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THE ^{236}U CAPTURE CROSS SECTION

FINAL TECHNICAL REPORT

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1. INTRODUCTION

This Final Report describes the work performed on a program of research to measure the capture cross section of ^{236}U under Contract AT(04-3)-167, Project Agreement 33 with the U. S. Atomic Energy Commission.

Radioisotopic power units have been shown to be practical in a number of applications, both in space missions and earth projects. It appears that a power source making use of the heat generated by the alpha decay of ^{238}Pu offers a number of advantages over isotopic fuels now in use.

The development of a ^{238}Pu power unit will require much more of this isotope than is presently available, thus necessitating an increased production effort. The production of ^{238}Pu from ^{236}U placed in a reactor flux requires a detailed knowledge of the energy dependence of the following reactions:

It is the objective of this program to obtain the cross section for the first of these reactions, ^{236}U neutron capture, as a function of neutron energy over the greater part of the energy range for which an appreciable reactor neutron flux exists. We have attempted to employ all possible checks and comparisons to verify the validity of the results presented.

2. EXPERIMENTAL PROCEDURES

The experimental facility used to obtain these measurements has been described in detail in the literature;^(1, 2) therefore, only a brief description of the facility will be given in this report. The Gulf General Atomic linear electron accelerator and a fansteel target provide a pulsed neutron source. The bremsstrahlung produced when electrons are stopped in the fansteel target yields neutrons via the (γ, n) process. The fast photoneutrons are partially moderated by cooling water that almost completely surrounds the target. The moderated neutrons then pass through an 18.6-m evacuated drift tube to the capture sample located at the center of a 4000-liter liquid scintillator.

Measurements were made at an electron energy of about 28 MeV with burst widths from 0.05 to 0.8 μ sec, repetition rates from 22.5 to 180 pulses per second and beam currents from 0.5 to about 1A.

Capture and self-indication measurements were obtained concurrently by cycling a ^{236}U sample in and out of the neutron beam between the neutron source and the capture sample (see Fig. 3). The self-indication sample shadows entirely the capture sample located at the center of the γ -ray detector.

For all measurements, except those below 1 eV, a 0.22-cm-thick boron nitride filter was placed in the beam to prevent overlap of low energy neutrons at the high repetition rate used (180 pps). The impurities in the filter ($\sim 3\%$) are elements with low absorption cross sections. Previous measurements⁽³⁾ indicate that the filter has a smooth $1/v$ absorption property in the energy region of interest.

The samples used in the measurements are listed in Table 1.

Table 1
 SAMPLES USED IN THE ^{236}U CAPTURE
 CROSS SECTION MEASUREMENTS

<u>Thickness</u> (Atoms/ barn)	<u>Application</u> (See below)	<u>Composition</u>
3.9×10^{-5}	2	$^{236}\text{U}^a$
1.62×10^{-4}	2	$^{236}\text{U}^a$
4.93×10^{-4}	2	$^{236}\text{U}^a$
6.15×10^{-4}	2	$^{236}\text{U}^a$
6.57×10^{-4}	1, 2, 4	$^{236}\text{U}^a$
9.47×10^{-4}	1, 2, 4	$^{236}\text{U}^a$
1.23×10^{-4}	3	$^{236}\text{U}^a$
3.63×10^{-4}	3	$^{236}\text{U}^a$
7.46×10^{-5}	5	$^{235}\text{U}^b$
1.53×10^{-3}	6	High purity gold
.485	7	Graphite, re-actor grade

1. Used in low energy capture cross section measurements
2. Used to determine resonance parameter in the resolved resonance region (capture samples).
3. Used to determine resonance parameter in the resolved resonance region (self-indication samples).
4. Used in high energy capture cross section measurements
5. Used to subtract the ^{235}U contribution from the ^{236}U sample
6. Used to measure low energy flux shape
7. Used to determine in-scattered neutron effects

- (a) These thicknesses were obtained by stacking from one to four foils of ^{236}U obtained from two slightly different lots of ^{236}U material. The isotopic compositions (%) for the two lots as determined by Oak Ridge National Laboratory are:

	<u>Lot No. 176A</u>	<u>Lot No. 201 A</u>
^{233}U	---	$.001 \pm .001$
^{234}U	$.001 \pm .0005$	$< .001$
^{235}U	$.172 \pm .002$	$.160 \pm .003$
^{236}U	$99.814 \pm .005$	$99.83 \pm .01$
^{238}U	$.013 \pm .002$	$.009 \pm .003$

The nonuranium impurities are negligible.

- (b) The isotopic composition (%) for the ^{235}U foil as determined by Tracerlab West, Richmond, California is:

^{234}U	$.997 \pm .005$
^{235}U	$93.121 \pm .015$
^{236}U	$.565 \pm .005$
^{238}U	$5.316 \pm .014$

The nonuranium impurities are negligible.

The sample thicknesses were determined from the weights and areas. The ^{236}U samples were rolled to uniform thickness at Oak Ridge National Laboratory. The uniformity of the foil thickness was checked by direct measurement or with X-ray photographs. All samples placed at the center of the gamma-ray detector had a diameter of about 5 cm, which is smaller than the diameter of the umbra of the neutron beam at the sample position.

3. MEASUREMENTS AND EXPERIMENTAL RESULTS

For convenience and clarity, the measurements for the three energy regions will be discussed separately. In all three regions it was assumed that neutron fission of ^{236}U could be neglected. This assumption is based on the fission measurements of Lamphere⁽⁴⁾ which indicates that the threshold for neutron fission is about 0.5 MeV. In addition, Leonard⁽⁵⁾ has shown from measurements of the fission cross section that this cross section is less than one barn at the peak of the 5.45 eV resonance.

3.1 0.01 TO 1 eV

This region is of particular importance since most of the neutrons in a thermal reactor spectrum will be contained within this interval. Ignorance of the energy dependence of the capture cross section can make the interpretation of pile oscillator and activation measurements difficult. A complete discussion of the technique employed in the low energy cross section measurements has been reported elsewhere⁽⁶⁾ and therefore only a brief outline will be given here.

Capture cross sections in this energy region have been determined at this facility for a large number of nuclides including gold, the rhenium isotopes, and several tungsten isotopes.^(6, 3) In each case there was good agreement with previous measurements.

3.1.1 Neutron Flux

The neutron flux spectrum was determined by measuring the time dependence of the capture rate for a thin gold sample (see Table 1) placed at the sample position in the detector. The flux spectrum is given by the capture rate divided by the neutron capture probability which was

calculated from the resonance parameters of the level at 4.906⁽⁷⁾ eV and a $1/v$ contribution at thermal of 4.09 barns (which gives a total of 98.8 barns for the thermal capture cross section). Multiple scattering and self-shielding effects were included in the calculation. The calculated gold neutron capture probability agreed within about 1% with that determined from capture measurements made at this laboratory.⁽⁶⁾ Above 1 eV the neutron flux was also determined with a thin BF_3 proportional counter. A self-shielding correction which amounted to about 4% at 1 eV was applied to the BF_3 data. It was found that the time dependence of the neutron flux above 1 eV behaves as $\phi(t) = KE^\alpha$ where t is the neutron flight time, E is the neutron energy, α is a constant and K is a normalization constant which depends on the capture sample used.

The constants K for gold and ^{236}U were determined by using the saturated resonance technique⁽⁸⁾ for the 4.906 eV level in gold and the 5.45 eV level in ^{236}U . Small corrections for multiple scattering, transmission, and resolution effects were made to the saturated resonance data. Errors in the constants K resulting from the uncertainties in the resonance parameters were negligible. The low energy flux (0.01 to 1 eV) for the ^{236}U sample is then given by the flux derived from the gold capture measurement times the ratio of the normalizing constant for ^{236}U to that of gold. The above procedure allows a determination of the neutron flux for the ^{236}U capture measurement in the energy region of interest with a minimum of uncertainty.

3.1.2 Detection Efficiency

For all measurements the capture detector was operated in a coincidence mode to effectively reduce the background counting rates. This was accomplished by optically decoupling the detector into two separate halves and requiring a coincidence between the signals from each half. The electronic criterion which determined whether an event was accepted was that the gamma-ray energy deposited in each half of the detector must

be greater than or equal to 1 MeV and the total energy deposited in the two halves must be between 3.5 and 10 MeV. It was conceivable that the efficiency could be somewhat different from resonance to resonance with the use of this mode, as a result of possible differences in the de-excitation processes which follow capture in one resonance compared to another. To insure that this was not an important effect, ^{236}U capture measurements were made up to 125 eV in the coincidence mode and also simultaneously in a mode in which the only requirement was that the total deposited gamma-ray energy be between 3.5 and 10 MeV. It was found that the ratios of capture areas obtained with the two modes were constant from level to level within the statistical uncertainties ($\approx 2\%$).

Some capture gamma rays created in the sample are attenuated and degraded in energy before leaving the sample. This effect could make the efficiency for detection of an event dependent on the position in the sample where the capture process occurs. However, the calculated difference in transmission for a gamma ray having an energy greater than 0.5 MeV created near the surface of the sample (which is the case for the saturated 5.45 eV resonance from which the flux normalization constant is obtained) and those created uniformly throughout the sample (as is the case at low neutron energies where the sample is very thin) is less than one percent for the thickest of the samples used.

Therefore the biasing and mode of operation of the detector cause only very small errors in the capture cross section.

3.1.3 Cross Section

Though the ^{236}U samples used for the measurement of the low energy capture cross section are about 99.82 percent ^{236}U , a small contaminant of ^{235}U ($\approx 0.16\%$) with a thermal cross section about two orders of magnitude larger than that of ^{236}U causes a significant contribution to the counting rate. Other impurities in the samples contribute only

negligibly to the counting rate. To provide data for an accurate subtraction of the ^{235}U contribution, measurements were also made with a ^{235}U sample (see Table 1). The contribution from impurities in the ^{235}U sample was negligible.

The capture cross section of ^{236}U , for the thin samples used in these measurements, may be written:

$$\sigma_{n, \gamma} = \left[\frac{C_6(t)}{M_6} - \frac{R C_5(t)}{M_5} \right] \frac{1}{s \phi(t) N_6}, \quad (1)$$

where $C_6(t)$ is the observed counting rate as a function of the neutron flight time t , for the ^{236}U sample, and $C_5(t)$ is the analogous quantity for the ^{235}U sample. The remaining quantities are defined as follows:

$\phi(t)$ = the neutron flux in units of neutrons/(cm² · sec)

s = sample area in cm²

N_6 = the number of ^{236}U atoms/barn

M_6 = the multiple scattering factor for the ^{236}U sample

M_5 = the analogous quantity for the ^{235}U sample

R = the ratio of the number of ^{235}U atoms/area in the ^{236}U sample to the number of ^{235}U atoms/area in the ^{235}U sample.

The multiple scattering factor is defined as the total neutron absorption probability divided by the probability of absorption of an incident neutron on the first interaction and it deviated from 1 by 2% or less in these measurements.

The ^{236}U capture cross section obtained is shown in Fig. 1. The points shown are the result of grouping the data points to a selected energy mesh ($\Delta E/E = 0.1$) and do not indicate the energy resolution used.

The residual cross section remaining after a subtraction of the positive energy level contributions was analyzed for negative-energy levels. It was assumed that one negative energy level having width parameters

Figure 1. Low energy neutron capture cross section of ^{236}U .

given by the average reduced neutron width and the average radiation width of the positive energy levels would be sufficient. By requiring that the sum of the capture cross sections calculated from this postulated level and the observed positive energy levels agree with the measured value at 0.0253 eV, it was found that the negative energy level is at -9.7 eV.

The calculated capture cross section from 0.01 to 1 eV resulting from both the negative energy level and the positive energy levels is shown as the solid curve in Fig. 1.

3.2 0-415 eV

In this energy region the resonances are generally well resolved and in many cases conditions were such that a determination of both the neutron and radiation widths was possible.

The resonance parameter determinations employed capture and self-indication area analysis. In most cases at least three capture and two self-indication samples were used - so that nine or more observables were obtained. In principle, only two observables are necessary to determine Γ_n and Γ_γ ; however, overdetermining the parameters allows an improvement in accuracy and permits checks for consistency between various sets of data.

3.2.1 Neutron Flux

The relative neutron flux as a function of time was measured with a thin BF_3 proportional counter. To eliminate pulse overlap at the high repetition rate used (180 pps) the boron nitride filter described previously was inserted in the flight path. The cross section of the filter consists of the $1/v$ absorption due to boron plus the energy independent scattering due to boron and nitrogen. As has been mentioned previously, the incident flux (without a filter) is given by $\phi(t) = KE^\alpha$. The filter transmission is given by $T = \exp\left(\frac{-\beta}{\sqrt{E}} - x \Sigma_s\right)$ where $\frac{\beta}{x}$ is the macroscopic absorption

cross section at 1 eV, Σ_s is the macroscopic scattering cross section, and x is the filter thickness. Therefore, the transmitted flux is given by

$$\phi(t) = K' E^{\alpha} \exp\left[\frac{-\beta}{\sqrt{E}}\right]. \quad (2)$$

A least squares fit was made to the BF_3 data (corrected for dead-time and self-protection effects) for $2 \text{ eV} \leq E \leq 1 \text{ keV}$ with α and β as adjustable parameters. The resulting fit was in excellent agreement with the data points and therefore Eq. 2 was used to calculate the relative flux at each point in the analysis. The flux was made absolute at the 5.45 eV resonance through the use of the saturated resonance technique.

As has been mentioned previously the effects of gamma-ray attenuation in the sample are negligible and were thus ignored.

3.2.2 Resonance Parameter Determinations

The measured capture areas, self-indication areas, and self-indication ratios were analyzed with the computer program TACASI⁽⁹⁾ which calculates the multiple scattering corrections and determines maximum likelihood estimates of Γ_{γ} and Γ_n and their uncertainties by iterative least squares fitting. The nearest neighbor resonances were included in the calculation. The shape of the resonance curves is also calculated and can be compared to the data points.

The results of the resonance parameter analysis are shown in Table 2 along with uncertainties (standard deviations). In all cases it was assumed that the resonances are excited by s-wave neutrons. Plots of curves in the $\Gamma_n, \Gamma_{\gamma}$ plane defined by the measurements used to determine the resonance parameters for the 5.45 eV resonance are shown in Fig. 2. Also shown is the error ellipse which shows the calculated uncertainties in the parameters. In Fig. 3, the observed counting rate as a function of neutron energy near the 5.45 eV resonance for grouped capture and self-indication data are compared with those calculated from the resonance parameters determined in this work.

Table 2
²³⁶U RESONANCE PARAMETERS

E_o^* (eV)	Γ_Y (meV)	Γ_n (meV)	Γ_n (meV) ^{(18)c}	Γ_n (meV) ⁽¹⁶⁾	Γ_n (meV) ⁽¹⁷⁾
-9.7 ± 1.0 ^a	----- ^b	1.6 ^{**}			
5.45	24.5 ± 1	2.16 ± .08	1.76 ± .21	1.95 ^d ± .4 ^e	2.4 ^f
29.7	-----	.585 ± .03	.61 ± .11		
34.0	20.9 ± 3.5	2.35 ± .13	2.6 ± 1.2		
43.7	22.0 ± 1.5	11.8 ± .6	19.0 ± 5.0		
63.1	-----	.034 ± .005			
71.1	23.3 ± .9	19.0 ± 1.0	40.0 ± 10.0		
86.0	24.3 ± 1.3	26.0 ± 2.0	44.0 ± 11.0		
101.7	-----	.8 ± .08			
120.2	24.0 ± 1.5	51.8 ± 4.0	53.0 ± 19.0		
124.2	21.0 ± 3.5	15.9 ± 1.9	8.0 ± 4.0		
133.7	-----	1.08 ± .09			
137.0	-----	.48 ± .1			
163.7	-----	2.09 ± .15			
192.6	-----	13.2 ± 1.3	94.0 ± 25.0		
194.0	18.0 ± 6.0	52.0 ± 13.0			
212.0	24.8 ± 1.3	98.2 ± 10.0	80.0 ± 30.0		
229.0	-----	2.34 ± .14			
243.0	-----	.3 ± .15			
272.4	21.5 ± 2.7	55.0 ± 15.0	100.0 ± 50.0		
288.2	-----	13.5 ± 2.0			
302.5	25.8 ± 1.8	83.5 ± 15.0	130.0 ± 70.0		
320.0	-----	5.8 ± .6			
334.4	-----	6.3 ± .4			
356.0	-----	.64 ± .1			
367.8	-----	.4 ± .3			
371.0	-----	13.8 ± 1.0			
379.3	24.8 ± 3.0	130.0 ± 30.0	190.0 ± 100.0		
415.0	-----	17.8 ± 2.0			

* Uncertainties in resonance energies are ≤ .5% for positive energy levels.

** The reduced neutron width shown here is the average value for the positive energy levels.

^a The stated uncertainty does not contain the uncertainty associated with the assumed radiation and neutron widths.

^b Where no radiation width is given the average value of Γ_Y was assumed in the determination of Γ_n .

^c There is a small difference in the resonance energies obtained in this work compared with the present measurements.

^d By assuming $\overline{\Gamma}_n^0 = 2.4$ meV and $\overline{\Gamma}_Y = 30$ meV, the negative energy resonance was found to occur at -8 eV.

^e A radiation width of 29 ± 7 meV was determined for this level.

^f A radiation width of 33 meV was deduced for this level.

Figure 2. Calculated curves in the $(\Gamma_\gamma, \Gamma_n)$ plane for several experimental capture areas (CA), self-indication areas (SA) and self-indication ratios (SR) for the 5.45 eV resonance in ^{236}U . The least squares determination of the resonance parameters and their uncertainties are shown by the error ellipse.

Figure 3. Comparison of observed and calculated resonance shape from capture and self-indication data for the 5.45 eV resonance in ^{236}U .

Capture sample thickness: 4.93×10^{-4} nuclei/barn
 Filter sample thickness: 1.23×10^{-4} nuclei/barn

In addition to the levels reported in Table 2, a number of possible very weak levels were observed that were either very close to a much stronger ^{236}U resonance or near a level in the ^{235}U impurity ($\sim 0.16\%$ in the samples used). In these cases it was not possible to obtain a value of Γ_n or even assurance that they were truly resonances of ^{236}U .

From the parameters of this set of (assumed) s-wave resonances, one can obtain an estimate of $\overline{\Gamma_n^0}$ (average reduced neutron width), $\overline{D_0}$ (mean level spacing), and S_0 (s-wave strength function). The method of Slavinskas and Kennett⁽¹⁰⁾ was used to determine these estimates and their biases. The results obtained are shown in Table 3 along with the strength functions obtained from the average high energy capture cross section measurements. In Figs. 4 and 5 comparisons of the observed and calculated width and spacing distributions are shown. In both cases there is reasonable agreement between the observed and calculated quantities.

3.3 415 eV - 20 keV

With the self-indication and capture samples employed in this investigation it is difficult to obtain the resonance parameters directly in this energy region. The samples available are thin even for cases where $\Gamma_n \geq \Gamma_\gamma$ so that it is difficult to obtain accurate neutron widths. It is possible to determine precisely the radiation width for the levels for which $\Gamma_n \gg \Gamma_\gamma$ but from the resonances up to 415 eV it was observed that the radiation width is constant (within the experimental errors) from level to level so nothing new is learned. It is possible to determine the neutron width for levels for which $\Gamma_n \lesssim \Gamma_\gamma$ but if only these levels were investigated above 415 eV one would be biasing the strength function toward a low value. Also above 415 eV p-wave resonances become more numerous and if analyzed as s-wave resonances, will tend to give too low a value of the strength function. Therefore, in this energy range average capture cross sections were measured. The analytical procedure is essentially the same as that employed for the low energy cross sections in Section 3.1.

Table 3

 ^{236}U AVERAGE PARAMETERS

<u>s-wave strength function $\times 10^4$</u>		<u>Calculation Method</u>
This work	$1.02^{+0.4}_{-0.2}$	(a)
	1.35 ± 0.3	(b)
Harvey and Hughes (1958 Ref. 18)	1.3 ± 0.4	(c)
<u>p-wave strength function $\times 10^4$</u>	2.3 ± 0.6	(b)
<u>Observed level spacing (eV)</u>		
This work	$15.4^{+2.2}_{-1.}$	(a)
Harvey and Hughes (1958 Ref. 18)	14 ± 4	(c)
<u>Average reduced neutron width (meV)</u>		
This work	$1.6^{+0.6}_{-0.3}$	(a)
Harvey and Hughes (1958 Ref. 18)	1.9 ± 0.6	(c)
<u>Average radiation width (meV)</u>	23.9 ± 1	(a)

Methods

- (a) Calculated from resonance parameters obtained from capture and self-indication data.
- (b) Calculated from measured average capture cross sections.
- (c) Calculated from resonance parameters obtained from total cross section data up to 140 eV. A 14% correction was applied to the level density for small resonances which were missed.

Figure 4. Comparison of the observed integral reduced neutron width distribution for ^{236}U and the integral of the Porter-Thomas distribution.

Figure 5. Comparison of the observed integral level spacing distribution for ^{236}U and the integral of the Wigner distribution.

However, at these energies, the contribution to the counting rate from the ^{235}U impurity was small and relatively constant, (as a function of energy) therefore, a correction of 2% was made to the data to remove the effect of this impurity.

Resonance energies for levels observed (but not analyzed for resonance parameters) between 415 eV and 1 keV are shown in Table 4. A level density plot is shown in Fig. 6. The dotted lines in this figure represent the 68% confidence limits of the level density as evaluated from 0 to 415 eV. It appears as though some levels have been missed at the higher energies.

Table 4

^{236}U RESONANCE ENERGIES (eV) FROM 415 eV to 1 keV
(UNCERTAINTY IN RESONANCE ENERGIES $\leq 0.5\%$)

431.	564.	691.	828.	969.
441.	577.	706.	848.	996.
465.	607.	721.	866.	
479.	618.	747.	889.	
500.	638.	771.	902.	
507.	648.	790.	931.	
537.	656.	807.	949.	
543.	674.	822.	956.	

3.3.1 Neutron Flux

Previous measurements⁽³⁾ made with the target used in this investigation have shown that the exponential dependence of the neutron flux

Figure 6. Number of observed ^{236}U levels as a function of neutron energy.

is valid for neutron energies of at least 40 keV, therefore, the neutron flux for the high energy capture cross section measurements was calculated from Eq. 2 employing the values of α and β deduced from the fit to the BF_3 data for $2 \text{ eV} \leq E \leq 1 \text{ keV}$. The effects of the accelerator-associated gamma flash were reduced by placing a 0.6 cm high purity lead filter in the flight path. There is no resonance absorption by impurities in the filter in the energy region of interest. Since the small lead resonances above 1 keV affect the transmission only negligibly no correction for this effect was applied. The use of the lead filter considerably reduces the gamma flash effect; however, as a further precaution, a ^{24}Na source was used to check for gain shifts which may remain. Below 20 keV the time-dependent gain shift present in the ^{236}U data was less than 2 percent and hence no correction was made to the data.

3.3.2 Average Cross Sections(0.5 to 20 keV)

The cross sections measured in this energy region are averages over the actual cross section which is not smooth but consists of resonance peaks. A correction must, therefore, be made to the values obtained from Eq. 1 to account for the self-shielding which is present near these peaks. The self-shielding correction was determined with the code $\text{SESH}^{(11)}$ which employs Monte Carlo techniques to sample the Porter-Thomas and Wigner distributions for the neutron widths and spacings, thereby determining the correction factor (average neutron capture probability/sample thickness x average cross section) for assumed values of the radiation width and level spacing (those obtained from the resolved resonances) and a guess value of the strength function. This factor also includes the correction for multiple scattering. Since the code also calculates the capture cross section, it is possible by an iterative procedure to obtain the strength function and the measured capture cross section, corrected for self-shielding and multiple scattering. This procedure was used to determine the s-wave strength function from the data points at low neutron energies

where this strength function predominates. Then using this value of the s-wave strength function, the p-wave strength function was determined by making a fit to the high energy data points. It was assumed that the s and p-wave radiation widths are the same and that the level spacing for p-wave resonances is given by $D_1 \sum g(J) = D_0$ (therefore $D_1 = 1/3 D_0$). The contribution to the cross section from d-wave neutron interactions is very small, never exceeding 1 percent of the cross section as calculated from the d-wave strength function reported by Seth.⁽¹²⁾ The correction for self-shielding and multiple scattering was generally small, exceeding 5 percent only below 1 keV. The maximum correction, 9 percent, was applied to the point at 0.55 keV.

The high energy ²³⁶U capture cross section is shown in Fig. 7. The uncertainties in the data points resulting from the neutron flux uncertainty and counting statistics vary from about 5 percent at the lowest neutron energies to about 10 percent at the highest energies. The scatter of the low energy points is primarily due to fluctuations in the number and the neutron widths of the levels contained within the averaging interval. The solid curve in this figure is the cross section calculated from the average parameters. The uncertainties in the strength functions obtained from these data are due mainly to uncertainties in the neutron flux, level spacing, radiation width, and the dependence of one strength function on the uncertainty in the other. This interdependence of the strength functions results from the fact that the sum of the cross sections obtained from the two strength functions should equal the measured capture cross section. The uncertainty resulting from counting statistics is generally small since the fit involves many data points. The strength functions and their uncertainties obtained from the average cross section measurements are listed in Table 3 along with the average parameters obtained from the resolved resonances.

The infinite dilution resonance integral from 0.5 eV, calculated with the resonance parameters up to 415 eV and the s- and p-wave strength functions above this energy is 350 ± 25 barns.

Figure 7. ^{236}U average capture cross section from .5 to 20 keV. The circles are the measured values. The curve is the calculated capture cross section for $D_0 = 15.4$ eV, $\Gamma_\gamma = 23.9$ meV, $S_0 = 1.35 \times 10^{-4}$ and $S_1 = 2.3 \times 10^{-4}$.

4. DISCUSSION

In the low energy region (below 1 eV) information about the capture cross section had been obtained previously from activation measurements and a total cross section measurement (see Table 5). In addition to the determinations shown in this table, Baumann⁽¹⁷⁾ has recently inferred a cross section of ~ 6 barns from an intercomparison of resonance integral measurements using two techniques; one which is dependent and the other which is independent of the thermal neutron capture cross section. For the present determination the thermal cross section was measured three times under optimum experimental conditions with two different sample thicknesses. In each case the determination happened to agree with the 5.1 barn value within ± 2 percent. The uncertainty in the 5.1 barn value shown is a conservative estimate which is larger than the reproducibility of the measurements. With the exception of the determination of McCallum, which may have been affected by uncertainties in the scattering cross section, there is agreement between each of the previous measurements and that of the present work, within the sum of the uncertainties. The recent activation measurements of Baumann which tend to support the 6-barn value of Halperin indicate however that there may be a systematic difference between the results of some activation measurements and the results of the present investigation.

Each of the groups that employed activation techniques to determine the thermal capture cross section has also obtained the resonance capture integral. These measurements along with that obtained in the present experiment are shown in Table 6.

The results of the activation measurements are generally in agreement or near agreement with the present determination within the sum of the uncertainties; but, it is clear that the activation measurements yield

Table 5
THERMAL CAPTURE CROSS SECTION FOR ^{236}U

<u>$\sigma_{\gamma}(\text{b})$</u>	<u>Method</u>	<u>Reference</u>
5. $\pm$ 2.	Activation	Berreth, 1962, Ref. 13
5.5 $\pm$.3	Activation	Cabell, 1958, Ref. 14
6. $\pm$ 1.	Activation	Halperin, 1958, Ref. 15
8.1 $\pm$ 1.8	Total minus scattering	McCallum, 1958, Ref. 16
5.1 $\pm$ 0.25	Capture	This work

Table 6
RESONANCE CAPTURE INTEGRAL FOR ^{236}U

<u>RI(b)</u>	<u>Method</u>	<u>Reference</u>
417 $\pm$ 25 } 419 $\pm$ 70 }	Activation	Baumann, 1967, Ref. 17
381	Activation	Berreth, 1962, Ref. 13
397 $\pm$ 34	Activation	Cabell, 1958, Ref. 14
450 $\pm$ 30	Activation	Halperin, 1958, Ref. 15
340 $\pm$ 40	Calculated by Harvey from resonance parameters and an estimate of the contribution above 384 eV	Harvey, 1958, Ref. 19
350 $\pm$ 25	Calculated from resonance parameters up to 415 eV and from the s- and p-wave strength functions above this energy	This work

somewhat higher values. It is interesting to note, however, that the ratio of the resonance integral to the thermal capture cross section is in better agreement in a comparison between the activation measurements and the present results. This may indicate a normalization error. It is difficult to understand how this could be the case for the present measurements since the normalization, or flux determination, is performed with a saturated resonance. The present determination of the resonance integral is consistent with the calculation by Harvey and Hughes^(18, 19) which was obtained from their resonance parameters and an estimated high energy contribution.

Very few resonance parameter investigations have been performed with ^{236}U . Table 2 gives the parameters determined by Harvey and Hughes, and McCallum from total cross section measurements and the results inferred by Baumann from self-shielding and boron shielding investigations.

As a result of the large difference between the thermal capture cross section obtained by McCallum and that determined from the present measurements, it is not reasonable to expect agreement on the parameters of the negative energy level.

There are large differences in the values of the neutron width of the 5.45 eV level obtained in the various experiments. An accurate calculation of the resonance integral requires primarily a precise determination of this neutron width since this level contributes the majority of the resonance integral.

Above 5.45 eV comparisons can only be made with the neutron widths of Harvey and Hughes. In general there is agreement with the present determinations; however, the values of Harvey and Hughes do appear to be higher in many cases. Many new levels were also observed in the present investigation.

There are, at present, no high energy capture cross section measurements that can be compared with those obtained in this investigation.

There are measurements in the hundreds of keV neutron energy region⁽²⁰⁾ but it is difficult to compare these with the present measurements which end at 20 keV. An indirect check of the measurements can be made by comparing the s-wave strength functions obtained from the average cross section data with that determined from the resolved resonances both in this work and that of Harvey and Hughes.⁽¹⁸⁾ As may be seen from Table 3, these values are all in good agreement. Since the errors are comparable for the two s-wave strength functions obtained in this work, the average value should be used in calculations for the energy region above 20 keV where no capture cross section data exist. It is also possible to compare the s- and p-wave strength functions obtained from this work with those of ^{238}U assuming that the strength functions are approximately the same for the two isotopes. The s-wave strength function obtained from the resolved resonances and that obtained from the unresolved resonance region are both in agreement with the ^{238}U values.⁽²¹⁾ The p-wave strength function obtained from the present measurements is in good agreement with the average of the reported values for ^{238}U .⁽²¹⁾

5. CONCLUSIONS AND RECOMMENDATIONS

The present investigation while providing data that are generally in agreement with previous results, where the latter are available, does indicate that some systematic effect may be present in the previous determinations of the thermal capture cross section and resonance integral. Further investigations, with the significantly improved ^{236}U targets that are now available, should be conducted to understand this problem.

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