Radiochemical studies on fission dynamics and nuclear decay data

R. Tripathi*, S. Sodaye, K. Sudarshan
Radiochemistry Division, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA
** email: rahult@barc.gov.in*

Due to its importance in the synthesis of trans- and heavy actinides through heavy ion reactions, fission continues to remain one of the important subjects. Correlation of fission survival probability with observables of fission such as mass and angular distribution is an important aspect of these studies. The anomaly in the angular distribution of fission fragments / products due to incomplete equilibration in *K*-degree of freedom, may not be necessarily accompanied with the suppression in the evaporation residue cross section. Thus, it is difficult to infer the information about the fusion suppression based on the anomaly in the gross fission fragment angular distribution as fusion suppression may depend on the fact that whether the fissioning system is reaching inside the saddle point or not which essentially decides whether the non-compound nucleus (NCN) fission mechanism is pre-equilibrium fission [1] or quasi-fission [2]. Our earlier studies on the mass resolved angular distributions at above barrier energies in ^{20}Ne,^{28}Si+^{232}Th reactions [3,4] showed that the correlation of angular distribution with the fission products mass can give information on this aspect. Recently, measurement of mass resolved angular distribution was carried out in ^{16}O+^{238}U reaction to investigate the dominant non-compound nucleus fission process as sub-barrier energy [5].

The overwhelming contribution from nuclear fission at the upper end of the periodic table makes it difficult to study the nuclear decay properties of nuclei in this mass region. Radiochemical separations can help in reducing the undesired background in the γ-ray spectrum due to the fission products. Apart from the fission products, radiochemical separations can also help in removing the background due to the radioactive decay products of the target nuclei. Decay studies have been carried out for ^{244}Bk [6] and ^{244}Am^{m,g} after radiochemical separations. These studies are briefly discussed in the following.

Mass resolved angular distribution to study fission dynamics

Mass resolved angular distribution of fission products using radiochemical method involves irradiation of the target along with the catcher foils covering suitable angular region. The catcher foils are subsequently assayed using gamma-ray spectrometry. In earlier studies on mass resolved angular distributions at above barrier energies in ^{20}Ne,^{28}Si+^{232}Th reactions [3,4], it was observed that the angular anisotropy for symmetric fission products was higher, indicating that the fissioning system is reaching inside the saddle point before fission which is the case of pre-equilibrium fission as was proposed earlier by Vorkapic and Ivanisevic [7] for ^{16}O+^{232}Th reaction [8]. Recently, mass resolved angular distribution was measured in ^{16}O+^{238}U reactions at sub-barrier energy at BARC-TIFR Pelletron-LINAC facility, Mumbai. A plot of angular anisotropy for as a function of fission product mass is shown in Fig. 1. It can be seen from the figure that the angular anisotropy

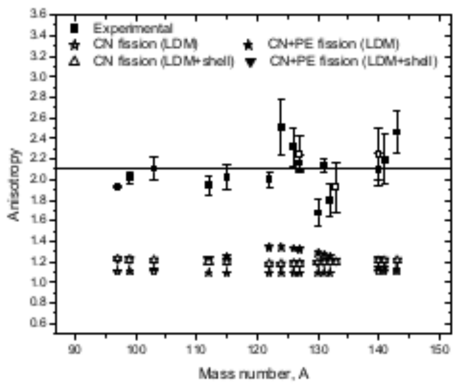

Fig. 1. Plot of angular anisotropy as a function of fission product mass [Phys. Rev. C **96**, 044608 (2017)]

is independent of mass asymmetry indicating quasi-fission to be the dominant mechanism at sub-barrier energy [5]. Angular anisotropies were calculated using statistical saddle point model (SSPM) [9] with the liquid drop model potential energy with and without shell corrections. Anisotropies calculated using SSPM were much lower compared to the experimental values indicting the contribution from NCN fission. Anisotropies were also calculated after including the contribution from NCN fission assuming it to be pre-equilibrium fission using a procedure similar to that given in ref [10], though, without scaling down the fission barrier. However, it can be seen from the figure that the angular anisotropies calculated even after including the contribution from pre-equilibrium are much lower compared to the corresponding experimental values. This observation also suggests quasi-fission to be the dominant mechanism at sub-barrier energy.

It is required to carry out more studies particularly those involving heavy projectiles to investigate whether there is a change in the mass dependence of angular anisotropy at above and sub-barrier energy.

Radiochemical studies on nuclear decay data

The decay data of heavy actinides is important for their radiometric assay as well as management of long-lived actinides which would produce various actinide isotopes when exposed to neutrons during the burning process. However, decay data of heavy actinides is scarce. Decay studies have been carried out on ^{244}Bk and ^{244}Am^{m,g} both decaying to ^{244}Cm. ^{244}Bk was produced in ^{238}U(^{11}B,5n) reaction at BARC-TIFR Pelletron-LINAC facility, TIFR, Mumbai and ^{244}Am^{m,g} were produced by neutron irradiation of ^{243}Am(n,γ) reaction in Dhruva reactor at Bhabha Atomic Research Centre. Both singles and coincidence γ-ray spectrometric measurements were carried out after radiochemical separation of isotopes of interest. In these studies, the half-life and ground state spin of ^{244}Bk have been revised. Based on these studies a partial decay scheme for ^{244}Bk was proposed which is shown in Fig 2 [6]. This decay scheme has been adopted in ref [11] and has been further evolved to a more comprehensive decay scheme in ref [12]. In the decay of ^{244}Am^{m}, level has been proposed in ^{244}Cm based on the observation of a new gamma-line in the

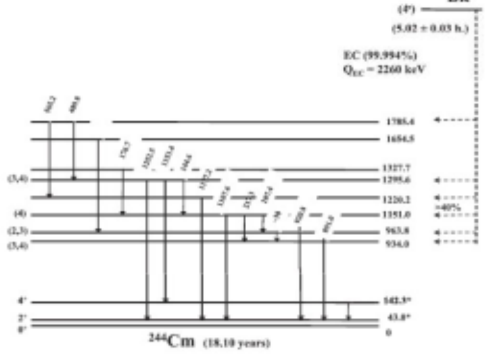

Fig. 2. Electron capture decay scheme of ^{244}Bk [J. Phys. G **41**, 125103 (2014)]

decay. In addition, the uncertainties on the intensities of the γ-rays of ^{244}Am^{m-g} have been reduced by nearly an order of magnitude.

It is required to develop fast radiochemical separation methods for heavier actinides which would provide the opportunity to carry out detailed decay studies on several heavy actinides.

Acknowledgements: I thankfully acknowledge all the co-workers and authors whose work has been discussed here.

References

[1] V. S. Ramamurthy and S. S. Kapoor, Phys. Rev. Lett. **54**, 178 (1985).

[2] W. J. Swiatecki, Phys. Scr. **24**, 113 (1981).

[3] R. Tripathi et al., Phys. Rev. C **88**, 024603 (2013).

[4] S. Sodaye et al., Phys. Rev. C **95**, 014612 (2017).

[5] T. N. Nag et al., Phys. Rev. C **96**, 044608 (2017).

[6] S. Sodaye et al., J. Phys. G **41**, 125103 (2014).

[7] D. Vorkapic and B. Ivanisevic, Phys. Rev. C **55**, 2711 (1997).

[8] B. John et al., Phys. Rev. C **51**, 165 (1995)

[9] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic Press, 1973) London.; I. Halpern and V. M. Strutinsky, in *Proceedings of the Second United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958*, edited by J. H. Martens *et al.* (United Nations, Switzerland, 1958), Vol. 15, p. 408.

[10] R. G. Thomas et al., Phys. Rev. C **67**, 041601 (R) (2003)

[11] C. D. Nesaraja, Nuclear data sheets for A=244, Nucl. Data Sheets **146**, 387 (2017).

[12] I. Ahmad et al., Phys. Rev. C **97**, 014324 (2018).