# An Evaluation of $\alpha$ (E) for $\mathrm{Pu}^{239}$ in the energy range 100 eV to 15 MeV 

by

M. G. Sowerby and B. H. Patrick A.E.R.E., Harwell.

## Abstract

An evaluation of $a(E)$, the ratio of capture to fission cross-sections, for $\mathrm{Pu}{ }^{239}$ has been made in the energy range 100 eV to 15 MeV . Between 100 and 600 eV and above 15 keV the evaluation recommends values in reasonable agreement with the previous evaluations of Douglas and Barry and Schmidt. In the energy range 600 eV to 15 kc V the values are in general about $70 \%$ higher than those previously recomended. Earlier evaluations relied mainly on the integral a measurements made in broad neutron spectra at KAPL. In the present work the capture cross-section is obtained by taking the accurately known total cross-section and subtracting the measured fission cross-section and the scattering cross-section calculated from recent values of resonance parameters. Alternative calculations of the capture cross-section have also been made and all are found to give consistent results. It is concluded that the KAPL a-values are inconsistent with the measured values of fission and total cross-section and the recent values of resonance parameters.

## 1.

## Introduction

This evaluation has been made to aid $\operatorname{Hart}^{(1)}$ in his new evaluation of $\mathrm{Pu}^{23}$
data which is to be used in the new cross-section set (FD 3) for fast reactor calculations. In practice it is the capture cross-section ( $\sigma_{n \gamma}$ ) which is required. However, few measurements of $\sigma_{n \gamma}$ have been made between 100 eV and 15 MeV and so this cross-section is usually deduced from the measurements of $a(E)$, the ratio of the capture to fission cross-sections. The evaluation is divided into three sections which will be considered in turn.
(i) Energies above 1 MeV where there are no experimental data.
(ii) Energies between 15 keV and 1 MeV where there are the results from several experiments.
(iii) Energies between 100 eV and 15 keV where there is very little direct information.

This evaluation is mainly concerned with this last energy region.

## 2. Energies above 1 MeV

There are no experimental data in this energy region. It is recommended that, following Douglas and Barry ${ }^{(2)}, \sigma_{n \gamma}$ be assumed proportional to $E^{-3 / 2}$, where $E$ is the neutron energy, the constant of proportionality being found from the data at 1 MeV .

## 3. Energies between 15 keV and 1 MeV

There are several series of measurements which gives $a$ in this energy region. The most accurate and reliable are those of Hopkins and Diven (3) and de Saussure et al ${ }^{(4)}$. The other data are listed by Douglas and Barry and can be used to confirm the accuracy of the more reliable data. The recommended curve, which is shown in Fig. 1, gives greatest weight to the data of de Saussure et al between 15 keV and 80 keV and to the data of Hopkins and Diven between 80 keV and 1 MeV .

The only $\mathrm{a}(\mathrm{E})$ measurements available until recently have been the KAPL data listed in Table I which were partially reported by Kanne et al ${ }^{(5)}$ and subsequently summarised by Sampson and Molino ${ }^{(6)}$. The results of these measurements have been the basis oí previous evaluations for $a(E)$ for $\mathrm{Pu}^{239}$ in the region below a few keV. Recently some Russian data in the region below 210 eV have become available. Ignatev and Kirpichnikov ${ }^{(7)}$, using four 8 cm diameter and 8-10 cm high NaI crystals to detect $\gamma$-rays and two photomultipliers coated with a paraffin-zinc sulphide mixture as neutron detectors, have produced the ratios of average fission $\left\langle\sigma_{n F}>\right.$ to average absorption $\left\langle\sigma_{n \gamma}+\sigma_{n F}>\right.$ cross-sections given in Table II. Also shown are the corresponding ratios of average capture to average fission cross-sections.

Wang Yung-chang et al ${ }^{(8)}$, using a similar technique to that used by Shi-di et al ${ }^{(9)}$ for measurements on $U^{235}$, have also produced some data. They used a large cadmium loaded scintillator on the pulsed reactor at Dubna and distinguished fission events from capture events by checking whether or not there were any delayed pulses following the prompt pulse due to fission or capture $\gamma$-rays. The delayed pulses were due to fission neutrons which were slowed down by the hydrogenous material in the scintillator and then captured in the cadmium. Table III gives their results for the average fission to average absorption cross-section and the corresponding ratios of average capture to average fission cross-sections.

The KAPL measurements were made in broad neutron spectra and therefore the data can only be considered to give some indication of the value of $a$. The Russian data are limited in number but indicate that $a$ is $\sim 0.8$ in the region 100 - 200 eV .

At the present time the only differential cross-section data available in the energy region 200 eV to 15 keV are the measurements of the total ( $\sigma_{\mathrm{nT}}$ ) and fission ( $\sigma_{n F}$ ) cross-sections. In order to obtain the capture cross-section
it is possible
(a) to calculate the capture cross-section using average resonance parameters
(b) to calculate the scattering cross-section $\left(\sigma_{n n}\right)$ and deduce the capture cross-section from the formula

$$
\begin{equation*}
\sigma_{n T}=\sigma_{n F}+\sigma_{n r}+\sigma_{n n} \tag{1}
\end{equation*}
$$

by using the measured values of $\sigma_{n T}$ and $\sigma_{n F}$.
It is better to calculate $\sigma_{n n}$ than $\sigma_{n \gamma}$ because
(1) the principal component of $\sigma_{n n}$ is the shape elastic cross-section which can be accurately deduced
(2) the compound elastic scattering cross-section, which is the remainder of the $\sigma_{n n}$ cross-section below the first known excited state at 8 keV , is less than $\sigma_{n \gamma}$ below 1 keV
(3) above 1 keV p-wave reactions become increasingly important, particularly for the fission and capture cross-sections, and the average fission and capture widths for p-wave reactions are not known. However, because of the energy dependence of the neutron width $\left(T_{n}\right)$ the $p$-wave compound elastic scattering cross-section is small below 10 keV and can be neglected. Therefore, the more accurate method of obtaining $\sigma_{n Y}$ over the energy range 200 eV to 10 keV is to calculate $\sigma_{n n}$ and use equation (1).
This technique was used by Uttley ${ }^{(10)}$ for $U^{235}$ and gives good agreement with the recent data of de Saussure et al ${ }^{(4)}$. The techiigue was also used for Pu ${ }^{239}$ by Uttley and James $(11)$ who concluded that the $\sigma_{n \gamma}$ values deduced above 600 eV were not reliable because both the average fission cross-section $\left(\left\langle\sigma_{n \mathrm{~F}}\right\rangle\right)$ and the quantity $\sqrt{E}\left\langle\sigma_{n F^{\prime}}\right\rangle / S_{0}$ show a sudden decrease at $\sim 600 \mathrm{eV}$. ( $S_{0}$ in this context is the local value of the swave strength function and $E$ is the neutron energy). Such a change in $\left\langle\sigma_{n F}\right\rangle$ may reflect in the average value of the compound elastic scattering cross-section ( $\left\langle\sigma_{c e}\right\rangle$ ) and so it is
necessary to examine the available experimental data to see if this is likely*
In order to see if the scattering cross-section changes abruptly above 600 eV the data obtained in the scattering measurements of Asghar ${ }^{(13)}$ have been investigated. Because of resonance self-shielding and the attenuation of the scattered neutrons in the sample it is not possible to extract values of $\sigma_{n n}$ from these data in regions of poor resolution (i.e. above 300 eV ). It is, however, possible to see qualitatively that there is no dramatic increase or decrease in the scattering cross-section above 600 eV .

The average total crass-section data of Uttley (23) decrease above 600 eV but not so dramatically as the fission cross-section vailues. (If the changes in resonance contributions to the average total and fission cross-sections were completely correlated then $\sqrt{E}<\sigma_{n F}>/ S_{0}$ would be constant).

The abrupt changes in $\left\langle\sigma_{n F}\right\rangle$ and $\left.\sqrt{E}<\sigma_{n F}\right\rangle / S_{o}$ could in principle be due to
(1) a fluctuation in the average value of one of the partial resonance widihs $\left(T_{n}, T_{r}\right.$ and $T_{F}$, the neutron, radiation and fission widths respectively)
(2) a fluctuation in the average level spacing
(3) the opening of another exit channel.

It could of course be due to a combination of one or more of these factors. Table $V$ shows roughly the effect on $\left\langle\sigma_{n n}\right\rangle,\left\langle\sigma_{n \gamma}\right\rangle,\left\langle\sigma_{n F}\right\rangle, \sqrt{E}\left\langle\sigma_{n F}\right\rangle / S_{0}$ and $\left\langle\sigma_{n T}\right\rangle$ of these changes. In drawing up the table the values of average resonance parameters given in Table IV have been used. These parameters were chosen because they are the most recent and comprehensive set available. It must be remembered in looking at Table $V$ that the changes in the resonance parameters for the two possible spin states ( $J=0,1$ ) have dieferent effects because their contributions to the partial cross-sections are not the same. It

[^0]can be seen that the most likely fluctuations ${ }^{\dagger}$ to cause the observed changes are an increase in the level spacing of the $J=0$ levels and a reduction in $\left\langle\Gamma_{n}\right\rangle$ for the $J=0$ levels. Therefore, it is concluded that, since the contribution to $\left\langle\sigma_{c e}\right\rangle$ due to the $i=0$ levels is small, it is unlikely that the abrupt change in $\left\langle\sigma_{n F}\right\rangle$ reflects in $\left\langle\sigma_{c a}\right\rangle$. Hence it is reasonable to calculate $\sigma_{n n}$ and deduce $\sigma_{n \gamma}$ from equation (1). However, it is recommended that this approach must be used with caution and large errors given to the calculated values of $\bar{\sigma}_{n n}$. (N.B. for the remainder of this paper the measured and calculated average cross-sections will be represented as < 0 , and $\bar{\sigma}$ respectively).

The scattering cross-section in the energy range below 8 keV consists of the s-wave shape elastic ( $\sigma_{\text {se }}$ ) and compound elastic ( $\sigma_{c e}$ ) scattering crosssections, the average values of which are given by the formulae below. These are valid for s-wave interactions in $\mathrm{Pu}^{239}$ for energies below 100 keV but the calculation has only been done below 10 keV because of p-wave effects. Above 8 keV there is a very small contribution from inelastic scattering but this can be neglected

$$
\begin{equation*}
\bar{\sigma}_{s e}=4 \pi \lambda^{2}\left[\sin ^{2}\left(\frac{R^{\prime}}{\lambda}\right)+\frac{\pi}{2} \sqrt{E} S_{0}\left\{\cos \left(\frac{2 R^{\prime}}{\lambda}\right)-1\right\}\right] \tag{2}
\end{equation*}
$$

$R^{\prime}=R\left(1-R_{0}^{\infty}\right), R$ is the interaction radius $\lambda n d R_{0}^{\infty}$ is the s-wave distant level parameter.

$$
\begin{equation*}
\bar{\sigma}_{c e}=2 \pi^{2} \lambda^{2} \sum_{J} \frac{g_{s}}{D_{s}}\left\langle\frac{T_{n} \Gamma_{n}}{\Gamma}\right\rangle_{J} \tag{3}
\end{equation*}
$$

where $g_{J}$ is the statistical weight, $J$ is the spin of the compound nucleus, $D_{J}$ is the level spacing and $T$ is the total width. Equation (3) can be

It seems likely that the low energy data are the result of a fluctuation because $\sqrt{\mathrm{E}}<\sigma_{\mathrm{nF}}>/ \mathrm{S}_{0}$ is well behaved from 600 eV to a few geV where p-waves become important.
simplified by using the relation

$$
\left\langle\frac{\Gamma_{n} \Gamma_{n}}{\Gamma}\right\rangle_{J}=R_{J} \frac{\left(\left\langle\Gamma_{n}\right\rangle_{J}\right)^{2}}{\langle\Gamma\rangle_{J}}
$$

where $R_{J}$ is the 'so-called' fluctuation factor to give

$$
\begin{equation*}
\overline{\sigma_{c e}}=2 \pi^{2} \lambda_{0}^{2} \sum_{J} g_{I} D_{J} S_{0}^{2} \frac{R_{J}}{\langle T\rangle_{J}} \tag{4}
\end{equation*}
$$

where $2 \pi \lambda_{0}$ is the neutron wavelength at 1 eV .
Calculations have been made of $R_{J}$ by assuming that
(a) The radiation width, $\Gamma_{\gamma}$, is constant
(b) the neutron width, $\Gamma_{n}$, has a Porter-Thomas distribution
(c) the fission width, $\Gamma_{f}$, has a $X^{2}$ distribution with $\nu$ degrees of freedom. Calculations have been done for $\nu$ with values of 1, 2 and 3. The results for $\nu=3$ agree well with similar calculations of Greebler and Goldman (15).

The values of $\bar{\sigma}_{\text {se }}$ and $\bar{\sigma}_{c e}$ which are shown in Table VI were calculated using the data given in Table IV. It is not really possible to say exactly what the values of $\nu$ are for the two spin states. The values of 2 and 1 for the states with spin 0 and 1 respectively are consistent with those expected from the channel theory of fission. Fortunately most of the compound elastic cross-section comes from the spin 1 levels and $R_{J}$ only alters in the energy region under discussion by $\sim 10^{\circ} \%$ if $\nu$ is changed from 1 to 3 . It is interesting to note that the contribution to the fission cross-section is approximately identical from the two spin states. The capture cross-section, like the compound elastic scattering cross-section, is mainly due to the spin 1 levels. The calculation of $\bar{\sigma}_{c e}$ using equation (4) can be compared with a calculation done using equation (3) in which $\left\langle\Gamma_{n} \Gamma_{n} / \Gamma\right\rangle$ was calculated using the data of Derrien et al. The values obtained for the energy intervals $100-200,200-300$ and $300-400 \mathrm{eV}$ are $3.58,7.10$ and 3.72 barns respectively which are in reasonable agreement with the values given in Table VI of 5.10, 7.90 and 3.76 barns.

Table VI also gives the recommended average total and fission cross-sections
and the deduced value of $a=\left\langle\sigma_{c}\right\rangle /\left\langle\sigma_{F}\right\rangle$. It has been assumed in the calculation of errors that the error in $\vec{\sigma}_{c e}$ is $50^{\circ} / 0$ of $\vec{\sigma}_{c e}$. The data are shom plotted in Fig. 2 together with the other experimental data thet are available. It can be seen that between 100 and 200 eV the calculated and experimental values agree within experimental error. At $\sim 10 \mathrm{keV}$ the calculated value agrees with an extrapolation to low energy of the data of de Saussure et al. Between 1 and 10 keV the calculated data are considerably higher than the two KAPL points - but, because of the large errors, not inconsistent with them. However, the KAFI data were measured in broad neutron energy spectra and so the values of a cannot be assigned to a single energy point. Therefore the recommended values of $a$ as a function of neutron energy are as follows
(i) the mean of the calculated and Soviet data between 100 and $200 \mathrm{eV}(0.69 \pm 0.12)$
(ii) the calculated values between 200 eV and 10 keV
(iii) the extrapolation of de Saussure et al data from 10 keV to 15 keV .

## 5. Discussion

The results of this evaluation agree reasonably with previous evaluations (2, 20) except in the energy range 600 eTV to 15 keV where higher values of $a(E)$ are obtained. The previous evaluetions in this energy range were based on the KAPL data. In order to discuss the discrepancies three other evaluations will be considered
(1) Schmidt ${ }^{(20)}$; an earlier version of this evaluation was used in the existing data set (DFN 184) for energies below 1 keV .
(2) Douglas and Barry ${ }^{(2)}$ which was used in DFN 184 above 1 keV .
(3) The recent evaluation of Greebler et al (21).

In his evaluation Schmiat obtained $a(E)$ values from a curve drawn through the KAPL data and deduced $\sigma_{n \gamma}$ from $a(E)$ and the measured fission cross-sections. He calculated $\sigma_{c e}$ from resonance parameters and his recommended $\sigma_{n T}$ values were obtained by summing the partial cross-sections including $\sigma_{\text {se }}$.

Douglas and Barry used the KAPI data for $a(E)$ and calculated $\sigma_{n r}$ by the same method as Schmidt. However they used the $\sigma_{n T}$ measurements to deduce $\sigma_{n n}$ by subtracting $\sigma_{n F}$ and $\sigma_{n r}$ from $\sigma_{n T}$.

The evaluation of Greebler et al is difficult to follow. They used the resonance parameters recommended by Schmidt ${ }^{(22)}$ and calculated $\bar{\sigma}_{n F}$ and $\bar{\sigma}_{n r}$ and hence deduced $\alpha(E)$. In the energy region above 200 eV , where average parameters were used, the calculated and experimental values of the average fission csoss-section disagree and so a "smooth" energy dependent correction term was used to correct the calculated values to the experimental ones. The capture crossmsection mas then obtained from the corrected $\bar{\sigma}_{n F}$ and the calculated values of $a(E)$. No use appears to be made of $\left\langle\sigma_{n r^{\prime}}\right\rangle$ data. One problem in comparing the present evaluation with that of Greebler et al is that different average resonance parameters have been used. If the calculations of $a(E)$ by Greebler et al are repeated with the parameters listed in Table IV then higher values of $\mathrm{c}(\mathrm{E})$ are obtained (e.g. at 1.5 keV the value calculated from the parameters in Table IV is 0.78 while the value obtained by Greebler et al is 0.65).

Two main criticisms of previous evaluations can be made
(1) They relied upon the KAPL data for $a(E)$
(2) They made little use of total cross-section data. Douglas and Barry, who used the measured total cross-section values to get the elastic scattering cross-section, employed $\sigma_{n T}$ data which are lower by up to $10^{\circ} / 0$ than the Uttley data ${ }^{(23)}$. Therefore the values of the scattering cross-section they obtained, which appeared to be of the correct magnitude, are lower than would be obtained if their method were repeated at the oresent time.
Finally the results of four different methods of obtaining $\alpha(F)$ from the available data, including the method used in Section 4, are compared to see if alternative approaches to the problem give consistent results. The calculations are described below
(A) The calculation done in Section 4.
(B) $\bar{\sigma}_{n \gamma}$ calculated using the formula

$$
\begin{equation*}
\bar{\sigma}_{n x}=2 \pi^{2} \lambda^{2} \sum_{J} g_{J} \sqrt{E} S_{0} \frac{\left\langle\Gamma_{x}\right\rangle}{\langle\Gamma\rangle} X_{J} \tag{5}
\end{equation*}
$$

where $X_{J}$ is the appropriate fluctuation factor and $S_{0}$ is taken to be $1.07 \times 10^{-4}, \alpha(E)$ is calculated by dividing $\bar{\sigma}_{n \gamma}$ by the experimental average fission cross-section.
(C) As for calculation (B) but with $\left\langle\sigma_{n F}\right\rangle$ replaced by calculated values ( $\bar{\sigma}_{n F}$ ) obtained from the equation equivalent to (5).
(D) The difference $\left\langle\sigma_{n T}\right\rangle-\left\langle\sigma_{n \mathrm{~F}}\right\rangle-\bar{\sigma}_{\mathrm{se}}$ is predominantly the sum of the compound elastic scattering and capture cross-sections for the $J=1$ levels with only a small contribution from the $J=0$ levels. If the $J=0$ contributions are calculated then $\bar{\sigma}_{c e}$ and $\bar{\sigma}_{n \gamma}$ for $J=1$ can be obtained with the aid of the relation

$$
\begin{equation*}
\frac{\bar{\sigma}_{c e}}{\overline{\sigma_{r \gamma}}}=\frac{\left\langle\Gamma_{m}\right\rangle R_{s}}{\left\langle T_{\gamma}\right\rangle X_{J}} \tag{6}
\end{equation*}
$$

This ratio of cross-sections is virtually independent of $\left\langle\Gamma_{F}\right\rangle$. In this calculation $\left\langle\Gamma_{n}\right\rangle$ was obtained from the s-wave strength function assuming that this was $1.07 \times 10^{-4}$ and independent of neutron energy and $a(E)$ is calculated using the experimental value of the average fission cross-section.

The results of the calculations are given for a limited number of energy intervals in Table VII which also shows the $a(E)$ values, based on the KAPL data, that are recommended by Schmidt ${ }^{(20)}$. The following conclusions can be drawn from the table -
(1) Above 600 eV all calculations give higher values of $a(E)$ than recommended by Schmidt from the KAPL data.
(2) (A) and (D), which used the measured $\left\langle\sigma_{n T}>\right.$ data, are in good agreement and both give $a(E) \sim 1$ above 600 eV .
(3) (B) rather than (C) gives values of $c(E)$ which follow more closely the fluctuations obtained with (A). This confirms that the fluctuations in $\sqrt{E}<\sigma_{n \mathrm{~F}}>/ S_{0}$ are mainly due to fluctriations in the $\mathrm{J}=0$ cross-sections.

It is therefore concluded that the recommended values of $\alpha(E)$ are supported by alternative calculations. If use is made of the measured total cross-section data then the high values of $a(E)$ obtained above 600 eV must be correct unless either the averase scattering cross-section is higher than one would calculate from average resonance parameters or there is another exit channel which opens above 600 eV . From the available experimental evidence both of these possibilities appear unlikely.

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TABLE I
Data of Kanne et 21

| Mean Energy <br> $(\mathrm{keV})$ | $a$ | Methoa* |
| :---: | :---: | :--- |
| 0.1 | $0.80 \pm 0.17$ | KAPL foils |
| 0.15 | $0.70 \pm 0.10$ | KAPL PPA |
| 1.25 | $0.60 \pm 0.12$ | KAPL foils |
| 3 | $0.53 \pm 0.18$ | KAPL PPA |
| 15 | $0.45 \pm 0.08$ | KAPL foils |
| 225 | $0.10 \pm 0.10$ | KAPL PPA |

*See ref. (5) for details.

TABLE II
Data of Ignater and Kirpichnikov

| Energy Range <br> $(\mathrm{eV})$ | $\left\langle\sigma_{\mathrm{nF}}\right\rangle /\left\langle\sigma_{\mathrm{nA}}\right\rangle$ | $\left\langle\sigma_{\mathrm{nr}}\right\rangle /\left\langle\sigma_{\mathrm{nF}}\right\rangle$ |
| :---: | :---: | :---: |
| $7-40$ | $0.57 \pm 0.05$ | $0.75 \pm 0.15$ |
| $40-106$ | $0.63 \pm 0.07$ | $0.59 \pm 0.18$ |
| $106-210$ | $0.57 \pm 0.10$ | $0.75 \pm 0.31$ |
| $7-210$ | $0.59 \pm 0.04$ | $0.69 \pm 0.12$ |

TABLE III
Data of Wang Yung-chang et al

| Energy range <br> $(\mathrm{eV})$ | $\left\langle\sigma_{\mathrm{nF}}\right\rangle /\left\langle\sigma_{\mathrm{nA}}\right\rangle$ | $\left\langle\sigma_{\mathrm{n} \gamma}\right\rangle /\left\langle\sigma_{\mathrm{nF}}\right\rangle$ |
| :---: | :---: | :---: |
| $0-50$ | $0.54 \pm 0.02$ | $0.85 \pm 0.07$ |
| $50-100$ | $0.58 \pm 0.02$ | $0.72 \pm 0.06$ |
| $100-150$ | $0.53 \pm 0.10$ | $0.89 \pm 0.36$ |
| $150-205$ | $0.49 \pm 0.13$ | $1.04 \pm 0.54$ |

TABLB IV
Values of Data used in celculation of $\sigma_{n n}$

| Quantity | Origin of Data | Value for spin $J$ or comment $J=0 \quad J=1$ |
| :---: | :---: | :---: |
| $S_{0}$ | Uttiey ${ }^{(23)}$ | Assumed to be same for $J=0,1$. <br> This has been checked using the data of Asghar (13). |
| $\mathrm{R}^{\prime}$ | Uttiey ${ }^{(23)}$ | $4 \pi\left(R^{\prime}\right)^{2}=10.3 \pm 0.15$ barns |
| $\left\langle T_{\gamma}\right\rangle$ | $\text { Derrien et al }{ }^{(14)}$ | $\left\langle T_{r}\right\rangle=41.6 \mathrm{meV}$ and assumed to be same for $J=0$ and 1 |
| $\left\langle T_{F}\right\rangle$ | $\text { Derrien et al }{ }^{(14)}$ | 1500 meV <br> 42 meV <br> These values are assumed to be independent of neutron energy. |
| $\left\langle T_{n}\right\rangle$ | $\text { Uttiey }{ }^{(23)}$ | $\left\langle\Gamma_{n}\right\rangle$ was calculated from the local values of $S_{0}$. |
| $\mathrm{D}_{\mathrm{J}}$ | Derrien et al ${ }^{(14)}$ | 9.6 eV 3.2 eV |
| Degrees of Freedom, $\boldsymbol{\nu}$, of $X^{2}$ distribution of fission widths | Derrien et al ${ }^{(14)}$ | 21 |

## TABLE V

Changes in observed cross-sections due to fluctuations in average resonance paramaters
(a) Expected

| Change in $J=0$ parameter |  |  |  |  |  | Change in $J=1$ parameter |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Effect on observed | $\left\langle\sigma_{n n}>\right.$ | $<\sigma_{n \gamma}{ }^{\prime}$ | $<\sigma_{n F}>$ | $\frac{\left.\sqrt{E}<\sigma_{n F}\right\rangle}{s_{0}}$ | $\left\langle\sigma_{n T}>\right.$ | $\left\langle\sigma_{\mathrm{nn}}\right\rangle$ | $\left\langle\sigma_{n \gamma}\right\rangle$ | $\left\langle\sigma_{n F}\right\rangle$ | $\frac{\left.\sqrt{E}<\sigma_{n F}\right\rangle}{S_{0}}$ | $<\sigma_{n T}>$ |
| $\left\langle T_{n}\right\rangle$ reduced | NC | NC | R | R | (R) | R | R | R | I | R |
| $\left\langle\Gamma_{\gamma}\right\rangle$ reduced | NS | NC | NC | NC | NC | (I) | R | (I) | (I) | NC |
| $\left\langle\Gamma_{F}\right\rangle$ reduced | (I) | (I) | R | R | NC | (I) | (I) | R | R | NC |
| Level spacing increased | NC | NG | R | R | (R) | R | R | R | I | R |
| Opening of another exit channel | NC | NC | R | R | NC | (R) | (R) | (R) | (R) | NC |

(b) Experimentally observed at 600 eV

| Cross-Section | $\left\langle\sigma_{n n}\right\rangle$ | $\left\langle\sigma_{n F}\right\rangle$ | $\frac{\sqrt{E}\left\langle\sigma_{n F}\right\rangle}{S_{0}}$ | $\left\langle\sigma_{n T}\right\rangle$ |
| :---: | :---: | :---: | :---: | :---: |
| Observed Change | NC | $R$ | $R$ | $(R)$ |

$N C=N o$ change,$\quad R=$ Reduced. $I=$ Increased. In brackets means change not so significant.

## TABLE VI

Values of Gross-Sections

| Bnergy <br> Interval | $\begin{gathered} \bar{\sigma}_{s e} \\ (b=\overline{s i n s}) \end{gathered}$ | $\begin{aligned} & \bar{\sigma}_{c e} \\ & (b a r n s) \end{aligned}$ | $\underset{\text { (barns) }}{\bar{\sigma}_{i n n}}$ | Assumed error $\text { in }\left\langle\sigma_{m n}\right\rangle$ | $\left\langle\sigma_{n T}\right\rangle$ | $<\sigma_{\mathrm{nF}}>$ <br> (b) | $\left\langle\sigma_{n Y}\right\rangle^{\prime}\left\langle\sigma_{n F}\right\rangle$ | Error |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 100-200 | 10.29 | 5.10 | 15.39 | 2.55 | 48.8 | 20.65 | 0.618 | 0.146 |
| $200-300$ | 10.29 | 7.90 | 18.19 | 3.95 | 50.0 | 19.22 | 0.655 | 0.221 |
| $300-400$ | 10.28 | 3.76 | 14.04 | 1.88 | 32.8 | 9.46 | 0.983 | 0.220 |
| 400-500 | 10.28 | 2.26 | 12.54 | 1.13 | 25.2 | 9.66 | 0.311 | 0.135 |
| $500-600$ | 10.27 | 8.16 | 18.43 | 4.08 | 40.2 | 17.45 | 0.248 | 0.240 |
| 600-700 | 10.27 | 2.26 | 12.53 | 1.13 | 23.4 | 4.22 | 1.339 | 0.300 |
| $700-800$ | 10.27 | 2.39 | 12.66 | 1.20 | 23.0 | 4.55 | 1.272 | 0.300 |
| $800-900$ | 10.26 | 2.34 | 12.60 | 1.17 | 22.4 | 4.32 | 1.268 | 0.303 |
| $900-1000$ | 10.26 | 4.65 | 14.91 | 2.33 | 27.7 | 6.36 | 1.011 | 0.383 |
| $1000-2000$ | 10.24 | 2.83 | 13.07 | 1.41 | 21.2 | 3.81 | 1.134 | 0.383 |
| 2000-3000 | 10.22 | 2.76 | 12.98 | 1.38 | 19.4 | 3.43 | 0.872 | 0.419 |
| $3000-4000$ | 10.20 | 2.59 | 12.79 | 1.30 | 18.1 | 2.63 | 1.019 | 0.506 |
| 4000-5000 | 10.18 | 2.41 | 12.59 | 1.20 | 17.2 | 2.32 | 0.987 | 0.527 |
| $5000-6000$ | 10.16 | 2.31 | 12.47 | 1.15 | - | 2.21 | - | - |
| 6000-7000 | 10.13 | 2.20 | 12.33 | 1.10 | 16.6 | 1.96 | 1.179 | 0.580 |
| 7000-8000 | 10.11 | 2.12 | 12.23 | 1.11 | 15.9 | 2.07 | 0.772 | 0.545 |
| $8000-9000$ | 10.09 | 2.04 | 12.13 | 1.02 | 15.7 | 2.16 | 0.653 | 0.488 |
| 9000-10,000 | 10.07 | 1.97 | 12.04 | 0.98 | 15.2 | 1.88 | 0.680 | 0.535 |

(8) Data of UttIey (23)
(b) Data of James ${ }^{(16)}$



## TABLE VII

Comparison of values of $a(E)$



[^0]:    *It might be imagined that this effect would not affect the $\eta$ measurements of Patrick et al ${ }^{(12)}$ but this is not true because the scattering cross-section is used in the calculation of $\eta$ and $\sigma_{n \gamma^{*}}$

