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High resolution fission probabilities for ^{229,230,232}Th and ^{233,236}U in (d,pf) reactions

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HIGH RESOLUTION FISSION PROBABILITIES FOR ^{229,230,232}Th AND ^{233,236}U IN (d,pf) REACTIONS

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Abstract : Simultaneous measurements of the fission probabilities and the fission fragment angular distributions in (d,pf) reactions, performed with a resolution of about 7 keV, reveal the presence of different types of fine structure. The thorium results can be interpreted in terms of pure rotational bands in the third well of the fission barrier while, for the uranium isotopes, states in the second well come also into play.

As soon as the existence of resonant states in the third well of the ^{231}Th fission barrier had been established,[1] a systematic search for similar states in different nuclei was undertaken at Saclay. Since these experiments require a good energy resolution, neutron induced fission reactions, associated with time-of-flight techniques, were used first.[1] However, this experimental procedure makes it all but impossible to determine simultaneously the all important associated fission fragment angular distributions, indispensable in the ulterior interpretation of the expected structure. On the other hand, (d,pf) reactions, despite a worse energy resolution, open up some other attractive possibilities such as feeding higher spin states, easy access to the fission fragment angular distributions and extension of the energy range to well below the neutron threshold. This paper presents the experimental set-up for such (d,pf) experiments as performed at the Saclay tandem and also summarizes results obtained for ^{229,230,232}Th (d,pf) and ^{233,236}U(d,pf) reactions.

The basic experimental apparatus[2] for all targets is identical. Proton energies were measured at an angle of 130° on the focal surface of a Q3D spectrometer by a set of two position sensitive single-wire proportional counters. The overall energy resolution was $\Delta E \simeq 7$ keV, except for the ^{239}Th target where it amounts to $\simeq 12$ keV due to chemical impurities in the target. The fission fragment angular distributions were determined[2] by means of direction-sensitive parallel plate avalanche detectors, PPAD. A(d,pf) event was defined as a fast coincidence between a fragment, detected by a PPAD, and a proton detected by a plastic scintillator set behind the proportional counters. The coincidence window was subsequently reduced by correcting for the proton time-of-flight through an identification of the proton trajectory in the Q3D. Typical fission probabilities, defined as the ratio of the number of such coincidences (corrected for the PPAD solid angle) to the number of detected protons, are shown in figs. 1 to 4.

For thorium isotopes, rather isolated broad resonances are observed below the fission threshold (Fig. 1) and a closer examination indicates the presence of fine structure superimposed on these resonances. The ^{230}Th data confirm and extend the results previously obtained[1] in (n,f) reactions. As for the neutron data, the (d,pf) data were also analysed in terms of pair of rotational bands with opposite parities in the third minimum of the ^{231}Th fission barrier. The compound nucleus formation cross section was obtained through a DWBA calculation and the fission barrier parameters were taken from the result of the analysis[1] of the neutron data. At forward angles ($0° < \theta < 30°$), the calculated values agree perfectly[2] with the experimental data. In particular, the $9/2^+$, $11/2^-$ and $13/2^+$ members of the rotational bands, non observable in the (n,f) reaction, are clearly identifiable in the (d,pf) data at the energies predicted from the (n,f) results. At sideward angles ($60° < \theta < 90°$), the calculation underestimates slightly the fission probability at certain energies but the angular distributions remain quite good. The ^{232}Th picture is more complex and, as for the (n,f) reaction, the (d,pf) reaction does not provide a crucial proof for the existence of the third well although the data fit very well with this hypothesis. The ^{229}Th(d,pf) results, for which no comparable neutron data exist, are beset by poorer energy resolution and larger statistical uncertainties than those ascribed to the remaining (d,pf) data presented in this paper. However, the fine structure observed at 5.7 MeV (Fig. 2) suggests the presence of two rotational bands with $\hbar^2/2\mathfrak{J}=2$ keV. The peak positions and the angular distributions are consistent with a value of $K=0$ for both rotational bands. One does, however, not explain why the high spin states $J=6$ or 7 are as intensely fed as the lower $J=2$ or 3 states.

The uranium isotopes display drastically different cross sections. As Figure 3 shows, pronounced structure exists over the whole energy range in the ^{233}U fission probability. The broad resonances observed with a poorer energy resolution by Goldstone et al.[3] at 4.35, 5.12 and 5.4 MeV, can be recognized with a slight energy shift. It is clear that not all the numerous resonances shown in Fig. 3 can be attributed to rotational states in a supposedly existing third well of the even-even ^{234}U fission barrier. A search for rotational bands, based on resonance spacings only, indicates that the 4.9 resonance could be made of a $K^\pi = 0^+$ band whereas the 5.2 group could be attributed to $K^\pi = 0^+$ and $K^\pi = 0^-$ bands.

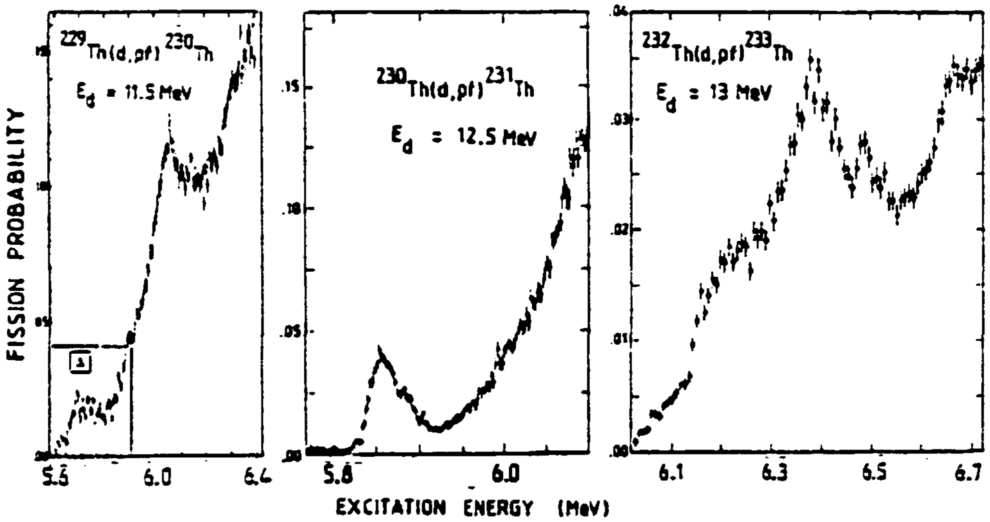

FIG. 1 Experimental fission probabilities for ^{229,230,232}Th (d,pf) reactions plotted against the excitation energy.

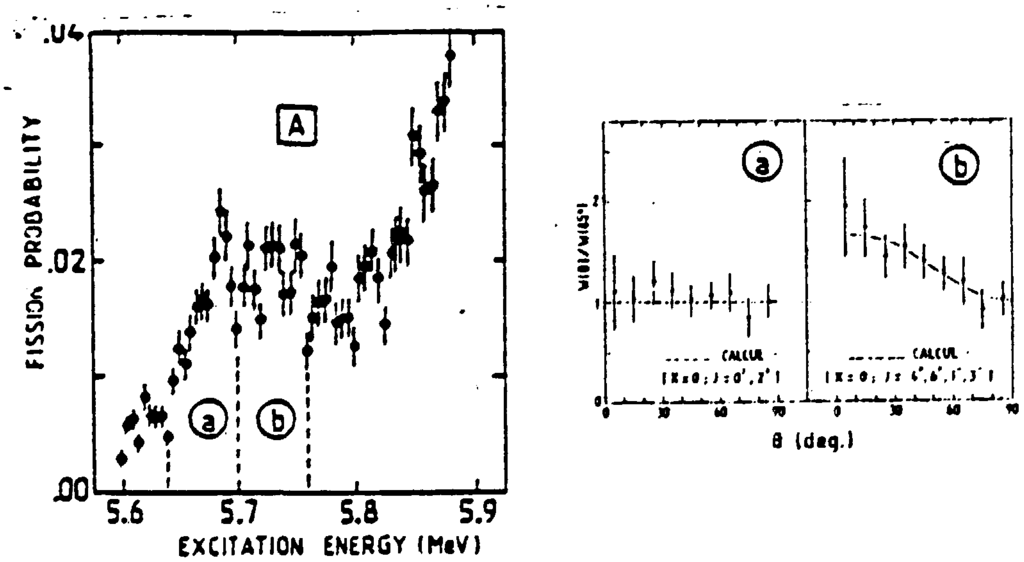

FIG. 2 Left : blow-up, [A], from Fig. 1 for ^{229}Th (d,pf). Right : fission fragment angular distributions in the regions (a) and (b) compared to the calculated curves.

There are, however, several arguments against this rotational band interpretation : the strength of the states to which J=6$^+$ or 7$^-$ were attributed turns out to be too great when compared to that of the J=2$^+$ or 3$^-$ states, and the fission fragment angular distributions taken in the individual resonances are practically identical (see Fig. 3) and independent of the attributed spins. An alternative explanation would be that one is observing class II compound states with an average spacing of 33 keV, a value in

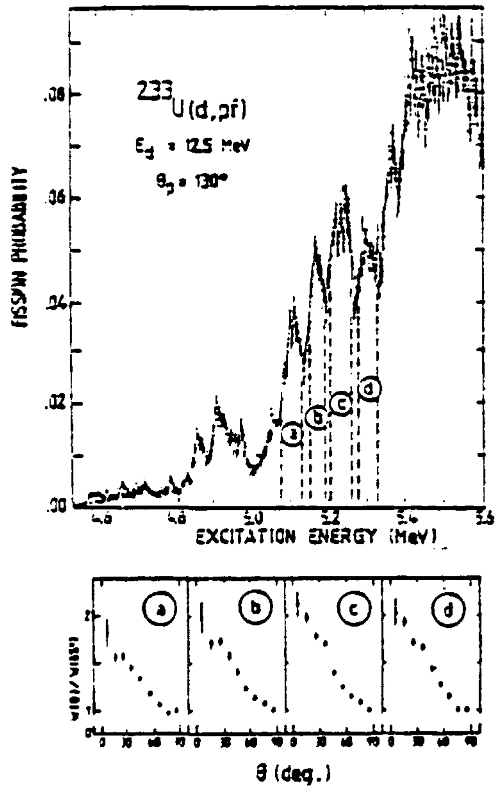

FIG. 3 Top : experimental fission probability for the ^{233}U (d,pf) reaction. Bottom : fission fragment angular distribution in regions (a,b,c,d).

agreement with the calculated depth[4] of the second well. In the ^{236}U fission probability, all structure is washed out except an accident at 6.1 MeV (Fig. 4). This lack of structure can be explained by a level density effect.

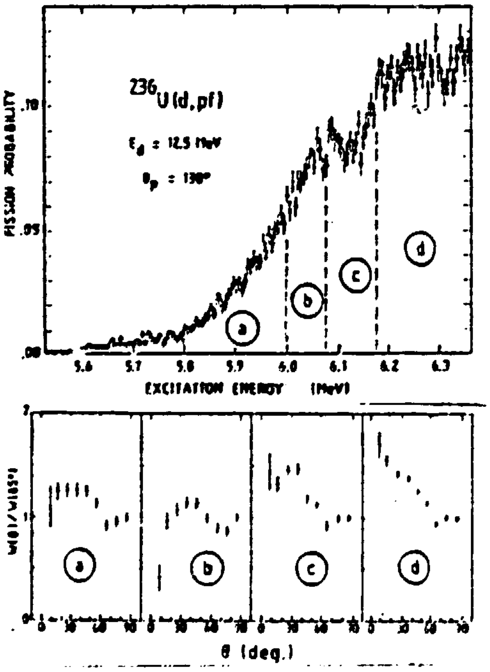

FIG. 4 Same as Figure 3 for the ^{236}U(d,pf) reaction.

Compared to the even-even ^{234}U, the even-odd ^{237}U has a bigger level density and its excitation energy above the bottom of the second well is higher. It is not surprising, then, that the class II levels can no longer be resolved and hence can no longer blur the observation of hypothetical class III states. This might be the explanation for the bump in the 6.1 MeV region where, as Fig. 4 shows, the angular distributions change rapidly with energy.

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