STATISTICAL FLUCTUATIONS AND INTERMEDIATE STRUCTURE IN FISSION

M. S. Moore
University of California, Los Alamos Scientific Laboratory
Los Alamos, NM 87545

ABSTRACT

For neutron-induced fission, intermediate structure in subthreshold-fissioning nuclides is relatively simple and is thought to be well understood. For suprathreshold fissioning species, the existence of strong intermediate structure is more difficult to establish. There are two reasons: 1) The magnitude of the observed effects relative to that of the expected statistical background structure is much less. 2) There may be nonstatistical effects in the entrance (neutron) channel as well as in the exit fission channels. In this paper, the evidence for intermediate structure in suprathreshold neutron-induced fission is reviewed, and the problem of extracting quantitative information from the data is addressed. In the language of doorway-state models of neutron capture and of fission, the observed correlations between average neutron and fission widths in the unresolved resonance region of (^{235}U+n) suggests that a common doorway should be considered.

INTRODUCTION

The discovery[1,2] of intermediate structure in neutron-induced fission of certain fissionable isotopes provided strong confirmation of the importance of shell corrections leading to a double-humped fission barrier.[3] In the case of fission occurring at excitations below the top of both humps in the barrier (subthreshold fission), the structure is quite pronounced. The problem was treated theoretically by Weigmann[4] and Lynn,[5] who provided a model of the fission process and a formalism to describe the structure. It is usually assumed that one can represent motion in the fission degree of freedom by the traversing of a two-humped one-dimensional potential barrier: the fissioning nucleus initially finds itself in one of the states in the first well (Class I states); these are coupled through the first barrier A to states in the second well (Class II states), which are coupled to the continuum through the second barrier B. The fission components of the wave function correspond to the vibrations in the first and second wells. Class I states are expected to show relatively large neutron widths and small fission widths, while Class II states show small neutron widths and large fission widths. The coupling between the two gives rise to intermediate structure. Analysis of subthreshold fission data[6] has been carried out to provide information on the shape of the barrier: The magnitude of the fluctuations is related to the barrier coupling parameters, and the level density of the Class II or intermediate structure states allows one to infer the effective excitation in the second well. In this connection, the significant advantages of a polarized-neutron and polarized-target measurement in studying intermediate structure should be noted. For (^{237}Np+n), Keyworth et al.[7] showed that each resonance belonging to an intermediate-structure clump has the same spin. This implies that such polarization measurements can be used as an additional tool to reveal nonstatistical behavior.

INTERMEDIATE STRUCTURE IN SUPRATHRESHOLD FISSION

Shortly after the discovery of intermediate structure in subthreshold fission, nonstatistical behavior was reported in the fission cross sections of fissile target nuclides, in particular ^{239}Pu and ^{235}U. The evidence was far less conclusive than that for the subthreshold-fissionable target species, however. This is primarily because the noise level of fluctuations arising from the expected statistical processes is relatively much larger for fissile targets. Certain of the statistical tests (e.g., the use of serial correlations[9] that had seemed to indicate nonstatistical behavior were found to be subject to misinterpretation because of end effects and finite sample size.[8] Only for (^{239}Pu+n) in the 1^+ state (which is very nearly a case of subthreshold fission) was the evidence[9] for nonstatistical structure in fission strong enough to be generally accepted. Even here, the evidence is clouded because of the very marked qualitative difference in the sizes of the average 0^+ and 1^+ fission widths and the strong probability that spin assignments are not completely correct.[10]

For (^{235}U+n), a considerable amount of structure was observed in the fission cross section,[11-13] but total cross section measurements[14] showed that much of this structure could be explained as fluctuations in the entrance channel, and these were generally assumed to be of statistical origin. The question is not to be answered as simply as in the case of subthreshold-fissioning species; it is required that one extract the average fission widths. More nearly complete data are needed: either the total, scattering, or absorption (capture) cross sections in addition to fission. One must also consider resolution effects. Dennis et al.[15] noted that tests based on runs distributions[16] and lengths of runs[17] are to be questioned if the energy step size is comparable to the coherence width (i.e. in suprathreshold fission, to the resolution width). Several studies[18-21] have suggested that the structure observed in $<\Gamma_f>$ for (^{235}U+n) is nonstatistical, and again polarization measurements[22] showed that each of the anomalous structures has definite spin. Beer and Käppeler[23] very recently analyzed the structure in $<\Gamma_f>$ for (^{235}U+n) to infer properties of the deformation potential, concluding that the second well is significantly deeper than earlier work had indicated.

INTERMEDIATE STRUCTURE IN THE NEUTRON (ENTRANCE) CHANNEL

In 1975, Perez et al.[24] reported evidence for intermediate structure in the radiative capture cross section of ^{238}U. Very recently, these and additional data obtained by a different experimental technique, but which showed the same nonstatistical behavior, were analyzed by Perez et al,[25] who used a doorway-state model[26] in order to obtain a parameterization of the intermediate structure resonances. Perez et al. relied on Monte-Carlo simulations and on two statistical tests, the Wald-Wolfowitz runs statistic[16] and an autocorrelation test, to check consistency of their results. The conclusions reached have far-reaching implications. If intermediate structure exists and is important in the entrance neutron channel in (^{238}U+n), then, following Müller and Rohr[27] and Kerouac,[28] it should be taken into account for all the actinide nuclides, including the fissile species. The analysis[22] of the polarized-neutron and polarized target measurements on the fission of (^{235}U+n) did suggest a possibility of intermediate structure in the average reduced neutron widths, in that the fluctuations were found to be larger than expected, and the average fission and reduced neutron widths are correlated, rather than slightly anticorrelated as expected from the models used to explain intermediate structure in subthreshold fission. If further study shows that this is a real effect (not an artifact of the analysis), then one has evidence of common doorways: the vibrational levels in the fission degree of freedom and certain of the few-quasiparticle levels constituting entrance channel doorways have a large overlap. In this connection, the doorway-state model of fission recently developed by Goldstone and Paul[29] may provide a clue. This model differs from those suggested earlier by Back[30] and by Glässel et al.[31] in that Goldstone and Paul recognize first-well vibrations as fission doorways. At subbarrier energies these first-well vibrations are ineffective as fission doorways, but at energies above the first barrier this is no longer the case, and the large vibrational amplitudes in the first well carried by such a doorway may allow the possibility of overlap with entrance channel doorways, thus leading to correlated widths.

EXPERIMENTS OF INTEREST

Three experiments that could illuminate the situation are suggested. First, it would be of interest to show what the mechanism of intermediate structure in the capture of neutrons by ^{238}U might be. Perez et al.[25] have assumed in their analysis that it is structure in the p-wave entrance channels. This could be checked by using the method developed by Corvi et al.[32,33] for assigning p-wave resonances in neutron capture by ^{238}U and ^{232}Th. The measurement has the additional advantage that it increases the sensitivity to intermediate structure by separating positive and negative parity entrance-channel contributions.

Next, it is crucial to verify the neutron- and fission-channel correlation for (^{235}U+n). Keyworth found that the gamma-ray background associated with the polarization measurement on ^{235}U was so high that no meaningful data could be obtained on the spin-dependent capture cross section, and the sample was too thin to permit the total cross section to be determined. We feel that the measurement should be repeated, with the objective of measuring spin-dependent capture as well as fission yields.

In the interim, a third experiment, the measurement of self-indication fission yields, might be useful. Following a suggestion by Weigmann,[34] who hopes to use the technique to reveal the Class II state or states in the 40-eV intermediate-structure clump in (^{237}Np+n) fission, one might be able to extract some information on the correlation of neutron and fission widths in certain of the unresolved structure in (^{235}U+n) by measuring the self-shielded fission yield with cooled samples. While the analysis of such data is not as simple as if the data were separated in spin, the measurement would be relatively easily done, and could be instructive.

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