Determination of fission barrier height using the multinucleon transfer reactions

K.R. Kean[1,2], K. Nishio[2], K. Hirose[2], M.J. Vermeulen[2],
H. Makii[2], R. Orlandi[2], K. Tsukada[2], A.N. Andreyev[2,3],
I. Tsekhanovich[4], and S. Chiba[1]
1): Tokyo Tech, 2): Heavy Element Nuclear Science Gr,
3): Univ. York. 4): Univ. Bordeaux

The fission barrier height, introduced by Bohr and Wheeler, is one of the most fundamental quantities to describe fission. In the classical liquid-drop picture, the fission barrier is created by a balance between the attractive surface tension and the repulsive Coulomb force of the nascent fission fragments, which evolves as a function of deformation in a rather simple (parabolic) way. The fission barrier of the macroscopic liquid-drop approach is dramatically modified by introducing shell correction energy, which results in a double-humped shape, as well known for typical actinide nuclei. Experimental data of the fission barrier height can be a benchmark for fission theory, thus the data are essential to develop a fission model with a high predictive power.

Up to now, fission barrier profile in actinide nuclei has been derived using neutron-induced fission and nucleon-transfer reactions with light projectiles, such as (d,p), (t,p), and $(^{3}\mathrm{He},d)$ reactions [1]. In these methods, the fission probability is usually measured as a function of excitation energy E^* of the compound nucleus that can fission. The height of the fission barrier is nearly equal to E^* of the nucleus at which the fission probability $P_\mathrm{f}(E^*)$ increases rapidly. However, such methods require the use of stable or long-lived target nuclei, which limits the range of accessible nuclei to be studied. This is why there exist only 33 nuclei in the best-suited actinide region, of which the fission barrier data are available.

Recently, we have demonstrated that reliable fission data, e.g., fission fragment mass distribution (FFMD), can be obtained via multinucleon transfer (MNT) reactions of an ^{18}O beam on actinide targets, such as ^{232}Th, ^{238}U, etc. [2,3]. Due to a large number of MNT channels accessible in reactions with an ^{18}O induced reactions, low-energy fission data of about 12 nuclides can be simultaneously taken in a single experiment. In the study of the $^{18}\mathrm{O} + {}^{238}\mathrm{U}$ reaction, for instance, the FFMDs for 12 isotopes of uranium, neptunium, and plutonium are reported. The results indicate the potential use of the MNT approach to expand the fission barrier data. Here, we report the results of the MNT reaction of $^{18}\mathrm{O} + {}^{237}\mathrm{Np}$ to derive fission barrier data [4].

The MNT reaction of $^{18}\mathrm{O} + {}^{237}\mathrm{Np}$ was studied to obtain fission barrier data, using the 162 MeV $^{18}\mathrm{O}$-beam supplied from the JAEA tandem accelerator facility in Tokai. A segmented silicon ΔE-E telescope was mounted at the forward angle to detect the ejectile nucleus generated in the MNT reaction. Taking advantage of the high resolving power to identify produced isotopes, we could unambiguously identify the ejectile nucleus, and thus the corresponding compound nucleus as well as the total excitation energy of the system E^* after the reaction. Here, we assume that all the excitation energy is stored in the compound nucleus, i.e. nucleus whose fission barrier height is to be derived. The kinetic-energy spectrum of the ejectile nucleus can be directly transformed to the excitation-energy E^* distribution of the compound nucleus $P_\mathrm{ex}(E^*)$. Fission of the compound nucleus is identified using multiwire proportional counters. The coincidence spectrum between ejectile nucleus and fission fragments is divided by $P_\mathrm{ex}(E^*)$ to obtain the excitation function of fission probability $P_\mathrm{f}(E^*)$, corrected by the detection efficiency of fission fragments.

Fig.1 shows the fission probability of ^{240}Pu obtained in the $^{237}\mathrm{Np}(^{18}\mathrm{O}, {}^{15}\mathrm{N})^{240}\mathrm{Pu}$ reaction. At the excitation energy E^* of around 6 MeV, the fission probability sharply rises, indicating the location of the fission barrier. Fission barrier is derived by fitting the data points with the Hill-Wheeler's expression for barrier penetration which includes the barrier height B_f, see the solid curve in Fig.1. In this method, we obtained $B_\mathrm{f} = 6.25(32)$ MeV for $^{240}\mathrm{Pu}$. As our measurement is sensitive to the fission threshold, which corresponds to the higher fission-barrier value of the double-humped barrier shape, we compared our value to the higher one, inner barrier for the case of ^{240}Pu. The data agree well with 5.80(20) MeV from the $^{238}\mathrm{Pu}(t,p)^{240}\mathrm{Pu}$ reaction [5]

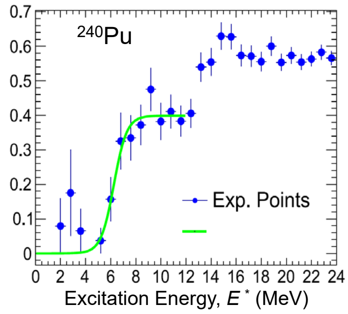

Fig.1 Fission probability of ^{240}Pu with excitation energy E^*. Blue points indicate experimental data, while the green curve is a theoretical fit. The excitation energy where the fission probability increases (around 6 MeV) corresponds to the fission barrier height.

and 6.05 MeV from RIPL3 data [6].We also determined the fission barriers of $^{239}\mathrm{Pu}$ and $^{239}\mathrm{Np}$, populated in the $^{237}\mathrm{Np}(^{18}\mathrm{O}, {}^{16}\mathrm{N})^{239}\mathrm{Pu}$ and $^{237}\mathrm{Np}(^{18}\mathrm{O}, {}^{16}\mathrm{O})^{239}\mathrm{Np}$ reactions, respectively. The value $B_\mathrm{f}(^{239}\mathrm{Pu}) = 6.14(12)$ MeV and $B_\mathrm{f}(^{239}\mathrm{Np}) = 5.86(09)$ MeV also agree with literature data within error. Our results showed the validity of deriving the fission barrier height in the MNT reactions using $^{18}\mathrm{O}$ beam. Other transfer channels can be also applicable to obtain the fission barrier data. Use of more exotic target materials such as ^{244}Pu, $^{243}\mathrm{Am}$, $^{248}\mathrm{Cm}$, $^{249}\mathrm{Bk}$, $^{249}\mathrm{Cf}$, and $^{254}\mathrm{Es}$ would further expand the information on the fission barriers of heavier and neutron-rich isotopes.

References

[1] In the following, the expression "$X\,(a\,,\,b)Y$" represents a nuclear reaction (nucleon transfer or nucleon exchange) "a (projectile) + X (target) → b (ejectile) + Y (compound nucleus) ", meanwhile "$(a\,,\,b)$" indicates the same with anonymous X and Y.
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