Sequence of Subbarrier Fission Resonances in ^{236}U†

P. D. Goldstone, F. Hopkins, R. E. Malmin, and P. Paul
Department of Physics, State University of New York, Stony Brook, New York 11794

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The reaction ^{235}U(d,p)^{236}U(f) was studied at $E_d = 13$, 15, and 17 MeV with $\theta_p = 60°$ and 140°. The proton spectra in coincidence with fission fragments show a series of new narrow subbarrier resonances in ^{236}U above the known resonance at $E_x = 5.12$ MeV. These are interpreted as vibrational modes orthogonal to and coupled weakly to the $K = 0^+$ fission vibration. Resonance centroids and experimental widths are extracted.

Subbarrier resonances at about 5-MeV excitation energy have been observed in the yield of direct-reaction–induced fission of many even-even actinide nuclei.[1] These are believed to arise from the coupling of the compound nuclear states in the first potential well to vibrations in the fission degree of freedom ("fission vibrations") in the second potential well. Additional resonances are then expected due to states in the second well which consist of a fission vibration coupled to orthogonal low-lying states in the second well, such as rotations and $K^\pi = 0^-, 1^-, 2^+, \ldots$ collective vibrations. The existence of some of these states has already been inferred from fits to fission probabilities.[1] In this Letter we report the first clear observation of such a series of narrow subbarrier resonances in fission of ^{236}U produced by the reaction ^{235}U(d,p).

The State University of New York at Stony Brook model FN tandem Van de Graaff was used to study the reaction ^{235}U(d,pf) at $E_d = 13$, 15, and 17 MeV. Coincident pairs of fission fragments were detected at ± 90° with respect to the beam axis in two thin-film plastic scintillator detectors[2] each of which subtended a solid angle of 1.25 sr. Outgoing protons were detected in a ΔE-E telescope placed out of the beam–fission-detector plane at $\theta_p = 60°$ and 140°. The solid angle of the telescope was 19.9 msr. Targets consisted of 60-μg/cm^2 isotopic ^{235}UO$_2$ evaporated onto 40-μg/cm^2 carbon foils. A 4.65-mg/cm^2 Al foil in front of the ΔE-E telescope eliminated fission fragments. The overall proton energy resolution was ~60 keV.

The proton-fission time spectrum was obtained from the differences in time between detection of a proton and detection of each of a complementary pair of fission fragments, summed electronically to yield a symmetric peak with a time resolution of 1.2 nsec full width at half-maximum (FWHM). Each accepted event was tagged by particle energy, proton-fission time, particle identification, and the summed pulse height in the fission detectors.

Differential (d,pf) cross sections were obtained from energy spectra of protons in coincidence with fission, corrected for small accidental contributions, assuming an isotropic proton-fission correlation. The energy calibration (± 30 keV) was obtained from elastic deuteron scattering. The excitation energies in ^{236}U were calculated using the 1971 mass evaluation of Wapstra and Gove.[3]

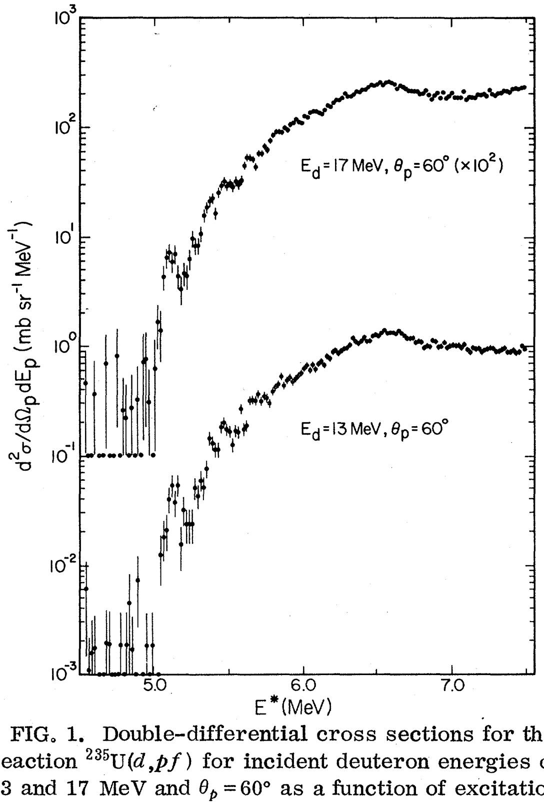

FIG. 1. Double-differential cross sections for the reaction ^{235}U(d,pf) for incident deuteron energies of 13 and 17 MeV and $\theta_p = 60°$ as a function of excitation energy in ^{236}U.

The (d,pf) cross sections as functions of excitation energy are shown in Fig. 1 for two bombarding energies. These logarithmic plots indicate a strong resonance at 5.12 MeV as well as additional resonances or shoulders on a steeply rising cross section. Below 5.1 MeV the cross section drops rapidly, having decreased by an order of magnitude at 5.0 MeV.

Previous work on the reaction ^{235}U(d, pf) by Back *et al.*[4] indicated a resonance at 5.0-MeV excitation energy based on the 1964 mass table.[5] A recalibration using the 1971 mass table raises this energy to 5.08 MeV, in reasonable agreement with the present results. In the reaction ^{234}U(t, pf) a very weak, narrow resonance at 5.0-MeV excitation and a distinct shoulder (or resonance) in the fission cross section at 5.15-MeV excitation have been reported.[6] A comparison with the present results suggests that the 5.15-MeV shoulder should be identified with the lowest resonance observed in ^{235}U(d, pf). In fact, with this identification, the narrow resonances we observe at 5.37 and 5.47 MeV (Fig. 1) explain the apparent change in slope of the fission probability observed in the previous (d, pf) study and the broad shoulder at 5.45 MeV observed in (t, pf).

Additional resonances at higher excitation energies become more pronounced in the linear plots shown in Fig. 2. In order to extract resonance parameters the "nonresonant" part of the cross section in the resonance region was subtracted from the data. To do this, the nonresonant cross section was computed from the equation

$$\sigma_{d,pf}(E_d, \theta, E^*) = \sum_{J\pi} \alpha(E_d, \theta, E^*, J^\pi) \times P_f(E^*, J^\pi), \qquad (1)$$

where α is the cross section for populating compound states in the first well in the (d, p) process and P_f is the average fission probability of compound states. In these calculations α was assumed to be independent of excitation energy and to be given by the statistical relation[6]

$$\alpha(E_d, \theta, J^\pi) = N_0 \frac{2J+1}{2} \exp\left(-\frac{(J+\frac{1}{2})^2}{2}\right) \times \sum_{j=|J-I_0|}^{J+I_0} \frac{\sigma_{\mathrm{DW}}{}^{j\pi}(E_d, \theta)}{(J+I_0) - |J-I_0| + 1}, \qquad (2)$$

where N_0 is a normalization constant, s is a spin cutoff factor, I_0 is the target spin, and $\sigma_{\mathrm{DW}}{}^{j\pi}$ was calculated using the distorted-wave Born-approximation (DWBA) code DWUCK and two sets of optical-model parameters.[7,8]

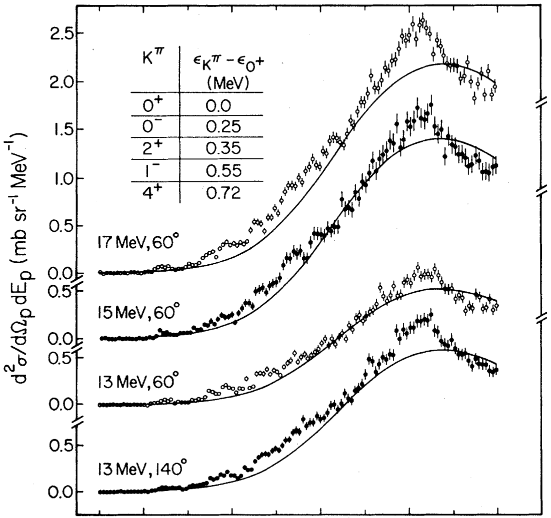

FIG. 2. Double-differential ^{235}U(d, pf) cross sections obtained at $E_d = 13$, 15, and 17 MeV. The solid lines represent fits to the smooth part of the yields calculated assuming complete damping as described in the text. The energies ϵ (relative to the $K^\pi = 0^+$ barrier) and quantum numbers of transition states used in the calculation appear in the inset.

The smooth fission probability was calculated using the result obtained by Lynn and Back[9] for complete damping of fission vibrational strength in both wells and total K mixing in the second well. The transition-state spectrum is assumed to consist of a series of rotational bands of different K^π with a rotational constant of 3.5 keV.[10] The transition-state energies have been taken from the relative positions of subbarrier resonances, with quantum numbers K^π following a reasonably expected sequence (see Fig. 2). Barrier parameters were varied to fit the nonresonant part of the 17-MeV, 60° data. Extracted barrier parameters were $E_A = 6.2$ MeV, $\hbar\omega_A = 1.2$ MeV, $E_B = 5.85$ MeV, $\hbar\omega_B = 0.9$ MeV. Fits to the data at other energies and angles were then obtained by using the corresponding stripping cross section $\sigma_{\mathrm{DW}}{}^{j\pi}$ as calculated with DWUCK. Both sets of optical-model parameters yield good fits to all 60° cross sections with no change of normalization. The calculated cross sections for 13 MeV, 140°, however, are too low by 30%. Therefore a different normalization was used to generate the nonresonant cross section in this case. The fits obtained with the parameters of Macefield and Middleton are indicated by the lines drawn through the data in Fig. 2.

When these smooth curves are subtracted from the fission cross sections, a set of resonances is clearly and consistently revealed (Fig. 3). The

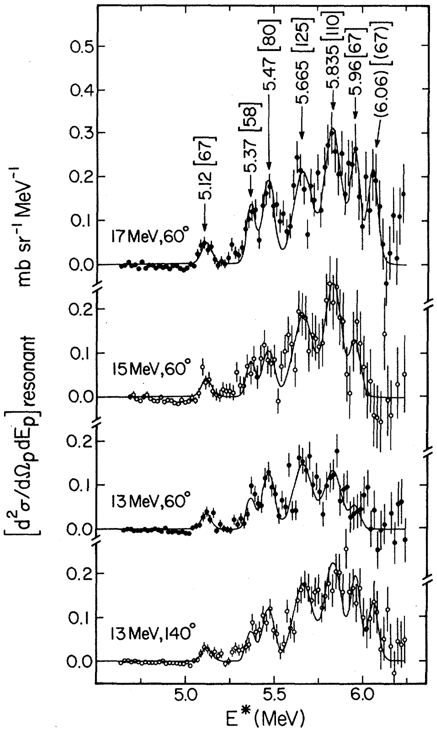

FIG. 3. Residual fission cross sections obtained after subtraction of the calculated smooth cross sections from the data. The solid lines result from a global fit with a series of Gaussians. Centroid energies (in MeV) and FWHM (in keV, in brackets) are given.

resonances have been fitted with a series of Gaussians yielding peak widths and positions indicated in Fig. 3.

Four noteworthy properties emerge: (1) The resonances do not appear to be appreciably damped even at 6 MeV, i.e., near the top of the barrier. (2) Their yields are comparable over a range in excitation energy for which the total fission yield rises by two orders of magnitude. (3) No resonances are observed at excitation energies lower than 5.1 MeV comparable in strength with the higher resonances. In none of our data is there any evidence for the weak resonance proposed in the reaction ^{234}U(t, pf) at 5.0 MeV. (4) The yields of the 5.84- and 5.96-MeV resonances vary substantially with bombarding energy while the rest have a weaker dependence.

Observations (1) through (3) strongly suggest that the observed resonances correspond to a weakly damped 5.12-MeV $K^\pi = 0^+$ fission vibration coupled to a series of low-lying excitations in other degrees of freedom (transition states).

Fission-barrier parameters extracted from analysis of fission cross sections depend critically on the choice of transition-state energies and quantum numbers. The many new resonances observed in this work make possible for the first time the accurate determination of the energies of a comprehensive set of transition states. While detailed measurements of the anisotropy of the fragment angular distribution relative to the recoil axis are needed for a positive identification of the resonance quantum numbers, the relative yields of the resonances and their dependence on bombarding energy and proton angle may be useful for this task, given knowledge of the changing spin and parity distribution $\alpha[E_a, \theta, J^\pi(E^*)]$ in the first well. Preliminary calculations with a more sophisticated model which includes resonances indicate that such an analysis requires a very detailed knowledge of the stripping cross sections. However, these calculations do indicate that none of the resonances we observe above 5.12 MeV can be due to the next $K^\pi = 0^+$ fission vibration; such a resonance would be much more strongly damped than the observed states.

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