Analysis of intermediate structure in the fission and capture cross sections of (^{235}U + n)

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Analysis of recent high resolution measurements of fission and capture cross sections of (^{235}U+n) between 2 and 32 keV has been done to extract the energy dependence of the average *s*-wave fission width and neutron strength function. A correlation analysis of the data indicates that the large fluctuations in α, the capture-to-fission ratio, are due to intermediate structure in the average fission width. The structure can be simulated by using a double-humped barrier model that takes into account coupling of class I and class II states in exactly the same way that has been used successfully to describe structure in subthreshold fission. These results suggest that the presence of intermediate structure is a general phenomenon in suprathreshold fission as well, and that, to describe such structure in the unresolved resonance region, one must include the coupling between class I and class II states.

The existence of pronounced structure in the fission cross section of (^{235}U + n) in the unresolved resonance region has been known for many years,[1–3] and it was commonly accepted that this structure is primarily due to modulation of the average fission width of the class I states by resonances in the second well.[4–7] However, measurements by Böckhoff and Dufrasne[8] of the total neutron cross section of ^{235}U showed that much of the structure in fission is also present in the total cross section, suggesting that at least part of the fluctuations may be an entrance channel phenomenon. Beer and Käppeler[9] noted that the entrance channel contribution can be removed by considering fluctuations in α, or, more properly $1/\alpha$, the fission-to-capture ratio. They found that the quantity $1/\alpha$ shows fluctuations much larger than would be expected if fission in (^{235}U + n) occurs through a few exit channels with individual width distributions given by the Porter-Thomas law, and estimated a second well spacing of 1000 eV for the modulations in $1/\alpha$ that they observed. There is also information available on the spin dependence of the fluctuations. Moore *et al.*[10] extracted spin-dependent fission cross sections of (^{235}U + n) from the polarized neutron and polarized target data of Keyworth *et al.*[11] and concluded that there are strong fluctuations consistent with intermediate structure in the spin-four component and probably in the spin-three component as well.

The present measurement of the fission and capture cross sections of (^{235}U + n), reported by Corvi *et al.*[12] and shown in Fig. 1, was done with much higher resolution than that of Beer and Käppeler. To analyze these data, we extracted an energy dependent *s*-wave neutron strength function S^0 and an average fission width $\langle \Gamma_f \rangle$ required to fit our absorption (fission + capture) and fission cross section, respectively. Both quantities were averaged over 100 and 200 eV bins. We then calculated the correlation coefficients of the various quantities involved; the results are listed in Table I, where correlations statistically significant at the 99% level or higher are italicized. From the correlations shown in Table I, we can draw several conclusions:

(1) The derived quantities $\langle \Gamma_f \rangle$ and S^0 are very strongly correlated with the measured quantities $1/\alpha$ and σ_a, respectively. This shows that the structures in $1/\alpha$ and

TABLE I. Correlation coefficients for various quantities obtained from the data of Corvi *et al.* (Ref. 12). Italicized entries correspond to significance levels >99%.

Correlated quantities	2–4 keV	4–6 keV	Energy range 6–10 keV	10–25 keV	2–25 keV
$\langle \Gamma_f \rangle : 1/\alpha$	*0.985*	*0.977*	*0.925*	*0.949*	*0.959*
$S^0 : \sigma_a$	*0.964*	*0.988*	*0.978*	*0.686*	*0.904*
$\sigma_f : \sigma_a$	*0.839*	*0.903*	*0.812*	*0.926*	*0.870*
$\sigma_f : \alpha$	*−0.723*	−0.383	−0.475	*−0.885*	*−0.617*
$\sigma_a : \alpha$	−0.232	0.050	0.131	*−0.646*	−0.174
$\sigma_\gamma : \alpha$	*0.899*	*0.826*	*0.857*	*0.888*	*0.868*
$\sigma_\gamma : \sigma_a$	0.213	*0.602*	*0.617*	−0.234	0.300

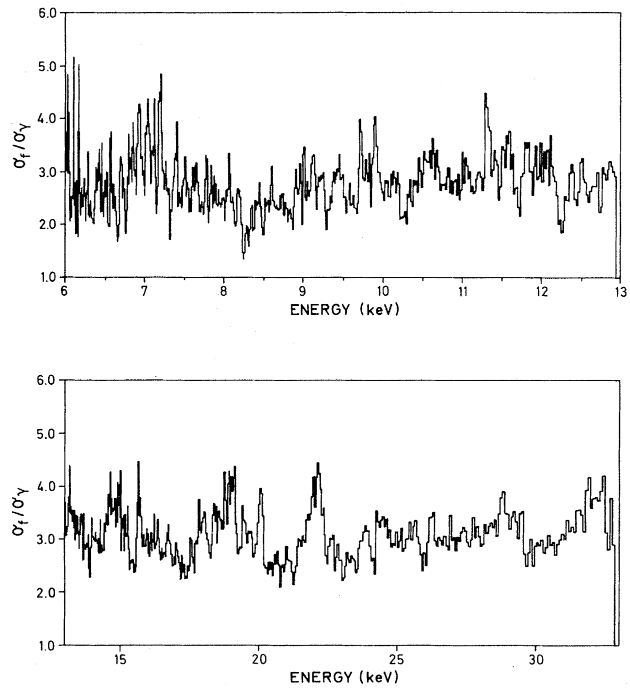

FIG. 1. The fission-to-capture cross-section ratio σ_f/σ_γ for (^{235}U + n) as measured by Corvi *et al.* (Ref. 12) versus neutron energy from 6 to 32 keV.

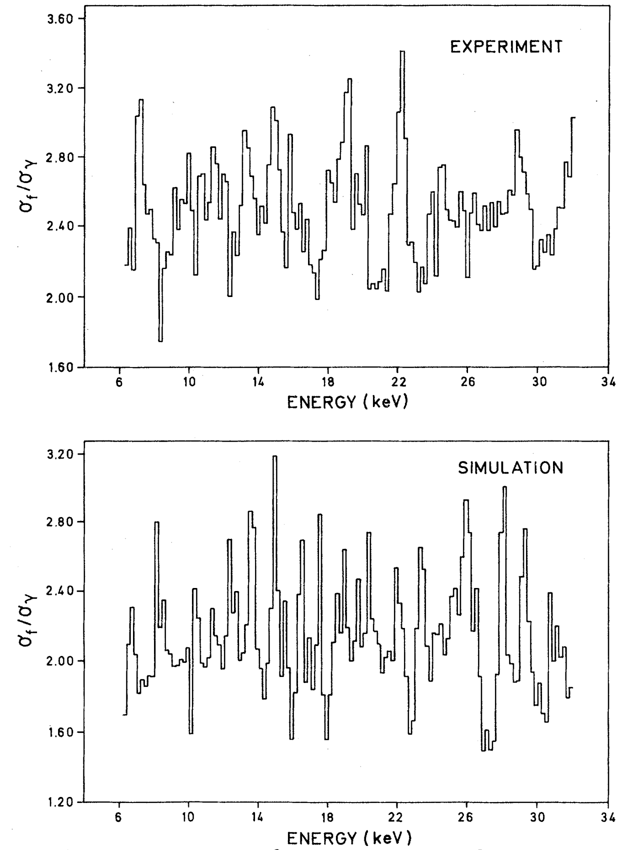

FIG. 2. Comparison of simulated σ_f/σ_γ for $D_{\mathrm{II}}=280$ eV with the renormalized experimental values; the averaging interval is 200 eV. The experimental data have been multiplied by a smoothly varying energy dependent factor in order to keep the local $\overline{\sigma_f/\sigma_\gamma}$ constant over the energy range of interest.

σ_a are valid measures of those in $\langle \Gamma_f \rangle$ and S^0. We can then restrict further discussion to correlations between measured quantities.

(2) The correlation of σ_a and σ_f shows that part of the structure is, in fact, an entrance channel phenomenon. We note that the variance of the fluctuations in the derived quantity S^0 is just what is expected if the neutron widths are Porter-Thomas distributed. (For example, from 6 to 10 keV with 200 eV bins, the strength-function variance is 0.014, compared to the expectation value $4/N=0.011$; from 10 to 25 keV with 500 eV bins, the observed value is 0.0043, compared to the expectation value of 0.0042.)

(3) The consistent and, in some cases, especially significant anticorrelation of σ_f and α suggests that part of the structure in σ_f is due to fluctuations in the fission width. We note that these are well outside the range of expectation from a statistical model that assumes fission widths that are chi-squared distributed with a few degrees of

TABLE II. Average parameters used for simulation study of intermediate structure in (^{235}U + n).

Nuclear radius	9.1 fm	
Effective binding energy	5.345 MeV	
Level density parameter (a)	25 MeV^{-1}	
Spin cutoff parameter (σ^2)	36.	
s-wave spacing, class II	variable	
	Spin 3^-	Spin 4^-
s-wave spacing, class I	0.953 eV	0.809 eV
Strength functions	0.946×10^{-4}	1.043×10^{-4}
Radiative widths	0.035 eV	0.035 eV
First barrier height[a]	-0.71 MeV	-0.61 MeV
Second barrier height[a]	-0.81 meV	-0.71 MeV
First barrier width ($\hbar\omega$)	1.04 MeV	1.04 MeV
Second barrier width ($\hbar\omega$)	0.60 MeV	0.60 MeV
Second minimum width ($\hbar\omega$)	0.50 MeV	0.50 MeV

[a]Relative to neutron separation energy.

TABLE III. Results of the simulation study of intermediate structure in (^{235}U + n), in the range 6—32 keV, with an averaging interval of 200 eV.

s-wave spacing, class II	70 eV	140 eV	280 eV	No intermediate	
Energy of second well	2.34 MeV	2.61 MeV	2.88 MeV	structure	Experiment
$\frac{\text{Standard deviation of } (1/\alpha)}{\langle 1/\alpha \rangle}$	0.118	0.143	0.158	0.057	0.118
Wald-Wolfowitz statistics:					
Number of high (low) values	62(67)	64(65)	55(74)	59(70)	60(69)
Number of runs	61	55	43	65	50
Levene-Wolfowitz statistics:					
Number of runs of length >3	9	12	17	5	9
Number of runs of length >4	0	3	4	2	6

freedom. (The observed value of the variance from 6 to 10 keV with 200 eV bins is 0.036; from 10 to 25 keV with 500 eV bins, it is 0.042. The expectation values would be a factor of 2 to 3 lower than those for the variance of S^0.)

(4) The lack of a significant correlation between σ_a and α indicates that the two above mechanisms that produce structure in the ^{235}U cross sections are independent. Contrary to the speculation made by Moore,[13] based on the correlation of the spin-dependent parameters S_3^0 and $\langle \Gamma_{f3} \rangle$ and S_4^0 and $\langle \Gamma_{f4} \rangle$ derived from the earlier analysis of Keyworth's data, we find no evidence for correlated neutron and fission widths or a common doorway.

(5) The strong correlation of σ_γ and α and the lack of a significant correlation between σ_a and σ_γ suggests that most of the fluctuation of σ_γ is due to the fluctuation of Γ_f in the Breit-Wigner denominator rather than of S^0.

We next carried out a simulation study of $1/\alpha$ for (^{235}U + n), using a double-humped-barrier model in which the assumptions are made that all the observed structure is due to s-wave neutron interactions and that the same mechanism applies for suprathreshold fission as has been found applicable for subthreshold fission: The class I fission widths are coupled to Lorentzian-shaped class II resonances with a coupling width that is Porter-Thomas distributed in each channel. The calculation is done by Monte Carlo sampling of class I and class II spacings according to a Wigner distribution, of the reduced neutron widths of the class I states according to a Porter-Thomas distribution in each spin state, and of the class II fission widths and coupling widths according to a Porter-Thomas distribution in each exit channel; an effective number of 2.4 and 2.0 fission channels has been assumed for spin three and spin four, respectively. The model used here is virtually identical to that used in our simulation study[14] of the class II fission structure in (^{244}Pu + n); the physical principles on which it is based were described in detail by Weigmann.[15] Average parameters used in the simulation are shown in Table II; the values for the s-wave average resonance spacings, strength functions, and radiative widths were taken from Ref. 10. The experimental data were corrected for p-wave fission and capture by renormalizing by a smoothly varying energy-dependent factor to account for the difference in the average value of s-wave and p-wave fission widths. As an example, Fig. 2 compares, for an averaging interval of 200 eV, the simulated $1/\alpha$ for $D_{\rm II}=280$ eV with the renormalized experimental values. The barrier heights given in Table II have been chosen such as to roughly reproduce the average s-wave contribution to $1/\alpha$. We varied the class II average spacing to obtain agreement with the observed structure in $1/\alpha$. We compared calculation to experiment by applying both the Wald-Wolfowitz runs distribution test as suggested by James[16] and the Levene-Wolfowitz runs-up-and-down test suggested by Baudinet-Robinet and Mahaux.[17] As noted by James,[7] we found the Wald-Wolfowitz test to be far superior. The results are shown in Table III. We obtain best agreement with the experimental data with a $D_{\rm II}$ spacing of 210 ± 70 eV, in disagreement with the estimate of 1000 eV obtained by Beer and Käppeler.[9] Our value of $D_{\rm II}$ is, however, in agreement with the value of $D_{\rm II}=280$ eV obtained by Cao *et al.* from an autocorrelation analysis of σ_f in the range 6 eV—3 keV. Under the assumption that the symmetries in nuclear shape are the same for the first and second wells, our value for the $D_{\rm II}$ spacing leads to a difference of 2.74 ± 0.14 MeV for the class I and class II minima, in reasonable agreement with the fission systematics of Bjørnholm and Lynn,[18] who list values ranging from 1.9 to 2.8 MeV for U and Np isotopes.

The success of this model, a calculation of subthreshold fission extended to suprathreshold energies, is somewhat surprising. It indicates that the second-well states are well defined and the coupling is no more than moderately weak even at energies well above the barrier. If this is so, then we expect intermediate structure to be present in any of the fissile actinides in which the second barrier is high enough to permit well-defined class II states. These results also suggest that current statistical prescriptions used in calculating unresolved resonance fluctuations for existing evaluated data sets (based on assumed Porter-Thomas statistical behavior of the class I states only) are not correct.

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