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Parameters of the Subthreshold Fission Structure in ^{242}Pu†

George F. Auchampaugh
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544

C. D. Bowman
National Bureau of Standards, Washington, D. C. 20234, G

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The neutron total cross section of ^{242}Pu has been measured from 600 eV to 81 keV using the new Lawrence Livermore Laboratory Linac. Parameters were obtained for those resonances below 4 keV with significant fission strengths. These parameters were used to study the fission widths of the intermediate structure in ^{242}Pu$+n$ and the coupling matrix elements between the levels in the primary and intermediate wells in the double-humped fission potential barrier. The results show that the couplings in ^{242}Pu$+n$ is very weak; the magnitude of the average coupling matrix element is less than 0.5 the level spacing in the primary well. The distribution of the fission widths of the levels in the primary well about their expected values is found to be consistent with a Porter-Thomas distribution, However, the distribution of the square of the coupling matrix element appears to require more than one degree of freedom, apparently implying two independent and equally accessible routes across the inner barrier to the deformed configuration. The Wigner distribution is shown to adequately describe the spacings between levels in the intermediate well. These measurements, taken together with Lynn's theory, suggest that fission from the 2741-eV resonance is primarily through the isomeric state. If verified experimentally, this would mean about a 10^4 increase in probability for isomeric fission compared to that induced by other reactions. Our results indicate comparable inner and outer barrier heights for the double-humped fission barrier in the compound system ^{245}Pu.

INTRODUCTION

Measurements have been made on the subthreshold fission cross section of ^{242}Pu by several authors.[1-3] These measurements have revealed pronounced clusters of resonances with relatively large fission strengths, separated by 500 eV to 1 keV, below the neutron fission threshold. The intermediate structure seen in subthreshold fissioning isotopes has been explained by Lynn[4] and Weigmann[5] in terms of a second minimum in the fission potential barrier which has been predicted by Strutinsky.[6] A lack of detailed information about the neutron strengths of the resonances in each cluster in ^{242}Pu has prevented a study of the fission widths of these resonances and consequently any properties of the intermediate barrier or of the levels in the second minimum. For this reason a high-resolution neutron time-of-flight measurement of the total cross section of ^{242}Pu was undertaken at the new Lawrence Livermore Laboratory (LLL) Linac with emphasis on determining the neutron widths of those resonances in each cluster seen in the fission cross section.

EXPERIMENTAL TECHNIQUE

The experimental details of the total cross-section measurement are given in Table I. Two iron-copper collimators, 0.51 m long, with axial holes 2.74 and 2.29 cm in diameter, located at 2.3 and 5.3 m, respectively, from a bare Ta target, defined the neutron beam prior to intercepting the Pu samples. The water coolant for the neutron target served as the moderator. The sample changer was located just after the second collimator. It contained the ^{10}B overlap filters, the two Pu samples, and a blank sample. The ^{10}B powder filter was used during the thin-sample measurement and the borated polyethylene filter during the thick-sample measurement. The Pu metal was mixed with 0.977 wt% of aluminum, cast into disks, and encapsulated in aluminum cans with 0.0039-cm Al windows. An unfilled aluminum can was used as the blank sample. A ^{10}B, 480-keV γ-ray detector located at 30 m from the Ta target along another flight tube oriented at 90° to the 253-m flight tube was used as an integral flux monitor. The events from this detector controlled the sample-in to sample-out time set at a ratio of 4 to 1. The neutron detector system consisted of four identical ^{6}Li-loaded glass scintillators mounted on RCA 4525 photomultiplier tubes. The current from each detector was integrated, double delay-line clipped, and passed through a zero-crossing differential discriminator. The window of each discriminator was set to bracket the ^{6}Li$(n, \alpha)^3$H peak in the scintillator. The outputs from each discriminator were mixed and sent back to the control room where they were reshaped by a fast discriminator. These stop pulses were then fed into an EG & G model TDC-100 time digitizer which had been started by a signal from a γ-sensitive detector located in the neutron target cell. The time digitizer was interfaced to a PDP-15 computer with 16 000 words of core memory which served as the data acquisition system for this experiment. To cover the entire energy region with good resolution in one run it was necessary to divide each memory location into three channels, each channel storing a maximum of 63 events. The computer was programmed to provide a live display of the data, automatically cycle the samples after a preset number of ^{10}B pulses had been recorded, and either dump memory onto Dectape after a sample change or onto IBM magnetic tape when a channel overflowed. Channel overflows occurred at a frequency of less than one every few hours due to the low counting rate (<300/sec) in this experiment.

The characteristics of the thick and thin ^{242}Pu samples used in this measurement are given in Table I. Each sample was cycled every 12 to 15 min with the blank sample. Approximately 40 h of data were accumulated for each sample.

TABLE I. Experimental details.

Time-of-flight parameters			
Electron pulse width	~40 nsec		
Pulse rate	720 pulses/sec		
Beam power	~8 kw		
Flight path	253.63 ± 0.1 m		
Overlap filters			
^{10}B in CH_2	0.6 g/cm^2 ^{10}B		
^{10}B powder	0.35 g/cm^2 ^{10}B		
Memory configuration			
channels	channel width (nsec)	energy interval (eV)	
0-4095	8	812 09-356 48	
4096-34815	16	356 48-907	
348 16-399 35	32	907-594	
Neutron detector			
four ^6Li-load glass scintillators			
Type	NE905		
Diameter	10 cm		
Thickness	1.3 cm		
^{242}Pu metal sample characteristics			
Isotopic composition	%		
^{238}Pu	0.188		
^{239}Pu	0.178		
^{240}Pu	1.352		
^{241}Pu	0.146		
^{242}Pu	98.136		
Sample no.	Weight	Diameter	Thickness
1	33.88 g	2.54 cm	0.0167 atoms/b
2	7.68 g		0.003 76 atoms/b

The neutron background present during the measurement was determined by "black" resonances in ^{242}Pu and by the 5.906-keV aluminum resonance. The neutron beam passed through approximately 0.4 cm of aluminum in the window at the end of the evacuated flight tube and the cans holding the ^6Li glass scintillators onto the photomultiplier tubes. Six ^{242}Pu resonances in the thick-sample run and three in the thin-sample run, along with the aluminum resonance, were used to determine the background. It was measured to be a constant 30% of the open beam spectrum up to 6 keV. Unfortunately, time did not permit the investigation required to determine the source of the background and to eliminate it. The data were normalized by assuming a 10-b potential scattering cross section between resonances below 6 keV.

DETERMINATION OF RESONANCE PARAMETERS

To extract resonance parameters from two independent sets of data, it is desirable to have both sets of data on the same energy scale. This is especially true when the sets of data are obtained with vastly different energy resolution and when the resonances of interest are not completely resolved. The fission cross-section data of Auchampaugh, Farrell, and Bergen[1] were used along with the present data to extract values of Γ_n and Γ_f. Since the resolution of the fission measurement made with neutrons from an underground nuclear explosion was much poorer than that from the present measurement, care was taken to ensure that the energy scales of the two sets of data were properly aligned. For convenience, the energy scale of the present measurement was adjusted to that of the fission measurement by requiring that all resonance energies in the cluster at 762.5 eV agree in both sets of data. The present measurement shows that this energy scale is incorrect and a new energy scale has been adopted which is correct for the 5.906-keV resonance in aluminum

A. Class I Resonance Parameters

The results of the analysis of the total cross-section data are given in Table II. The Harvey-Atta area-analysis code[7] was used to extract values of Γ_n from the total data for those resonances in the fission clusters at 762.5, 1836, 2741, 3112, 3568, and 3670 eV. The neutron width for the

TABLE II. ^{242}Pu resonance parameters.

E (eV)	Γ_n (meV)	Γ_f (meV) [a]	E_{II} (eV)	$\Gamma^{II}_{\lambda'' f}$ (meV)	$\Gamma^{II}_{\lambda'' f} H_{\lambda' \lambda''}^2$ (eV^3)	$\overline{H_{\lambda''}^2}$ (eV^2)
595.2	28.9 ± 2.9	0.026 ± 0.007			0.72	
600.1	7.9 ± 0.8	0.134 ± 0.043			3.53	
610.9	10.1 ± 1.9	0.084 ± 0.026			1.95	
639.1	4.2 ± 0.6	<0.05			0.75	
665.0	2.7 ± 0.5	<0.08			0.77	
669.5	12.5 ± 1.0	0.11 ± 0.04			0.93	
693.4	32.3 ± 3.0	0.28 ± 0.06			1.33	
711.9	100 ± 16	0.048 ± 0.017			0.12	
727.9	3.2 ± 0.8	<0.06			0.08	
736.8	120 ± 17	0.61 ± 0.14			0.39	
755.6	115 ± 18	1.65 ± 0.39			0.08	
762.5	3.8 ± 1.1 [b] 4.3 ± 0.5 [e]	>256; >80 [c]	~762.5	<909 [d] >85		<9.5 >0.9
788.5	100 ± 30	1.24 ± 0.49			0.83	
794.5	275 ± 30	0.043 ± 0.009			0.05	
825.2	7.3 ± 1.0	0.17 ± 0.06			0.68	
837.9	35.0 ± 4.2	0.049 ± 0.017			0.28	
856.7	31.2 ± 3.1	0.17 ± 0.06			1.51	
866.1	11.0 ± 1.5	0.048 ± 0.018			0.50	
879.1	50 ± 5.0	0.031 ± 0.012			0.43	
886.8	24.8 ± 2.5	0.015 ± 0.006			0.22	
923.4	46.8 ± 5.0	0.037 ± 0.011			0.96	
1696	39.1 ± 5.5	0.067 ± 0.020			1.33	
1708	93.2 ± 12.1	0.001 ± 0.0005			0.02	
1737 1739	9.1 ± 2.4 21.5 ± 3.6	0.10 ± 0.03			0.96	
1751	9.4 ± 2.8	0.51 ± 0.20			3.78	
1762	85.4 ± 10.2	0.017 ± 0.004			0.09	
1783	<4 0.022 ± 0.009 [e]	>0.18			>0.50	
1789	<4 0.13 ± 0.01 [e]	>1			>2.20	
1806	12.9 ± 3.7	0.13 ± 0.05			0.09	
1820	4.1 ± 3.8	0.38 ± 0.37			0.09	
1836	<4 3.0 ± 0.3 [e]	>102; >30 [c]	1836	<89 [d] >34		<29.9 >11.4
1862	4.9 ± 3.6	0.49 ± 0.39			0.28	
1881	84.3 ± 10.9	0.056 ± 0.013			0.11	
1891	4.1 ± 4.6	0.96 ± 1.13			2.70	
2699	250 ± 38	0.11 ± 0.03			0.18	
2734	108 ± 15	0.094 ± 0.031			0.006	
2741	6.9 ± 2 [f]	1.45 ± 0.63 0.51 ± 0.22 [c]	2741	<2.6 >1.6		<167 >103
2756	220 ± 31	0.031 ± 0.016			0.008	
2772	2.8 ± 1.0 [f]	0.91 ± 0.42			0.87	
3107	<3 [f] 0.28 ± 0.05 [e]	>3.4			>0.084	
3112	<3 [f] 1.2 ± 0.1 [e]	>21; >5.8 [c]	3112	<480 [d] >11.3		<72 >1.7
3135 3142	226 ± 32 40.2 ± 12.1	1.22 ± 0.25			0.82	
3156	52.3 ± 11.9	0.1 ± 0.04			0.19	
3164	3 ± 1.5	0.8 ± 0.5			2.16	
3412	380 ± 61	0.09 ± 0.03			2.16	
3422	10.4 ± 5 [f]	<0.3			<6.40	
3438	7.8 ± 4 [f]	<0.3			<5.06	

TABLE II *(Continued)*

E (eV)	Γ_n (meV)	Γ_f (meV)[a]	E_{II} (eV)	$\Gamma^{\mathrm{II}}_{\lambda'' f}$ (meV)	$\Gamma^{\mathrm{II}}_{\lambda'' f} H_{\lambda' \lambda''}{}^2$ (eV^3)	$\overline{H_{\lambda''}{}^2}$ (eV^2)
3451	220 ± 29	0.13 ± 0.03			1.75	
3472	78 ± 17	<0.1			<0.88	
3485	102 ± 19	0.28 ± 0.08			1.79	
3496	122 ± 23	0.36 ± 0.10			1.76	
3521	95 ± 21	<0.2			<0.40	
3532	<4 [f] 0.32 ± 0.05 [e]	>3			>3.89	
3558	<4 [f] 0.12 ± 0.03 [e]	>1			>0.10	
3568	<4 [f] 1.2 ± 0.1 [e]	>14.6; >4.3 [c]	~ 3568	<1835 [d] >11		<186 >1.1
3581	143 ± 24	0.18 ± 0.05			0.04	
3588	8.2 ± 4 [f]	<0.8			<0.35	
3620	13.7 ± 5 [f]	0.29 ± 0.16			0.72	
3629	5.5 ± 3 [f]	<1.9			<3.19	
3651	155 ± 25	0.67 ± 0.18			0.22	
3670	13.9 ± 5 [f]	7.1 ± 3.2 3.2 ± 1.4 [c]	~ 3670	<12 >5.7		<229 >101
3698	13.1 ± 5 [f]	<0.3			<0.23	
3712	12.2 ± 5 [f]	0.81 ± 0.38			1.43	
3721	940 ± 200	0.05 ± 0.03			0.13	
3734	9.4 ± 5 [f]	0.19 ± 0.16			0.78	
3773	246 ± 44	0.21 ± 0.08			2.18	
3790	62 ± 22	0.07 ± 0.04			1.02	
3812	683 ± 130	0.15 ± 0.06			3.11	
3836	948 ± 161	0.05 ± 0.02			1.42	

[a] Fission widths determined with a $\Gamma_\gamma = 30$ meV except where noted otherwise.
[b] Calculated from total cross-section peak height.
[c] Fission widths determined with a $\Gamma_\gamma = 6$ meV.
[d] Upper limits computed by the expression $\Gamma^{\mathrm{II}}_{\lambda'' f} = [\sum_{\lambda' \neq \lambda''} (\Gamma^0_{\lambda' n} \Gamma_{\lambda' f} / \Gamma^0_{\lambda'' n})^{1/2}]^2$. See text for further explanation.
[e] Determined from fission areas setting $\Gamma = \Gamma_f$.
[f] Obtained from data of F. Simpson, Simpson, and Miller (Ref. 8).

762.5-eV resonance of 3.8 ± 1.1 meV (superscript b) was determined from the value of the peak height of this resonance in the total cross-section data (the strong Doppler effect at this energy, the fact that the resonance was situated on the tail of a very large resonance, and the small size of the resonance prevented an accurate determination of its complete area). At 762-eV resolution broadening is negligible and the shape of a small resonance is strongly influenced by the Doppler effect. Under such conditions the peak height of a resonance is directly related to Γ_n and is independent of Γ at least to first order in the parameter $1/\beta = \Gamma/2\Delta$. Values of Γ_n with the superscript f were obtained from the data taken recently by Simpson, Simpson, and Miller[8] at Oak Ridge National Laboratory. The statistical quality of their data is better than ours and consequently has revealed some of the smaller resonances not definable in the present data. The neutron widths of the resonances at 1783, 1789, and 1836 eV which were not statistically definable in the present total data have been set less than the smallest neutron width measured in the 1836-eV cluster. A lower limit to Γ_n for those resonances for which only an upper limit could be set can be obtained from the fission data by setting $\Gamma_f = \Gamma$. These values of Γ_n are given with a superscript e.

The fission areas corrected for a small γ-ray contribution of magnitude 0.007 A^1_γ (capture area, calculated from the neutron widths) and a value of $\Gamma_\gamma = 30 \pm 5$ meV were used to deduce the values of Γ_f. Only lower limits on Γ_f could be determined for the 762.5-, 1836-, 3112-, and 3568-eV resonances. For the 762.5-eV resonance the measured neutron width was too close to that obtained from the fission area assuming $\Gamma_f \cong \Gamma$ to permit an accurate determination of Γ_f. For the other three resonances Γ_n was not measurable, only upper limits could be given for Γ_n.

The lower limits on Γ_f (superscript c) were based upon a capture width of 6 meV. If some of the six strong fission resonances are the class II states, then the appropriate capture width used in determining Γ_f should be that for the intermediate well. An estimate of this capture width was made using the following approximate expression for the ratio of capture widths in the two wells:

$$\frac{\Gamma_\gamma^{\mathrm{II}}}{\Gamma_\gamma^{\mathrm{I}}} \simeq \frac{D_{\mathrm{II}}}{D_{\mathrm{I}}} \frac{\int_0^{E_{\mathrm{II}}} d\epsilon\, \epsilon^3 \rho_{\mathrm{II}}(E_{\mathrm{II}}-\epsilon)}{\int_0^{E_B} d\epsilon\, \epsilon^3 \rho_{\mathrm{I}}(E_B-\epsilon)} .$$

The level density used in this calculation was that developed in a paper by Britt *et al.*[9] The ground-state energy, E_{II}, in the intermediate well was obtained from the ratio of $\rho_{\mathrm{II}}/\rho_{\mathrm{I}}$ normalized by the measured ratio of level spacings $D_{\mathrm{II}}/D_{\mathrm{I}}$.[1] For $E_{\mathrm{II}} = 1.76$ MeV, $D_{\mathrm{II}}/D_{\mathrm{I}} = 32.1$ and $E_B = 5.05$ MeV (neutron binding energy in the compound system ^{243}Pu) a value of 0.2 was calculated for $\Gamma_\gamma^{\mathrm{II}}/\Gamma_\gamma^{\mathrm{I}}$ or for a $\Gamma_\gamma^{\mathrm{I}} = 30$ meV, $\Gamma_\gamma^{\mathrm{II}} = 6$ meV.

B. Class II Resonance Parameters

In a very weak coupling situation where the magnitude of the coupling matrix element $|\langle H''\rangle|$ is less than the average class I level spacing D_{I}, the unperturbed class II fission width $\Gamma_{\lambda'' f}^{\mathrm{II}}$ to a very good approximation is just equal the sum of the measured fission widths, $\Gamma_{\lambda'' f}^{\mathrm{II}} \simeq \Gamma_{\lambda'' f} + \sum_{\lambda' \neq \lambda''} \Gamma_{\lambda' f}$, where $\Gamma_{\lambda'' f}$ is the perturbed class II fission width. For those cases where it is not possible to accurately determine the fission width of the resonance making the largest contribution to the sum, an upper limit on $\Gamma_{\lambda'' f}^{\mathrm{II}}$ can be set using the following expression:

$$\Gamma_{\lambda'' f}^{\mathrm{II}} \simeq \Big[\sum_{\lambda' \neq \lambda''} (\Gamma_{\lambda' n}^{0} \Gamma_{\lambda' f}/\Gamma_{\lambda'' n}^{0})^{1/2} \Big]^2 .$$

Upper limits of $\Gamma_{\lambda'' f}^{\mathrm{II}}$ (superscript d) were calculated from the above expression for the resonances at 762.5, 1836, 3112, and 3568 eV assuming that the values of Γ_n determined from the fission areas with $\Gamma_f = \Gamma$ represent lower limits to the class II neutron widths, $\Gamma_{\lambda'' n}^{0}$. These values of $\Gamma_{\lambda'' f}^{\mathrm{II}}$ are probably an overestimate to a realistic upper limit on $\Gamma_{\lambda'' f}^{\mathrm{II}}$. In fact, applying the same equation to the states at 2741 and 3670 eV results in values of $\Gamma_{\lambda'' f}^{\mathrm{II}}$ an order of magnitude larger than that observed. The lower limits of $\Gamma_{\lambda'' f}^{\mathrm{II}}$ represent sums of the measured fission widths, using the smaller of the two limits of the fission widths for the strongest resonances, within each cluster.

In summary, the determination of the fission width of the strongest peak in a subthreshold fission cluster of resonances in a very weak coupling situation, and therefore the determination of the class II fission width, is really rather difficult. This comes about since the nearly pure class II state possesses essentially all of the class II fission width and derives neutron width (and class I capture width) only from close-by class I states. The neutron and capture widths usually, therefore, are much smaller than the fission width for the nearly pure class II state. Therefore both total and fission cross-section measurements determine only Γ_n, unless both cross sections are measured with accuracies far exceeding that possible with techniques presently available. Also, even if such measurements could be made with the necessary accuracy there still remains the question of the correct value of the capture width to use in determining Γ_f. The upper and lower limits for Γ_f^{II} listed in Table II cannot be much improved, we believe, by the type of experiments reported here. It is important to note also that the upper limits are arrived at via a theoretical consideration that is yet to be confirmed in detail. Some caution therefore is appropriate even in the use of these limits.

There are two important exceptions in ^{242}Pu + n where values for Γ_f^{II} can be determined; the resonances at 2741 and 3670 eV. In these cases the value for Γ_f^{II} is anomalously small, perhaps owing simply to Porter-Thomas fluctuations[10] in the class II fission width. Also the neutron width is relatively large, probably owing to the proximity of neighboring resonances with large values of Γ_n. In these cases the comparison of fission and total cross sections do give fairly well defined values for the class II fission widths. In the case of the 2741-eV resonance, if we take a value for Γ_f^{II} midway between the limits given in Table II we obtain $\Gamma_f^{\mathrm{II}} \simeq 2.1 \pm 0.5$ meV which is only one third as large as our estimate of the class II capture width $\Gamma_\gamma^{\mathrm{II}}$. In this case, then, three fourths of the fission should be via γ decay into the second minimum to form the isomer which then decays by fission, one fourth of the fission should be prompt fission. A fission cross-section measurement carried out with few nanosecond timing resolution should show distinctly the tail associated with the 30-nsec half-life of the ^{243}Pu isomer.[11] By determining the relative magnitude of isomeric vs prompt fission, one would get the first experimental measure of the class II capture width $\Gamma_\gamma^{\mathrm{II}}$ which could be compared with Lynn's estimate. At this resonance the ratio prompt/iosmeric fission would be about 10^4 times larger than has been measured in any other reaction on any other nucleus. Similar experiments also might be possible on the 3670-eV resonance.

Values of the product of the square of the coupling matrix element, $H_{\lambda' \lambda''}{}^2$, and the class II fission width for each class I state λ' were computed from the equation $H_{\lambda'\lambda''}{}^2\Gamma^{\text{II}}_{\lambda''f} \simeq \Gamma_{\lambda'f}(E^{\text{I}}_{\lambda'} - E^{\text{II}}_{\lambda''})^2$, assuming $|E^{\text{I}}_{\lambda'} - E^{\text{II}}_{\lambda''}| \gg \Gamma^{\text{II}}_{\lambda''f}$ or $|\overline{H_{\lambda''}}|$, and are given in Table II. The range of values of the average of the square of the coupling matrix element, $\overline{H_{\lambda''}{}^2}$, for each group of resonances were obtained from the upper and lower limits on $\Gamma^{\text{II}}_{\lambda''f}$ and the average values of $H_{\lambda'\lambda''}{}^2\Gamma^{\text{II}}_{\lambda''f}$. The fact that $|(\overline{H^2})^{1/2}|/D_{\text{I}}$ is less than 0.5 using the upper limits on $\overline{H_{\lambda''}{}^2}$ and that $\overline{\Gamma^{\text{II}}_f} \ll D_{\text{I}}$ strongly suggests that in ^{242}Pu + n the class II states are well below the saddle barrier and are very weakly coupled to the class I resonances.

DISTRIBUTIONS OF MEASURED PARAMETERS

The reported fission data[1] on ^{242}Pu revealed 53 narrow groups of resonances (class I) below 30 keV with an average spacing between groups of 553 eV. A detailed analysis of six of these groups below 4 keV believed to be levels (class II) in the intermediate well gives an average spacing of 583 eV, indicating that most of the groups observed below 30 keV are indeed levels in the second well. Since the target nucleus is even, the Wigner single-spacing repulsion surmise[12] should be valid between these levels. To test this assumption a histogram of the number of levels in 100-eV bins versus their spacing has been plotted and compared with the Wigner frequency function. This comparison is made in Fig. 1. The solid curve is a Wigner distribution for 53 levels with an average spacing of 553 eV. The spacings between class II levels appear to be well represented by a single-spacing Wigner distribution within the finite size of this sample.

The method of Wilets[13] was used to determine the number of degrees of freedom, ν_{eff}, of the χ^2 distribution function governing the class I fission widths about their expected values, $\Gamma_{\lambda'f} - \overline{\Gamma_f} = \Gamma_{\lambda'f} - \langle\Gamma^{\text{II}}_{\lambda''f}H_{\lambda''}{}^2\rangle_{\text{av}}/(E^{\text{I}}_{\lambda'} - E^{\text{II}}_{\lambda''})^2$ and that of the product of the square of the coupling matrix elements and the fission width $\Gamma^{\text{II}}_{\lambda''f}H_{\lambda'\lambda''}{}^2 = \Gamma_{\lambda'f}(E^{\text{I}}_{\lambda'} - E^{\text{II}}_{\lambda''})^2$, for each of the six groups of resonances. The results are given in Table III. The errors are computed from the expression for $\delta\nu_{\text{eff}}/\nu_{\text{eff}}$ given by Wilets, assuming an average error of 40% for the quantities $\Gamma^{\text{II}}_{\lambda''f}H_{\lambda'\lambda''}{}^2$ and $\Gamma_{\lambda'f} - \overline{\Gamma_f}$. If all the resonances are considered as one group, weighting each $\Gamma^{\text{II}}_{\lambda''f}H_{\lambda'\lambda''}{}^2$ and $\Gamma_{\lambda'f} - \overline{\Gamma_f}$ by their average values for each individual group, then $\nu_{\text{eff}}(\Gamma^{\text{II}}_{\lambda''}H_{\lambda'\lambda''}{}^2) = 1.88 \pm 0.24$ and $\nu_{\text{eff}}(\Gamma_{\lambda'f} - \overline{\Gamma_f}) = 0.89 \pm 0.11$. These determinations did not include the very strong fission resonances nor the resonances at 755.6 and 3107 eV for which the quantities $\Gamma^{\text{II}}_{\lambda''f}H_{\lambda'\lambda''}{}^2$ are sensitive to the exact position of the class I level. The results for the quantity $\Gamma_{\lambda'f} - \overline{\Gamma_f}$ strongly suggest a Porter-Thomas[10] distribution. The square of the coupling matrix elements or equivalently $\Gamma^{\text{II}}_{\lambda''f}H_{\lambda'\lambda''}{}^2$ for a given group does not appear to obey a Porter-Thomas distribution in view of the low (<1%) probability of observing a value of ν_{eff} greater than 1.88 for a set of 63 Porter-Thomas quantities. This probability was determined by randomly selecting 63 values from a Porter-Thomas distribution of mean 1, determining ν_{eff} for each set of 63, repeating the procedure a large number of times and comparing the number of times ν_{eff} exceeded 1.9 to the total number of sets. The low probability for observing a ν_{eff} greater than 1.9 suggests that

TABLE III. Statistical information on the intermediate structure. The two columns give the effective number of degrees of freedom for the quantity $\Gamma^{\text{II}}_{\lambda''f}H_{\lambda'\lambda''}{}^2$ and the quantity $\Gamma_{\lambda'f} - \overline{\Gamma_f}$, respectively.

E^{II} (eV)	ν_{eff} $(\Gamma^{\text{II}}_{\lambda''f}H_{\lambda'\lambda''}{}^2)$	ν_{eff} $(\Gamma_{\lambda'f} - \overline{\Gamma_f})$
762.5	2.0 ± 0.5	0.89 ± 0.17
1836	1.3 ± 0.3	1.05 ± 0.30
2741	1.1 ± 0.5	1.47 ± 0.55
3112	1.9 ± 0.7	0.72 ± 0.40
3568	2.2 ± 0.5	0.59 ± 0.18
3670	3.2 ± 1.0	0.83 ± 0.23

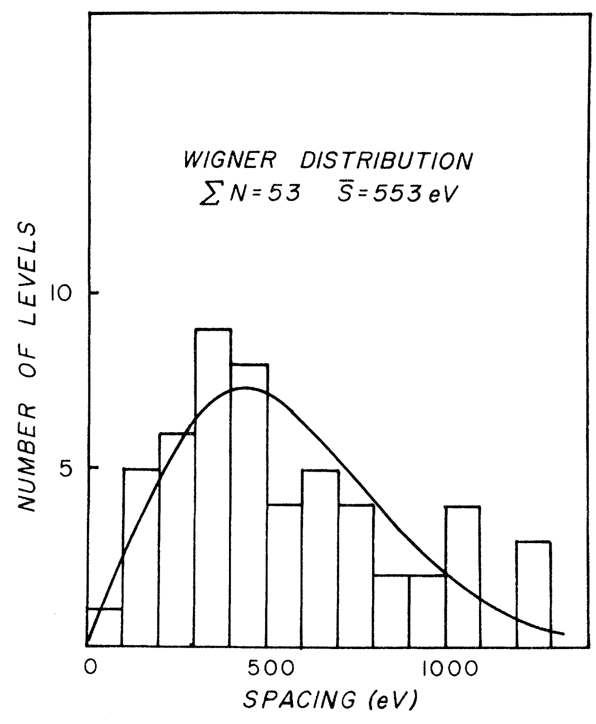

FIG. 1. Differential histogram of the observed nearest level spacings S in 100-eV bins for ^{242}Pu. The solid curve is for a Wigner single population distribution with an average spacing $\overline{S}$ of 553 eV.

$H_{\lambda'\lambda''}{}^2$ is governed by a χ^2 distribution of more than one degree of freedom.

Since the spin of these fission resonances excited by s-wave neutrons on ^{242}Pu is $\frac{1}{2}^+$, it is unlikely that the value for $\nu_{\rm eff}$ can be explained by several K values associated with the same total angular momentum J. In the absence of a bias in the sample, which appears not to exist, the only remaining explanation of the large value of $\nu_{\rm eff}$ for $H_{\lambda'\lambda''}{}^2$ is that two independent and about equally accessible routes across the inner barrier to the deformed configuration exist. This possibility could be investigated in neighboring nuclei further by carrying out total cross-section measurements on ^{244}Pu for which high quality fission data already exist,[1] and perhaps also by more extensive neutron fission measurements on ^{240}Pu.

FISSION BARRIER HEIGHTS

The parameters $\langle \overline{H_{\lambda''}{}^2}\rangle_{\rm av}$ and $\langle \Gamma^{\rm II}_{\lambda'' f}\rangle_{\rm av}$, averaged over the class II states, can be related to the penetrabilities through the inner and outer barriers, respectively, of a double-humped fission potential barrier or, for parabolic inner and outer barriers

$$2\pi \frac{\langle \Gamma^{\rm II}_{\lambda'' f}\rangle_{\rm av}}{D_{\rm II}} = \frac{1}{1+\exp[(2\pi/\hbar\omega_B)(V_B - E_B^*)]}$$

and

$$(2\pi)^2 \frac{\langle \overline{H_{\lambda''}{}^2}\rangle_{\rm av}}{D_{\rm I} D_{\rm II}} = \frac{1}{1+\exp[(2\pi/\hbar\omega_A)(V_A - E_B^*)]} ,$$

where E_B^* is the binding energy of a neutron in the ^{243}Pu compound system. Limits on $\langle \Gamma^{\rm II}_{\lambda'' f}\rangle_{\rm av}$ and $\langle \overline{H_{\lambda''}{}^2}\rangle_{\rm av}$ were obtained by averaging the upper and lower limits on the individual quantities $\Gamma^{\rm II}_{\lambda'' f}$ and $\overline{H_{\lambda''}{}^2}$ for the six class II states given in Table II. This results in the following limits on the quantities

$$\left(\frac{V_i - E_B^*}{\hbar\omega_i}\right)_{i=A,B}:$$

$$0.7 \text{ MeV} < \frac{V_A - E_B^*}{\hbar\omega_A} < 0.9 \text{ MeV}$$

and

$$0.8 \text{ MeV} < \frac{V_B - E_B^*}{\hbar\omega_B} < 1.3 \text{ MeV} .$$

Estimates of the curvature parameters $\hbar\omega_A$ and $\hbar\omega_B$ by Britt *et al.*[9] using fission isomer half-lives and spontaneous fission half-lives for some of the lighter Pu isotopes indicate that $\hbar\omega_A$ is greater than $\hbar\omega_B$ and may be at least 1.5 times $\hbar\omega_B$. Whether or not $\hbar\omega_A \geq \hbar\omega_B$, at least for reasonable ratios of $\hbar\omega_A/\hbar\omega_B$, our results indicate comparable inner and outer barrier heights for the double-humped fission barrier in the compound system ^{245}Pu.

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