{235}U)\\ &- 0.0024({}^{240}Pu:{}^{235}U)\\ &- 0.0103({}^{241}Am:{}^{235}U).\end{aligned}$$

The $^{239}Pu:^{235}U$ fission cross-section ratio data of Carlson and Behrens[17] and the $^{240}Pu:^{235}U$ ratio calculated from ENDF/B-IV evaluated fission cross section files were used to make the corrections. The ^{241}Pu beta-decay half life of 14.4 ± 0.4 years, based on an average of three published values,[18-21] was used to calculate a 1.00 at.% ^{241}Am buildup in the ^{241}Pu sample at the midtime of our experiment. The $^{241}Am:^{235}U$ ratio was calculated from ENDF/B-IV evaluated fission cross-section files.

A number of effects contribute systematic errors to our experimental results. These effects are summarized in Table 6. The estimate of energy dependence in detector efficiency was obtained from studies of pulse-height distributions of the detectors as functions of energy. (See Table 7 and Ref. 10.)

Table 6. Systematic errors in the ratio experiment.

Effect	Error size (%)	Correction made	Resultant Uncertainty in ratio (%)
Electronic deadtime	2 max	Yes	<0.01
Accidental coincidences between detectors	<0.1	No	<0.1
Neutron scattering in aluminum foils, etc.	4 max 0.4 typical	Yes	1.0 max 0.1 typical
Out-of-time neutron background	<0.1	No	<0.1
Time-independent background from amplifier noise, pileup, and spontaneous fission	20 max <0.1 typical	Yes	0.4 max <0.01 typical
Energy-dependent detector efficiency	<0.75	No	<0.75
Impurities in samples	3 max	Yes	<0.3 for E_N >1 MeV <0.1 for E_N <1 MeV

Table 7. Efficiencies of three modular fission chambers as functions of neutron energy and bias level relative to the reference levels.

Modular chamber No.	Reference channel	Channel No.	Efficiency (%) within energy intervals					
			1.01–96.2 keV	0.0962–1.01 MeV	1.01–2.06 MeV	2.06–5.38 MeV	5.38–9.72 MeV	9.72–82.8 MeV[a]
1[b]	10	10	100.	100.	100.	100.	100.	100.
		26	94.6±0.0	94.6±0.0	94.6±0.0	94.5±0.0	94.5±0.1	94.6±0.1
		28	91.6±0.1	91.5±0.0	91.4±0.0	91.4±0.1	91.3±0.1	91.4±0.1
		32	81.2±0.1	80.7±0.0	80.5±0.1	80.3±0.1	80.1±0.1	79.7±0.2
		34	73.4±0.1	72.8±0.0	72.4±0.1	72.1±0.1	71.7±0.1	70.9±0.2
		38	54.2±0.1	53.3±0.1	52.7±0.1	52.2±0.1	51.3±0.1	50.0±0.2
2[c]	23	23	100.	100.	100.	100.	100.	100.
		30	96.0±0.2	95.7±0.0	95.7±0.1	95.7±0.1	95.5±0.1	95.5±0.2
		32	90.3±0.2	89.7±0.1	89.7±0.1	89.6±0.1	89.2±0.2	89.4±0.3
		34	80.5±0.2	79.9±0.1	79.7±0.1	79.6±0.2	78.8±0.2	79.0±0.4
		35	74.5±0.2	73.8±0.1	73.5±0.1	73.6±0.2	72.5±0.3	72.8±0.4
		39	48.9±0.2	48.1±0.1	47.8±0.1	47.7±0.2	46.9±0.3	47.6±0.5
4	12	12	100.	100.	100.	100.	100.	100.
		25	96.1±0.4	95.8±0.1	95.7±0.1	95.5±0.1	95.0±0.1	95.5±0.2
		27	90.9±0.4	90.6±0.1	90.1±0.1	90.0±0.1	89.5±0.2	89.9±0.3
		29	82.6±0.4	82.1±0.1	81.6±0.1	81.4±0.2	80.8±0.2	81.7±0.3
		31	72.2±0.4	71.5±0.1	70.8±0.2	70.5±0.2	69.5±0.3	71.2±0.4
		35	50.4±0.4	49.7±0.2	48.9±0.2	49.0±0.2	47.9±0.3	49.4±0.4

[a]Almost all of the neutrons in this energy interval have energies less than 30 MeV.

[b]See Fig. 2 for a plot of several pulse-height distributions.

[c]See Fig. 3 for a plot of several pulse-height distributions.

Table 8. Fission cross-section ratio ^{241}Pu:^{235}U.

Low energy (MeV)	Center energy (MeV)	Ratio[a]	Error[b] (%)
3.5703E+01			
3.3037E+01	3.4331E+01	0.958	7.54
3.0663E+01	3.1816E+01	1.050	6.74
2.8539E+01	2.9572E+01	1.110	6.36
2.6631E+01	2.7560E+01	1.008	6.18
2.4911E+01	2.5749E+01	0.976	5.71
2.3354E+01	2.4113E+01	1.053	5.23
2.1940E+01	2.2630E+01	0.997	4.98
2.0652E+01	2.1281E+01	1.013	4.72
1.9475E+01	2.0050E+01	0.947	4.59
1.8397E+01	1.8925E+01	0.990	4.22
1.7407E+01	1.7892E+01	0.991	3.91
1.6495E+01	1.6942E+01	1.050	3.62
1.5654E+01	1.6066E+01	0.970	3.49
1.4876E+01	1.5257E+01	0.994	3.29
1.4155E+01	1.4508E+01	1.015	3.15
1.3485E+01	1.3814E+01	1.083	3.04
1.2862E+01	1.3168E+01	1.100	2.98
1.2282E+01	1.2567E+01	1.139	2.94
1.1740E+01	1.2006E+01	1.106	2.85
1.1234E+01	1.1483E+01	1.140	2.73
1.0753E+01	1.0993E+01	1.149	2.58
1.0315E+01	1.0533E+01	1.192	2.45
9.8972E+00	1.0103E+01	1.143	2.34
9.5046E+00	9.6979E+00	1.127	2.24
9.1351E+00	9.3171E+00	1.092	2.13
8.7868E+00	8.9584E+00	1.084	2.04
8.4581E+00	8.6201E+00	1.097	1.95
8.1476E+00	8.3007E+00	1.095	1.87
7.8540E+00	7.9988E+00	1.078	1.83
7.5760E+00	7.7131E+00	1.112	1.79
7.3126E+00	7.4425E+00	1.102	1.79
7.0627E+00	7.1860E+00	1.157	1.75
6.8255E+00	6.9425E+00	1.1[illegible]9	1.75
6.6000E+00	6.7113E+00	1.197	1.79
6.3856E+00	6.4915E+00	1.258	1.83
6.1815E+00	6.2823E+00	1.223	1.92
5.9871E+00	6.0831E+00	1.256	1.98
5.8017E+00	5.8933E+00	1.290	2.02
5.6248E+00	5.7122E+00	1.286	2.09
5.4559E+00	5.5394E+00	1.298	2.09
5.2945E+00	5.3743E+00	1.247	2.11
5.1402E+00	5.2165E+00	1.258	2.13
4.9926E+00	5.0656E+00	1.242	2.13
4.8513E+00	4.9212E+00	1.279	2.11
4.5660E+00	4.7158E+00	1.238	1.52
4.3420E+00	4.4615E+00	1.208	1.56
4.1170E+00	4.2273E+00	1.213	1.53
3.9091E+00	4.0111E+00	1.229	1.52
3.7166E+00	3.8110E+00	1.223	1.55
3.5380E+00	3.6256E+00	1.241	1.51
3.3719E+00	3.4535E+00	1.210	1.51
3.2174E+00	3.2933E+00	1.244	1.49
3.0732E+00	3.1440E+00	1.238	1.43

Table 8. (continued)

Low energy (MeV)	Center energy (MeV)	Ratio[a]	Error[b] (%)
2.9385E+00	3.0047E+00	1.261	1.41
2.8125E+00	2.8745E+00	1.237	1.41
2.6944E+00	2.7525E+00	1.255	1.36
2.5837E+00	2.6382E+00	1.219	1.32
2.4796E+00	2.5308E+00	1.244	1.27
2.3817E+00	2.4299E+00	1.251	1.23
2.2895E+00	2.3349E+00	1.280	1.19
2.2025E+00	2.2454E+00	1.242	1.18
2.1204E+00	2.1609E+00	1.277	1.16
2.0429E+00	2.0811E+00	1.282	1.16
1.9343E+00	1.9875E+00	1.284	0.92
1.8341E+00	1.8832E+00	1.313	0.91
1.7415E+00	1.7869E+00	1.324	0.89
1.6558E+00	1.6979E+00	1.350	0.88
1.5763E+00	1.6153E+00	1.374	0.86
1.5023E+00	1.5386E+00	1.372	0.85
1.4335E+00	1.4673E+00	1.380	0.84
1.3692E+00	1.4008E+00	1.375	0.85
1.3092E+00	1.3387E+00	1.355	0.88
1.2531E+00	1.2807E+00	1.374	0.86
1.2005E+00	1.2264E+00	1.321	0.86
1.1511E+00	1.1754E+00	1.284	0.87
1.1048E+00	1.1276E+00	1.272	0.90
1.0611E+00	1.0826E+00	1.288	0.90
1.0200E+00	1.0403E+00	1.264	0.95
9.8129E-01	1.0004E+00	1.273	0.98
9.4471E-01	9.6274E-01	1.291	0.95
9.1014E-01	9.2718E-01	1.305	0.94
8.7743E-01	8.9356E-01	1.337	0.95
8.4646E-01	8.6174E-01	1.309	0.98
8.1710E-01	8.3159E-01	1.350	0.99
7.8027E-01	7.9837E-01	1.352	0.87
7.4588E-01	7.6278E-01	1.330	0.88
7.1371E-01	7.2953E-01	1.313	0.91
6.8358E-01	6.9840E-01	1.311	0.93
6.5532E-01	6.6923E-01	1.298	0.96
6.2878E-01	6.4184E-01	1.305	1.01
6.0381E-01	6.1611E-01	1.311	1.03
5.8031E-01	5.9189E-01	1.302	1.03
5.5815E-01	5.6907E-01	1.282	1.06
5.3724E-01	5.4755E-01	1.295	1.07
5.1748E-01	5.2722E-01	1.286	1.13
4.9879E-01	5.0801E-01	1.311	1.11
4.6433E-01	4.8110E-01	1.304	0.04
4.3332E-01	4.4843E-01	1.305	0.98
4.0532E-01	4.1897E-01	1.308	1.01
3.7995E-01	3.9233E-01	1.298	0.99
3.5689E-01	3.6815E-01	1.288	1.04
3.3586E-01	3.4614E-01	1.328	1.06
3.1664E-01	3.2604E-01	1.368	1.09
2.9903E-01	3.0765E-01	1.357	1.15
2.8284E-01	2.9077E-01	1.373	1.21
2.6794E-01	2.7524E-01	1.390	1.26
2.5418E-01	2.6092E-01	1.371	1.30
2.4146E-01	2.4770E-01	1.386	1.34
2.2966E-01	2.3545E-01	1.385	1.41
2.1872E-01	2.2409E-01	1.409	1.46
2.0853E-01	2.1353E-01	1.414	1.52
1.9904E-01	2.0370E-01	1.388	1.56
1.9019E-01	1.9454E-01	1.380	1.60

Table 8. (concluded)

Low energy (MeV)	Center energy (MeV)	Ratio[a]	Error[b] (%)
1.8191E-01	1.8598E-01	1.352	1.65
1.7416E-01	1.7797E-01	1.374	1.71
1.6343E-01	1.6867E-01	1.412	1.46
1.5367E-01	1.5844E-01	1.369	1.55
1.4475E-01	1.4911E-01	1.360	1.65
1.3659E-01	1.4059E-01	1.415	1.68
1.2910E-01	1.3277E-01	1.397	1.70
1.2221E-01	1.2559E-01	1.371	1.79
1.1586E-01	1.1897E-01	1.288	1.91
1.0999E-01	1.1287E-01	1.360	1.94
1.0455E-01	1.0722E-01	1.396	1.99
9.9512E-02	1.0199E-01	1.351	2.06
9.4827E-02	9.7127E-02	1.410	2.13
9.0464E-02	9.2607E-02	1.374	2.28
8.6396E-02	8.8395E-02	1.355	2.44
8.2596E-02	8.4464E-02	1.379	2.42
7.9041E-02	8.0789E-02	1.393	2.52
7.5712E-02	7.7350E-02	1.363	2.78
7.2588E-02	7.4125E-02	1.259	2.55
6.9653E-02	7.1098E-02	1.277	2.67
6.6893E-02	6.8252E-02	1.344	2.69
6.4294E-02	6.5574E-02	1.319	2.74
6.1844E-02	6.3051E-02	1.237	2.80
5.9531E-02	6.0671E-02	1.336	2.80
5.6643E-02	5.8060E-02	1.232	2.63
5.3961E-02	5.5277E-02	1.319	2.64
5.1464E-02	5.2690E-02	1.273	2.75
4.9137E-02	5.0281E-02	1.277	2.79
4.6965E-02	4.8033E-02	1.264	2.91
4.4933E-02	4.5932E-02	1.386	2.94
4.3030E-02	4.3966E-02	1.359	3.15
4.1246E-02	4.2124E-02	1.309	3.31
3.9571E-02	4.0395E-02	1.290	3.13
3.7995E-02	3.8771E-02	1.354	3.20
3.5114E-02	3.6512E-02	1.330	2.49
3.2548E-02	3.3795E-02	1.356	2.57
3.0254E-02	3.1370E-02	1.290	2.54
2.8194E-02	2.9197E-02	1.295	2.64
2.6337E-02	2.7242E-02	1.351	2.67
2.4658E-02	2.5477E-02	1.342	2.83
2.3135E-02	2.3878E-02	1.334	2.92
2.1748E-02	2.2426E-02	1.209	3.00
2.0483E-02	2.1101E-02	1.410	3.11
1.9325E-02	1.9831E-02	1.389	3.14
1.8262E-02	1.8782E-02	1.221	3.28
1.7285E-02	1.7763E-02	1.373	3.30
1.6384E-02	1.6825E-02	1.379	3.49
1.5552E-02	1.5960E-02	1.274	3.61
1.4781E-02	1.5159E-02	1.265	3.65
1.4067E-02	1.4417E-02	1.174	3.76
1.3403E-02	1.3729E-02	1.252	3.71
1.2785E-02	1.3088E-02	1.228	3.82
1.2208E-02	1.2491E-02	1.351	4.05

[a] Corrected for impurities in ^{241}Pu sample.

[b] Error indicates counting error expressed as a standard deviation. Total errors may be estimated by combining the normalization error of 1.20% and the estimated overall systematic error of 1.0% in quadrature with the counting errors in the table.

Results and Comparisons

Our data are shown over the energy range 0.01 to 30 MeV in Fig. 4 and compared with others in Figs. 5, 6, and 7. See Table 8 for a listing of our data. The data of Käppeler and Pfletschinger[1] (0.014 to 1.13 MeV) are in good agreement with our data. The points of White and Warner[2] (1.0, 2.25, 5.4, and 14.1 MeV) are 2-4% higher than our data; however, the data of White, Hodkinson, and Wall[3] (0.040, 0.067, 0.127, 0.312, and 0.505 MeV) are in general agreement. The 0.024-MeV point of Perkin, White, Fieldhouse, Axton, Cross, and Robertson[4], obtained by taking the ratio of the reported ^{241}Pu and ^{235}U fission cross sections, agrees with our data; however, a comparison is difficult since the ratio is not smooth in this part of the energy region. The data of Smith, Smith, and Henkel[5] cover an energy range from 0.12 to 21 MeV. From 0.1 to 1 MeV, these data points have broad energy resolution and have a different shape than our data. Above 1 MeV, the energy resolution improves and the shape of these data is in fair agreement with our work; however, they appear to have a normalization about 10-15% higher than ours.

Our ratio data are reported over the energy range 0.0005 to 0.050 MeV in Fig. 8 as a histogram representing energy averaging over predetermined energy intervals. Corrections for the impurities in the ^{241}Pu sample have been made, and Table 9 contains a listing of these data. Comparisons with the data of Blons[6] and James[7] are also shown in Fig. 8. Total errors for Blons' average fission cross sections lie between 3 and 7%. James' average fission cross sections have errors of 4.9% for ^{241}Pu and 6% for ^{235}U. The ENDF/B-IV evaluated fission cross-section file for ^{235}U was used to obtain values for the ^{241}Pu fission cross section over broad energy intervals from 0.0005 to 0.050 MeV. These values also appear in Table 9.

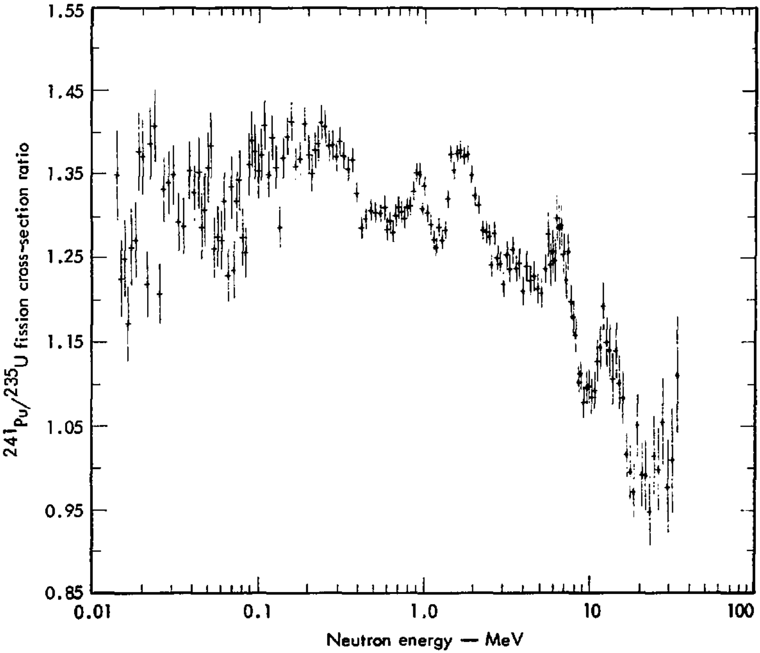


Fig. 4. Ratio of the ^{241}Pu to ^{235}U fission cross sections in the energy range 0.010 to 30 MeV. Present work is given by +. The statistical error bars are shown on each point. See Table 8 for listing.

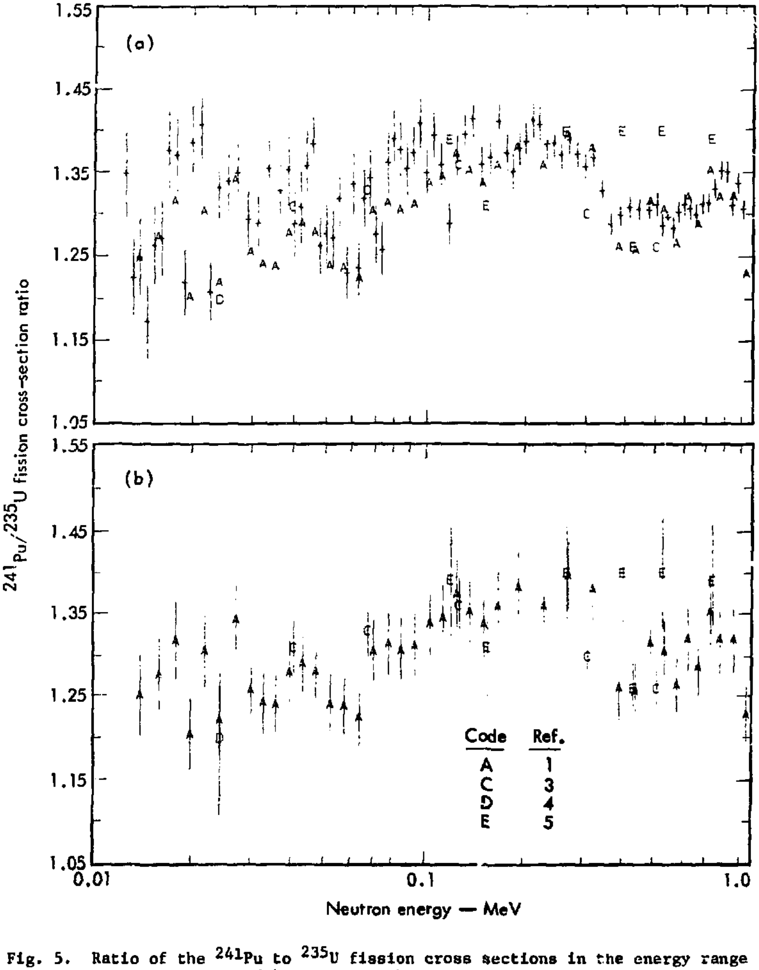


Fig. 5. Ratio of the ^{241}Pu to ^{235}U fission cross sections in the energy range 0.010 to 1 MeV. (a) Present work is given by +. The statistical error bars are shown on each point. Present work is compared with others. (b) Letter codes indicate the work of others. Error bars represent total error.

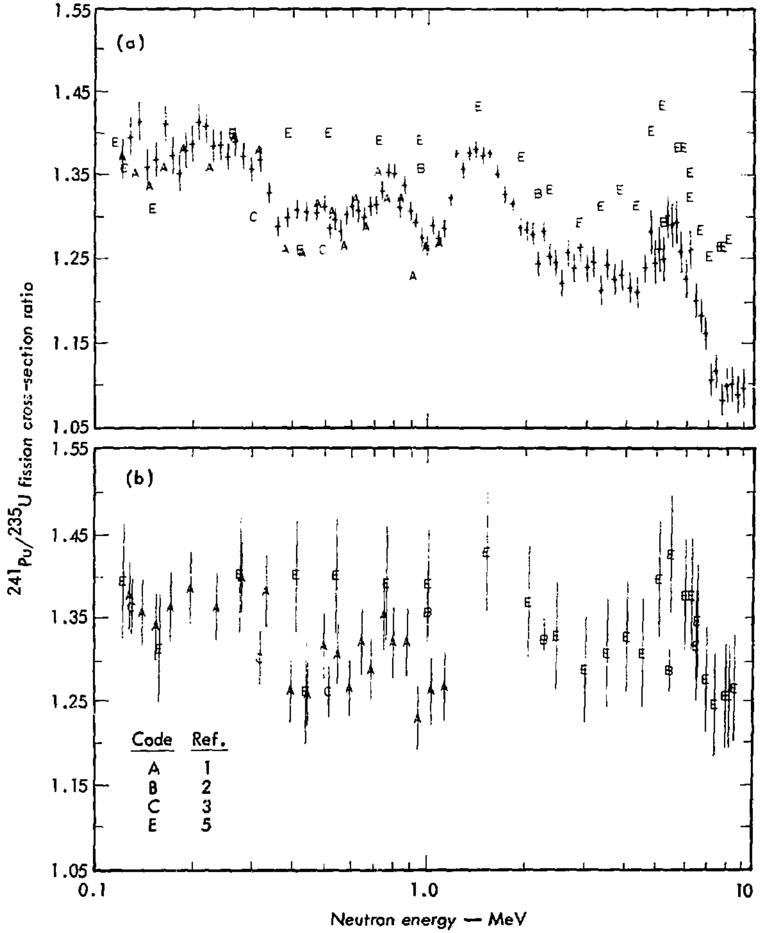


Fig. 6. Ratio of the ^{241}Pu to ^{235}U fission cross sections in the energy range 0.1 to 10 MeV. (a) Present work is given by +. The statistical error bars are shown on each point. Present work is compared with others. (b) Letter codes indicate the work of others. Error bars represent total error.

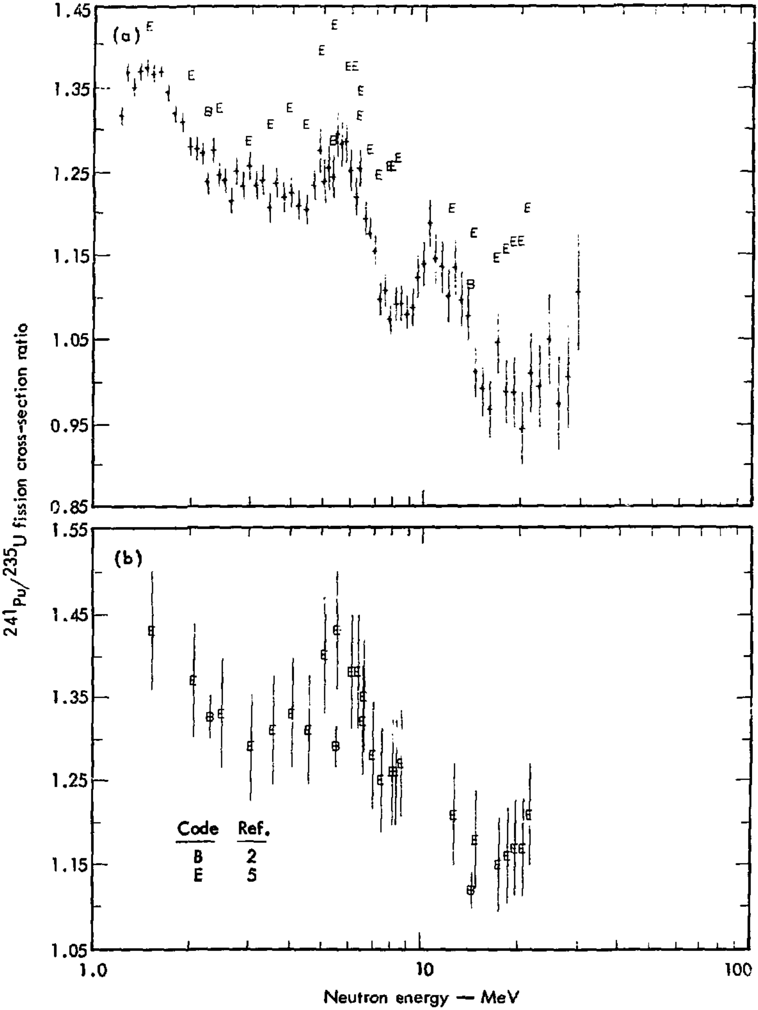


Fig. 7. Ratio of the ^{241}Pu to ^{235}U fission cross sections in the energy range 1.0 to 30 MeV. (a) Present work is given by +. The statistical error bars are shown on each point. Present work is compared with others. (b) Letter codes indicate the work of others. Error bars represent total error.

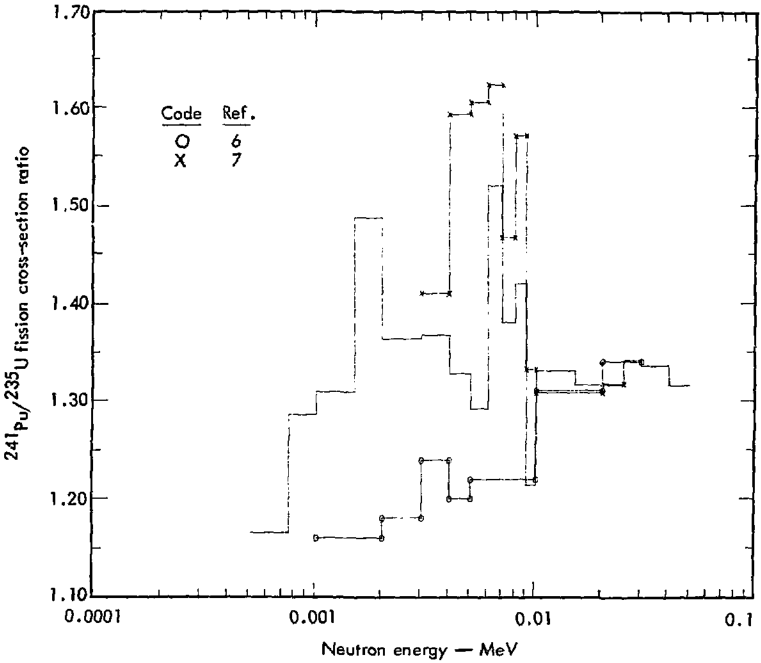


Fig. 8. Ratio of the ^{241}Pu to ^{235}U fission cross sections in the energy range 0.0005 to 0.050 MeV. Data appear as a histogram representing energy averaging over predetermined energy intervals. Present work is shown by the line of segments connecting the energy intervals. Letter codes indicate the work of others.

Table 9. Energy averaged fission cross sections and their ratio.

Energy range (MeV)	Average ratio $^{241}Pu:^{235}U$ [a]	Statistical uncertainty of ratio[b] (%)	Average fission cross section for ^{241}Pu[c] (barn)	Average fission cross section for ^{235}U[d] (barn)
0.040 to 0.050	1.315	1.40	2.443	1.862
0.030 to 0.040	1.336	1.33	2.650	1.984
0.025 to 0.030	1.342	1.70	2.856	2.128
0.020 to 0.025	1.316	1.66	2.968	2.255
0.015 to 0.020	1.316	1.56	3.096	2.353
0.010 to 0.015	1.331	1.38	3.526	2.648
0.009 to 0.010	1.214	2.73	3.742	3.082
0.008 to 0.009	1.419	2.59	4.356	3.069
0.007 to 0.008	1.380	2.51	4.397	3.187
0.006 to 0.007	1.520	2.37	5.255	3.458
0.005 to 0.006	1.291	2.20	4.999	3.871
0.004 to 0.005	1.328	2.05	5.746	4.327
0.003 to 0.004	1.367	1.88	6.583	4.814
0.002 to 0.003	1.364	1.71	7.347	5.386
0.0015 to 0.002	1.488	2.04	9.753	6.554
0.001 to 0.0015	1.309	1.93	11.33	8.653
0.00075 to 0.001	1.285	2.77	10.93	8.509
0.0005 to 0.00075	1.165	2.56	15.56	13.35

[a]Corrected for impurities in ^{241}Pu sample. The average ratio was obtained using the expression

$$\text{average ratio from } E_1 \text{ to } E_2 = \frac{\int_{E_1}^{E_2} R\, \sigma_{235}\, dE}{\int_{E_1}^{E_2} \sigma_{235}\, dE} ,$$

where R is our normalized fission cross-section ratio of $^{241}Pu:^{235}U$ and σ_{235} is the ENDF/B-IV evaluated fission cross-section file for ^{235}U. These values were found to be essentially equivalent to those obtained using the expression

$$\text{average ratio from } E_1 \text{ to } E_2 = \frac{1}{E_2-E_1} \int_{E_1}^{E_2} R \, dE \; .$$

[b]Indicates counting error expressed as a standard deviation. Total errors may be estimated by combining the normalization error of 1.20% and the estimated overall systematic error of 1.0% in quadrature with the counting errors in the table.

[c]Obtained using the expression

$$\text{average fission cross section from } E_1 \text{ to } E_2 = \frac{1}{E_2-E_1} \int_{E_1}^{E_2} \sigma_{235} \, dE \; .$$

[d]The ENDF/B-IV evaluated fission cross-section file for ^{235}U was used to obtain the average fission cross section. Obtained using the expression

$$\text{average fission cross section from } E_1 \text{ to } E_2 = \frac{1}{E_2-E_1} \int_{E_1}^{E_2} \sigma_{235} \, dE \; .$$

Summary

Figures 4 through 8 and Tables 8 and 9 present our results for the neutron-induced fission cross-section ratio ^{241}Pu:^{235}U measured continuously over an energy range from 0.001 to 30 MeV. Normalization of our ratio was done using two independent means, i.e., the threshold cross-section method applied in the MeV energy range and direct normalization to evaluated fission cross sections at thermal neutron energy. The comparison of our results with previous data sets demonstrated the advantage of a continuous measurement over a wide energy range in defining the cross-section ratio as a function of energy. Since the structure in the ^{241}Pu:^{235}U fission cross-section ratio below 0.050 MeV is in part due to the ^{235}U, it would be better to measure the fission cross section of ^{241}Pu relative to the ^{6}Li (n,α) reaction in this energy region.[22]

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