STUDY THE FISSION DYNAMICS OF ^{225}Pa NUCLEI AROUND THE SUB-BARRIER ENERGY*

R. Dubey, P. Sugathan, A. Jhingan, T. Banerjee, N. Saneesh

Inter University Accelerator Centre, Aruna Asaf Ali Marg
New Delhi — 110067, India

G. Kaur, M. Thakur, R. Mahajan

Department of Physics, Panjab University, Chandigarh — 160014, India

I. Mukul

Department of Particle Physics and Astrophysics, Weizmann Institute of Science
Rehovot 76100, Israel

D. Siwal

Department of Chemistry
2401 Milo B. Sampson Ln., Bloomington, Indiana 47405, USA

(Received January 18, 2016)

^{225}Pa nuclei exhibit a fusion-fission mechanism below the fusion barrier energy. Mass angle distribution measurements indicate absence of non-compound events at this bombarding energy. The effect of asymmetric fission mode on mass distribution of fission fragments is visible at low excitation energy (31.8 MeV).

DOI:10.5506/APhysPolB.47.953

1. Introduction

Mass division of actinide nuclei has still remained an unresolved problem since the discovery of nuclear fission [1]. In recent studies, there has been some insight provided in this mass region through the measurements of mass and energy distribution of fission fragments (FF) [2]. This study is important not only for the theoretical understanding of the fission process, but also for application in the formation of super heavy elements [3]. Hence, there has

* Presented at the XXXIV Mazurian Lakes Conference on Physics, Piaski, Poland, September 6–13, 2015.

been a renewed interest in the study of the dynamical process in nuclear fission induced by heavy-ion reaction. Among the various fission processes, fissioning of light actinide nuclei produced through heavy-ion reactions has gained significant interest. Two modes of fission paths have been suggested at low excitation energies [4]. One of the fission modes leads to symmetric mass division with a slightly elongated scission configuration and other leads to asymmetric mass division with a more compact scission configuration [5].

Apart from fusion-fission, the existence of non-compound events (NCN) adds further complexity to the reaction dynamics. NCN is found to be a competing reaction channel for heavy-ion induced reaction. The contribution of NCN events can lead to enhancement of mass distribution below the barrier [6]. However, considering the mass distributions of FF for ^{19}F + ^{209}Bi and ^{16}O + ^{209}Bi, it has been suggested that the mass width for ^{19}F + ^{209}Bi is higher compared to ^{16}O + ^{209}Bi at below the barrier energies [7]. The reason for stronger enhancement of mass width is due to the presence of asymmetric components. In the case of ^{225}Pa (^{16}O + ^{209}Bi), no significantly broader mass distribution has been suggested. Since both reactions have low $Z_{\mathrm{P}}Z_{\mathrm{T}}$ (< 800) and zero target static deformation, there is a better chance to form a complete compound nucleus.

To understand this problem, we measured mass and mass angle distribution of the same compound nucleus ^{225}Pa populated through the different reaction ^{19}F + ^{206}Pb around the fusion barrier. The reaction under study has $Z_{\mathrm{P}}Z_{\mathrm{T}} = 736$ (< 800) and the target nucleus is spherical. Hence, one can expect that this reaction will form a fully equilibrated system and fission will follow after the fusion-fission path.

2. Experiment details and data analysis

Measurements of fission fragments from reaction ^{19}F + ^{206}Pb were carried out at the 15 UD Pelletron accelerator facility of Inter University Accelerator center (IUAC), New Delhi. Pulsed beams of ^{19}F with 89 MeV and 112 energies were used to bombard on the ^{206}Pb target. Time width of the ^{19}F pulsed beam was 1 ns and its repetition rate was 250 ns. Typical beam intensity was 1–2 pnA. The thickness of the ^{206}Pb enriched target was $\sim 110\ \mu\mathrm{g/cm}^2$ on a carbon backing of $\sim 20\ \mu\mathrm{g/cm}^2$. The backing faced the beam to avoid the energy loss of heavy fragments in the backing. The fission fragments were detected in large area multi-wire proportional counters (MWPC) [8]. At 89 MeV beam energy, the folding angle was 162° and it was equal to 159° at highest beam energy 112 MeV. Each MWPC has an active width of 20 cm and height of 10 cm. Separation between position sensitive wires is 1.27 mm and an end-to-end delay is equal to 160 ns in X frame and 80 ns in Y frame. Front detector placed at 35 cm from target covers the scattering angles between 25° and 60°, and the back detector covers the scattering angles between 110° and 140° at a distance of 27 cm away from the target. Two silicon detectors were placed at ±10° with respect to the beam axis to monitor the beam position on the target during the experiment.

The fission fragments were separated from the elastic and quasi-elastic particles by time of flight and energy loss signal in the MWPC. From the calibrated X and Y position signals, the polar angles (θ, ϕ) are extracted. Velocities of fission fragments in laboratory frame are calculated by using polar angles and Viola systematics. $V_{\|}$ was deduced from the velocities of two fragments in the direction of folding angle. $V_{\perp}$ was determined from the projection of the fragment velocities onto the azimuthal plane. $V_{\|}$ is adjusted such that it became equal to velocity of compound nucleus in the center-of-mass frame $((V_{\|} - V_{\rm cm}, V_{\perp}) = (0,0))$. It is a pre-condition for the selection of events with full momentum transfer in fission process and it has been shown inside the white rectangular gate of Fig. 1. Only the events within the rectangle marked as FF were used to gate the mass spectrum.

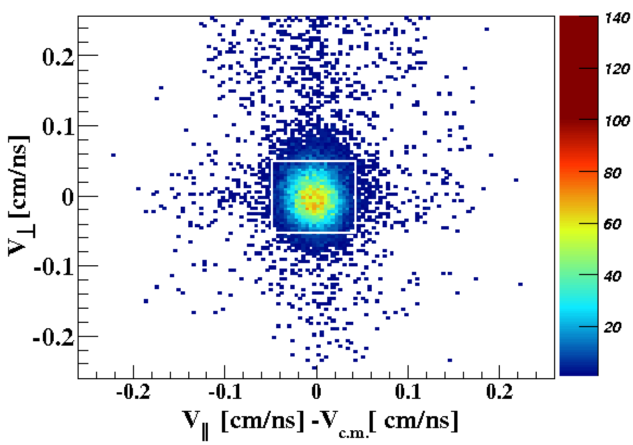

Fig. 1. Measured distribution of velocity components of FF at beam energy of 89 MeV for the reaction ^{19}F + ^{206}Pb $\longrightarrow$ ^{225}Pa*. Full momentum transfer fission events are shown inside white rectangular box and transfer fission events are lying around this rectangular box.

3. Results and conclusion

Dependence of mass ratio on emission angle in centre-of-mass frame ($\theta_{\rm cm}$) for fission fragments (mass–angle correlation) of reactions ^{19}F + ^{206}Pb around capture barrier energies has been shown in Fig. 2 (a), (b). $\theta_{\rm cm}$ of fission fragments is lying between 110°–160° at 5% below and 20% above the fusion barrier. There has been no mass–angle correlation observed around sub-barrier energies. In the same mass region, for ^{19}F, ^{16}O + ^{208}Pb and ^{16}O + ^{197}Au reactions, no mass–angle correlation has been suggested [9–11] and $\theta_{\rm cm}$ for fission fragments were found in the approximately same range [10, 11]. This infer that the fission of these nuclei follows after the complete compound nucleus formation around sub-barrier energies. The mass ratio distribution of FF from compound nucleus has been plotted by projecting X axis of mass–angle correlation plot.

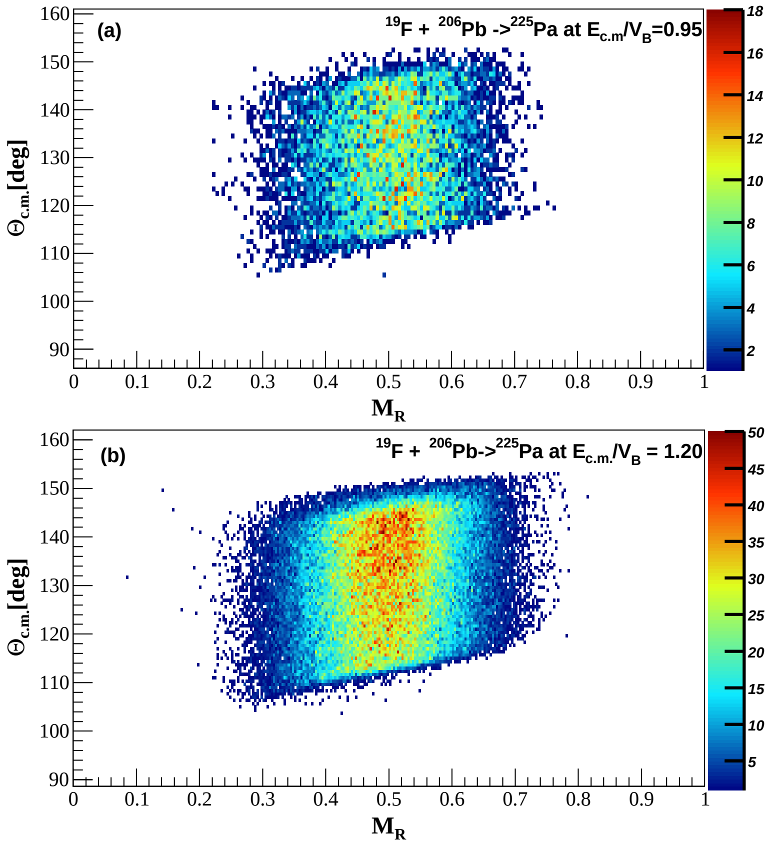

Fig. 2. FF mass–angle correlations for reactions ^{19}F + ^{206}Pb $\longrightarrow$ ^{225}Pa* at (a) 5% below the fusion barrier and (b) 20% above the fusion barrier. No mass–angle correlation for ^{225}Pa nuclei are observed around barrier energies.

It has been observed that the mass ratio distribution of FF from compound nucleus, with fully equilibrated mass degree of freedom, is Gaussian in shape with peak position at $A_{\rm CN}/2$ ($A_{\rm CN}$ is the mass of the compound nucleus). Fission properties of this kind of nuclei are found to be similar to the liquid drop kind of fission. The fission fragments mass ratio distribution of ^{225}Pa formed via ^{19}F + ^{206}Pb fusion at 31.8 MeV excitation energy was obtained in the present work. From Fig. 3, it seems that there is a better chance for fission of ^{225}Pa nuclei around the mass asymmetry $(\eta) = 0.17$ (corresponding to mass division 132/93). The mass division of ^{225}Pa nuclei can be influenced by the shell closure in the heavy fragments due to its proximity to doubly magic ^{132}Sn ($Z = 50$, $N = 82$) [11]. In other words, at this excitation energy, asymmetric components of FF are competing with a pure symmetric division of ^{225}Pa nucleus. The fusion barrier energy for the present reaction corresponds to 35 MeV excitation energy. The observed broad mass widths below barrier energies suggest that the shell effects persistent at low excitation energy (< 35 MeV) could influence the fission mode leading to increased contribution of asymmetric fission events [11].

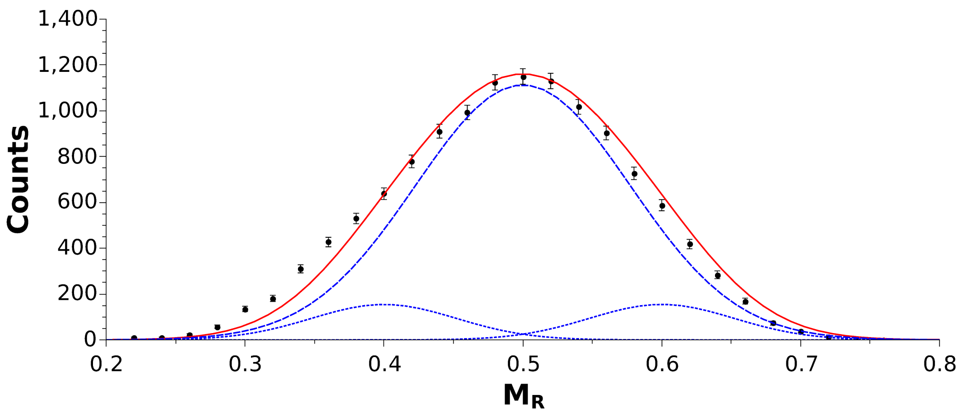

Fig. 3. Measured mass ratio ($M_{\rm R}$) distribution of fission fragments for the reaction ^{19}F + ^{206}Pb $\longrightarrow$ ^{225}Pa* at $E_X = 31.8$ MeV energy. Gaussian fitted with solid (red) line is the sum of all three dotted (blue) Gaussians. Their $M_{\rm R}$ peak positions are lying around 0.5 (larger Gaussian), 0.41 (left Gaussian — centroid of light fragment mass around 93), 0.59 (right Gaussian — centroid of the heavy fragment mass around 132), respectively.

The present work reports on nuclear fission in the light actinide ^{225}Pa nuclei. Mass distribution measurements of ^{225}Pa nuclei are carried out to understand the fission properties. At lower excitation energies, it has been observed that the shape of mass distribution exhibits a slight deviation from the Gaussian and reveals a slight departure from symmetric mass division of the FF as well. Here, the deviation of mass distribution from the Gaussian for ^{225}Pa nuclei suggests the contributions coming from asymmetric components during fission process. The presence of NCN events in present mass–angle correlation measurements for ^{225}Pa nuclei is almost negligible. However, only a limited number of experimental studies have been reported on the two different fission modes through mass distribution measurements using heavy-ion induced reactions. Hence, it will be interesting to extend the study of statistical and dynamical effects on the fission modes of nuclei produced through collisions of two heavy nuclei.

One of the authors (R.D.) acknowledges the financial support from the Council of Scientific Industrial Research, Government of India.

REFERENCES

[1] L. Meitner, O.R. Frisch, *Nature* **143**, 239 (1939).

[2] A. Rusanov *et al.*, *Phys. At. Nucl.* **70**, 1679 (2007).

[3] Y.T. Oganessian *et al.*, *Phys. Rev. C* **74**, 044602 (2006).

[4] R.C. Jensen, A.W. Fairhall, *Phys. Rev.* **109**, 942 (1958).

[5] Y. Nagame *et al.*, *Phys. Lett. B* **387**, 26 (1996).

[6] K. Banerjee *et al.*, *Phys. Rev. C* **83**, 024605 (2011).

[7] L.M. Pant, R.K. Choudhury, A. Saxena, D.C. Biswas, *Eur. Phys. J. A* **11**, 47 (2001).

[8] A. Jhingan *et al.*, *Rev. Sci. Instrum.* **80**, 123502 (2009).

[9] R. du Rietz *et al.*, *Phys. Rev. C* **88**, 054618 (2013).

[10] S. Appannababu *et al.*, *Phys. Rev. C* **83**, 034605 (2011).

[11] R. Dubey *et al.*, *Phys. Lett. B* **752**, 338 (2016).