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NEUTRON CAPTURE, FISSION AND TOTAL CROSS SECTION
MEASUREMENTS ON ^{240}Pu FROM 20 eV TO 30 keV

R. W. Hockenbury, W. R. Moyer and R. C. Block
Rensselaer Polytechnic Institute
Troy, N. Y.

Send Proofs to: Dr. R. W. Hockenbury
Nuclear Science Department
Rensselaer Polytechnic Institute

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ABSTRACT

The neutron capture and fission cross sections of ^{240}Pu have been measured from 20 eV to 30 keV. Transmission measurements were also made from 30 to 500 eV. The capture data were normalized using the transmission results to minimize the uncertainty in absolute normalization. The average capture cross section has been determined from 6 to 30 keV. The s-wave average radiation width has been found to be (0.0295 ± 0.0015) eV. Resonance parameters to 500 eV and an s-wave strength function of $(1.10 \pm 0.27) \times 10^{-4}$ have also been obtained. Sub-threshold fission structure was observed up to 30 keV. The level spacing for sub-threshold fission was found to be (710 ± 200) eV. Comparisons of all our results are made to previously published data.

INTRODUCTION

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The neutron capture and fission cross sections of ^{240}Pu are of interest in the design of the Pu fast breeder reactor (LMFBR) since the percentage of ^{240}Pu in this type reactor can be appreciable. Several published^{1,2} and unpublished measurements have been made to determine the average s-wave radiation width and/or the keV capture cross section. Since ^{240}Pu also exhibits sub-threshold fission³, any capture measurement must account for the fission events which take place. Capture and fission measurements are also made more difficult because of the sample activity which includes spontaneous fission.

The initial goal in this work was to measure the keV capture cross section. The high-low bias method⁴ was used with a large liquid scintillator thus obtaining the capture and fission cross sections simultaneously. Preliminary analysis of our keV data gave an average radiation width which was inconsistent with results of other laboratories. In order to obtain a consistent set of data, we extended our capture analysis to the resonance region and also made transmission measurements. The capture data were normalized to the transmission results to reduce the uncertainty in absolute normalization. The resonance parameters up to 500 eV were determined by combining the capture and transmission data. The neutron widths are in good agreement with those of Kolar and Böckhoff¹. However, the average radiation width is 0.0295 eV which is $\approx 27\%$ greater than that of Weigmann and Schmid². The sub-threshold fission structure was observed up to about 30 keV.

EXPERIMENTAL APPARATUS

Since most features of the Rensselaer capture measurement facility have been reported previously⁵, only a brief description will be given here. Electrons from the Rensselaer Linac strike a Ta target producing photoneutrons, some of which then strike a polyethylene moderator placed at $\sim 135^\circ$ with respect to the target. A series of B_4C , Pb and Fe collimators form a 6.0 cm diameter neutron beam at the capture detector.

Two ^{240}Pu samples, prepared by Los Alamos Scientific Laboratory, were used. The samples were an alloy of Pu-Al, about 1.2% Al by weight, sealed in Al cans. The Al container walls were 0.0254 cm thick in the neutron beam direction, thus giving a total of 0.1016 cm of Al in the beam. The weight per cent of ^{240}Pu was about 97% giving a thickness of 0.00130 atoms/barn.

The neutron capture detector is a 1.25 m diameter liquid scintillator located at 25.66 m from the neutron source. Since the ^{240}Pu samples were very radioactive, mostly from spontaneous fission, special precautions were taken to reduce electronic gain shifts. Preliminary tests showed that using a 0.15 cm thick lead liner to attenuate low energy photons and reducing the photomultiplier voltage decreased the gain shift to less than four per cent. Actually any remaining gain shift would cancel out in the normalization. Additional count rate tests show there was no long term gain shift during the experiment. A ^{10}B liner was used to prevent scattered neutrons from returning to the sample.

Two 40 cm diameter photomultipliers were connected to a conventional preamplifier and amplifier system. The amplifier output was connected to two window discriminators, one was set to give an output for all detector pulses from 3-15 MeV (gamma ray energy) and the other discriminator was set to give an output pulse for input pulses from 6-17 MeV. The lower discriminator was connected to the PDP-7 on-line computer and the upper discriminator was used as a routing device such that pulses from 3-6 MeV were stored in channels 1-3840 and pulses from 6-15 MeV were stored in channels 3841-7680. The PDP-7 was used in the (MB+1) mode, similar to a hard-wired analyzer, because of the high background counting rate due to the sample activity. The measured dead-time of the PDP-7 in this mode was 2.5 microseconds.

The relative neutron flux and transmission measurements were made with a ^{10}B -NaI neutron detector on the same flight path as the capture detector but located at 27.89 m.

The Linac was run at a repetition rate of 480 pps and a burst width of 100 nanoseconds for the primary absorption data. The burst width was a compromise between resolution and intensity. The overlap filter was B_4C with a 0.32 cm Pb filter to reduce beam flash. The neutron flux measurements were made with a burst width of 10 nanoseconds. Resonance filters of Al and Na were left in during all the measurements to determine the background at 2.8 and 35 keV. These filters gave convenient energy points for the background and introduced a minimum structure in the beam below thirty keV. A separate low energy run was made with

Co and Mn filters for background determination at 337 and 132 eV. Another capture measurement was made for normalization purposes with a Au sample on the front face of the ^{240}Pu samples.

Transmission measurements were made with a burst width of 20 nanoseconds at a repetition rate of 480 pps. The time-dependent background was measured with Al, Na and Co filters which were left in the beam. The ^{240}Pu samples were alternately cycled in and out of the neutron beam along with the equivalent amount of Al (as in the ^{240}Pu containers).

ANALYSIS

Capture cross sections are determined by measuring the number of capture events and incident neutron flux as a function of neutron energy. The observed capture counting rate is:

$$C_{\gamma}(E_i) = \mu \phi(E_i) \frac{\sigma_c(E_i)}{\sigma_t(E_i)} \left[1 - e^{-N\sigma_t(E_i)} \right] M_i \quad (1)$$

where $C_{\gamma}(E_i)$ = background corrected detector counts in channel i

μ = capture detector efficiency

$\phi(E_i)$ = incident number of neutrons which impinged on the sample in channel i .

$\sigma_c(E_i)$, $\sigma_t(E_i)$ = capture and total cross section at energy E_i

N = sample thickness (in atoms/barn)

M_i = multiple scattering and self-shielding factor

Previous experiments³ have shown the presence of sub-threshold fission in the energy range from 800 to 3000 eV. In order to separate the capture and fission contributions, the high-low bias

technique was used. This method is based on the difference in detector pulse-height spectra due to prompt fission gamma rays and to neutron capture gamma rays. Since the fission gamma spectrum as seen by the detector extends to greater pulse heights than that for capture, a high bias can be set where most of the events are caused by fission. Using a high and a low bias, two sets of data were recorded simultaneously which can be written as:

$$L(E_i) = \phi(E_i) \left\{ u_c \frac{\sigma_c(E_i)}{\sigma_t(E_i)} \left[1 - e^{-N\sigma_t(E_i)} \right] + u_f \frac{\sigma_f(E_i)}{\sigma_t(E_i)} \left[1 - e^{-N\sigma_t(E_i)} \right] \right\} M_i \quad (2)$$

$$H(E_i) = \phi(E_i) \left\{ \epsilon_c \frac{\sigma_c(E_i)}{\sigma_t(E_i)} \left[1 - e^{-N\sigma_t(E_i)} \right] + \epsilon_f \frac{\sigma_f(E_i)}{\sigma_t(E_i)} \left[1 - e^{-N\sigma_t(E_i)} \right] \right\} M_i \quad (3)$$

where: $\sigma_f(E_i)$ = fission cross section at energy E.

$L(E_i)$ = low bias (3-6 MeV) counts in channel i.

$H(E_i)$ = high bias (6-15 MeV) counts in channel i.

u_c, u_f = fraction of capture and fission events between 3 and 6 MeV.

ϵ_c, ϵ_f = fraction of capture and fission events between 6 and 15 MeV.

The capture yield is then:

$$Y_c(E_i) = \frac{\sigma_c(E_i)}{\sigma_t(E_i)} \left[1 - e^{-N\sigma_t(E_i)} \right] M_i = \frac{L(E_i) - \frac{u_f}{\epsilon_f} H(E_i)}{\phi(E_i) \left[u_c - \frac{u_f}{\epsilon_f} \epsilon_c \right]} \quad (4)$$

and the fission yield is:

$$Y_f(E_i) = \frac{\sigma_f(E_i)}{\sigma_t(E_i)} \left[1 - e^{-N\sigma_t(E_i)} \right] M_i = \frac{H(E_i) - \frac{\epsilon_c}{u_c} L(E_i)}{\phi(E_i) \left[\epsilon_f - \frac{\epsilon_c}{u_c} u_f \right]} \quad (5)$$

Assuming thin sample approximations are valid, the low and high bias counting rates are written in terms of the capture and fission cross sections as:

$$L(E_i) \simeq N\phi(E_i) \{u_c \sigma_c(E_i) + u_f \sigma_f(E_i)\} \quad (6)$$

$$H(E_i) \simeq N\phi(E_i) \left\{ \epsilon_c \sigma_c(E_i) + \epsilon_f \sigma_f(E_i) \right\} \quad (7)$$

Rearranging:

$$\sigma_c(E_i) = \frac{L(E_i) - \frac{u_f}{\epsilon_f} H(E_i)}{N\phi(E_i) \left[u_c - \frac{u_f}{\epsilon_f} \epsilon_c \right]} \quad - \text{thin sample} \quad (8)$$

$$\sigma_f(E_i) = \frac{H(E_i) - \frac{\epsilon_c}{u_c} L(E_i)}{N\phi(E_i) \left[\epsilon_f - \frac{\epsilon_c}{u_c} u_f \right]} \quad - \text{thin sample} \quad (9)$$

The capture normalization can then be made (1) by the saturated capture resonance method, or (2) by normalizing to transmission data. In the first method, the peak capture counting rate

C_p for a low energy resonance is (assuming no fission):

$$C_p = u \phi(E_i) \frac{\sigma_c(E_i)}{\sigma_t(E_i)} \left[1 - e^{-N\sigma_t(E_i)} \right] M_i \quad (10)$$

where: $u = u_c + \epsilon_c$

for a thick sample, $\Gamma_y \gg \Gamma_n$, and good resolution:

$$C_p = u \phi(E_i) \quad (11)$$

Thus the product of detector efficiency and absolute flux is determined at energy E_i . This method is useful for isotopes with

a suitable low energy resonance. The capture pulse height spectrum fraction can usually be measured as a function of neutron energy to determine its constancy. This method is limited by the requirements for the sample to be thick at resonance and for $\Gamma_Y \gg \Gamma_n$. Otherwise corrections must be made using the resonance parameters thus introducing an additional uncertainty.

The second normalization method has fewer restrictions than the first method. The area of the same resonance is measured in capture and in transmission. The neutron width must be much smaller than the radiation width and for this condition, the resonance capture area, A_Y , is proportional to $g\Gamma_n$ as can be seen below:

$$A_Y = N \int \sigma_c(E_i) dE_i \quad (\text{for thin samples}) \quad (12)$$

$$A_Y = \frac{\pi}{2} N g \Gamma_Y \quad (13)$$

$$A_Y \propto g \frac{\Gamma_n \Gamma_Y}{\Gamma_n + \Gamma_Y} \quad (14)$$

and for $\Gamma_Y \gg \Gamma_n$

$$A_Y \propto g \Gamma_n \quad (15)$$

The neutron width can be determined from the transmission data since $g = 1$ for ^{240}Pu s-wave resonances. The resonance capture area can be calculated including self-protection and multiple scattering corrections by using a Monte Carlo code and is quite insensitive to the radiation width used. The absolute

normalization is obtained from the calculated area and the summed counts over the resonance:

$${}_u \phi(E_o) = \frac{\sum_i [L(E_i) + H(E_i)] \Delta E_i}{A_y \text{ (Calc.)}} \quad (16)$$

where:

A_y (calc.) = calculated area

ΔE_i = energy increment per channel

In both methods of normalization the product of detector efficiency and absolute flux at any energy E_i is then obtained from the relative neutron flux measurement $F(E_i)$:

$${}_u \phi(E_i) = {}_u \phi(E_o) \frac{F(E_i)}{F(E_o)} \quad (17)$$

where:

$F(E_o)$ = relative flux at reference energy E_o .

The ratios of ${}^{uc}/{}_u$ and $\epsilon_c/{}_u$ are obtained from ratios of the high and low bias counting rates for a resonance where fission is negligible. Accurate spectrum measurements using the ${}^{240}\text{Pu}$ samples could not be made because of the high sample activity. The fractions ${}_u f$ and ϵ_f were determined by measuring the prompt fission gamma spectrum of a ${}^{252}\text{Cf}$ fission chamber in the same geometry as for the ${}^{240}\text{Pu}$ experiment. The fission gamma spectrum of ${}^{235}\text{U}$ in similar geometry in the same detector was measured to be quite similar to the ${}^{252}\text{Cf}$ spectrum. It is assumed that the fission gamma spectrum as seen by the detector is the same for ${}^{252}\text{Cf}$ and ${}^{240}\text{Pu}$. Since the fission contribution is generally small relative

to capture in the keV region, an uncertainty in u_f and ϵ_f causes little change in the capture result. For example, changing the ratio u_f/ϵ_f in eqn. 4 by 100% produces about a 10% change in the capture yield. Other normalization methods for the fission data were not possible. For example, since the thermal fission cross section of ^{240}Pu is small relative to that of the ^{239}Pu (1.4 weight%) and ^{241}Pu (0.5 weight %) impurities, the impurities would dominate the observed thermal fission counting rate. Also, previous results for the fission widths of the sub-threshold groups are not sufficiently reliable for normalization purposes.

DATA REDUCTION

The primary absorption data consisted of four separate runs which were summed into one set for analysis. Checks of the individual runs before summing showed there were no drifts in gains or timing during the measurement period. The raw data for both the capture and neutron detectors were corrected for dead-time losses, time independent and time dependent background.

The relative neutron flux was obtained from the neutron flux data after correcting for backgrounds, the change in relative efficiency of the ^{10}B as a function of neutron energy and for the air path attenuation between the capture sample and the neutron detector.

The transmission data were corrected for dead time effects and backgrounds. The Harvey-Atta⁶ code was used for area analysis of the resonances from 20 to 500 eV.

The resonance at 92.5 eV was used to normalize the capture data to the transmission results (as explained previously). For

this resonance, $\Gamma_n \ll \Gamma_\gamma$ and since this was a thin sample, the transmission data area analysis gives $g\Gamma_n$ directly. The resonance capture area A_γ was then calculated by our Monte Carlo program⁷ using several values for the radiation and neutron widths.

The insensitivity of the calculated capture area A_γ to the value of the radiation width is evident in both parts of Figure 1. A vertical line is drawn through the lower family of curves of A_γ vs Γ_n corresponding to the Γ_n from the transmission data. The upper part of the figure shows that A_γ is relatively constant for large changes in the radiation width. The capture area A_γ was taken equal to that evaluated for $\Gamma_\gamma = 0.030$ eV and $\Gamma_n = 0.0033$ eV (from the transmission data). This A_γ and the sum of the high and low bias counting rates for this resonance were used to obtain σ_0 (92.5 eV) as explained previously.

Using the cross-calibration to the Au foil, another normalization was obtained. The 60.2 eV Au resonance area, previously cross-calibrated to the "black" Ag resonance at 5.19 eV, provided the product σ_0 (60.2) which could then be compared to the σ_0 (92.5) by using the relative neutron flux. A third normalization to an almost "black" resonance in ^{240}Pu at 20.46 eV was obtained. Since the capture yield at this resonance peak was 0.89, and not unity, a correction is required to obtain the product σ_0 (20.46). This can also be compared to the other two normalizations by using the relative flux data. All normalizations agreed to within the statistics of the worst ($\pm 8\%$). The Au calibration was inferior

due to relatively poor capture statistics. The 20.46 eV normalization was also inferior because the relative neutron flux was overly sensitive to the background correction since the B_4C overlap filter was becoming opaque at this energy. For these reasons, the normalization to the transmission data of the 92.5 eV resonance was the most satisfactory. The accuracy of the absolute normalization is determined by the statistical accuracy of the 92.5 eV resonance capture and transmission data. The standard deviation of the net capture counts is $\pm 0.25\%$. The uncertainty in Γ_n from the transmission data is $\pm 2.8\%$ which gives an uncertainty of $\pm 3.0\%$ in A_γ (92.5). Thus the total uncertainty in the absolute normalization is $\pm 3.8\%$.

RESONANCE ANALYSIS

By assuming various values of Γ_n and Γ_γ , the capture areas for all the resonances were calculated with the Monte Carlo program. These results were combined with those of the Harvey-Atta program in a conventional area analysis to get resonance parameters shown in Table I. In some cases, where $\Gamma_n \ll \Gamma_\gamma$, the ^{240}Pu samples were too thin for good transmission results, and an average value of $\Gamma_\gamma = 0.0295$ eV was used with the capture data to determine the neutron width. In all the cases reported here, the fission correction from the high bias data was negligible for most resonances and never exceeded 10%.

Assuming all the observed resonances are s-wave, the s-wave strength function $\Gamma_{n/D}^o$ was found to be $(1.10 \pm 0.27) \times 10^{-4}$ in good agreement with previous results.¹ The average radiation

width of $\bar{\Gamma}_\gamma = 0.0295 \pm 0.0015$ eV from our results is 27% larger than that of Weigmann.² The average level spacing, D, equals 13.7 eV for the 20 to 500 eV region. Table I shows there is good agreement between our values for the neutron widths and those of Ref. 1. This is true for all cases whether the neutron width was determined from transmission data alone, transmission combined with capture data or capture data alone.

KEV ANALYSIS

The capture and fission yields were calculated using equations 4 and 5. Two energy regions are shown in Figures 2 and 3. The clean separation of the capture and fission components can be seen in Figure 2 which shows the lowest energy group due to sub-threshold fission. The gap in Figure 3 is due to the Al filter used for background determination.

Above 10 keV, sample thickness corrections are less than 2% and were not made. The correction for capture due to the impurities ^{239}Pu and ^{241}Pu is less than 2% in the keV region.

The keV capture cross section data were compared to calculations using the theory of Lane and Lynn⁸. The average capture cross section for resonances of spin J and partial wave of angular momentum ℓ is:

$$\sigma_{J\ell} = \frac{\pi^2}{k^2} \frac{2J+1}{2I+1} \sum_j \frac{\langle \Gamma_{\lambda J}(n\ell j) \rangle \langle \Gamma_{\lambda J}(\gamma) \rangle}{\langle D_{\lambda j} \rangle \langle \Gamma_{\lambda J} \rangle} \int_0^\infty (d_{\lambda J}) \quad (18)$$

where $j = \text{channel spin } (I \pm \frac{1}{2})$

$\langle \Gamma_{\lambda J}(nlj) \rangle = \text{average neutron width}$

$\langle \Gamma_{\lambda J}(\gamma) \rangle = \text{average radiation width}$

$\langle \Gamma_{\lambda J} \rangle = \text{average total width}$

$\langle D_{\lambda J} \rangle = \text{average spacing}$

$$S(\alpha_{\lambda J}) = \left\langle \frac{\Gamma_{\lambda J}(nlj) \Gamma_{\lambda J}(\gamma)}{\Gamma_{\lambda J}} \right\rangle \left[\frac{\langle \Gamma_{\lambda J}(nlj) \rangle \langle \Gamma_{\lambda J}(\gamma) \rangle}{\langle \Gamma_{\lambda J} \rangle} \right]^{-1}$$

$S(\alpha_{\lambda J}) = \text{a correction factor for the difference between the ratio of average widths and the average of the ratio of widths.}$

The average s-wave radiation width was taken to be $\Gamma_\gamma = 0.030$ eV and the s-wave strength function was taken as 1.1×10^{-4} . The capture cross section was calculated for various values of p-wave radiation widths and strength functions and compared to the averaged data. Above about 8 keV, the p-wave contribution is equal to or greater than the s-wave contribution, thus the calculations are more sensitive to the p-wave parameters. Since the product of the p-wave radiation width and strength function determines the p-wave contribution, unambiguous results cannot be obtained for either quantity individually.

The capture data were averaged over 2 keV energy regions from 6 to 28 keV (Table II). An overall uncertainty of $\pm 8\%$ is estimated for statistical and systematic errors for each 2 keV averaged cross section. In Fig. 4, the averaged experimental capture data are compared to calculated values for a p-wave radiation width of 0.030 eV and a p-wave strength function of $S^1 = 2.8 \times 10^{-4}$. Increasing the p-wave radiation width to 0.033 eV would improve the agreement, particularly above 15 keV.

Comparisons have been made in Fig. 5 to an evaluated capture cross section by Yiftah, et al.⁹ and to a statistical ladder construction by Dyos.¹⁰ Table IV gives the parameters used by Yiftah, Dyos and our s-wave parameters. The experimental results are generally lower than the Yiftah curve below about 15 keV, while Dyos curve is low over the entire range, probably due to his lower value for the p-wave strength function.

FISSION RESULTS

The prominent structure in the fission data shown in Fig. 2 and 3 is due to sub-threshold fission. Since the ^{240}Pu fission cross section is small away from the sub-threshold fission groups, the ^{239}Pu and ^{241}Pu impurities contribute about 30% of the observed counts. Corrections for fission in ^{239}Pu and ^{241}Pu have not been made in Fig. 3. Because of the impurities and the relatively poor statistics for net fission results, only the energies of the fission groups are given in Table III. By comparing the average energy width (~ 60 eV) of one fission cluster to the experimental resolution, it is obvious that the individual resonances in one group are not resolved above ~ 2 keV. Also at higher energies, fission groups are not resolved. The average spacing of the groups, in the resolved region is $D_{II} = 710 \pm 200$ eV compared to a spacing D_I of 13.7 eV for levels in the first minimum of ^{241}Pu . The level spacing D_{II} corresponds to an excitation energy of about 3.1 MeV implying that the second minimum discussed by Strutinsky¹¹ and Lynn¹² is about 2.3 MeV above the first minimum in the double-humped potential barrier. Other results for

the fission data will be presented in a future publication.

CONCLUSIONS

Resonance parameters have been obtained from 20 to 500 eV. The neutron widths, level spacing and s-wave strength function are in excellent agreement with those of Kolar and Böckhoff.¹ The radiation width from our results ($\Gamma_\gamma = 0.0295$ eV) is larger than that reported by Weigmann.² The average capture cross section has been determined from 6 to 30 keV. Estimates of the average p-wave radiation width and the p-wave strength function are obtained from comparisons of the keV capture cross section data and calculated capture cross sections.

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FIGURE CAPTIONS

- Figure 1. Capture Area A_γ vs. Γ_n and Γ_γ .
- Figure 2. Capture and Fission Yield/N for ^{240}Pu From 575 to 1075 eV
- Figure 3. Capture and Fission Cross Sections for ^{240}Pu from 4 to 30 keV
- Figure 4. Averaged Capture Cross Section and Calculated Values for ^{240}Pu .
- Figure 5. Experimental and Evaluated Capture Cross Section of ^{240}Pu

TABLE I

 ^{240}Pu Resonance Parameters

E (eV)	RPI		Ref. 1		Ref. 2
	Γ_n (meV)	Γ_γ (meV)	Γ_n (meV)	Γ_γ (meV)	
20.46	2.2 ± 0.6	(30) ^a	2.7 ± 0.3	-	-
38.37	17.0 ± 0.5	25.5 ± 0.8	19.2 ± 0.9	20.0 ± 2.0	
41.79	14.2 ± 0.5	32.8 ± 1.0	16.8 ± 0.9	21.8 ± 2.0	
66.71	53.2 ± 1.0	27.4 ± 0.6	55.9 ± 2.2	23.5 ± 2.0	
72.82	21.5 ± 0.5	27.0 ± 0.6	22.0 ± 1.0	21.0 ± 2.0	
90.81	12.7 ± 0.3	39.5 ± 1.0^b	13.5 ± 0.6	19.5 ± 2.0	
92.53	3.3 ± 0.1	-	3.0 ± 0.2	-	
105.1	47.5 ± 1.5	37.5 ± 1.0^b	45.5 ± 2.5	26.0 ± 2.5	
121.7	15.0 ± 0.5	(30)	14.5 ± 0.9	12.5 ± 2.0	
130.9	0.19 ± 0.03	(30)	0.15 ± 0.06	-	
135.4	20.6 ± 0.5	(30)	18.5 ± 1.1	24.5 ± 2.5	
152.0	13.8 ± 0.5	29.5 ± 1.1	14.2 ± 1.0	21.5 ± 2.0	
162.8	9.0 ± 0.3	27.5 ± 0.9	8.6 ± 1.0	20.0 ± 3.0	
170.2	17.5 ± 0.5	27.3 ± 0.9	13.7 ± 1.2	22.0 ± 2.0	
185.9	18.8 ± 0.5	28.8 ± 0.9	16.3 ± 1.2	22.0 ± 2.0	
192.2	0.3 ± 0.04	(30)	0.20 ± 0.12	-	
199.8	1.0 ± 0.1	(30)	0.94 ± 0.1	-	
239.3	13.8 ± 0.6	27.7 ± 1.0	12.2 ± 0.7	21.5 ± 2.5	
260.4	25.0 ± 0.9	30.5 ± 1.0	23.2 ± 1.2	24.0 ± 2.3	
287.1	137.0 ± 0.4	33.0 ± 1.1	138.2 ± 7.0	26.0 ± 2.0	
304.9	7.4 ± 0.2	(30)	7.2 ± 0.7	-	
318.5	6.0 ± 0.3	(30)	5.2 ± 0.5	-	
320.8	20.0 ± 0.6	(30)	19.3 ± 1.0	21.0 ± 2.5	
338.5	7.4 ± 0.3	(30)	5.7 ± 0.6	-	
346.0	17.7 ± 0.5	(30)	16.5 ± 0.7	21.5 ± 2.5	
363.8	30.4 ± 1.5	32.8 ± 1.7	32.5 ± 1.3	25.0 ± 2.5	
372.1	16.0 ± 1.5	27.5 ± 0.3	13.8 ± 0.8	21.5 ± 3.0	
405.1	102.6 ± 6.0	30.0 ± 0.2	108.5 ± 5.0	26.0 ± 2.3	
419.2	6.2 ± 0.3	(30)	6.1 ± 0.7	-	
446.2	2.2 ± 0.2	(30)	1.6 ± 0.3	-	
448.7	18.7 ± 3.5	(30)	16.5 ± 1.2	26.5 ± 3.0	
466.9	2.4 ± 0.2	(30)	3.1 ± 0.6	-	
473.4	4.3 ± 0.3	(30)	4.2 ± 0.5	-	
494.2	6.4 ± 0.3	(30)	5.8 ± 1.1	-	
499.4	17.0 ± 2.2	33.5 ± 1.5	19.3 ± 1.4	21.5 ± 2.5	

a Use $\Gamma_\gamma = 0.030$ eV to determine Γ_n .

b ^{239}Pu impurity at these energies.

TABLE II

 ^{240}Pu CAPTURE CROSS SECTION
2 keV Groups

Energy (keV)	Average Capture Cross Section ^a (barns)
6-8	1.39
8-10	1.36
10-12	1.24
12-14	1.16
14-16	1.11
16-18	1.07
18-20	1.02
20-22	0.91
22-24	0.93
24-26	0.94
26-28	0.85

^a Overall uncertainty of each group: $\pm 8\%$

TABLE III
ENERGIES OF SUB-THRESHOLD FISSION GROUPS

E (eV)	E (eV)
793	8920
1420	10200
1930	11500
3000 ^a	12500
4970	13400
5130	16500
5310	17500
6570	20100
7060	26800
7520	28400
8130	

^a Ref. 2

TABLE IV
AVERAGE PARAMETERS FOR ^{240}Pu

	s-wave		p-wave	
	Γ_γ (eV)	S^o	Γ_γ (eV)	S'
This Work	0.0295	1.10×10^{-4}	a	a
Yiftah	0.032	1.37×10^{-4}	0.032	2.5×10^{-4}
Dyos	0.030	1.05×10^{-4}	0.030	1.98×10^{-4}

a. See discussion in text

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5