UNCLASSIFIED
(Approved for Publication)

United Kingdom Atomic Energy Authority

RESEARCH GROUP

Report

Mass spectrometric measurements of the ratio of neutron capture to fission for ^{239}Pu and ^{241}Pu and of the absorption and capture cross sections of ^{239}Pu, ^{240}Pu and ^{241}Pu for Maxwellian neutrons.

M. J. CABELL M. WILKINS

Chemistry Division,

Atomic Energy Research Establishment,

Harwell, Berkshire.

1966

U.D.C.
546.799.4.02:539.17
539.173.4

MASS SPECTROMETRIC MEASUREMENTS OF THE RATIO OF NEUTRON CAPTURE TO FISSION FOR ^{239}Pu AND ^{241}Pu, AND OF THE ABSORPTION AND CAPTURE CROSS SECTIONS OF ^{239}Pu, ^{240}Pu AND ^{241}Pu, FOR MAXWELLIAN NEUTRONS.

by

M.J. Cabell

M. Wilkins

ABSTRACT

Mixtures of highly-enriched samples of ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu have been irradiated, with cobalt monitors, for nearly ten months in an almost uncontaminated Maxwellian neutron spectrum ($r = 7.5 \times 10^{-4}$) with a temperature of 116°. Results obtained from mass analyses of the samples, both before and after irradiation, and the 2200 m/sec constants derived from them, were as follows:-

		Alpha (ratio of capture to fission)	Absorption cross section (barns)	Capture cross section (barns)
For the reactor spectrum	^{239}Pu	0.441 ± 0.022	1201 ± 47	367 ± 19
	^{240}Pu	-	-	297 ± 15
	^{241}Pu	0.341 ± 0.013	1482 ± 39	377 ± 15
For 2200 m/sec neutrons	^{239}Pu	0.377 ± 0.023	1012 ± 40	275 ± 15
	^{240}Pu	-	-	273 ± 14
	^{241}Pu	0.356 ± 0.017	1367 ± 37	359 ± 16

Chemistry Division,
U.K.A.E.A. Research Group,
Atomic Energy Research Establishment,
HARWELL, Berks.

April 13th 1966.
HL66/2064 (C.4)

In an earlier paper[1] the present authors have described experiments in which synthetic mixtures of highly enriched plutonium isotopes were irradiated in the flux scanning tube of one of the fuel elements of the high-flux reactor PLUTO so that alpha (the relative probability of an absorbed neutron being captured rather than causing fission) could be measured for ^{241}Pu. A knowledge of the neutron spectra of the irradiation positions was then used to deduce the value of alpha for 2200 m./sec. neutrons (α_o) from the measured values ($\hat{\alpha}$).

It was shown that three different mixtures were necessary if this measurement was to be made precisely. The first mixture, which consisted largely of ^{239}Pu and ^{241}Pu, was used to measure the rate of formation of ^{242}Pu from ^{241}Pu, and the rate of destruction of ^{241}Pu, both relative to the ^{239}Pu content. The second mixture consisted largely of ^{239}Pu and ^{242}Pu, and was used to measure the rate of destruction of ^{239}Pu, and the rate of formation of ^{240}Pu from ^{239}Pu, relative to the comparitively unchanged ^{242}Pu. The third mixture, which consisted mainly of ^{240}Pu and ^{242}Pu, was used to measure the rate of conversion of ^{240}Pu to ^{241}Pu, again relative to the ^{242}Pu content. In this way the rates of all the relevant transformations occurring in the mixtures could be measured, except 1) that at which ^{242}Pu was destroyed by neutron capture, and 2) that at which ^{242}Pu was formed indirectly by the sequence $^{241}Pu \xrightarrow{\beta^-} {}^{241}Am \xrightarrow{n,\gamma} {}^{242g}Am \xrightarrow{\text{k-capture}} {}^{242}Pu$. Both these reactions are relatively slow; their magnitudes can be obtained by calculation.

Now irradiation positions in the core of a reactor, such as those chosen, have the virtue that the neutron flux in them is sufficiently high that measurable changes are produced relatively rapidly. In this instance, for example, an irradiation of 48 days duration produced neutron doses of up to 5×10^{20} neutrons per cm^2 and, in the spectrum conditions prevailing, this resulted in some 50 per cent of the initial ^{241}Pu being destroyed.

There are, however, certain disadvantages in using this type of irradiation position. These arise from the high epithermal to thermal flux ratios, and the high thermal and epithermal flux gradients, associated with them.

Thus, due to the fact that the flux scanning tube was only 0.25 in. in diameter, the samples could not be irradiated along-side each other but had to be placed in separate irradiation cans which were then strung end to end. As a result, in some instances a desired reaction rate applicable to one sample could only be obtained by interpolation from the results obtained from samples above and below it in the string i.e. from positions where the neutron spectrum was different. The experiments were designed such that uncertainties in this interpolation procedure were kept as small as possible, but the necessity for it was still undesirable.

More important than this, however, was the fact that the very presence of epithermal neutrons made corrections for their effects necessary. In Table 1 we have listed the recommended neutron cross section data currently available for the plutonium nuclides under consideration. It will be deduced from this Table that, whenever epithermal neutrons are present, their effects will contribute appreciably to all the relevant reaction rates. When corrections are made for these contributions, uncertainties in the epithermal index, in the epithermal cut-off function and in WESTCOTT'S s values will all increase the overall error.

Of great importance in this respect is the uncertainty introduced into the capture cross section of ^{242}Pu which could only be obtained by calculation. Typically this cross section was increased from a thermal value of 19.8 ± 1.1 barns to a reactor value of 142 ± 21 barns (for $r = 0.08$).

In the present paper we describe some further measurements of α_o for ^{241}Pu. The method employed is similar to that of the earlier measurements, but the neutron spectrum employed for the irradiations was almost entirely devoid of epithermal neutrons, and the samples were placed alongside each other so that they received almost the same neutron dose each.

EXPERIMENTAL DETAILS

1) Mass spectrometric measurements

These were made using an A.E.I. Type MS5 mass spectrometer, as already described [1]. At least twenty, and usually fifty, consecutive measurements

were made of each isotopic ratio of interest.

2) Target materials and treatment

The target materials were prepared and treated as described previously [1]. At least five aliquots from each irradiated sample, and at least ten aliquots from each non-irradiated mixture, were taken for separate mass analysis.

3) Monitors

For measurement of neutron dose during the main irradiations, cobalt monitors, approximately 1 cm long (weight ca.1 mg), of 0.005 in. diameter pure metal wire were used. Cobalt-aluminium alloy wires (1 per cent cobalt, 0.050 in. diameter) and gold-aluminium wires (0.10 atom per cent gold, 0.018 in. diameter) were used for thermal flux gradient and epithermal index measurements respectively. The method employed to count these monitors, and to interpret measurements made with them, are discussed elsewhere [3].

Fission neutron flux and neutron temperature data were obtained for us by staff of the Research Reactors Division. For the former measurements ^{58}Ni monitors were used; for the latter, manganese-lutetium monitors.

4) Irradiations

For the main irradiation, a weighed cobalt monitor was placed alongside each marked sample ampoule and the two were wrapped in aluminium foil. Fourteen samples (5 of the ^{239}Pu - ^{241}Pu mixture, 5 of the ^{239}Pu - ^{242}Pu mixture and 4 of the ^{240}Pu - ^{242}Pu mixture) and monitors were prepared in this way, then tight-packed together, in no particular order, in the bottom 4 cm. of a 2 cm. diameter aluminium can. Crumpled aluminium foil was placed over the samples to hold them in position, then the lid of the can was cold-welded on to provide secondary containment of the activity. The can was then placed in a second can (a standard Type A, 3 in. isotope can) for the irradiation.

The irradiation was in the 10G position of the No.4 Hobson-Honeycomb unit of the DIDO reactor; this position was at the far end of the unit, nearest the reactor core. The number 4 Hobson unit fitted into the 6HGR7 hole of the reactor. This is a circular hole which penetrates the concrete biological shield almost

radially to the reactor tank, and extends to the inner edge of the graphite reflector, its axis being 12 in. below the reactor centre line. The irradiation can was therefore separated from the nearest fuel rod (A1) by a total thickness of 6 in. aluminium alloy and 24 in. heavy water.

The irradiation was for 295.6 ± 0.1 days and was terminated prematurely by a mechanical failure in the Hobson unit which necessitated its complete removal from the reactor. During the irradiation the reactor was at full power for about 82 per cent of the time i.e. for over 97 per cent of that scheduled.

CALCULATIONS AND RESULTS

1) Neutron spectrum measurements in the irradiation position

In preliminary experiments using small cadmium boxes of 0.030 in. wall thickness, cadmium ratios were determined for the gold monitors. $(R_{Cd})_{Au}$ was found to be 61.7 at the end of the irradiation position nearest the reactor and 81.3 at the other end, about 5.5 cm away. These correspond to $r\sqrt{T/T_o}$ being 9.77×10^{-4} and 7.38×10^{-4}; we have taken the mean value of $(8.6 \pm 1.2) \times 10^{-4}$ as applying to our samples. With a neutron temperature of 116° this corresponds to $r = (7.5 \pm 1.0) \times 10^{-4}$.

For measurements of the neutron flux gradients in the irradiation position, a thin drilled graphite liner was machined to fit a Type A irradiation can. By its use cobalt-aluminium monitors could be accurately positioned for irradiation. With this equipment it was found that during irradiation a) the thermal flux fell off almost linearly from top to bottom along the axis of the can at a rate of 4.0 per cent per cm., that b) the thermal flux gradient was 2.0 per cent per cm across one (presumed to be the vertical) diameter of the can, and that c) the thermal flux was almost constant (to within ± 0.2 per cent) across the diameter of the can at right angles to the first. These results lead us to expect that the neutron doses received by some samples in the main irradiation are likely to differ by at least 4 per cent from those received by others.

By means of simultaneous irradiations of cobalt and ^{58}Ni monitors, the ratio of the fission flux density to the thermal flux density in the irradiation

position was found to be 7×10^{-4}.

Measurements were also made with manganese-lutetium monitors, since the ratio of the activities produced by the two components of the mixture is a function of the neutron temperature of the irradiation. The neutron temperatures at the two ends and in the centre of the irradiation position were found to be 117°, 120° and 112°. We have taken the mean value of $116 \pm 4^{\circ}$ as being applicable to our samples.

2) Mass spectrometric measurements

For the following calculations we use the same symbols and expressions (simplified) as in our earlier paper [1]. Isotopic ratios are also defined as before i.e. $R_1 = N_{0,0}/N_{9,0}$, $R_2 = N_0/N_9$, $R_3 = N_{1,0}/N_{9,0}$, $R_4 = N_1/N_9$,

$R_5 = N_{2,0}/N_{9,0}$, $R_6 = N_2/N_9$, $R_7 = N_{0,0}/N_{2,0}$, $R_8 = N_0/N_2$,
$R_9 = N_{9,0}/N_{2,0}$, and $R_{10} = N_{1,0}/N_{2,0}$

and for λ_1, we again use $(1.428 \pm 0.006) \times 10^{-4}$ days $^{-1}$.

^{240}Pu - ^{242}Pu mixtures

For the unirradiated mixture R_7, R_9 and R_{10} were found to be 1.3780 ± 0.0004, 0.01614 ± 0.00004 and 0.01063 ± 0.00002 respectively. Results from the irradiated samples were then fitted to the expression

$$\exp[(\hat{\sigma}_2 - \hat{\sigma}_0)i] = R_8(1 + M)/R_7 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which M is a small correction factor common to all such samples. In this way $\exp[(\hat{\sigma}_2 - \hat{\sigma}_0)i]$ was deduced, and from this $(\hat{\sigma}_0 - \hat{\sigma}_2)$. Now, from the data of Table 1 we obtain:-

$$\hat{\sigma}_2 = (19.8 \pm 1.1) + (1520 \pm 250)r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

so that, for $r = (7.5 \pm 1.0) \times 10^{-4}$, we have $\hat{\sigma}_2 = 21.0 \pm 1.2$ barns. Thus $\hat{\sigma}_0$ can be obtained.

Results for the four irradiated samples are summarised in Table 2. They give a mean value for $(\hat{\sigma}_0 - \hat{\sigma}_2)$ of 275.5 ± 12.2 barns (standard error). When the error in R_7 (± 0.03 per cent) is accounted for also, this result becomes 275.5 ± 12.4 barns. Hence $\hat{\sigma}_0 = 296.5 \pm 12.5$ barns, and this is the value to be used for all samples in the irradiation.

^{239}Pu - ^{242}Pu mixtures

For the unirradiated mixture R_1, R_3, and R_5 were found to be 0.005254 ± 0.000008, 0.001980 ± 0.000010 and 0.26309 ± 0.00081 respectively. Results from mass analyses of the irradiated samples were fitted to the expression:-

$$\exp [(\hat{\sigma}_2 - \hat{S}_9)i] = R_5 / R_6 + N \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which N is a small correction factor. From $\exp [(\hat{\sigma}_2 - \hat{S}_9)i]$, $(\hat{S}_9 - \hat{\sigma}_2)$ and hence $\hat{S}_9$, can be obtained.

The results are set out in Table 3 and give a mean value for $(\hat{S}_9 - \hat{\sigma}_2)$ of 1180 ± 22 barns (standard error), and a value of 1180 ± 32 barns when the uncertainty in R_5 is accounted for also. Hence $\hat{S}_9$ = 1201 ± 32 barns, and this is the value to be used for all samples in the irradiation.

The same samples can also be used for a measurement of $\hat{S}_9 / \hat{\sigma}_9$. Here the expression

$$\hat{S}_9 / \hat{\sigma}_9 = (1 - \exp(-\hat{S}_9 i)) / ((1 + B)(R_2 \exp(-\hat{S}_9 i) - R_1 \exp(-\hat{\sigma}_0 i)) \quad \ldots\ldots (4)$$

is employed. The results are listed in Table 4 and give a mean value for $\hat{S}_9 / \hat{\sigma}_9$ of 3.270 ± 0.063 (standard error). When uncertainties in $\hat{S}_9$(± 2.7%), $\hat{\sigma}_0$(± 4.2%) and R_1(± 0.2%) are also considered, $\hat{S}_9 / \hat{\sigma}_9$ becomes 3.270 ± 0.114. Combining this result with that for $\hat{S}_9$, as obtained above, we have $\hat{\sigma}_9$ = 367 ± 16 barns, and this is the value to be used for all samples in the irradiation.

^{239}Pu - ^{241}Pu mixtures

For these R_1, R_3 and R_5 were found to be 0.04634 ± 0.00010, 2.9231 ± 0.0047 and 0.02275 ± 0.00005 respectively. Results from mass analyses of the irradiated samples were fitted to the expression:-

$$R_3 \exp(-\hat{S}_1 i - \lambda_1 t) = R_4 \exp(-\hat{S}_9 i) - P \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

in which P is a small factor common to all such samples. Having obtained $\exp(-\hat{S}_1 i - \lambda_1 t)$, $\hat{S}_1$ can be obtained, since $\exp(\lambda_1 t)$ is known to be 1.0431 ± 0.0002. The various factors are listed in Table 5 and give a mean value for $\hat{S}_1$ of 1482 ± 11 barns (standard error). Taking uncertainties in $\hat{S}_9$, R_3, P and $\lambda_1 t$ into account also, $\hat{S}_1$ becomes 1482 ± 35 barns, and this is the value to be used for all samples.

Finally, the same samples are used to deduce $\hat{S}_1/\hat{\sigma}_1$. In this case the expression used is

$$\hat{S}_1/\hat{\sigma}_1 = [R_3(1 - \exp(-\hat{S}_1 i))] / [0.9820(1 + E)(R_6 \exp(-\hat{S}_9 i) - R_5 \exp(-\hat{\sigma}_2 i) - Q)] \quad \ldots(6)$$

where Q is another small factor common to all ^{239}Pu ^{241}Pu mixtures and 0.9820 is a factor which corrects the measured amount of ^{242}Pu produced for the proportion resulting from the sequence $^{241}Pu \xrightarrow{\beta^-} {}^{241}Am \xrightarrow{n,\gamma} {}^{242g}Am \xrightarrow{\text{k-capture}} {}^{242}Pu$. [We have obtained this factor from the knowledge that the initial ^{241}Pu was separated from ^{241}Am 380 days before the commencement of the irradiation, and by assuming the following for our irradiation conditions; ^{241}Am has a neutron capture cross section of 622 barns, neutron capture by ^{241}Am produces 16-hour ^{242g}Am and 152-year ^{242m}Am in the ratio 5.17 to 1, ^{242g}Am has a fission cross section of 2900 barns and decays 16 per cent to ^{242}Pu. (4)].

The results are presented in Table 6 and give a mean value for $\hat{S}_1/\hat{\sigma}_1$ of 3.931 ± 0.042 (standard error). Taking uncertainties in $\hat{S}_9$, $\exp(\lambda_1 t)$, R_3, R_5, $\hat{\sigma}_2$ and the correction factor into account also, gives $\hat{S}_1/\hat{\sigma}_1 = 3.931 \pm 0.111$, and this is our main result.

Combining $\hat{S}_1/\hat{\sigma}_1 = 3.931 \pm 0.111$ and $\hat{S}_1 = 1482 \pm 35$ barns gives $\hat{\sigma}_1 = 377 \pm 14$ barns, the value appropriate to our samples.

DERIVATION OF α_o FOR ^{241}Pu

$\hat{S}_1/\hat{\sigma}_1$ is related to $\hat{\alpha}$ for ^{241}Pu by the expression

$$\hat{S}_1/\hat{\sigma}_1 = (1 + 1/\hat{\alpha}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and $\hat{\alpha}$ is related to α_o by the equation

$$(1 + \hat{\alpha}) = (1 + \alpha_o)(g_a + r\, s_a)/(g_f + r\, s_f)$$

in which g_a and s_a etc. have their usual meanings. Using $\hat{S}_1/\hat{\sigma}_1 = 3.931 \pm 0.111$ expression (7) gives $\hat{\alpha} = 0.341 \pm 0.013$. Based on values for g_a and g_f given by WESTCOTT et al. (2,5), and the resonance integral data for ^{241}Pu given in Table 1, we have calculated $(g_a + r\, s_a)/(g_f + r\, s_f)$ to be (0.9886 ± 0.0075) for $r = (7.5 \pm 1.0) \times 10^{-4}$ and $T = 116 \pm 4^{\circ}$. In consequence, we conclude that α_o for ^{241}Pu is 0.356 ± 0.017.

DERIVATION OF OTHER NUCLEAR CONSTANTS

In the determination of ratios of cross sections (such as $\hat{S}_9/\hat{\sigma}_9$ and $\hat{S}_1/\hat{\sigma}_1$) possible systematic, as opposed to random, errors in the measurement of neutron dose have no effect, since only the products of cross sections and flux terms are involved, and the former have been determined individually using a set of monitors whose activities were measured at the same time and under the same conditions; systematic errors in the dose terms therefore cancel out. However, when a single cross section is determined, this source of uncertainty makes a contribution.

This fact has been taken into account in compiling Table 7 in which all the cross section results are collected together. It has been assumed that possible systematic errors in neutron dose arise from three sources i.e. 1) uncertainty in the absolute activities of the cobalt standards used to calibrate the ionization chamber ($\pm$ 2 per cent), 2) uncertainty in calibrating the ionization chamber with the cobalt standards ($\pm$ 1 per cent), and 3) uncertainty in the 2200 m/sec neutron capture cross section of ^{59}Co (which was taken to be 37.4 $\pm$ 0.6 barns). Due to these additional errors, uncertainties in the individual cross sections quoted in Column 2 of Table 7 differ somewhat from those given previously in this paper.

Table 7 is divided into two parts. In the first part those quantities which were measured directly are given. In the second part derived quantities are listed; thus, as examples, σ_9 is derived from S_9 and S_9/σ_9, and $\sigma_{f,9}$ (the fission cross section of ^{239}Pu) is given by $(S_9 - \sigma_9)$ etc.

In the second column of the table the experimental values for the reactor spectrum are given. From these the corresponding 2200 m/sec data have been derived (column 4), by the use of the conversion factors given in column 3, which were obtained by adjusting the g and s factors given by WESTCOTT [5,6] and CRITOPH [7] so that they are compatible with the data of Table 1. Finally, in the last column of the table, we list, for convenient comparison, the current recommended values for the various nuclear parameters. Some of these values have already been given in Table 1; the rest are taken from the work of WESTCOTT et. al. [2]

DISCUSSION

In order to make the interpretation of our results more certain, we have sought for this work an intense source of thermal neutrons. In this search we have been successful. In the irradiation position chosen the thermal, fission and epithermal flux densities were about 6.4×10^{12} n/cm^2/sec, 4.5×10^9 n/cm^2/sec and 4.8×10^9 n/cm^2/sec per ln E interval, respectively. Moreover the thermal neutrons almost certainly followed an unperturbed Maxwell-Boltzmann distribution pattern since, not only was the position separated from the nearest source of fission neutrons by about two feet of heavy water, but the measured neutron temperature ($116 \pm 4^\circ$) was very close to the temperature of the surrounding graphite - a thermocouple embedded in the graphite reflector in a position similar to that adjacent to the sample, recorded a temperature of 118°.

The measured neutron doses also showed a distribution pattern which might have been predicted from the known flux gradients in the irradiation position. Thus the largest neutron dose measured differed from the smallest by 4.6 per cent. From the flux change from one side of the irradiation can to another, a difference of 4 per cent was to be expected; a few millimetres mis-alignment of the monitors in the can would easily account for the slightly larger difference.

The results we have obtained are summarised in Table 7 and the 2200 m/sec values derived from them are compared with the current recommended values. It will be observed that there is good agreement between the two sets of data in all cases. In the particular case of alpha for ^{241}Pu, which was the main object of these measurements (and also in the case of the capture cross section of ^{241}Pu), our figures are, in fact, more precise than those recommended.

The recommended data for ^{239}Pu and ^{241}Pu have been taken from the recent survey by WESTCOTT et. al. [2] and were obtained, not as the results of individual measurements, but by a least-squares fitting procedure, taking into account all the published data for these nuclides and the relationships between them. It is therefore more appropriate to compare our results, not with the final results of

the survey, but with the input data which went into it, and to consider the values given here as possible additional data to be included when further surveys of this type are made in the future.

With this aim in view we have abstracted the data for alpha and for neutron absorption and capture, considered by WESTCOTT et. al. and have listed it, without comment, in Table 8. Full details are given in the original paper.

Considering ^{239}Pu first, a comparison of the values in Table 8 with the present results will show that, although there is general agreement, the values reported here are likely to have only a small effect on future weighted means for S_9 and σ_9, and almost no effect in the case of α_9. (The value for α_9 given here is less precise than the lower figure given in Table 8 i.e. 0.356 ± 0.0092, which is derived from earlier work by one of us [8,9]).

For ^{241}Pu however, the situation is very different. It will be noted that the values reported here for S_1, σ_1 and α_1 are all more precise than any corresponding figure in Table 8. (The value given to α_1 in Table 8 i.e. 0.388 ± 0.023, is derived from earlier work by the present authors which we would now consider superseded [1]). They will therefore have a very large effect when ^{241}Pu data are surveyed again in the future.

REFERENCES

1) M.J. CABELL and M. WILKINS. J.Inorg. Nucl. Chem. 27, 2481-2491 (1965).

2) C.H. WESTCOTT, K. EKBERG, G.C. HANNA, N.J. PATTENDEN, S. SANATANI, and P.M. ATTREE. Atomic Energy Review, 3, 3-60 (1965).

3) M.J. CABELL and M. WILKINS. A.E.R.E. R 5122 (1966).

4) J.R. STEHN, M.D. GOLDBERG, R. WIENER-CHASMAN, S.F. MUGHABGHAB, B.A. MAGURNO and V.M. MAY. Brookhaven National Laboratory Report BNL 325, Second Edition, Supplement No.2 (February 1965).

5) C.H. WESTCOTT private communication (1965)

6) C.H. WESTCOTT. Chalk River Report, CRRP960 (July 1962)

7) E. CRITOPH. Chalk River Report, CRRP 1191 (March 1964)

8) M.J. CABELL and L.J. SLEE. J. Inorg. Nucl. Chem. 25, 607-614 (1963)

9) M.J. CABELL and L.J. SLEE. Addendum to A.E.R.E. R 4173 (September 1963)

TABLE 1

2200 m/sec NEUTRON CROSS SECTIONS AND RESONANCE INTEGRALS (ABOVE 0.45 eV) OF PLUTONIUM ISOTOPES [1, 2]

	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
2200 m/sec cross section (barns)				
for absorption	1008.1 ± 4.9	-	1391 ± 22	-
for fission	742.4 ± 3.5	<0.1	1009 ± 9	<0.9
for capture	265.7 ± 3.7	281 ± 7	382 ± 21	19.8 ± 1.1
Resonance integral (above 0.45 eV)(barns)				
for absorption	519 ± 15	-	707	-
for fission	324 ± 9	-	541 ± 14	-
for capture	195 ± 12	8453 ± 600	166	1220 ± 200

TABLE 2

RESULTS FOR ^{240}Pu - ^{242}Pu MIXTURES (EQUATION 1)

(M = 0.0015)

	Sample			
	11	12	13	14
$i \times 10^{-20} (n/cm^2)$	1.334	1.335	1.355	1.310
R_8 / R_7	0.9589	0.9647	0.9650	0.9615
$\exp[(\hat{\sigma}_2 - \hat{\sigma}_0)i]$	0.0404	0.0345	0.0342	0.0378
$(\hat{\sigma}_0 - \hat{\sigma}_2)$ barns	303.1	258.1	252.1	288.6

TABLE 3

RESULTS FOR THE ^{239}Pu - ^{242}Pu MIXTURES (EQUATION 5)

(N = 0.0003)

	Sample				
	6	7	8	9	10
$i \times 10^{-20}$ (n/cm^2)	1.353	1.315	1.313	1.336	1.358
R_5/R_6	0.8610	0.8583	0.8549	0.8491	0.8470
$\exp[(\hat{\sigma}_2 - \hat{S}_9)i]$	0.8613	0.8586	0.8552	0.8494	0.8473
$(\hat{S}_9 - \hat{\sigma}_2)$ barns	1104	1160	1191	1221	1222

TABLE 4

RESULTS FOR ^{239}Pu - ^{242}Pu MIXTURES (EQUATION 4)

	Sample				
	6	7	8	9	10
$i \times 10^{-20}$ (n/cm^2)	1.353	1.315	1.313	1.336	1.358
R_2	0.05818	0.05746	0.05765	0.05842	0.05848
$\exp(-\hat{S}_9 i)$	0.8588	0.8562	0.8528	0.8470	0.8447
$\exp(-\hat{\sigma}_0 i)$	0.9607	0.9618	0.9618	0.9612	0.9605
B	0.0206	0.0203	0.0201	0.0205	0.0209
$\hat{S}_9 / \hat{\sigma}_9$	3.080	3.193	3.272	3.374	3.431

TABLE 5

RESULTS FOR ^{239}Pu - ^{241}Pu MIXTURES (EQUATION 5)

(P = 0.0025)

	Sample				
	1	2	3	4	5
$i \times 10^{-20} (r/cm^2)$	1.308	1.301	1.316	1.362	1.344
R_4	2.6939	2.6994	2.7068	2.6989	2.7139
$\exp(-\hat{S}_9 i)$	0.8547	0.8554	0.8539	0.8492	0.8510
$\exp(-\hat{S}_1 i - \lambda_1 t)$	0.7867	0.7891	0.7899	0.7832	0.7892
$\hat{S}_1$	1511	1497	1472	1485	1447

TABLE 6

DERIVATION OF $\hat{S}_1 / \hat{\sigma}_1$ (EQUATIONS 5 and 6)

($Q = 0.00007$)

	Sample				
	1	2	3	4	5
R_6	0.18385	0.17899	0.18348	0.18868	0.18977
$\exp(-\hat{S}_9 i)$	0.85468	0.85538	0.85389	0.84915	0.85100
$\exp(-\hat{\sigma}_2 i)$	0.99725	0.99727	0.99724	0.99714	0.99718
$(1-\exp(-\hat{S}_1 i))$	0.17937	0.17694	0.17612	0.18307	0.17678
$(1 + E)$	1.00146	1.00143	1.00144	1.00151	1.00148
$\hat{S}_1 / \hat{\sigma}_1$	3.968	4.035	3.909	3.958	3.787

TABLE 7

SUMMARY OF ALL CROSS SECTION RESULTS

Cross section or ratio of Cross sections	Value obtained for reactor neutrons	Conversion factor	Value obtained for 2200 m/sec neutrons	Current recommended value
Measured Directly				
S_9 (barns)	1201 ± 47	1.1866 ± 0.0061	1012 ± 40	1008.1 ± 4.9
α_9	0.441 ± 0.022	1.0460 ± 0.0071	0.377 ± 0.023	0.3580 ± 0.0054
σ_0 (barns)	297 ± 15	1.0858 ± 0.0030	273 ± 14	281 ± 7
S_1 (barns)	1482 ± 39	1.0841 ± 0.0024	1367 ± 37	1391 ± 22
α_1	0.341 ± 0.013	0.9886 ± 0.0075	0.356 ± 0.017	0.379 ± 0.021
Measured Indirectly				
σ_9 (barns)	367 ± 19	1.352 ± 0.023	275 ± 15	265.7 ± 3.7
$\sigma_{f,9}$ (barns)	834 ± 51	1.1344 ± 0.0050	735 ± 45	742.4 ± 3.5
σ_1 (barns)	377 ± 15	1.051 ± 0.023	359 ± 16	382 ± 21
$\sigma_{f,1}$ (barns)	1105 ± 42	1.0966 ± 0.0071	1008 ± 40	1009 ± 9

TABLE 8

2200 m/sec INPUT DATA USED BY WESTCOTT et. al. [2]

	^{239}Pu			^{241}Pu		
	S_9 (barns)	σ_9 (barns)	α_9	S_1 (barns)	σ_1 (barns)	α_1
	1029 ± 42	283 ± 10	0.356 ± 0.0092	1379 ± 50	374 ± 86	0.388 ± 0.023
	1004 ± 30	265 ± 12	0.362 ± 0.0092	1372 ± 40		
	1004 ± 12					
	1007 ± 7.4					
Mean Values	1006.56 ± 6.42	275.6 ± 7.7	0.3590 ± 0.0065	1374.7 ± 31.2	374 ± 86	0.388 ± 0.023
This work	1012 ± 40	275 ± 15	0.377 ± 0.023	1367 ± 37	359 ± 16	0.356 ± 0.017