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EXPERIMENTAL STUDY OF THE FISSION DYNAMICS FOR THE ^{240}Pu NUCLEUS AT LOW EXCITATION ENERGY[1]

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The energy dependence of some characteristics of fission has been studied for the fissioning nucleus ^{240}Pu. The variations of kinetic energies and fragment masses from ^{239}Pu(d, pf) have been measured as a function of the excitation energy of ^{240}Pu. These results have been analysed together with those from studies of spontaneous fission and isomeric fission, as reported by other authors. The results tend to demonstrate the existence of two modes of fission, the first mode superfluid and the other viscous; these modes depend on the nature of the fissioning state.

A good knowledge of the fission would require a complete dynamical description [1]. All the approaches have shown that inertial and damping effects have still to be investigated. A direct method to get such information is the measurement of the fragment mass and the fragment kinetic energy at several excitation energies of the nucleus undergoing fission. Hence, we have studied, from the ^{239}Pu(d, pf) reaction, the variation in these parameters with energy in the range from 4.1 to 9.5 MeV. Furthermore, we have extended our analysis to the ^{240}Pu spontaneous and isomeric fission reported elsewhere [2, 3].

A complete description of the experimental procedure is given in another paper [4]. The Tandem Van de Graaff accelerator at the Centre d'Études de Bruyères-le-Châtel was used to provide a beam of 11.8 MeV deuterons. The protons emitted in the ^{239}Pu(d, pf) reaction were detected at an angle of 90° relative to the direction of the deuteron beam. The fission fragments were detected with two pairs of semi-conductor diodes at angles of 0° and 90° relative to the recoil axis of the fissioning nucleus. Coincidence events between fragment and proton pulses have been recorded. Each event, corresponding to a given pair of fragment detectors, was converted into the ^{240}Pu excitation energy E_{exc}, heavy fragment mass m_H^* and total kinetic energy E_K. These two last quantities have been deduced using a method similar to that of Schmitt [5] and corrected for prompt neutron emission.

Fragment angular anisotropy. The results related to the fragment anisotropy have been reported in a previous paper [6]. The dependence of the excitation energy on the anisotropy presents, at about 5 MeV, a broad structure already reported [7, 8]. In our data another structure appears also at a lower energy (E_{exc} = 4.65 MeV). This last one does not seem to have been reported yet. Such structures have been described as due to the vibrational states in the second well of the ^{240}Pu doublehumped fission barrier. Moreover they are assumed more or less as coupled to the compound II-class states [9]. As for the 5 MeV resonance [8], the high value of the observed anisotropy at $E_{exc} =$ = 4.65 MeV seems to imply the assigment of $K^\pi = 0^+$ for this resonance.

Total kinetic energy. The average of the overall total fragment kinetic energy distribution ($\overline{TKE}$) is plotted as a function of the ^{240}Pu excitation energy in Fig. 1. In the excitation energy range from 4.75 to 9.5 MeV and for fragments emitted at 0° and 90° to the recoil axis, these variations are well fitted by straight lines having negative slopes [$(\mathrm{d}\,\overline{TKE}/\mathrm{d}E_{exc})_{0°} = -0.42 \pm 0.03$ and $(\mathrm{d}\,\overline{TKE}/\mathrm{d}E_{exc})_{90°} = -0.45 \pm 0.03$]. These values are definitely smaller than the one reported by Milton et al. (-0.54 ± 0.04) [10] but higher than the value deduced from neutron induced fission experiments (0.35 ± 0.05) [11].

At about E_{exc} = 4.65 MeV, where a sharp resonance was found in the variation of the fragment anisotropy as a function of E_{exc}, a peak in TKE appears for the 0° fragments. These features are consistent with the hypothesis of prominent contribution at 0° for low K-component levels weakly coupled to the other degrees of freedom than fission.

Recent results related to the ^{240}Pu spontaneous and isomeric fission [2, 3] are also plotted in Fig. 1. The TKE values for these two states (at E_{exc} = 0 and 2.35 MeV) are, within experimental errors, aligned with the maximum value for the 0° fragments at E_{exc} = 4.65 MeV. The deduced value of the slope is 0.95 ± 0.09.

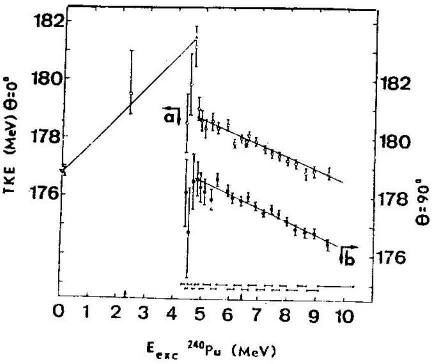

Fig. 1. Variation in the $\overline{TKE}$ as a function of the E_{exc} of ^{240}Pu. Curve a is related to fragments at 0° to the recoil axis, curve b to fragments emitted in the perpendicular direction. For the sake of clearness curve b has been shifted from curve a by 2 MeV. ▽ are Ref. [2], □ Ref. [3], × Ref. [13], ○ and ● refer to this work.

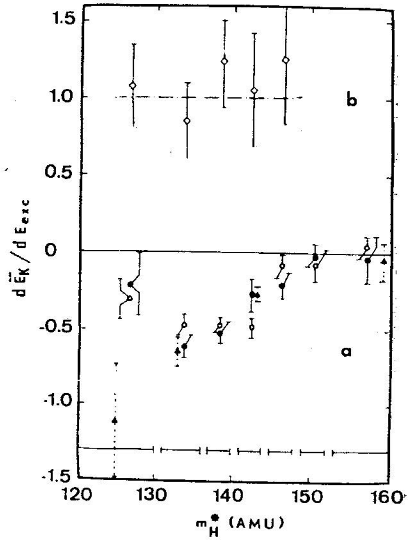

Fig. 2. Variations in $\mathrm{d}\bar{E}_K/\mathrm{d}E_{exc}$ as a function of m_H^*. Curve a is related to the data in the excitation energy range from 4.75 to 9.5 MeV. Black and white dots (●, ○) are our data at 90° and 0°, respectively. Black triangles (▲) are from Ref. [10]. Curve b (◇) is related to the ground and isomeric states and the 4.65 MeV states at 0°.

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Hence, the analysis of TKE versus E_{exc}, from 0 to 9.5 MeV excitation energy, shows clearly two contrasting behaviours.

Total kinetic energy versus fragment mass. In order to formulate the observed variations more precisely, we have investigated the linear dependence of the average total fragment kinetic energy $E_K(m_H^*)$ on the excitation energy. In Fig. 2, we present the variation of their slopes as a function of the heavy fragment mass. In the excitation energy range from 4.75 to 9.5 MeV, there appears, in curve 2a, a strong decrease in E_K with an increasing E_{exc} in the region of $m_H^* = 130-140$ AMU. This behaviour is in contrast to that at symmetry and in the wings of the mass distribution where only small changes occur. We plot, in curve 2b, the values deduced from the same procedure and related to the ground state, the isomeric state and the 4.65 MeV states. Although the statistics are poor we may conclude that the slope $(\mathrm{d}\bar{E}_K/\mathrm{d}E_{exc})$ remains constant for every mass.

Heavy fragment mass. For completeness, we present, in Fig. 3, the average value of the heavy fragment mass distribution $\langle m_H^* \rangle$ as a function of the compound nucleus excitation energy. The heavy fragment mass prior to the neutron emission is calculated assuming from 4.75 to 9.5 MeV the same relative average number of neutrons versus the fragment mass $\bar{\nu}_P(m^*)$ as in the thermal neutron induced fission of ^{239}Pu [3]. Moreover we assume a linear dependence of the average value of the total number of neutrons $\bar{\nu}_P$ with a slope $\mathrm{d}\bar{\nu}_P/\mathrm{d}E_{exc} = 0.13\ n/\mathrm{MeV}$ [12]. In these hypotheses, $\langle m_H^* \rangle$ remains constant and equal to the corresponding value of the thermal neutron induced fission of ^{239}Pu [13]. Assuming for the 4.65 MeV states the value of $\bar{\nu}_P$ related to the spontaneous fission [12] or the value of $\bar{\nu}_P$ obtained from the same hypothesis as for $E_P \geqslant 4.75$ MeV, we find two adjacent values and equal to the corresponding values at 0 and 2.35 MeV. They are approximately lower by 1 AMU than those above 4.75 MeV.

All the experimental results tend to demonstrate the existence of two modes of fission characterized by different damping effects. These effects reveal the dissipation of pre-scission kinetic energy into the other degrees of freedom than fission.

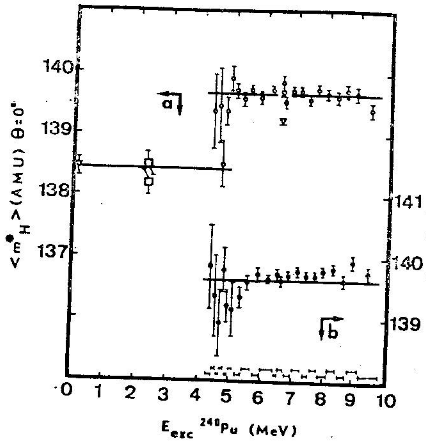

Fig. 3. Variations of $\langle m_H^* \rangle$ as a function of the ^{240}Pu excitation energy. Same conventions as in Fig. 1 are used.

First, for isomeric and the 4.65 states, corresponding to weakly coupled states, the major part of the ^{240}Pu excitation energy is transferred into the fragment kinetic energy; just a small part of the ^{240}Pu excitation energy is thus dissipated into the fragment excitation energy. Considering that the mass distribution remains identical for these states and for the ground state, then the Coulomb repulsion energy in the vicinity of the scission point does not change. We may conclude the same variation in the pre-scission kinetic energy as in the compound nucleus excitation energy. This supports strongly the hypothesis of weak damping between the saddle and the scission points as already suggested by Swiatecki and Bjørnholm [14]. The isomeric and the 4.65 MeV states seem to follow superfluid paths very close to those of the ground state during the fission process.

Secondly, the states of excitation energy higher than 4.75 MeV corresponding to strongly coupled states are fissioning with the fragment kinetic energy decreasing when the ^{240}Pu excitation energy increases. Then they appear to follow viscous paths. The attendant increase in the excitation energy with the ^{240}Pu excitation energy tends to deform them. Moreover, since the deformability of a nucleus depends on its mass, we must find a variation in $\bar{E}_K$ with m_H^*. This feature clearly appears in Fig. 2a. On the other hand, these states have adjacent paths since the fragment mass division are in average identical. Finally these paths are, near the scission point, definitely different from the superfluid ones.

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