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Study of Fission Dynamics in ^{213,215,217}Fr Formed in Heavy-Ion Induced Reaction

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Abstract. The present investigation mitigates the existing ambiguities regarding the influence of entrance channel effects and neutron shell closure in Fr nuclei to a considerable extent. The same CN when populated through different reactions shows no discernible signatures of entrance channel effects. The requirement of saddle shell corrections for the description of pre-scission neutron multiplicity, spanning excitation energy ranging 40 MeV and above in mass region 200 is also not evidenced.

1 Introduction

Nuclear fission is a complex process involving rapid re-arrangement of nucleons through large scale collective motion with a delicate interplay of macroscopic and microscopic phenomena on the potential energy surface [1, 2]. Nuclear fission remains to be an important reaction not only from fundamental physics point of view, but also for our understanding of synthesis of Super Heavy Elements (SHEs) through fusion reactions and applications in energy production.

Fission hindrance, enhanced pre-scission particle and giant dipole resonance (GDR) γ-ray multiplicities observed in hot nuclei suggested the effects of nuclear dissipation slowing down the fission process [3–6]. To account for frictional effects, Kramers diffusion model formalism with modified fission width, referred to as Kramers-modified statistical model [7] was included in the standard statistical theory. Despite astounding success of the statistical model in describing the decay of a hot rotating compound nucleus (CN), the conclusions drawn are at times prone to ambiguities due to involved assumptions and case specific parameter adjustment. The different combinations of the input parameters [8–11] *viz.* the quantal scaling of both the parameters, the level density at ground and saddle and the fission barrier, transient time, formation time of the compound nucleus, saddle to scission time and dynamical delay are empirically fitted to describe the experimental evaporation residue (ER) / fission cross-sections or / and pre-scission neutron multiplicity (ν_{pre}).

Inconsistencies related to the influence of entrance channel effects and neutron shell closure at excitation energies (E*) 40 MeV and above on ν_{pre}, fission and ER excitation functions are noted to exist in the literature [11–17]. This is observed particularly for the nuclei in mass region A $\sim$ 200 that has been studied both experimentally and theoretically for last few decades to perceive the persistence of shell corrections at the saddle deformation. Owing to a dearth of systematic and simultaneous analysis of the fission observables, these ambiguities in the interpretation of fission still remains unresolved.

The measurement of $\nu_{\rm pre}$ for ^{213}Fr [13] reported comparatively low sensitivity to dissipation due to the shell closure at $E^* \sim 50$ MeV. However, an ER excitation measurement of ^{213}Fr [14] on the other hand suggested lower stability of CN against fission. A recent work using an extended version of the statistical model treating dissipation strength as the only adjustable parameter also reported an underestimation of $\nu_{\rm pre}$ data for ^{213,215,217}Fr nuclei in the range $E^* \sim$ 50–80 MeV when fitted simultaneously with their fission excitation functions, exhibiting no extra stability from $N = 126$ shell closure [15]. These studies corroborate the view that no consistent picture has emerged from modeling each fission observable independently. Therefore, a simultaneous description of the experimental data and a systematic study for Fr nuclei is further required.

Recent systematic studies [16, 17] have reported a deviation of measured $\nu_{\rm pre}$ for ^{213}Fr formed through reactions ^{16}O+^{197}Au and ^{19}F+^{194}Pt from the general predictions of the entrance channel effect. A conclusive understanding for this apparent inconsistency could not be reached. In-fact, high fission timescales were reportedly required in the form of CN formation time [16] and fission delay [17] to explain the excess $\nu_{\rm pre}$ of ^{19}F+^{194}Pt than ^{16}O+^{197}Au reaction.

In this work, we report that dynamical model based on 1D Langevin equation coupled with statistical decay framework can unambiguously describe the measured data in shell closed nuclei ^{213}Fr and its non-shell closed isotopes ^{215,217}Fr.

2 Model Description

The 1D over-damped Langevin equation used for the dynamical part of fission in the present work has the numerical form as [18, 19] :

$$q_{n+1} = q_n + \frac{T(q)}{\beta(q)M}\frac{dS}{dq}\tau + \sqrt{\frac{T(q)}{\beta(q)M}}\tau w_n\,, \tag{1}$$

where q is the fission or collective coordinate described as ratio of half the distance between the future fragments and the radius of the compound nucleus, τ is Langevin time step, $\beta(q)$ is the reduced friction parameter, w_n is the Gaussian distributed random number with variance 2.

The necessity for an entropy $S(q)$ dependent driving force employed in the present calculations has been emphasized by Fröbrich [20] and Lestone et al. [21]. It is pointed out that the nuclear driving force $K = -dV/dq + (da(q)/dq)T^2$ is not only a negative conservative force but also contains a term that emerges from the thermodynamical properties of the fissioning nuclei that enters the dynamics via the level density parameter $a(q)$. The deformation dependent level density $a(q)$ has the form $a(q) = \tilde{a_1}A + \tilde{a_2}A^{2/3}B_s(q)$, where A is the mass number of the compound nucleus (CN) and $B_s(q)$ is dimensionless functional of surface energy [19]. The values of the parameters are taken from Ignatyuk's prescription from Ref. [22] which exhibits weakest coordinate dependence on level density.

When a stationary flux over saddle configuration is reached after a delay time, the decay of the CN is modelled by an adequately modified statistical model. In order to have continuity when swiching from dynamical to statistical model, an entropy dependent fission width [19] is incorporated in the latter. In the present model, the emission widths of light particles (n, p, α, d) and giant dipole γ quanta are calculated with Blann [23] and Lynn [24] parametrization, respectively. The evaporation of pre-scission particles (n, p,

α, d, γ) along Langevin trajectories is assumed to be a discrete process and is stimulated by Monte-Carlo techniques.

For a simultaneous study of ν_{pre} with ER, fission and fusion cross-sections, the present dynamical calculations are performed with a temperature dependent friction (TDF) of Refs. [20, 25, 26] without adjusting any of the model parameters to achieve a consistent description of the fission observables. The maximum of $\beta(q)$ in TDF corresponds to the ground state, minima at the saddle configuration that is followed by an increase in dissipation during descent due to energy gain. $\beta(q)$ depends on excitation energy of the hot CN as well. The present stochastic model is based on Bohrs hypothesis and entrance channel effects are not included in the calculations. To account for sufficient statistics, 10^7 Langevin trajectories are considered in the model calculations.

3 Results and Discussion

Figures 1 and 2 show the results of 1D-Langevin dynamical calculations compared with experimental data of $\nu_{\rm pre}$ (Figure 1), ER, fission and fusion excitation functions (Figure 2) for $N = 126$ neutron shell closed nucleus ^{213}Fr formed through ^{16}O+^{197}Au [27], ^{19}F+^{194}Pt [13–15, 28] reactions and its non-shell closed isotopes ^{215}Fr formed through ^{18}O+^{197}Au [29], ^{19}F+^{196}Pt [13–15] reactions and ^{217}Fr formed through ^{19}O+^{198}Pt [13–15, 28] reaction studied across a wide range of excitation energies (E^*).

The results of the statistical calculations from the present model are also shown in Figure 1 and Figure 2 as dashed (red) line. These calculations are performed with the same code with Langevin dynamics turned off. The statistical calculations under-predicts the measured $\nu_{\rm pre}$ data (panels (a) – (d)), even more as excitation energy increases. The present dynamical calculations with TDF form factor are found to be in agreement with the measured data of $\nu_{\rm pre}$, ER, fission and fusion cross-sections for the neutron shell closed nuclei ^{213}Fr and non shell closed nuclei ^{215,217}Fr in a broad range of excitation energies from 40 to 80 MeV. It must be noted that, the present model without any microscopic corrections can simultaneously describe the experimental data of four fission observables at these excitation energies, irrespective of the neutron shell nature of the nuclei.

The model is also found to simultaneously reproduce all the four fission observables for reactions forming same compound nuclei viz. ^{16}O+^{197}Au and ^{19}F+^{194}Pt populating ^{213}Fr, and fission, ER and fusion cross-sections for reactions ^{18}O+^{197}Au and ^{19}O+^{196}Pt

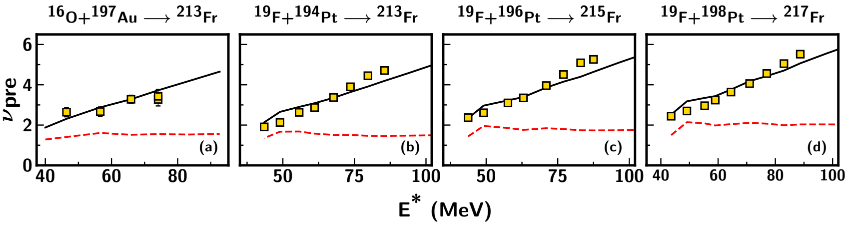

Figure 1. Comparison of measured and calculated pre-scission neutron multiplicity ($\nu_{\rm pre}$) for compound nuclei ^{213}Fr, ^{215}Fr and ^{217}Fr. The continuous line (black) represents dynamical calculations performed with temperature dependent friction (TDF) and dashed line (red) represent results of statistical model calculation.

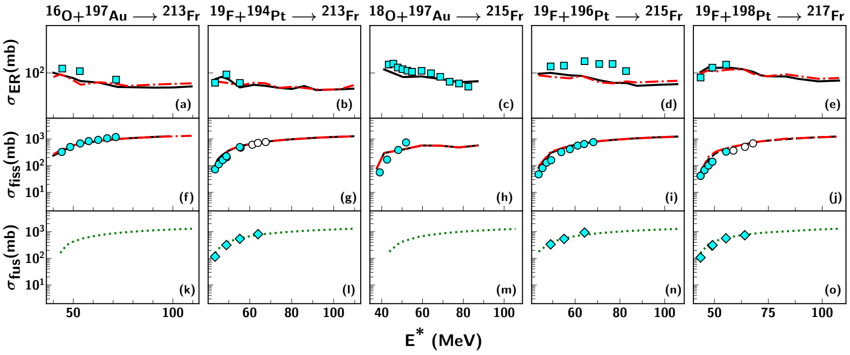

Figure 2. Comparison of measured and calculated evaporation residue ($\sigma_{\rm ER}$), fission ($\sigma_{\rm fiss}$), and fusion cross-sections ($\sigma_{\rm fus}$) as a function of excitation energy. The continuous and dashed lines have the same meaning as in Figure 1. The calculated fusion cross-section is represented by dotted line (green).

populating ^{215}Fr, at similar excitation energies. These observations are in contrast with the recent studies [16,17] that reported a deviation of measured $\nu_{\rm pre}$ data of ^{213}Fr from the general predictions of entrance channel effects. The present work displays no significant evidence of entrance channel dynamics between these two pair of reactions.

4 Conclusion

On the basis of present analysis we conclude that, without many of the assumptions and parameter adjustments as made in some of the recent statistical model analysis, the stochastic dynamical model can simultaneously reproduce the available data of $\nu_{\rm pre}$, fission, ER and fusion excitation functions for neutron shell closed nuclei, ^{213}Fr and its non-shell closed isotopes ^{215,217}Fr without the need for including any extra shell or entrance channel effects. There appears to be no discernible influence of N=126 neutron shell structure on the measured fission observables in the medium excitation energy range.

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References

[1] R. Vandenbosch, J.R. Huizenga, *Nuclear fission* (Academic Press, New York, 1973).
[2] H.J. Krappe, K. Pomorski, *Theory of Nuclear Fission*, Lecture Notes in Physics **838** (Springer, Heidelberg, 2012).
[3] A. Gavron *et al. Phys. Rev. Lett.* **47** (1981) 1255.
[4] M. Thoennessen *et al. Phys. Rev. Lett.* **59** (1987) 2860.
[5] J. Newton, et al., *Nucl. Phys. A* **483** (1988) 126.
[6] D.J. Hofman, B.B. Back, P. Paul *Phys. Rev. C* **51** (1995) 2597.

[7] H. Kramers *Physica* **7** (1940) 284.

[8] D. Hinde, et al., *Nucl. Phys. A* **452** (1986) 550.

[9] K. Mahata, S. Kailas, S.S. Kapoor, *Phys. Rev. C* **74**(2006) 041301(R).

[10] D. Mancusi, R.J. Charity, J. Cugnon, *Phys. Rev. C* **82** (2010) 044610.

[11] K. Golda, et al., *Nucl. Phys. A* **913** (2013) 157.

[12] K. Mahata, S. Kailas, S.S. Kapoor, *Phys. Rev. C* **92** (2015) 034602.

[13] V. Singh, et al., *Phys. Rev. C* **86** (2012) 014609.

[14] V. Singh, et al., *Phys. Rev. C* **89** (2014) 024609.

[15] V. Singh, et al., *J. Phys. G: Nucl. Part. Phys.* **48** (2021) 075104.

[16] C. Schmitt, et al., *Phys. Rev. C* **97** (2018) 014616.

[17] M. Shareef, et al., *Eur. Phys. J. A* **52** (2016) 342 .

[18] P. Fröbrich I.I. Gontchar, *Physics Reports* **292** (1998) 131-237.

[19] I. Gontchar, L.A. Litnevsky, Fröbrich, *Computer Physics Communications* **107** (1997) 223.

[20] P. Fröbrich, *Nucl. Phys. A* **787** (2007) 170

[21] J.P. Lestone, S.G. McCalla, *Phys. Rev. C* **79** (2009) 044611.

[22] A.V. Ignatyuk, et al., *Yad. Fiz.* **21** (1975) 1185.

[23] M. Blann, *Phys. Rev. C* **21** 1770 (1980).

[24] J.E. Lynn, *Theory of Neutron Resonance Reactions* (Clarendon,Oxford, 1969).

[25] D. J. Hofman, B. B. Back, P. Paul *Phys. Rev. C* **51** (1995) 2597.

[26] I. Gontchar, et al., *Z Phys. A* **359** (1997) 149.

[27] D.J. Hinde, et al., *Nucl. Phys. A* **452** (1986) 550.

[28] K. Mahata, et al., *Phys. Rev. C* **65** (2002) 034613.

[29] L. Corradi, et al., *Phys. Rev. C* **71** (2005) 014609.