Nuclear split in fission

K. Hirose[1)], K. Nishio[1)], S. Tanaka[2)], R. Lèguillon[1)], H. Makii[1)], I. Nishinaka[3)], R. Orlandi[1)], K. Tsukada[1)], J. Smallcombe[4)], M. J. Vermeulen[1)], S. Chiba[5)], Y. Aritomo[2)], T. Ohtsuki[6)], K. Nakano[7)] S. Araki[7)], Y. Watanabe[7)], R. Tatsuzawa[8)], N. Takaki[8)], N. Tamura[9)], S. Goto[9)], I. Tsekhanovich[10)], and A. N. Andreyev[11,1)]

1) : ASRC, JAEA 2): Kindai Univ. 3): QST 4): TRIUMF 5): Tokyo Tech. 6): Kyoto Univ. 7): Kyushu Univ. 8): Tokyo City Univ. 9): Niigata Univ. 10): Univ. of Bordeaux 11): Univ. of York

Treatment of radioactive wastes of long-lived minor actinides, produced in a light-water reactor, is one of urgent issues to be solved in the usage of nuclear power. One of the options is to transmute these nuclides into shorter-lived fission products by irradiating them with higher-energy neutrons in a so-called accelerator-driven system (ADS). Thus, in such case, fissioning nuclei have higher excitation energies. Design of the ADS requires high-energy neutron-induced fission data.

Nuclear fission is a phenomenon where a nucleus deforms and finally splits into two lighter nuclei. Since a probability distribution of masses of both fission fragments, *i.e.*, fission fragment mass distribution (FFMD), sensitively reflects the deformation path, it is of essential importance to observe the fragment masses for the elucidation of fission mechanism. However, the available FFMDs in terms of nuclides and excitation-energy range are quite limited.

A highly excited nucleus decays either via fission or via neutron emission which leads to a different nucleus with a lighter mass and lower excitation energy. The latter then decays again either via fission or via neutron emission. This competition between fission and neutron emission continues until the excitation energy of the descendant nucleus drops below its fission barrier. As shown in Fig. 1, a ^{240}U nucleus with a high excitation energy, for example, can evaporate several neutrons. Therefore, in a fission measurement of the initially highly excited state, several lighter isotopes with different excited states are included. The so-called *multi-chance fission* concept is well known to explain the structure of fission cross sections, but its impact on the FFMD have not been studied in detail.

In this work, we investigated the effects of multi-chance fission on the FFMDs [1]. For this purpose, we have measured a large set of FFMD ($^{237\text{-}240}$U, $^{239\text{-}242}$Np and $^{241\text{-}244}$Pu) with a wide coverage in the excitation energy (10–60 MeV) using multi-nucleon transfer channels in the ^{18}O+^{238}U reaction (see also [2]). The experimental data were interpreted by combining a dynamical fission model based on the fluctuation-dissipation theorem and a concept of the multi-chance fission. From the present analysis, it is clarified that the experimental FFMD consists of fission of six nuclides as shown by the dashed lines in Fig. 2, and it is evident that the observed mass-asymmetric distribution, *i.e.* a double-humped shape, remaining at such a high-excitation energy is caused by fission of the lower-excited lighter isotopes. Furthermore, the FFMDs for fission of highly excited nucleus were obtained like the black dashed line shown in Fig. 2, which is an important observable to understand the fission mechanism. The result of this work opens the high-energy fission research.

This work is supported by "Comprehensive study of delayed-neutron yields for accurate evaluation of kinetics of high burn-up reactors" and "Development of prompt-neutron measurement in fission by surrogate reaction method and evaluation of neutron-energy spectra" by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT). This work was partly done with in an IAEA CRP on beta-delayed neutrons (F41030). The Langevin calculations have been done using the cluster computer system (Kindai-VOSTOK) which is supported by "Research funds for External Fund Introduction" by Kindai University. This work was also supported partly by STFC of the United Kingdom.

References

[1] K. Hirose *et al*., Phys. Rev. Lett **119**, 222501 (2017).
[2] R. Lèguillon *et al*., Phys. Lett. B **761**, 125 (2016).

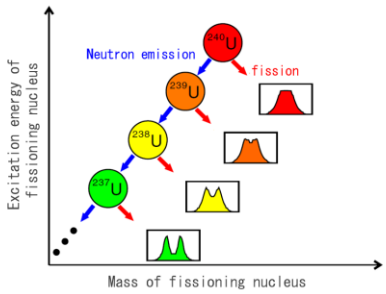

Fig. 1 An example illustrating the process for fission and neutron evaporation from an initially excited nucleus, ^{240}U.

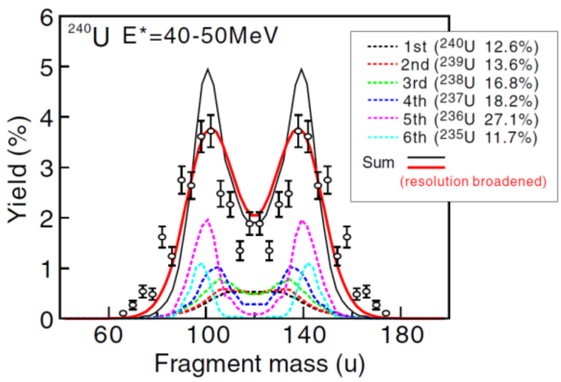

Fig. 2 Open circles are the observed FFMD for the initial ^{240}U nucleus populated at 45 MeV. This FFMD is a mixture of contributions from $^{235\text{-}240}$U as shown by dashed curves, populated by multiple neutron emission. Each curve is calculated by a Lagevin equations with a fraction determined by statistical model. The obtained theoretical curve is broadened with the experimental resolution to make a direct comparison with the measured data.