Nature of the coupling in subthreshold fission of ^{238}Np

G. F. Auchampaugh, M. S. Moore, J. D. Moses, R. O. Nelson, R. C. Extermann, and C. E. Olsen
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

N. W. Hill and J. A. Harvey
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

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High-resolution measurements of total and fission cross sections for neutrons on ^{237}Np in the region of the subthreshold fission structures near 40 and 120 eV have been made with samples cooled to liquid nitrogen temperature. The previously accepted normalization of the fission cross section is found to be too low by a factor of 3. Extensive one- and two-fission-channel multilevel *R*-matrix fits to the data and statistical analyses of the fine structure at 40 and 120 eV fail to differentiate between the two proposed coupling schemes in ^{238}Np: very weak coupling of the class I states to a narrow class II state or moderately weak coupling of the class I states to a broad class II state.

[NUCLEAR REACTIONS ^{237}Np(n,f), ^{237}Np(n,total); measured $\sigma_T(E_n)$, $\sigma_f(E_n)$, 1 eV $\lesssim E_n \lesssim$ 600 eV; samples cooled to LN; *R*-matrix and statistical analyses, class I and class II states.]

I. INTRODUCTION

Although intermediate structure in subthreshold fission was first observed in the neutron-induced fission of ^{237}Np (Refs. 1 and 2), and the structure at 40 eV has been extensively studied,[3,4] the nature of the coupling between the first and second wells of the ^{238}Np fission barrier remains unknown. Inspection of high-resolution fission data[4] reveals that several levels are strongly enhanced in the fission channel, so that the mixing between the class II level underlying the intermediate structure and the class I background is neither extremely weak nor very strong. The mixing can, however, be attributed to two very different physical causes, as discussed by Bjørnholm and Lynn.[5] In the simplest case, the two classes of states may be weakly mixed because of a high intermediate barrier. Bjørnholm and Lynn refer to this kind of mixing as moderately weak mixing to a narrow class II state. Alternatively, the class II state may have a very large fission width that leads to weak mixing owing to rapid decay of the class II state. This is known as very weak mixing to a broad class II state. The data for ^{237}Np have not clearly distinguished between these alternatives. Although the fission strength is distributed among several levels, a substantial amount of fission background appears to be underlying these levels, and Paya *et al.* conjectured[6] that this broadly distributed fission component could be the heretofore unobserved class II state characteristic of weak coupling owing to rapid decay. The implication is that the outer fission barrier is more penetrable than the inner one.

Shortly after intermediate structure was discovered in the fission of (^{237}Np + n), a direct test to determine the nature of the coupling was carried out by Weigmann *et al.*[7] If no unobserved state underlies the 40-eV structure, then, based on the best data available in 1969, most of the fission strength would be concentrated in one level, that with the largest fission width, at 39.9 eV. The wave function of this level was thus expected to be large in the region of deformation corresponding to the second minimum, and the radiative decay of this state should show second-well properties, i.e., line spectra with a maximum energy of 3.3 MeV, instead of the bell-shaped continuum with a 5.5-MeV end point that is observed for first-well transitions. Weigmann *et al.* measured the spectrum resulting from radiative decay of the 39.9-eV level, comparing it with that for other levels, and saw no significant difference. They concluded that the 39.9-eV level does not carry the class II strength and conjectured that an unobserved broad level must exist. These results were generally accepted as showing that ^{237}Np + n is a case of very weak coupling to a broad class II state.

This interpretation was challenged by the results of Plattard *et al.*,[4] who reported an additional weak level at 39.7 eV, which appeared to have a substantially larger fission width than that at 39.9 eV. However, Plattard's data did not have adequate energy resolution and statistical precision to establish the presence or the absence of a broad resonance underlying the 40-eV intermediate structure, nor did the best available total-cross-section data have sufficient energy resolution to permit unambiguous analysis of the resonance at 39.7 eV, and so the nature of the coupling remained in question.

Our work was an attempt to resolve this question by measuring the fission and total cross sections with very good energy resolution in order to (1) expose any underlying broad resonance near 40 eV, if possible, and (2) obtain good enough resonance parameters to permit detailed analysis of the fine structure of the class II fission resonances at 40 and 120 eV. Experimental procedures are discussed in Sec. II. The *R*-matrix analysis of the data is discussed in Sec. III; statistical analyses of the resulting resonance parameters are given in Sec. IV; and the results of this work are discussed in Sec. V.

II. EXPERIMENTAL MEASUREMENTS AND NORMALIZATION

A. Total cross-section measurements

Data were collected from two separate runs. At the Oak Ridge Electron Linear Accelerator (ORELA) in the first run, two 12.7-mm-thick lithium-glass scintillation detectors were used; one edge mounted on an RCA 8854 phototube and placed at 78.017 m; the other face mounted and placed 78.203 m from the neutron target. The sample diameter was 9.906 mm. Samples of ^{237}Np metal of thicknesses (25.83 ± 0.17) and $(168.73\pm0.68)\times10^{18}$ atoms/mm^2 were used. The samples were cooled to liquid nitrogen temperature (77 K) to reduce Doppler broadening. The accelerator repetition rate was 95 Hz and the burst width was 36 ns. Filters of 0.762-mm-thick cadmium and 6.35-mm thick lead were used to eliminate overlap neutrons and reduce the effects of the gamma flash from the target. Useful data were collected for about 170 h for each sample thickness.

The second run was made some months later to investigate the class II state at 119 eV which was obscured by the 120 eV resonance in the cadmium filter used in the first run. The cadmium filter was replaced by a ^{10}B filter, 4.5 mg/mm^2 in thickness. Only the face-mounted detector at 78.203 m and the thicker sample were used. The accelerator was operated with 35-ns bursts at a repetition rate of 1000 Hz. Useful data were collected for about 100 h.

B. Fission cross-section measurement

The fission cross-section measurement was done at the WNR pulsed-spallation neutron facility at the Los Alamos Meson Physics Facility, at a nominal flight path of 30 m, using samples cooled to 84 K. The design and operation of the cryogenic ionization chamber used to carry out the measurement of the fission cross section is described in Ref. 8. The chamber contained 1.35 g of ^{237}Np in the form of NpO_2, deposited on 0.0127-mm-thick stainless steel backings; 0.042 g of ^{235}U in the form of U_3O_8 on a similar backing; and 0.008 g of ^{6}Li in the form of ^{6}LiF deposited on a 0.025-mm-thick titanium backing. The uranium and neptunium deposits had areal densities of $\sim\frac{1}{2}$ mg/cm^2. The signal from the ^{6}Li foil was used to measure the shape of the neutron flux, and that from the ^{235}U deposit to normalize the fission cross section. Data were obtained with a burst width of 150 ns and with channel widths on the time digitizer of 64 ns, covering the energy range from 1 to 10^4 eV.

C. Fission cross-section normalization

Our preliminary normalization, based on relative masses of the ^{235}U and ^{237}Np deposits, suggested that the fission cross section of Plattard *et al.*,[4] which was normalized to the fission cross section of Paya *et al.*,[1] is too low by a factor of 3. This conclusion was reinforced by the observation of resonances in a slight contaminant of ^{239}Pu in our ^{237}Np deposits. Samples of the ^{237}Np material from which the deposits were fabricated were assayed by isotope dilution for ^{239}Pu content; the results showed that the ^{237}Np material contained 571 ± 29 ppm ^{239}Pu. The expected ratio, if the normalization of Plattard *et al.* were correct, was 188 ppm. To resolve the question beyond any doubt, we made a high-energy normalization run of the ^{237}Np-to-^{235}U ratio with this chamber using the value measured by Behrens[9] as the normalization standard. The results of this measurement showed that the normalization of the resonance data of Plattard *et al.*[4] is too low by a factor of 2.91 ± 0.08. Our data agree, within $\sim10\%$, with those of Jiacoletti and Brown[10] for the strongest resonances in the 40-eV cluster and for other resonances where their sensitivity to gamma radiation is not important.

III. *R*-MATRIX ANALYSIS

A. General

The total and fission cross sections were analyzed using the multilevel, multichannel, *R*-matrix code MULTI,[11] which fits the shapes of both cross sections simultaneously or individually by a least-squares search on resonance parameters. The resolution function applied to the theoretical curve took into account thermal motion of the neptunium atoms in the crystal lattice, neutron pulse-width broadening caused by neutron slowing-down time in the moderator surrounding the production target, and the thickness of the detector (for the transmission measurements). The energy resolution near the 40-eV cluster was limited by the zero-point vibration of the cooled target atoms, and is as good as can reasonably be achieved with a cooled solid sample. At the 120-eV cluster, the thermal motion of the atoms and the neutron pulse-width broadening contributed about equally to the resolution function.

B. One fission channel

The simultaneous multilevel analysis of the total and fission cross sections was carried out from 2 to 600 eV, with primary attention given to the regions of the observed intermediate structures near 40 and 120 eV. A one-fission-channel reduced *R*-matrix formalism was used to calculate the cross sections. In general, we varied the fission width, neutron width, resonance energy, and, below about 60 eV, the radiation width. For those resonances whose shapes were not sensitive to the radiation width, the radiation width was fixed at 40.8 meV. Examples of the quality of the data and fits to the data in the regions of the 40- and 120-eV clusters are given in Figs. 1—4. A list of the resonance parameters and a complete presentation of the total and fission cross-section data are given in Ref. 12.

C. Number of fission channels

The results of Kuiken *et al.*,[13] along with the spin assignments of Keyworth *et al.*,[3] suggest that the class II

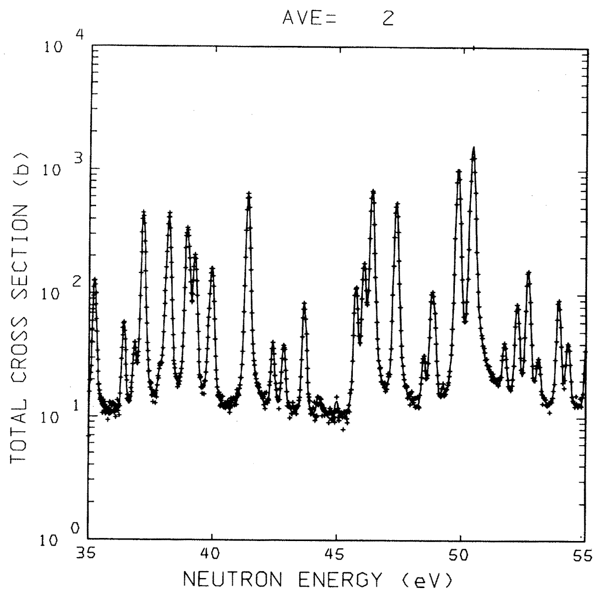

FIG. 1. Neutron total cross section of ^{237}Np from 35 to 55 eV. The data have been averaged by two time-of-flight channels. The solid curve represents the one-channel R-matrix fit to the data.

state at 40 eV may have more than one K component, which normally requires at least a two-fission-channel formalism. However, if the resonances in the 40-eV cluster acquire their fission strength from a single state of mixed K, then the two-channel formalism reduces to a single-channel formalism. Extensive one- and two-channel fits were made to the resonances near 40 eV. No improvement in the fit was achieved with two fission channels over that with one fission channel, even between resonances. The ratios of fission amplitudes for the two channels were approximately constant for all major resonances in the 40-eV cluster, which would be consistent with a class II state of mixed K.

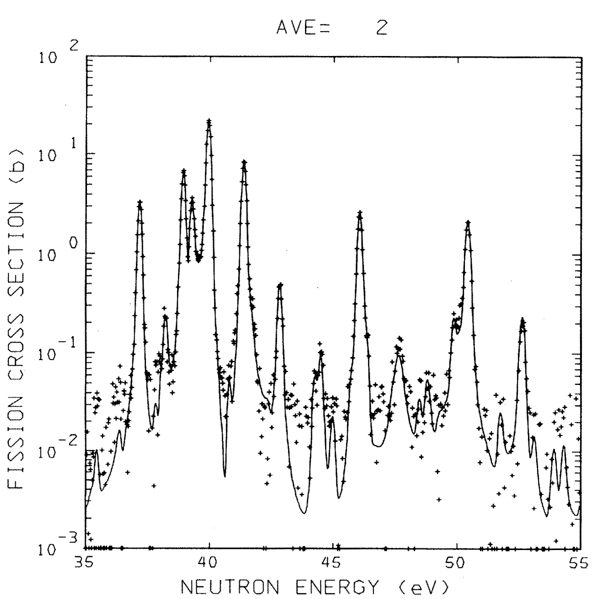

FIG. 2. Neutron fission cross section of ^{237}Np from 35 to 55 eV. The data have been averaged by two time-of-flight channels. The solid curve represents the one-channel R-matrix fit to the data.

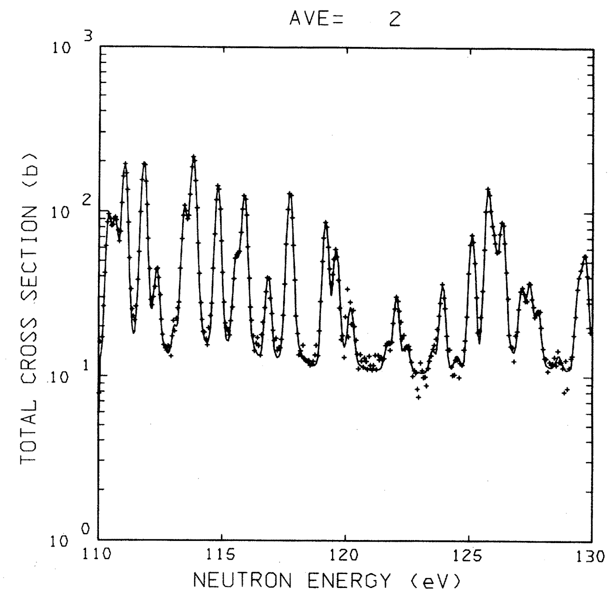

FIG. 3. Neutron total cross section of ^{237}Np from 110 to 130 eV. The data have been averaged by two time-of-flight channels. The solid curve represents the one-channel R-matrix fit to the data.

D. The 39.7-eV resonance

The analysis of the 40-eV cluster by Plattard et al.[4] suggested a resonance at 39.7 eV with a fission width

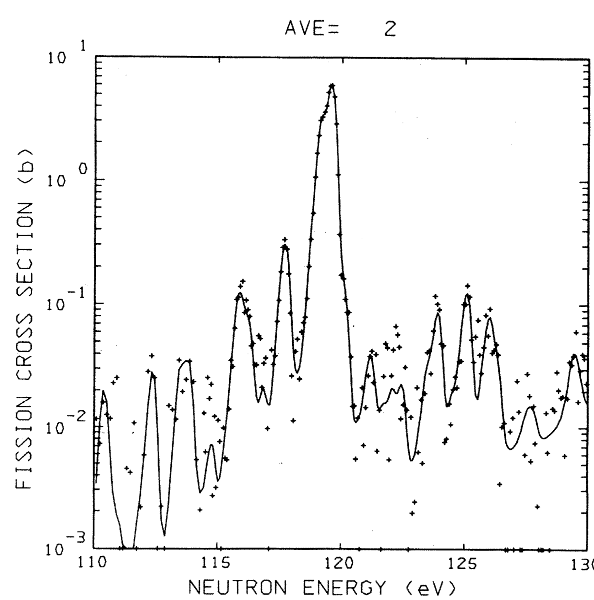

FIG. 4. Neutron fission cross section of ^{237}Np from 110 to 130 eV. The data have been averaged by two time-of-flight channels. The solid curve represents the one-channel R-matrix fit to the data.

larger than that of the prominent resonance seen in the fission cross section at 39.9 eV. In our high-resolution total-cross-section data, the 39.7-eV resonance is clearly evident (see Fig. 5). However, we find the fission width of the 39.7-eV resonance to be 2.5 μeV instead of 1687 μeV obtained by Plattard *et al.* Our data are thus consistent with the view that the major portion ($\sim$63%) of the fission strength of the class II state at 40 eV is contained in the resonance at 39.9 eV.

For the 39.7-eV resonance, we find a radiation width of about a factor of 2 smaller than the average radiation width for ^{237}Np. If the 39.7-eV resonance were to contain most of the class II strength, then we might expect it to gamma decay to class II states and, therefore, to have a different radiation width than the nearby class I resonances. Based on a statistical calculation using a level density appropriate for the second-well deformation, Bjørnholm and Lynn[5] obtained a value for the class II radiation width of about 30 meV, about $\frac{3}{4}$ as large as the capture width of the class I resonances. Furthermore, a reanalysis of the data of Keyworth *et al.*[3] in conjunction with our higher resolution data suggests that the 39.7-eV resonance has spin 2 rather than spin 3, as is characteristic of the 39.9-eV resonance and of all resonances in the 40-eV cluster. Therefore, we conclude it is unlikely that the 39.7-eV resonance is predominantly a $J=3$ class II resonance.

E. Multiple scattering and a broad class II resonance

Careful analysis of Paya *et al.*[6] of the resonances in the fission cross section near 40 eV indicated the presence of a residual background cross section beneath the resonances. Assuming this background to be a broad resonance, they obtained the following parameters: $E_0=44.35$ eV, $\Gamma_f=14$ eV, and $\Gamma_n=7.3\times10^{-6}$ eV. However, they recognized, as did Plattard *et al.*,[4] that multiple scattering of the neutron beam from the components of the fission chamber can lead to an apparent enhancement of fission background near the cluster; this background could resemble a broad resonance underlying the narrow intermediate structure. Plattard *et al.* designed their fission chamber to reduce neutron scattering so that the multiple-scattering contribution to the cross section near the hypothesized broad resonance would be <3 mb. However, their data did not provide a definitive answer concerning the presence of the postulated broad resonance. Their best fit gave only an upper limit: $E_0=40.53$ eV, $\Gamma_f<214$ eV, and $\Gamma_n<56.3\times10^{-6}$ eV. The meaning of these broad-resonance parameters is not clear. Our simulation studies with a broad resonance, which we discuss in Sec. IV, show that it does not appear as a resonance in the fission cross section, and in fact, may not produce an enhancement in the cross section between resonances. Generally, a broad resonance is observable only through enhancement of the asymmetries in the line shapes of the class I fission structure, and not as a broad residual background.

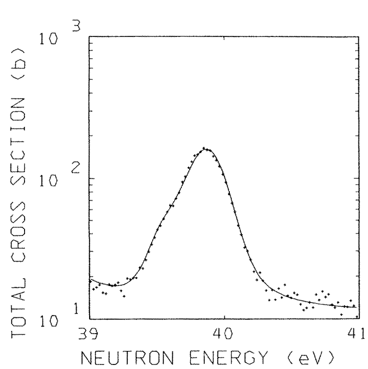

FIG. 5. Neutron total cross section of ^{237}Np in the region of the 39.9-eV resonance. The 39.7-eV resonance is clearly evident on the low-energy side of the 39.9-eV resonance.

In our measurement, no serious attempt was made to minimize multiple scattering effects; however, the geometry was such that an analytic first-order correction was easy to calculate by a method similar to that described by Moore *et al.*[14] The level of the residual background fission cross section above the 40-eV cluster, where the scattering enhancement is largest, was observed to be a factor of 3 larger than that of Plattard *et al.*,[4] relative to the strength of the narrow resonances in the cluster. By applying the correction for multiple scattering, the residual background was completely removed to within the statistical precision of the data.

IV. ANALYSIS OF DATA IN TERMS OF VERY WEAK VERSUS MODERATELY WEAK COUPLING SCHEMES

A. General

In attempting to determine whether the class II resonances in ^{238}Np are mixed via very weak coupling (broad-level case) or moderately weak coupling (narrow-level case), we carried out three analyses. We examined the sensitivity of the *R*-matrix fit to the presence of a broad level using simulated cross sections. In addition, we analyzed the level-spacing distribution for the presence of an extra level, which should be present for moderately-weak mixing, but not present in the broad-level case. Finally, we analyzed the distributions of experimental fission widths and energies under both assumptions. The following sections discuss these topics in more detail.

B. Sensitivity of *R*-matrix fit to the broad-level hypothesis

A broad resonance coupled to a group of much narrower resonances produces level-level interference effects that are most pronounced between resonances. We investigated the effect of such a resonance on the total and fission cross sections, and the sensitivity of the *R*-matrix fitting procedure to the broad resonance by generating and fitting simulated cross sections. For comparison and as a check of the numerical procedures, we generated cross sections for the narrow-level case as well.

For the broad-level case, the class II fission width was equal to the class I level spacing (1 eV) and the class II coupling width was much smaller (1.2 meV). For the narrow-level case these values of the coupling and fission widths of the class II state were interchanged. Reduced neutron widths and energy eigenvalues of the class I states were sampled from a Porter-Thomas distribution and a Wigner distribution. The class II state was located at the center of the interval. The squares of the coupling matrix elements between the class II and class I states were sampled from a Porter-Thomas distribution with a mean value calculated from the coupling width. The signs of the coupling matrix elements were chosen at random. The class I and class II radiation widths used were 40 meV. The widths and energies of the R-matrix levels were calculated after diagonalizing the interaction matrix. The total and fission cross sections were calculated with these parameters and fitted simultaneously with MULTI. This procedure was repeated until we acquired a representative sample of the possible cross sections for each case.

We made the following observations concerning the results of this study. In general, the total cross section is not as sensitive to the broad resonance as the fission cross section is. The broad resonance, which acquires only a small neutron width, is difficult to see in the total cross section. However, in the fission cross section, the effect of the broad resonance is seen very strongly between resonances, although in most cases there is no evidence of a resonance in the vicinity of the class II state. (A few cases show a Teichmann "nonresonance"[15] near the class II state, with a shape quite different from that of the neighboring class I resonances.) In other cases, the fission cross section looks qualitatively similar to that of some of the narrow-level cases.

The similarity of some of the narrow- and broad-level cross sections is a result of the uncorrelated signs of the matrix elements (fission amplitudes), and thus, of the large number of cross sections that can result from the various combinations of these fission amplitudes. This does not mean that a broad-level fission cross section can be reproduced exactly without the broad resonance; there is a unique relation between the fission amplitudes and the cross section in the one-channel formalism. However, it does mean that for real data with non-negligible background and statistical fluctuations, it is usually possible to achieve an acceptable fit without requiring the broad resonance. In other words, the pronounced level-level interference effects that occur at the microbarn level—which would distinguish between the broad-level and narrow-level cases—might be masked by background and by statistical uncertainties in the data, particularly between resonances.

Rather than trying to generate real data to determine the level of background and statistics at which a broad resonance could be detected, we investigated whether MULTI could locate the correct parameter set if we had ideal data. We found that the rate of convergence to the correct solution is more sensitive to the starting value of the fission width of the broad level than to the starting values of its resonance energy and neutron width. If the starting value of the fission width is, for example, a factor of 5 smaller than the correct value, then convergence is so slow that it may not be practical to run the problem to completion. Furthermore, if background and statistical effects are important, then it is very likely that the problem would terminate at a local minimum without finding the correct solution. We conclude that the problems associated with fitting a fission cross section to ascertain the presence or absence of a broad resonance are rather formidable and that to draw strong conclusions solely on the basis of a least-squares fit is unjustified.

C. Statistical analysis of the level-spacing distribution

A test for the nature of the mixing can be based on the long-range order in the level-spacing distribution.[16] Because a class II state mixes into the class I states over a relatively narrow energy region, it can be expected to affect the local level density. If the density is integrated over the region of enhanced fission widths, then the number of levels should be one larger than the number present without mixing, provided that all levels are observed. In the narrow-level case, we might hope to see all enhanced levels; therefore, the extra resonance might be present. On the other hand, if the class II state is broad, then no extra level will be present because we do not observe the broad resonance.

The usefulness of a test based on these considerations clearly depends on the quality of the data on both sides of the strongly enhanced region. If all levels are observed, then an extra level should stand out in the enhanced region. If, however, we systematically miss levels away from the enhanced region, but see all levels with large fission widths, we may mistakenly conclude that an extra level is present in the strongly enhanced region.

Cumulative plots for levels of both spins for the regions from 15 to 60 eV and from 90 to 140 eV are shown in Figs. 6 and 7. The solid line in Fig. 6 is a least-squares fit to the data below 40 eV extrapolated to the region above 40 eV. The solid line in Fig. 7 is an extrapolation of this fit to the region above 90 eV. It is apparent that an anomaly occurs in the region of the 40-eV cluster.

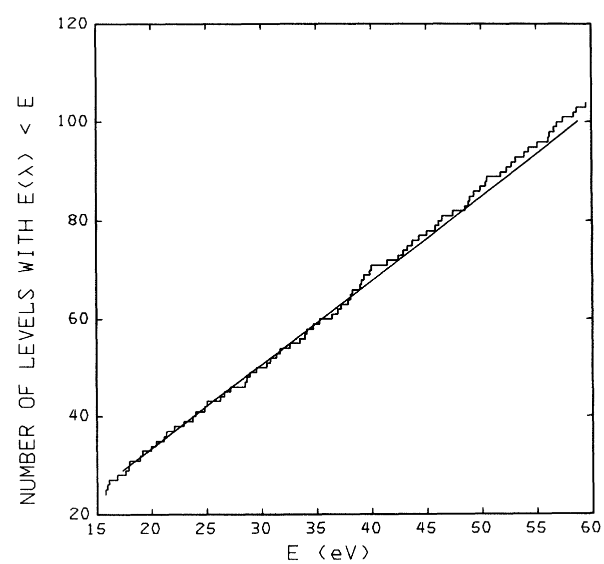

FIG. 6. Cumulative staircase plot of the number of levels E_λ with an energy $<E$ vs the neutron energy for the energy region from 15 to 60 eV. The solid curve represents a linear fit to the data below 40 eV.

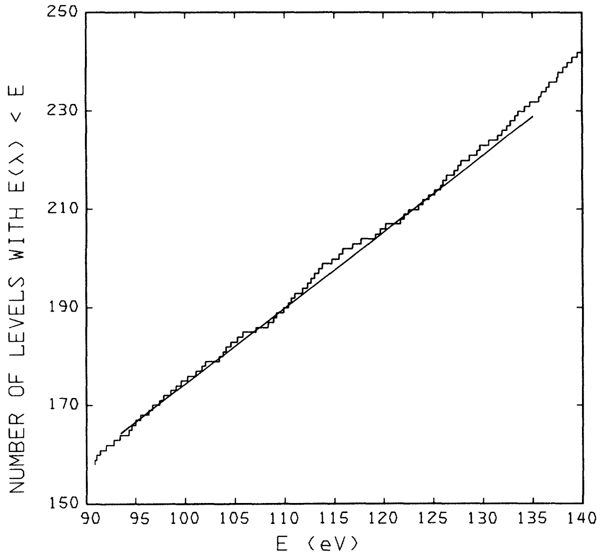

FIG. 7. Cumulative staircase plot of the number of levels E_λ with an energy $<E$ vs the neutron energy for the energy region from 90 to 140 eV. The solid curve is an extrapolation of the linear fit to the data below 40 eV.

To determine whether the anomaly at 40 eV is an indication that we have moderately weak mixing (narrow-level case) or an artifact, we have analyzed the level spacing distribution by first using the Moore-Keyworth missing-level estimator[17,18] to establish the average spacing from the neutron-width distribution. We next used the Δ_3 statistic[16] (which was put on a quantitative basis by Georgopulos and Camarda[19]) to establish the average spacing and number of missing levels in the sequence; one level near 39 eV was omitted. Agreement of the average spacing obtained in these two ways should allow us to draw useful conclusions from the spacing distribution.

Unfortunately, the results of this study are ambiguous. The Moore-Keyworth method for all resonances below 120 and, separately, between 120 and 240 eV, gives the average spacing at 0.51 ± 0.03 eV. The Georgopulos-Camarda estimate gives the most probable number of missing levels as 0^{+4}_{-0} for the first 100 resonances and an average spacing of $0.57^{+0.00}_{-0.02}$. If the true average spacing is as low as 0.51, and if the missing levels are distributed uniformly, except in the region around 30—40 eV, then the anomaly that is so apparent in Fig. 6 would essentially disappear. Although this analysis slightly favors the interpretation that the class II state is narrow, it is inconclusive.

D. Statistical analysis of fission-width and coupling-matrix-element distributions

The fine structure of the resonances at 40 and 120 eV has been analyzed for both broad- and narrow-level hypotheses. Both analyses, discussed below, give satisfactory fits to the data. We assume in either case that the resonances near a given class II level draw their fission strength entirely from that level. Figure 8 shows Lorentzian strength functions (smoothed curve) typical of

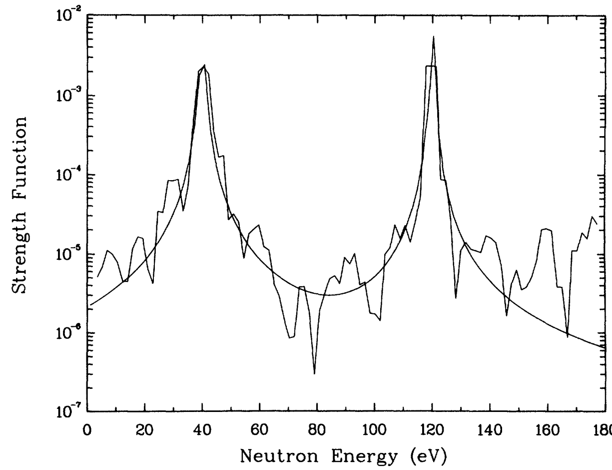

FIG. 8. Fission strength function for $^{237}Np + n$ from 0 to 180 eV. The smooth curve is typical of the fit for either the narrow- or broad-level case.

fits by either method, along with the measured fission strength functions

$$S_f(E)=\frac{1}{I}\sum_{E_\lambda\in E\pm I/2}\Gamma_{\lambda(f)},\quad I=5\text{ eV}\ .$$

The data are well accounted for by the class II states, even in the wings. (The poor fit above 160 eV is owing to the presence of another class II state at higher energy, which is not included in the fits.) Further assumptions specific to the method of analysis are given below.

For a narrow class II resonance, we used the method of Lynn and Moses,[20] which yielded the energies of a set of hypothetical uncoupled class I resonances and the class II state, as well as the squares of the coupling matrix elements. The spreading width describing the distribution of fission widths of the mixed states is given by

$$W=2\pi\langle H^2\rangle/D\ ,$$

where $\langle H^2\rangle$ is the average of the squared coupling matrix elements. Table I gives the spreading and total fission widths for the 40- and 120-eV structures. The range of values given reflects different numbers of resonances included in the analysis. The squared matrix elements divided by their averages should follow a Porter-Thomas distribution. We have fitted this normalized matrix element distribution to a χ^2 distribution of ν degrees of freedom ($\nu=1$ for a Porter-Thomas distribution) and obtained the ν_c values given in Table I. They are lower than expected, but not alarmingly so.

If the width of the class II state is much larger than the resonance spacing, then the analysis of Lynn and Moses[20] does not apply. In this case, the observed fission widths and the matrix elements connecting the class I and II states are related by[5]

$$\Gamma_{\lambda(f)}=\frac{H^2_{\lambda_I,\lambda_{II}}\Gamma_{\lambda_{II}(f)}}{(E_\lambda-E_{\lambda_{II}})^2+\frac{1}{4}\Gamma^2_{\lambda_{II}(f)}}\ . \qquad (1)$$

If, as expected,[5] the squared matrix elements follow a

Porter-Thomas distribution, then the widths have a Porter-Thomas distribution about an energy-dependent average value:

$$\langle \Gamma_{(f)}(E) \rangle = \frac{\langle H^2_{\lambda_I,\lambda_{II}} \rangle \Gamma_{\lambda_{II}(f)}}{(E - E_{\lambda_{II}})^2 + \frac{1}{4}\Gamma^2_{\lambda_{II}(f)}} . \quad (2)$$

In this case, the observed resonance parameters $\{\Gamma_{\lambda(f)}, E_\lambda\}$ can be used to extract the best values of $\langle H^2_{\lambda_I,\lambda_{II}} \rangle$, $\Gamma_{\lambda_{II}(f)}$, and $E_{\lambda_{II}}$, using the method of maximum likelihood. The parameters $\langle H^2 \rangle$, $\Gamma_{\lambda_{II}(f)}$, and $E_{\lambda_{II}}$ are varied to maximize the likelihood function assuming the fission widths $\Gamma_{\lambda(f)}$ follow a Porter-Thomas distribution whose average value is given by Eq. (2). In practice, we fit all fission widths below $E=130$, 140, and 150 eV simultaneously, using a sum of two Lorentzians of the form given by Eq. (2). The class II coupling widths ($2\pi\langle H^2 \rangle / D$, for $D=1$) and fission widths from this analysis are listed in Table I. The spread in these values reflects the different upper energy limits in the analyses. Note that the coupling width is much less than the fission width, as required if Eq. (1) is valid. The ν_f value is found by analyzing the distribution of the quantities $\Gamma_{\lambda(f)} / \langle \Gamma_{(f)} \rangle$. A ν_f of unity implies that a good fit was obtained and that the results are consistent with the starting assumption that the coupling matrix elements follow a Porter-Thomas distribution.

The fits by both methods are very similar and either accounts satisfactorily for the data. In fact, the results are formally similar if the fission and coupling widths are interchanged. Hence, we cannot distinguish between the broad- and narrow-level cases by fitting the fine structure.

V. DISCUSSION

We have attempted to determine the relative sizes of the coupling and fission widths of the subthreshold resonances in ^{238}Np by measuring and analyzing the fission and total cross sections with great care and by analyzing the resulting resonance parameters by a variety of techniques. We believe we have succeeded to the extent that we have carried these techniques as far as they can reasonably be taken with current technology. We have not succeeded in providing a clear answer to the nature of the coupling in ^{238}Np. The multilevel analysis neither requires nor precludes the presence of a broad resonance underlying the 40-eV structure. The statistical analysis of the resonance-spacing distribution gives some indication that an anomalous intruder level is present at 40 eV, but the data also permit the alternate hypothesis. The fine structure resulting from the coupling of the class II resonances at 40 and 120 eV to the nearby class I resonances can be analyzed equally well under the assumption that either the coupling or fission width is dominant.

TABLE I. Analysis results of the fission width data for the narrow- and broad-level cases.

	Narrow-level case		
$E_{\lambda_{II}}$ (eV)	$\Gamma_{\lambda_{II}(c)}$ (eV)	$\Gamma_{\lambda_{II}(f)}$ (meV)	ν_c
40	1.6–2.2	12.7–13.6	0.6–0.8
119	0.6–0.7	12.2–12.4	0.7–0.9
	Broad-level case		
$E_{\lambda_{II}}$ (eV)	$\Gamma_{\lambda_{II}(c)}$ (meV)	$\Gamma_{\lambda_{II}(f)}$ (eV)	ν_f
40	12.9	2.5	1.0
119	9.9–10.7	1.2–1.5	1.0

Other evidence on the type of structure associated with the ^{238}Np fission barrier is inconclusive as well. The fast fission data favor the narrow-level hypothesis and, therefore, a more penetrable inner barrier.[5] However, the results of Weigmann *et al.*[7] suggest that the outer barrier is more penetrable than the inner barrier (broad-level hypothesis). We believe that this dilemma will not be resolved by precise measurements of the type described here, but by a more sensitive measurement of the type carried out by Weigmann *et al.* Unfortunately, their experiment did not distinguish between gamma rays from the decay of the class II state and gamma rays from the fission process. With our factor-of-3 larger fission width for the 39.9-eV resonance, the calculated fission contribution to the gamma-ray spectrum may now be comparable to that from the decay gamma rays and, therefore, cannot be ignored. An experiment designed to distinguish these two sources of gamma rays could provide the needed evidence to resolve the question we have attempted to address here.

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