FISSION DYNAMICS OF ^{192,202,206,210}Po COMPOUND NUCLEI BY NEUTRON MULTIPLICITY MEASUREMENTS*

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This paper reports a summary of the experimental results on pre- and post-scission neutron multiplicities ($M_{\rm pre}$ and $M_{\rm post}$) from ^{192,202}Po compound nuclei populated by ^{48}Ti+^{144,154}Sm systems at 72 MeV excitation energy, studied using the National Array of Neutron Detectors (NAND) at IUAC, New Delhi. The experimental neutron yields along with already existing data for ^{12}C+^{194}Pt and ^{18}O+^{192}Os are compared with predictions from the statistical model of compound nuclear decay including the strength of nuclear dissipation as a free parameter. $M_{\rm pre}$ values obtained from the present analysis do not show any specific dependence on the $(N-Z)/A$ values of the fissioning nuclei. In order to explain the experimental neutron multiplicities, the entrance channel effects are important.

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1. Introduction

Recently, the stability of heavy nuclei formed in heavy-ion induced fusion–fission (FF) reactions has become a topic of ample interest. Conventionally, heavy-ion reactions used to produce heavy elements are assumed to proceed in two subsequent steps: the fusion, after full equilibration, is followed by the

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de-excitation, the latter being dominated by a competition between light-particle evaporation and fission [1]. For lighter systems, a fully equilibrated compound nucleus (CN) is formed, whereas in the case of heavier systems, the full equilibration does not take place and the system re-separates leading to appearance of quasi-fission (QF) along with pure FF. The fused CN may then de-excite by emission of particles to the evaporation residue, or may itself undergo a fission (CN fission). Finally, we have two fission components, one which passed through the CN phase (fission) and the other which did not (QF) [2, 3]. The fission process is delayed with respect to the statistical picture of CN decay due to dissipation. Apart from the nuclear dissipation, the factors affecting the fission time scale are the shell effects in the fission barrier height and the density of nuclear levels [4]. The possibility of synthesis of super-heavy elements is based on the expectation of their stability against fission due to shell effects [5]. Recently, Singh *et al.* [6] and Sandal *et al.* [7] carried out neutron multiplicity measurements for the CN ^{213,215,217}Fr and ^{210,212,214,216}Rn to study the effect of neutron shell closure. In the present work, the experimental measurements of pre-scission multiplicity ($M_{\rm pre}$) are extended over a wider range of $(N-Z)/A$ and entrance channel mass-asymmetry (α) for CN of Po isotopes. Here, we have measured the $M_{\rm pre}$ for two systems: ^{48}Ti+^{144}Sm and ^{48}Ti+^{154}Sm at 72 MeV excitation energy. The experiment was carried out using a ^{48}Ti beam from the 15 UD Pelletron + LINAC accelerator facility of the Inter University Accelerator Center, New Delhi, India [8]. In the present study, we have also included the systems ^{12}C+^{194}Pt and ^{18}O+^{192}Os leading to ^{206}Po and ^{210}Po, respectively, for which experimental data for $M_{\rm pre}$ are already available [9, 10]. The selected systems extend from the neutron-deficient ^{192}Po ($N_{\rm CN}=108$) to the neutron-rich ^{210}Po. We also perform a detailed statistical model analysis for the four systems.

2. Data analysis and results

The discrimination of γ rays from neutrons was performed using the pulse-shape discrimination (PSD) based on zero-crossover and the time-of-flight technique (TOF) with IUAC-made PSD modules [11].

Considering the prompt γ peak as reference, the TOF spectra are calibrated using a precision TAC calibrator. The calibrated and gated TOF spectra are converted to the neutron energy (E_n) spectra. The resulting energy spectra of neutrons detected in coincidence with fission fragments were fitted assuming their emission from three moving sources, namely CN evaporation (pre-scission) and two fission fragments (post-scission). The emitted pre- and post-scission neutrons were assumed to be isotropic in their rest frames. A multiple-source least-square fitting procedure, using the Watt expression [12], was used to obtain the neutron multiplicity ($M_{\rm pre}$ and $M_{\rm post}$)

and the temperature ($T_{\rm pre}$ and $T_{\rm post}$) for each neutron source from the measured neutron energy spectra. The temperature of the fissioning nucleus, $T_{\rm pre}$, was calculated as: $T_{\rm pre} = \sqrt{(E^*/a)}$, where E^* is the CN excitation energy and a is the level density parameter. $T_{\rm post}$ was determined from the fits, assuming that it is the same for both fission fragments. The neutron multiplicities obtained from fitting the spectra obtained for ^{192,202}Po are given in Table I, while the actual fits are shown in Fig. 1.

TABLE I

Experimental values of neutron multiplicities $M_{\rm pre}$, $M_{\rm post}$, temperatures of the neutron sources $T_{\rm pre}$, $T_{\rm post}$, and χ^2 values for ^{192,202}Po CN data.

CN	$M_{\rm pre}$	$2M_{\rm post}$	$M_{\rm total}$	$T_{\rm pre}$	$T_{\rm post}$	χ^2/N
^{192}Po	1.92(18)	2.80(12)	4.72(19)	1.93(15)	1.45(7)	2.1
^{202}Po	2.90(20)	3.28(10)	6.18(22)	1.780(97)	1.12(4)	1.9

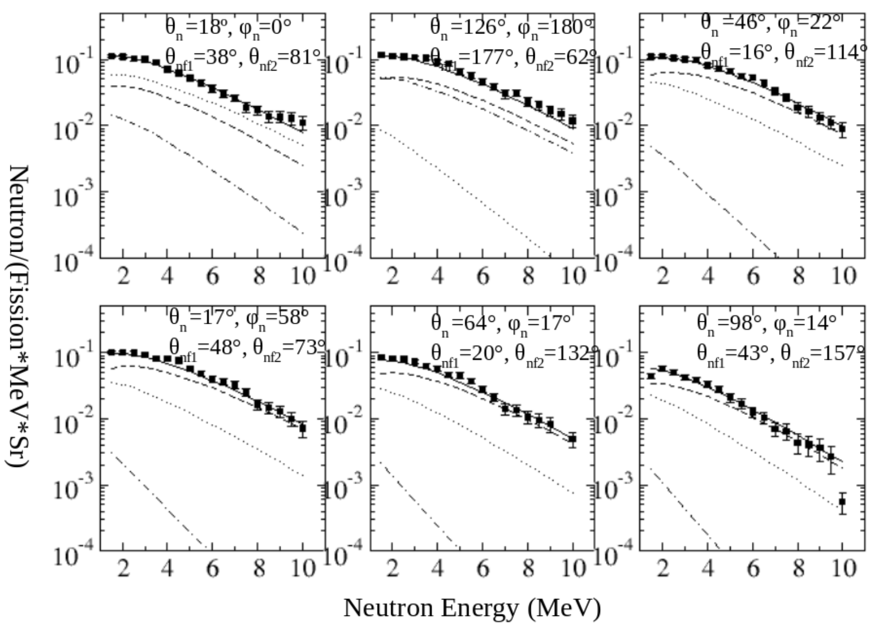

Fig. 1. Double-differential neutron energy spectra for the 48 Ti+ 144 Sm system at 72 MeV excitation energy, for six of the neutron detectors. The pre-scission contribution is shown by the dotted line whereas the dashed and dash-dotted lines depict the post-scission contribution from the complementary fragments. The solid black line represents the sum of the different contributions. Here, θ_n and ϕ_n refer to the polar and azimuthal angles of the neutron detectors whereas θ_{nf1} and θ_{nf2} are the relative angles between the emitted neutrons and the fission fragments.

The experimental $M_{\rm pre}$ values are plotted in the left panel of Fig. 2 as a function of $(N-Z)/A$ for different polonium isotopes. The $M_{\rm pre}$ values for three Fr isotopes are also shown for comparison. $M_{\rm pre}$ is found to increase with $(N-Z)/A$ for both Po and Fr nuclei. No significant effect of the shell closure at $N=126$ (for ^{210}Po and ^{213}Fr) is observed.

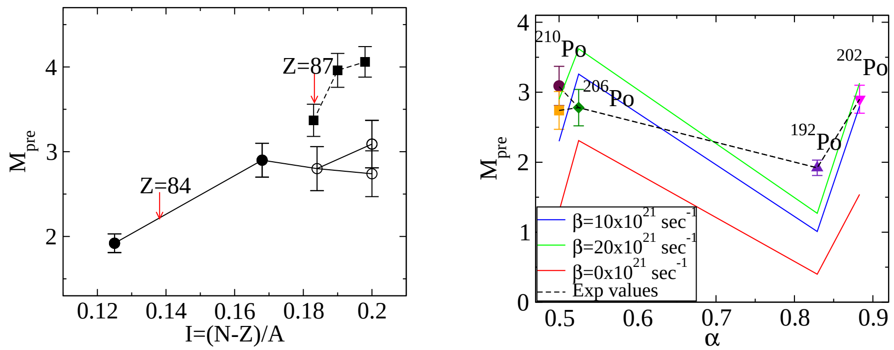

Fig. 2. Left panel: $M_{\rm pre}$ as a function of $(N-Z)/A$ for Po $(Z=84)$ and Fr $(Z=87)$ isotopes. Right panel: $M_{\rm pre}$ as a function of mass-asymmetry (α) for different systems. Present data is denoted by solid circles. Experimental values for ^{192,202}Po (present work) are measured at the excitation energies of 72.6 and 72.3 MeV respectively, those for ^{206}Po and ^{210}Po, measured at the excitation energies of 76.7 and 73.5 MeV, are taken from Ref. [9] and Ref. [10], respectively, and denoted by empty circles. The data for ^{213,215,217}Fr isotopes at the excitation energies of 74.0, 75.4 and 74.0 MeV (solid squares) are taken from Refs. [6, 13].

3. Theoretical calculations

According to the statistical model (SM), a CN either decays by fission or forms a stable evaporation residue along with the emission of light particles such as n, p, α particles and γ rays. The Bohr and Wheeler fission width $\Gamma_{\rm BW}$ is obtained from the transition-state model of fission [14]. The particle and γ-emission widths used in the present work are obtained from the Weisskopf formula [15].

The fission barrier in the present calculation includes the shell correction to the liquid-drop nuclear mass. The difference between the experimental and the liquid-drop model (LDM) masses, denoted by δM, is given as $\delta M = M_{\rm exp} - M_{\rm LDM}$. The fission barrier of a CN carrying angular momentum is then given as

$$B_{\rm f}(l) = B_{\rm f}^{\rm LDM} - (\delta_{\rm g} - \delta_{\rm s})\,, \tag{1}$$

where $B_{\rm f}^{\rm LDM}$ is the LDM fission barrier and $\delta_{\rm g}$ and $\delta_{\rm s}$ are the shell correction energies for the ground state and the saddle configuration, respectively. The level density parameter used in the present work was taken from the work of Ignatyuk *et al.* [16], which includes shell effects at low excitation energies and takes an asymptotic form at high excitation energies.

The right panel of Fig. 2 shows the SM predictions along with the experimental values of the $M_{\rm pre}$ as a function of the entrance channel mass-asymmetry α for the four compound nuclei ^{192,202,206,210}Po. From this plot, it is evident that the dissipation strength β in the range of (10–20) $\times$ 10^{21} sec^{-1} can reproduce the experimental $M_{\rm pre}$ values for the ^{18}O+^{192}Os and ^{48}Ti+^{154}Sm systems, whereas for the ^{12}C+^{194}Pt, a smaller value of β is required. However, for the ^{48}Ti+^{144}Sm reaction, the experimental value of $M_{\rm pre}$ is not fitted even with $\beta = 20 \times 10^{21}$ sec^{-1}. The values of α, critical Businaro–Gallone mass asymmetry $\alpha_{\rm BG}$ [17], along with experimental $M_{\rm pre}$ values for the different systems are shown in Table II. Here, $\alpha < \alpha_{\rm BG}$ for all the systems except for ^{12}C+^{194}Pt, where $\alpha > \alpha_{\rm BG}$.

TABLE II

Systems investigated in the present work.

System	E^* [MeV]	Exp. $M_{\rm pre}$	α	$\alpha_{\rm BG}$
^{48}Ti+^{144}Sm$\to$^{192}Po	72.6	1.92 ± 0.18	0.5	0.861
^{48}Ti+^{154}Sm$\to$^{202}Po	72.3	2.90 ± 0.20	0.525	0.851
^{12}C+^{194}Pt$\to$^{206}Po	76.7	2.8 ± 0.26	0.883	0.847
^{18}O+^{192}Os$\to$^{210}Po	73.5	3.09 ± 0.28 2.74 ± 0.27	0.829	0.844

It is well-understood that the fusion path followed by a temperature-equilibrated di-nuclear system is quite different for systems with $\alpha > \alpha_{\rm BG}$ than those with $\alpha < \alpha_{\rm BG}$ [12]. From the present precise analysis of several systems, it may be further observed that the time interval required to form a fully equilibrated CN is smaller for systems with $\alpha > \alpha_{\rm BG}$ than for those with $\alpha < \alpha_{\rm BG}$. Consequently, the number of emitted neutrons is lower for the ^{12}C+^{194}Pt reaction, as compared to the other systems, because the neutrons emitted during the formation phase of CN also contribute to the $M_{\rm pre}$ value. It is also worth mentioning that the experimental values of $M_{\rm pre}$ include the neutrons emitted in three phases: *(i)* during the formation phase of CN, *(ii)* during the pre-saddle stage and *(iii)* in the saddle-to-scission stage. The present SM calculations took into account neutrons emitted from phase *(ii)* and *(iii)* only, but not from *(i)*. Consequently, the β parameter is not introduced in stage *(i)*. This results in an unexpected large value of β for the ^{192}Po CN as compared to other systems, see Fig. 2 (right panel), and calls for a close look at the entrance channel dynamics of the above system.

4. Summary and conclusion

A systematic study of Po CN covering a wide range of neutron numbers ($N = 108$ to 126) was carried out using the neutron multiplicity as a probe. There is no particular effect of the $N = 126$ shell closure on the general trend of $M_{\rm pre}$ values as a function of $(N - Z)/A$. The time interval required to form a fully equilibrated CN has been shown to be shorter for the ^{206}Po CN, which results in fewer pre-scission neutrons emitted and, consequently, a smaller β value needed to reproduce the experimental $M_{\rm pre}$ values. On the other hand, $M_{\rm pre}$ for ^{192}Po could not be reproduced even with a very large value of β. However, the SM analysis of $M_{\rm pre}$ for ^{202}Po does not indicate any special role of the time interval required to form a fully equilibrated CN. This indicates that the dynamics plays an important role not only in the entrance channel but also in the de-excitation of the CN.

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