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Intermediate structure in the neutron-induced fission cross section of ^{236}U

Winifred E. Parker,* J. Eric Lynn, George L. Morgan, and Paul W. Lisowski
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Allan D. Carlson
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

Nat W. Hill
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
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Neutron-induced fission of ^{236}U has been measured at the Los Alamos Neutron Scattering Center with a white neutron source using a fast parallel plate ionization chamber at a flight path of $\sim$ 56 m. In the resonance and the intermediate resonance region, very little of the previously reported structure was detected. Only five resonance structures were observed. Additionally, the width of the 5.45 eV resonance is approximately 100 times smaller than previously reported. An explanation for the discrepancies between old data and data reported here is discussed. New fission widths for resonances from 5.45 eV to 10.4 keV are reported. The new data are in agreement with theoretical estimates.

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I. INTRODUCTION

The nonfissile nuclides of the actinide group of elements commonly display intermediate structure in their neutron-induced fission cross sections in the resonance energy region [1,2]. This structure is usually narrow and very pronounced, showing up clearly even when fission in most of the fine-structure resonances is unobservable. The spacing of the intermediate resonances is about two orders of magnitude greater than that of the fine-structure resonances. The explanation [3,4] of the intermediate structure is found in the double-humped fission barrier of the actinides, which arises from the shell structure of deformed nuclei [5]. This allows the existence of a group of quasistable states of the superdeformed nucleus associated with the secondary potential well in the fission barrier. These states (usually known as class-II states to distinguish them from the class-I states of the normal primary deformation) can have significant fission probability, are much less dense than their class-I counterparts owing to the relative shallowness of the secondary well, and are mixed only weakly with the class-I states because of the barrier separating the two wells.

Although very few of these intermediate resonances have been measured in adequate detail, the data we have from observations on several isotopes of uranium, neptunium, plutonium, americium, and curium are in qualitatively systematic agreement with other information that has been obtained on the double-humped fission barrier from other sources, such as spontaneously fissioning isomers and fast-neutron-induced fission cross sections in addition to theoretical calculations (for a review, see Ref. [6]). The nucleus ^{232}U is essentially fissile to slow neutrons; the several resonances measured over the energy range of a few hundreds of eV above thermal neutron energy [7–9] have substantial fission widths, no obvious intermediate structure being discerned either among these resolved resonances or in the more poorly resolved region up to 20 keV, thus indicating relatively strong mixing between the class-I and class-II states. The nucleus ^{234}U has rather strong intermediate structure in its fission cross section, which has been measured up to several tens of keV neutron energy [10]. These resonances are rather broad, the lowest, at 580 eV, for example, encompassing tens of class-I levels, with a summed fission width of over 100 meV. By contrast, the fission cross section of ^{238}U shows only weak and very narrow intermediate resonances [11,12], fission only being measurable in very few fine-structure resonances within each group, the summed fission widths being of the order of 1 meV. The class-II resonance spacing is still very similar to that of ^{234}U, however, being of the order of 1 keV. Similar trends with neutron number of the target nucleus have been observed for the plutonium isotope sequence ^{238,240,242,244}Pu. One marked exception to this picture, until now, has been the cross section of ^{236}U.

With these observed systematics, we would expect such structure in the fission cross section of ^{236}U to have properties midway between those of ^{234}U and ^{238}U. The most detailed measurement of the fission cross section of ^{236}U made prior to the work we report here is that of Theobald *et al.* [13], while Cramer and Bergen [14] made a more extended survey of the cross section several keV beyond this. In Ref. [13], most resonances up to 415 eV were reported as having fission widths in the few tenths of meV range, but no intermediate resonance effects were

*Present address: Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550.

observed. The average fission cross section measurement of Ref. [14] appears to be a factor of about 30 lower than calculated from the resonance parameters of Ref. [13] in the overlapping range, but again, no intermediate structure is apparent. Such a lack of intermediate resonances would imply a very low or nonexistent inner barrier between the primary and secondary wells in the ^{237}U compound nucleus, in sharp contrast to the value of 1 MeV or more (relative to the neutron separation energy) found for its neighbors. One explanation for the previously observed data was that the 5.45–415 eV energy region consisted of the tail of an intermediate structure with maximum strength located at a higher energy. A second explanation was that the ^{236}U isotope showed evidence for the $(n,\gamma f)$ reaction [15]. The $(n,\gamma f)$ reaction was first used to interpret the relatively narrow distribution of the fission widths of low-energy neutron resonances of ^{238}Pu [16].

Because of the discrepancies in absolute cross-section values found in the earlier work and the puzzling lack of intermediate structure discussed above, we have undertaken a new measurement of the neutron-induced fission cross section of ^{236}U.

II. EXPERIMENTAL PROCEDURE

The ^{236}U(n,f) experiment was performed at the Los Alamos Neutron Scattering Center (LANSCE) spallation neutron source. The LANSCE facility uses the 800 MeV pulsed proton beam from the Los Alamos Meson Physics Facility linac. The proton beam is compressed in a proton storage ring (PSR). The PSR delivered a current of 80 μA at 20 Hz. Extracted protons strike a split target composed of two 10-cm-diam tungsten cylinders located above and below the moderator and produce spallation neutrons, which are moderated to produce a white neutron source ($\sim$ 17 neutrons per incident proton), extending to energies above 100 keV. The neutron beam pulse is 270 ns at the base of the triangle and 125 ns full width at half maximum (FWHM) with 50 ms between beam bursts. Neutron energy is measured by time of flight over the distance between the neutron moderator and the detectors. The distance between the moderator and the ^{236}U target was 56.18 m. The flight path was at an angle of 90° with respect to the (vertical) incident proton beam and at an angle of 15° with respect to the perpendicular to the moderator. Further details of the neutron source are described in a previous publication [17].

The fission reaction rate was measured in a fast parallel plate ionization chamber holding multiple foils about 1 cm apart. Neutron-induced fission reactions are detected through the ionization of the chamber gas by the recoiling fission fragments. The gas used was 30% argon and 70% CH_4 at a pressure of 2.026×10^5 Pa (1520 mm Hg). A fission fragment deposits large amounts of energy in the chamber, and so the fission events are easily resolved from the background alpha particles. It is important to note that this fission chamber allows direct measurement of fission fragments. Previous measurements did not directly detect fission fragments [13,14]; the importance of this difference is discussed in the following section.

Oxide fission targets of ^{235}U and ^{236}U were 10.16 cm in diameter deposited on steel foils. The neutron beam is larger than the diameter of the deposits. Data were taken simultaneously from two ^{236}U deposits, two ^{235}U deposits, and one ^{10}B deposit. The two ^{236}U deposits weighed 17 800 and 22 060 μg (219.56 and 272.10 μg/cm^2). The ^{235}U targets were included because the fission widths of ^{236}U were calculated relative to the integrated fission cross section of ^{235}U from 7.8 to 11 eV. The ^{10}B target was included to continuously monitor the shape of the neutron energy spectrum of the beam. The ^{236}U deposits had impurities of 0.3% of ^{235}U and 0.9% of ^{233}U. The masses of the ^{235}U and ^{236}U targets, as well as the ^{233}U contaminant mass, were determined by alpha counting. Results of mass spectroscopic analyses were used to identify the ^{235}U contamination in the ^{236}U deposits since the alpha particles associated with the ^{235}U could not be resolved from other groups for the ^{236}U deposits used in this experiment. The measurement of the ^{235}U(n,f) reaction in this experiment allowed a direct subtraction of the ^{235}U fission resonances from the ^{236}U fission resonance data. In contrast with ^{235}U, the resonance structure from the small amount of ^{233}U in the ^{236}U samples did not cause confusion with identification of the ^{236}U resonances. This was confirmed by an investigation of the available resonance data for ^{236}U and ^{233}U and also by direct comparison with recent measurements of the ^{233}U fission cross section over this same energy range [18]. Therefore the presence of ^{233}U impurity in the ^{236}U fission targets did not require a direct subtraction of ^{233}U fission resonances from the ^{236}U data.

A time signal generated by the passage of a proton pulse from the LAMPF accelerator through a time pickoff unit was used to start a time digitizer which is capable of recording multiple events per start. This time digitizer was stopped by an event from any one of the fission or ^{10}B(n,α) detectors. Data were collected in a sequence of 8 h runs on a Microvax III computer using the XSYS data acquisition system. The energy scale for the ^{236}U(n,f) measurements was established from transmission measurements of resonances in iron and aluminum and from resonances in the ^{235}U fission cross section.

III. DISCUSSION

In the measurements reported here, we obtain results for the fission cross section of ^{236}U that are lower than reported in Ref. [14] and much lower than those of Ref. [13]. Indeed, of the 16 resonances below 415 eV, for which fission was stated to be observed in Ref. [13], only in the lowest, at 5.45 eV, do we observe fission, and our measured fission width is only 1.3 μeV, to be compared with 0.29 meV reported in Ref. [13].

How does one account for this serious discrepancy between the previous measurements and our new data? We report a significantly smaller number of resonance groups, and in addition, our measured fission widths are approximately two orders of magnitude smaller than previously reported. We attribute the difference between our data and previously published work to two sources. The first source of the discrepancies is illustrated in Fig. 1. Figure 1(a) shows resonance data for ^{236}U before the 0.3% of ^{235}U contaminant has been subtracted, and Fig. 1(b) shows resonance data for ^{235}U. This spectrum shows counts versus channel number, and the higher-energy resonances corresponding to shorter flight times appear at the lower channel numbers. It is clear that subtraction of the ^{235}U contaminant is necessary in the analysis of the ^{236}U fission resonance structure. The ^{236}U sample used in Ref. [14] had a 0.15% ^{235}U contaminant, still a significant amount of impurity. It is extremely important to note that the data in Ref. [14] were never corrected for this ^{235}U impurity. The ^{236}U resonances are small enough that there is no structure in the Cramer data that can be unequivocally shown to have arisen from ^{236}U fission [14].

The second source which results in the large difference between the fission widths we report and those of Ref. [13] is at least partially a result of the detection of capture γ rays in that experiment. The fission widths of the resonances were determined in Ref. [13] using a system based on the detection of fission neutrons. A neutron-neutron coincidence was taken to be the signature for a fission event. The detection of capture γ rays was significantly reduced by pulse shape discrimination. The sensitivity to capture γ's of this detector was determined with several actinides (not including ^{236}U) to be less than 0.13% of the fission sensitivity. If the fission widths of the resonances had been comparable to their capture widths, then this level of discrimination would have been sufficient for an accurate measurement of the fission widths. However, for very weak subthreshold fission resonances with fission widths in the μeV range, the detection of capture γ rays can be comparable to or greater than the detection of fission neutrons. ^{236}U was not one of the actinides used in the determination of the relative sensitivity to capture γ rays for the work in Ref. [13]. A number of effects which may be different for ^{236}U compared with the actinides used in the relative sensitivity measurements need to be considered: fission neutron spectra, fission neutron multiplicity, neutron capture spectra, capture γ-ray multiplicity, and binding energy. These differences can be exacerbated due to the coincidence required and the energy biases placed on each detector. The sensitivity which was determined may not be appropriate for ^{236}U. Also, the large uncertainty in the normalization procedure must be included. These effects may suggest that essentially all the response referred to as fission in Ref. [13] was really due to capture γ rays. The relatively narrow distribution of the apparent fission widths observed in Ref. [13] would therefore simply be a reflection of the near constancy of the radiation widths from level to level. Data from the present measurements for the 5.45 eV resonance are shown in Fig. 2.

Apart from the 5.45 eV resonance, we observe fission in four groups of resonances, at 1280, 2960, 6300, and 10 400 eV. Figure 3 shows these four fission groups as well as a possible fifth fission resonance at 9600 eV. This last resonance had so few counts that it was not analyzed. We resolve the group at 1280 eV into three separate fine-structure resonances. The 1280 eV group, discussed in detail below, is shown in Fig. 4. The structure at 2960 eV is probably a single fine-structure resonance, while those at 6300 and 10 400 eV could be either single resonances

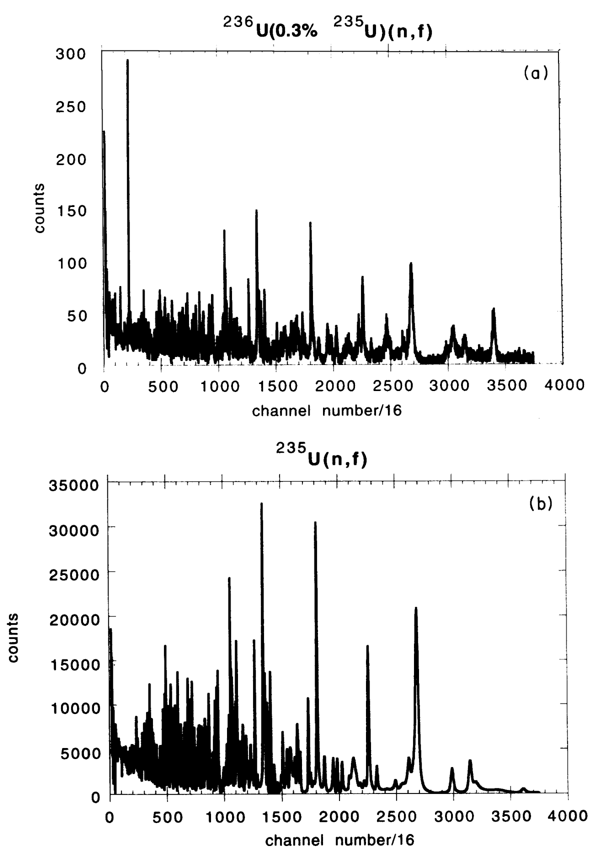

FIG. 1. Fission resonances of (a) ^{236}U before subtraction of the ^{235}U (0.3% contamination) and (b) ^{235}U. Spectra range from 4 to 11 000 eV and are shown as counts versus channel number; the low-energy peaks appear at high channels.

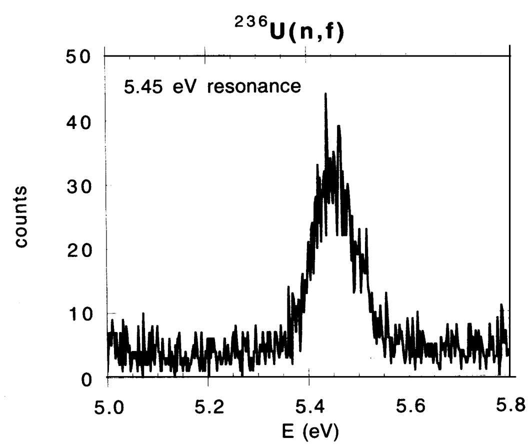

FIG. 2. The ^{236}U(n, f) cross section near the 5.45 eV resonance. Data in this figure have been grouped into bins 0.002 eV wide.

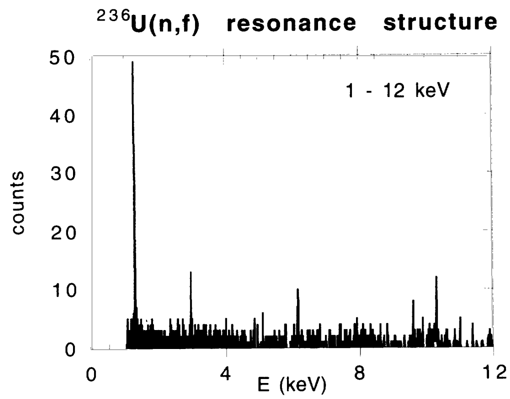

FIG. 3. The $^{236}U(n,f)$ cross section from 1 to 12 keV. Data indicate four resonances at 1.280, 1.2688, 6.300, and 10.400 keV. A possible fifth resonance is seen at 9.6 keV.

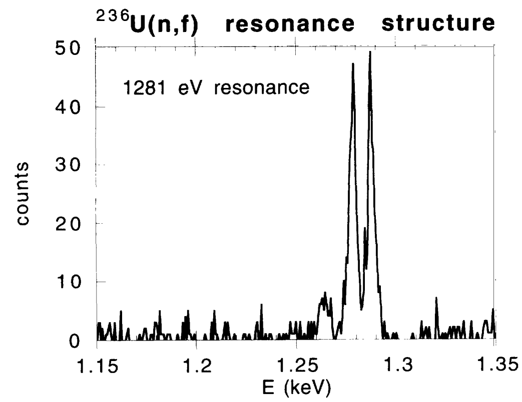

FIG. 4. The $^{236}U(n,f)$ cross section at 1280 eV.

or narrow clusters of resonances.

The measurement of the area of a fission resonance is related to its fission width Γ_f by the integral of the Breit-Wigner formula for fission, which is

$$\int \sigma_f dE = \pi\sigma_0\Gamma_f/2 \ , \tag{1}$$

where

$$\sigma_0 = 4\pi\lambda\!\!\!^{-}_0{}^2\frac{g\Gamma_n}{\Gamma} = \frac{2.608\times10^6}{E_0(\mathrm{eV})}\left(\frac{A+1}{A}\right)^2\frac{g\Gamma_n}{\Gamma} \ . \tag{2}$$

In the above equations, Γ is the total width, Γ_n is the neutron width, E_0 is the resonance energy, and A is the mass of the nucleus.

After correcting for the difference in flight path lengths for the ^{235}U and ^{236}U targets, the ^{236}U fission widths for each resonance peak are experimentally determined by

$$\int \sigma_f dE = \left[\int_{\Delta E\mathrm{I}}\sigma_{\mathrm{U5}}dE\right]\left[\frac{F_{\mathrm{U5}}N_{\mathrm{U5}}}{F_{\mathrm{U6}}N_{\mathrm{U6}}}\right]\left[\frac{\int_{\Delta E\mathrm{II}}\sigma_{\mathrm{B}}dE}{\int_{\Delta E\mathrm{I}}\sigma_{\mathrm{B}}dE}\right]\left\{\frac{(C_{\mathrm{U6}(\Delta E\mathrm{II})}/C_{\mathrm{B}(\Delta E\mathrm{II})})}{(C_{\mathrm{U5}(\Delta E\mathrm{I})}/C_{\mathrm{B}(\Delta E\mathrm{I})})}\right\} \ , \tag{3}$$

where the counts for a particular ^{236}U fission resonance at energy E in the energy interval ΔEII is $C_{\mathrm{U6}(\Delta E\mathrm{II})}$, the counts in the boron detector is $C_{\mathrm{B}(\Delta E\mathrm{I})}$ or $C_{\mathrm{B}(\Delta E\mathrm{II})}$, and the counts in the ^{235}U detector in the ΔEI range is $C_{\mathrm{U5}(\Delta E\mathrm{I})}$. The energy range ΔEI is from 7.8 to 11 eV where the integrated $^{235}U(n,f)$ cross section $\int\sigma_{\mathrm{U5}}dE$ equals 246.5 eV b and is known to 1% accuracy [19,20]. This provides a normalization for the measurements in this work. Dead-time corrections in Eq. (3) essentially cancel out. The ratio $F_{\mathrm{U5}}/F_{\mathrm{U6}}$, which is the ratio for ^{235}U to ^{236}U of corrections for lost fission fragments which are below the bias or lost in the deposits, is assumed to equal 1. The quantity $N_{\mathrm{U5}}/N_{\mathrm{U6}}$ is the ratio of ^{235}U atoms to ^{236}U atoms in the respective fission targets. In the above expression, σ_{B} is the $^{10}B(n,\alpha)$ cross section. The ratio of the counts in the boron detector to the integrated boron cross sections for each energy range, $C_{\mathrm{B}(\Delta E\mathrm{II})}/\int_{\Delta E\mathrm{II}}\sigma_{\mathrm{B}}dE$ and $C_{\mathrm{B}(\Delta E\mathrm{I})}/\int_{\Delta E\mathrm{I}}\sigma_{\mathrm{B}}dE$, provides the energy dependence of the neutron spectrum [20]. For the 5.45 and 1291.7 eV levels, fission widths are calculated using experimentally determined radiation widths [15]. The remaining levels do not have experimentally determined radiation widths, and so an unweighted average of radiation widths given in Ref. [15] was used to calculate the fission widths. The average radiation width is 24 meV. A summary of resonance energies and the corresponding fission widths is given in Table I. The energies for the 1268.8, 1281.7, 1291.7, and 2958.9 eV resonances in Table I were adopted from the energy scale of Carraro and Brusegan [21].

The spacings of the three resonances near 1280 eV are 10.0±1.1 and 14.3±1.2 eV. These uncertainties are a result of statistical uncertainties in the determination of the positions of the peaks. Assuming that a single class-II state (carrying fission width amplitude, but negligible neutron width) is mixing with nearby class-I states (carrying neutron width amplitude and negligible fission), one of these spacings, or their sum, ought to correspond with at least one pair of resonances (not necessarily nearest neighbors) in the total cross section of ^{236}U which has been measured by Carraro and Brusegan [21]. We believe that there is less than half a percent error on our absolute energy scale at these energies. The spacing test then leads to the following choice for the resonance positions:

channel number 3608, $E = 1291.7$ eV

(on energy scale of Ref. [21]) ,

TABLE I. Resonance energies and corresponding fission widths.

$E_{\lambda\mathrm{II}}$ (eV)[a]	Γ_f (meV)[b]
5.45	0.0013±0.0001
1 268.8	0.82±0.03[c]
1 281.7	7.7±5.0[c]
1 291.7	0.93±0.11
2 958.9	1.4±0.6[c]
6 300	10.8±6.[c,d]
10 400	4.6±2.6[c,d]

[a]Errors in resonance energies are less than 0.5%.
[b]Errors in Γ_f are primarily due to the error in the reported value for Γ_γ in Ref. [15].
[c]Γ_f is calculated using $\Gamma_\gamma = 24 \pm 4$ meV. This value of Γ_γ is an unweighted average of radiation widths for ^{236}U given in Ref. [15].
[d]Since no information on the value of $g\Gamma_n$ is available, Γ_f is calculated assuming $g\Gamma_n = 100 \pm 40$ meV. An alternate calculation made assuming that $g\Gamma_n$ equals 500 meV gave $\Gamma_f = 9.1 \pm 3.0$ meV for the 6300 eV resonance and 3.9±1.4 meV for the 10 400 eV resonance.

channel number 3622, $E = 1281.7$ eV ,

channel number 3642, $E = 1268.8$ eV ,

which has spacings of 10.0±1.1 and 12.9±1.2 eV.

Using the neutron widths of Ref. [21] and radiation widths as described above and accepting that the third level is indeed the 1268.8 eV resonance, we find fission widths of 0.93, 7.7, and 0.82 meV, respectively, for the three listed resonances. The sum of these, 9.45 meV, is essentially the fission width of the underlying class-II level in a weak mixing interpretation of the intermediate resonance (see Sec. III 5 c of Ref. [6]). In this picture, the 1281.7 eV resonance contains more than 80% of the class-II state. The squared coupling matrix elements $\langle\lambda_\mathrm{I}|H_c|\lambda_\mathrm{II}\rangle^2$ (where H_c is the coupling term in the Hamiltonian explicitly separating deformation and intrinsic degrees of freedom) for the other two levels are 9.8 and 14.4 eV^2. The mean-squared coupling matrix element is 12 eV^2; the error on this is large owing to the expected Porter-Thomas fluctuations of the squared matrix elements. After expressing this as a mixing "width" for the intermediate resonance,

$$\Gamma_{\mathrm{II}(c)} = 2\pi\langle\lambda_\mathrm{I}|H_c|\lambda_\mathrm{II}\rangle^2/D_\mathrm{I} \qquad (4)$$

(where $D_\mathrm{I} \approx 15$ eV [21] is the mean spacing of the class-I levels), we can apply the usual statistical assumption and the Hill-Wheeler barrier penetrability formula

$$2\pi\Gamma_{\mathrm{II}(c)}/D_\mathrm{II} = N_{\mathrm{eff},A}/[1+\exp(2\pi V_A/\hbar\omega_A)] \qquad (5)$$

to obtain the inner barrier height V_A. The numerical values we employ in this procedure are, for the mean spacing of class-II levels, $D_\mathrm{II} \approx 2.6$ keV (from our data), for the effective number of transition states at the inner barrier, $N_{\mathrm{eff},A} = 2.4$, and for the inner barrier penetrability parameter, $\hbar\omega_A = 0.8$ MeV [6]. The result is $V_A \approx 0.67$ MeV, about 0.5 MeV lower than the value deduced from analysis of the fast neutron fission cross section [6]. From the class-II fission width, the value of the outer barrier height deduced using the formula analogous to (5) is $V_B \approx 0.88$ MeV (with $\hbar\omega_B = 0.52$ MeV [6]). This is close to the value found in Ref. [6].

An alternative interpretation is that a very broad class-II level, with fission width of the order of D_I or more, underlies all three resonances and the mixing is extremely weak. While the magnitude of the coupling matrix elements then deduced from the resonance fission widths becomes consistent with an inner barrier height considerably greater than 1 MeV, the outer barrier sinks to about 0.25 MeV, which is even more inconsistent with the fast neutron fission analysis of Ref. [6].

In assessing whether or not there is a real problem in reconciling the rather low value of the inner barrier that comes from our analysis compared with the result obtained from the fast neutron fission cross-section measurements, we must bear in mind that the data from just one narrow intermediate resonance is a notoriously poor statistical sample. Porter-Thomas fluctuations affect not only the magnitude of the class-II fission and coupling widths, but also the matrix elements connecting to individual class-I levels. Furthermore, in this very weak coupling regime the total fission cross-section area of the intermediate resonance is very strongly affected by the Poissonian distribution of the separation between the class-II state and its nearest class-I neighbor. Although the intermediate resonances at higher energy do not give us the important direct information on dissolution of the class-II state into the fine-structure resonances, their overall sizes can give some indication of the typicality of the 1280 eV group. The integrated cross sections for each group are given in Table II. We note that $A_{\lambda\mathrm{II}}\sqrt{E_{\lambda\mathrm{II}}} \equiv \int dE\,\sigma_f\sqrt{E_{\lambda\mathrm{II}}}$ is comparable between the group at 1280 eV and those at higher energies. We also note that although we have taken the class-II level spacing D_II as 2 keV (mainly from the single spacing between the lowest groups), there are larger gaps at the higher energies, suggesting either very weak intermediate resonances or a larger class-II mean spacing than that used in our analysis.

Some quantitative assessment of the coupling strength can be obtained from the three higher groups by using the formula (see Sec. VI of Ref. [6]) for the average area,

TABLE II. Resonance energies, integrated cross sections, and integrated cross section/$\sqrt{\text{resonance energy}}$ for each group.

$E_{\lambda\mathrm{II}}$ (eV)	$A_{\lambda\mathrm{II}}$ (b eV)[a]	$A_{\lambda\mathrm{II}}/\sqrt{E_{\lambda\mathrm{II}}}$ (b eV$^{3/2}$)
1 280	5.8	208
2 959	1.1	59
6 300	5.7	452
10 400	1.5	153

[a]$A_{\lambda\mathrm{II}} = \int \sigma_f dE$ is calculated from Eq. (3).

$$A_{\lambda \mathrm{II}} = 2\pi^2 \lambda^2 |H_c| (\Gamma_{\mathrm{I}(n)}/D_{\mathrm{I}}) \Gamma_{\mathrm{II}(f)} (1/\Gamma_{\mathrm{II}} + 1/\Gamma_{\mathrm{I}}) , \quad (6)$$

under the assumption of very weak mixing of narrow class-II levels with the class-I states. From the average of the three groups, we obtain, for the mean modulus of the coupling matrix elements,

$$|H_c| \approx 1 \text{ eV} . \quad (7)$$

With this value, Eqs. (4) and (5) lead to an inner barrier height V_A of about 1 MeV. Although this is in much closer agreement with the fast neutron fission cross-section analysis, its comparison with the "microscopic" analysis of the 1280 eV group stresses the large statistical uncertainties inherent in the detailed coupling of the levels.

IV. SUMMARY

We have measured the neutron-induced fission cross section of ^{236}U in the neutron energy region from about 1 eV to more than 10 keV, using the LANSCE pulsed neutron source facility. Fission particles were detected and counted directly using ionization chamber techniques. The fission cross section in this energy region was found to be much smaller than had previously been reported. We explain this as being due either to the detection of fission products from ^{235}U impurity (which has a much greater fission cross section than ^{236}U) or to detection systems that do not discriminate well enough against capture gamma rays.

Unlike the earlier measurements, we find that only a few resonances have a significant fission component. These are mostly in well-separated groups characteristic of intermediate structure. Within the double-humped fission barrier interpretation of intermediate structure in fission cross sections, we find that the lowest-energy group, at 1280 eV, which has resolvable fine structure, appears to be anomalously strong in relation to the parameters of the fission barrier that have been deduced from the fast neutron fission cross section above about 0.5 MeV neutron energy. The anomalous strength appears to arise mainly from the coupling between the class-I state (fine-structure levels) and this particular class-II (intermediate) state of the superdeformed nucleus between the inner and outer humps of the fission barrier; the fission width of the class-II state has about the value that would be expected from the previously known height of the outer barrier. However, the integrated fission strengths of the higher-energy groups at 2960, 6300, and 10 400 eV are much more consistent with the fission barrier analysis of the fast neutron cross-section data. The discrepancy for the coupling width of the 1280 eV group is probably due to Porter-Thomas fluctuations.

Although the 5.45 eV resonance has a measurable fission width, it does not appear to be very close to a class-II state. The value of its fission width, 1.3 μeV, is small enough that it could be associated with a (probably bound) class-II state some tens or a few hundred eV distant.

We have thus resolved a long-standing problem in the nuclear structure of the actinides, namely, the apparent absence of intermediate structure associated with the superdeformed phase of the ^{237}U compound nucleus. We have shown that such intermediate structure does exist for this nuclide, although at a much weaker fission cross-section level than had been previously sought, and the characteristics of this structure are reasonably consistent with the systematic trends of the fission barrier parameters as determined from other experimental evidence on the actinide nuclei.

[1] D. Paya, H. Derrien, A. Fubini, A. Michaudon, and P. Ribon, J. Phys. (Paris) **29**, 159 (1968).

[2] E. Migneco and J. P. Theobald, Nucl. Phys. **A112**, 603 (1968).

[3] J. E. Lynn, *The Theory of Neutron Resonance Reactions* (Oxford University Press, New York, 1968); Harwell Report No. AERE-R5891, 1968; *Nuclear Structure*, Proceedings of the Dubna Symposium (IAEA, Vienna, 1968).

[4] H. Weigmann, Z. Phys. **214**, 7 (1968).

[5] V. M. Strutinsky, Ark. Fys. **36**, 629 (1967); Nucl. Phys. **A195**, 420 (1967).

[6] S. Bjørnholm and J. E. Lynn, Rev. Mod. Phys. **52**, 725 (1980).

[7] G. D. James, Nucl. Phys. **55**, 517 (1964).

[8] G. Auchampaugh, C. D. Bowman, and J. E. Evans, Nucl. Phys. **A112**, 329 (1968).

[9] J. Farrell, Los Alamos Report No. LA-4420, 1970, p. 3.

[10] G. D. James, J. W. T. Dabbs, J. A. Harvey, N. W. Hill, and R. H. Schindler, Phys. Rev. C **15**, 2083 (1977).

[11] R. C. Block, R. W. Hockenbury, R. E. Slovacek, E. B. Bean, and D. S. Cramer, Phys. Rev. Lett. **31**, 247 (1973).

[12] F. C. Difillipo, R. B. Perez, G. de Saussure, D. K. Olsen, and R. W. Ingle, Nucl. Sci. Eng. **63**, 153 (1977).

[13] J. P. Theobald, J. A. Wartena, H. Weigmann, and F. Poortmans, Nucl. Phys. **A181**, 639 (1972).

[14] J. D. Cramer and D. W. Bergen, Los Alamos Report No. LA-4420, 1970, p. 74.

[15] S. F. Mughabghab, *Neutron Cross Sections* (Academic, New York, 1984), Vol. 1, Pt. B.

[16] C. D. Bowman, G. F. Auchampaugh, W. F. Stubbins, T. E. Young, F. B. Simpson, and M. S. Moore, Phys. Rev. Lett. **18**, 15 (1967).

[17] P. W. Lisowski, C. D. Bowman, G. J. Russell, and S. A. Wender, Nucl. Sci. Eng. **106**, 208 (1990).

[18] A. D. Carlson, W. E. Parker, P. W. Lisowski, G. Morgan, N. Hill, K. Meggers, and S. J. Seestrom (private communication, 1993).

[19] A. D. Carlson, S. J. Friesenhahn, W. M. Lopez, and M. P. Fricke, Nucl. Phys. **A141**, 577 (1970).

[20] A. D. Carlson, W. P. Poenitz, G. M. Hale, R. W. Peelle, D. C. Dodder, C. Y. Fu, and W. Mannhart, National Institute of Standards and Technology Internal Report No. 5177, ENDF-351, 1993.

[21] G. Carraro and A. Brusegan, Nucl. Phys. **A257**, 333 (1976).