# SHORT-RANGE INTERMEDIATE STRUCTURE OBSERVED IN THE $^{237}$Np NEUTRON SUBTHRESHOLD FISSION CROSS SECTION

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The $^{237}$Np nucleus is not fissionable by slow neutrons, because the fission barrier in $^{238}$Np is 650 keV above the neutron binding energy. Nevertheless, the penetration of this fission barrier[1] leads to a small subthreshold fission cross section which can be measured using the intense neutron sources now available.

The interaction of resonance neutrons with $^{237}$Np has been studied with the Saclay linear accelerator used as a pulsed neutron source, in order to obtain more information on the fission barrier and the mechanism of subthreshold fission induced by slow neutrons.[2] This study has been undertaken in the same manner as earlier investigations of $^{235}$U[3] and $^{239}$Pu,[4] by measuring both the total and fission cross sections of $^{237}$Np up to about 4 keV. The overall resolution at 100 eV was 3.7 nsec/m for transmission and 18 nsec/m for fission measurements.[5-7]

(1) The total cross section is very similar to those of odd-$A$ nuclei with mass numbers close to 237. Individual resonances have been analyzed

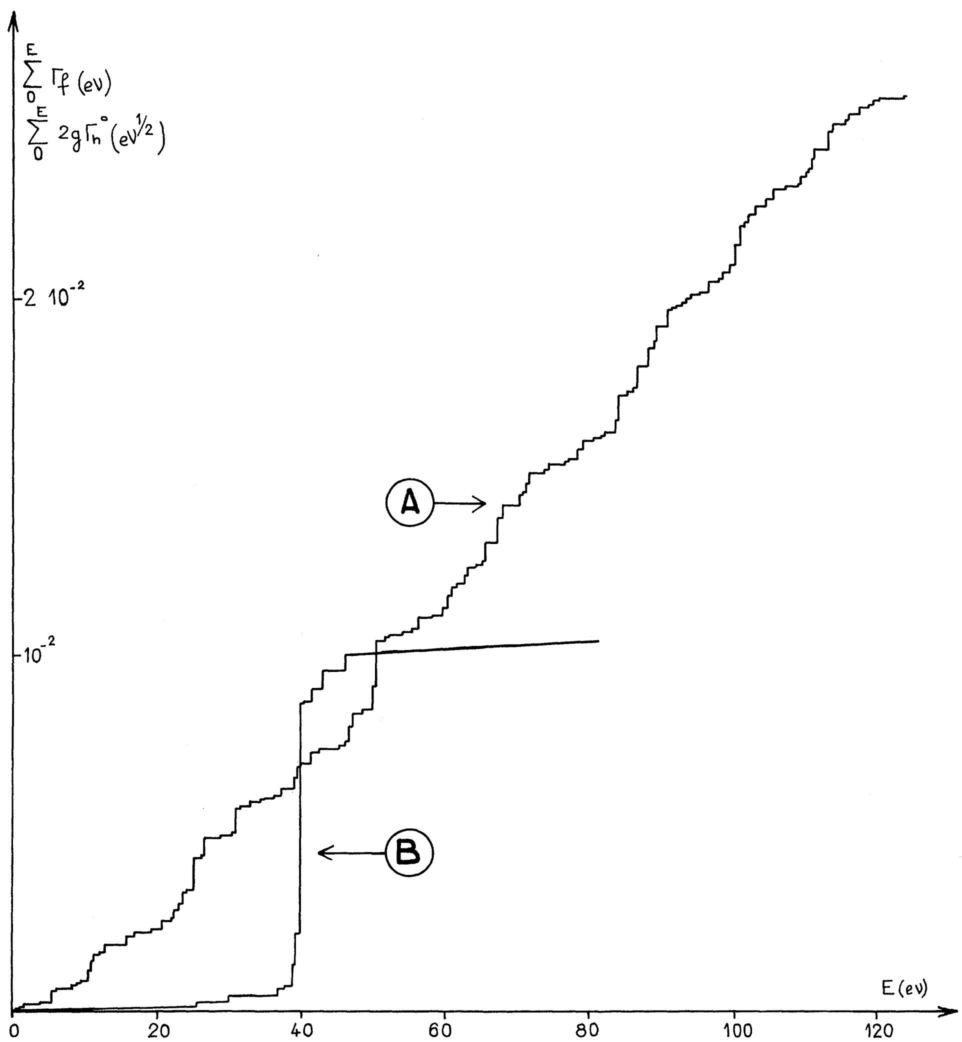


FIG. 1. Curve $A$ shows the cumulative sum of the reduced neutron widths $2g\Gamma_n{}^0$ plotted as a function of $E$. Curve $B$ shows, in the same manner, the cumulative sum of the fission widths.

up to 230 eV using standard methods.[3] The cumulative sum of the reduced neutron widths is plotted as a function of $E$ in Fig. 1 (curve $A$). There is no evidence of any systematic variation in the distribution of the resonance parameters either from this curve in the range 0-125 eV or from the behavior of the total cross section at higher energies (up to 4 keV) where broadening of the experimental resolution prevents a detailed analysis.

(2) The behavior of the fission cross section is radically different from that of the total cross section and of the fission cross section of the other nuclei studied up to now. Instead of showing a regular pattern, it is composed of high peaks (which may contain several resonances) at definite energies: 40, 118, 198, $\cdots$, etc. up to 4 keV. There are 17 such peaks (or "structures") below 1 keV with a mean level spacing of about 60 eV, which is roughly 100 times greater than the average level spacing of the compound nucleus states observed in transmission. Between the peaks, the fission cross section is almost too small to be measured.

Relatively poor resolution limits the analysis to the fission resonances situated below about 80 eV. The large resonances in the "structure" at 40 eV were resolved and can be analyzed. Outside this "structure," a large number of very weak fission resonances do not emerge above the background. It is possible nevertheless to set an upper limit ($\Gamma_{f\,\max}$) on the fission width of these resonances; arbitrarily, their fission width was taken equal to $\frac{1}{2}\Gamma_{f\,\max}$ (with an uncertainty of $\frac{1}{2}\Gamma_{f\,\max}$).

The cumulative sum of the fission widths for all the resonances observed in transmission up to 80 eV is plotted as a function of energy in Fig. 1 (curve $B$). Curve $B$ shows a very sharp rise around 40 eV which corresponds to the energy of the first "structure" observed in fission. Although the resonances situated between 35 and 45 eV represent only 14% of the total number of resonances observed in transmission below 80 eV, they contribute 90% to the total sum

$$\sum_{E=0}^{E=80\text{ eV}} \Gamma_f.$$

The fission-width distribution of all transmission resonances below 80 eV is plotted in Fig. 2 (curve $B$). This histogram is clearly inconsistent with one single distribution of an $x^2$ family. It can be fitted (curve $D$) with the sum of two distributions: one having $\langle\Gamma_f\rangle_1 = 0.009$ meV and $\nu = 1$ (small fission resonances), the other having $\langle\Gamma_f\rangle_2 = 0.4$ meV and $\nu = 1$ (large fission resonances). The parameters of the former distribution are approximate since only half of the small fission resonances were actually observed. Nevertheless, the large fission width of the 39.9-eV resonance is still outside the fit. The ratio of the populations of the two distributions is 0.18. It seems, therefore [in contrast to the case[8] of $^{239}$Pu], that these two distributions do not correspond to the two spin states, whose statistical factor ratio here is $\frac{5}{7}$.

The experimental fission cross section has been compared with a "simulated" one, calculated from a set of parameters selected at random but obeying the usual statistical distributions. In particular the "simulated" fission width distribution was assumed to be the same as the one shown in Fig. 2 (curve $D$) and described above.

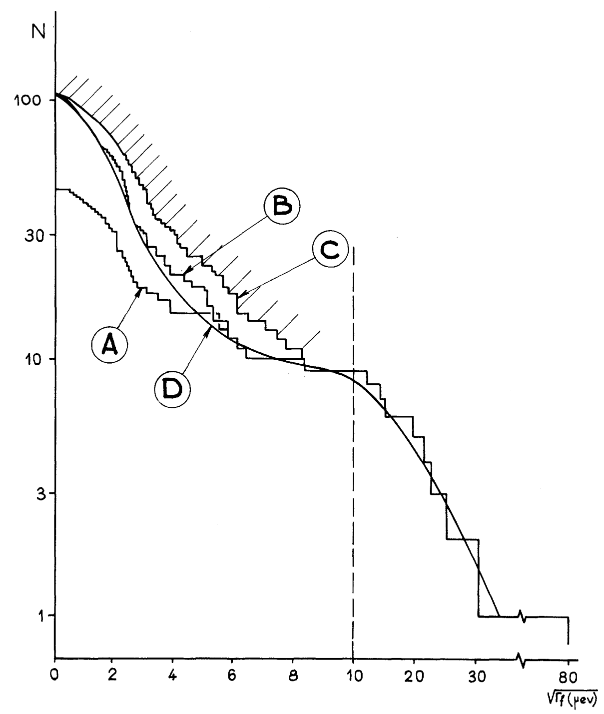


FIG. 2. Fission width distribution of the resonances situated below 80 eV. $N$ is the number of resonances having a value of $\sqrt{\Gamma_f}$ greater than the abscissa. $A$, resonances actually observed in the fission cross section; $B, C$, all the resonances observed in transmission below 80 eV. For the resonances not seen in fission, $\Gamma_f$ is set equal either to $\frac{1}{2}\Gamma_{f\max}$ (curve $B$) or to $\Gamma_{f\max}$ (curve $C$). The dashed area is forbidden. $D$, theoretical distribution (see the text). Note the change of scale at $\sqrt{\Gamma_f} = 10(\mu\text{eV})^{1/2}$ and the break between 30 and 80 $(\mu\text{eV})^{1/2}$.

Both the experimental and the "simulated" fission cross sections were then averaged with a rectangular weighting function (10 eV wide) every 10 eV. Between 0 and 160 eV, the variance of the averaged values of the experimental fission cross section is three times higher than that of the "simulated" one. This comparison confirms the presence of an intermediate structure in the neutron subthreshold fission cross section of $^{237}$Np.

The total cross section does not show any anomaly at the energies of the peaks or "structures" observed in fission. For example, curve *A* in Fig. 1 varies smoothly through the energies 40 and 118 eV where two "structures" show up in fission. Therefore, it does not seem that the intermediate structure in the fission cross section can be explained by the formation of the compound nucleus through "doorway states" in the entrance channel.[9] Rather, it appears that only the coupling of the compound nucleus states to the fission exit channels is more intense at some discrete energies (40 eV, 118 eV, etc.). Thus, it seems that only a more thorough understanding of the fission process can explain this phenomenon. It has been suggested[10] that the compound-nucleus states could be coupled to intermediate stationary states situated between the two humps of a double-humped fission barrier.[11] The intermediate structure could then be due to these intermediate stationary states acting as "doorway states" in the fission exit channels. Consequently, all the large fission resonances belonging to any of the observed "structures" should have the same spin and parity as those of the corresponding doorway state. The need to measure the spins of the resonances in the "structure" at 40 eV is therefore obvious.

We note that the level spacing distribution of the big peaks observed in fission seems to obey the Wigner law (one population only) as if they were all coupled to the same spin and parity.

It would be of great interest also to determine whether other nuclei (fissile or nonfissile) exhibit a similar behavior for the fission channels which are above the neutron binding energy. Correlations have already been found in $^{235}$U [12,3] that could be explained by such an effect of intermediate structure.

Lastly, the intermediate structure observed in the $^{237}$Np subthreshold fission cross section presents a minimum at zero neutron energy. This fact, by itself, explains the low value of the thermal neutron fission cross section[2]; it is unnecessary to appeal to the mechanism of subthreshold fission proposed by Rae,[2] for it does not seem to apply to $^{237}$Np.

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