PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 85, No. 2
August 2015
pp. 323–333

An overview of the recent results on fission dynamics from the NAND facility

B R BEHERA
Department of Physics, Panjab University, Chandigarh 160 014, India
E-mail: bivash@pu.ac.in

DOI: 10.1007/s12043-015-1047-z; ***e*Publication:** 21 July 2015

Abstract. This paper summarizes the results of some of the recent fusion–fission experiments carried out at the National Array of Neutron Detectors (NAND) Phase-01 installed at the Pelletron+ LINAC accelerator facility of Inter-University Accelerator Centre (IUAC), New Delhi. Pre-scission neutron multiplicity excitation functions are measured for the ^{213,215,217}Fr, ^{210,212,214,216}Rn and ^{206,210}Po compound nuclei populated through the fusion of the ^{19}F+$^{194.196,198}$Pt, ^{16,18}O+^{194,198}Pt and ^{12}C+^{194,198}Pt systems, respectively. Pre-scission neutron yields from these reactions are compared with the extensive statistical model calculations to look for the effects due to the compound nucleus shell closure, N/Z ratio of the compound nucleus, magnitude of the saddle-point shell corerction and fission time-scale.

Keywords. Neutron multiplicity; pre-scission neutron; National Array of Neutron Detectors; fusion–fission.

PACS Nos 25.70.Ji; 25.70.Gh; 24.10.Pa

1. Introduction

Dissipation phenomena are well known in the dynamics of macroscopic systems. Evidence for dissipation in strongly interacting systems like nucleus has been accumulated from a large number of studies of nuclear dynamics at temperatures of the order of a few MeV [1,2]. Recently, dissipative dynamics is also found to play a crucial role in the evolution of matter at extremely high densities and temperatures created in collisions between two heavy nuclei at ultrarelativistic energies [3]. In another recent paper, Auerbech and Shlomo [4] pointed out that the strength of the dissipation-to-entropy density ratios obtained from nuclear systems at low as well as very high temperature are very similar. At present, exploring dissipation phenomena is one of the challenges in nuclear physics.

Dissipation in nuclear dynamics in the mean-field regime accounts for the coupling of the collective motion with the intrinsic nucleon degrees of freedom. The energy spectrum of intrinsic motion has a well-defined shell structure on the strength of nuclear dissipation. In particular, a scan of nuclear dissipation across the neighbourhood of a closed shell nucleus can reveal the effect of shell closure [6].

Nuclear dissipation manifests itself in heavy-ion-induced fusion–fission reactions by the enhancement of pre-scission evaporation of neutrons, other light particles and photons with respect to the predictions of the standard statistical model of compound nuclear decay. An enhancement of the evaporation residue cross-section is also observed. Dissipation hinders or slows down the fission process, causing an increase in the number of evaporated particles and γ-rays prior to fission [5–8]. In the statistical model the strength of the nuclear dissipation is treated as a free parameter and its value is obtained from fitting of the experimental data. The dissipation strength obtained experimentally thus depends on the magnitude of other nuclear properties like the separation energy, the level density and the fission barrier used in the statistical model calculations. One may like to know to what extent the shell corrections in these nuclear properties affect the fitted values of the dissipation strength. A proper understanding of such issues are important to attribute the value of the best-fit dissipation parameter to the true dissipative property of the compound nucleus (CN). Furthermore, any shell effect in dissipation is expected to be revealed in its best-fit values when shell corrections in all the other nuclear properties are accounted for in the statistical model calculations.

In another aspect it is also of considerable interest to explore the effect of N/Z in compound nuclei (CN) for a given element on the strength of nuclear dissipation. Measurement of pre-scission neutron multiplicities from an isotopic chain will be a suitable tool for this purpose [9–11]

The exact determination of fission barrier height is essential to understand the dynamics of the fusion–fission process and prediction of superheavy elements. The attempt to extract shell correction to the fission barrier from the experimental fission barrier using the fission data in heavy-ion-induced fusion–fission reaction is rather scarce. In few of the recent studies it is shown that inclusion of neutron multiplicity data along with fission and evaporation residue data and its simultaneous fitting helps in the extraction of the shell correction energies [12].

In an attempt to understand a few of these aspects, a series of experiments for measuring neutron multiplicities were carried out at the NAND facility [3] of Inter-University Accelerator Centre (IUAC) Pelletron+LINAC accelerator facility. Neutron multiplicities were measured for the ^{19}F+^{194,196,198}Pt, ^{16,18}O+^{194,198}Pt and ^{12}C+^{194,198}Pt systems. Details of these experiments and results can be found in [5–13]. In this paper an attempt has been made to summarize the results of these experiments. This paper is organized as follows. First, a brief introduction to the formalism of statistical model used in these anaysis is given followed by the summary of results for the ^{19}F+^{194,196,198}Pt, ^{16,18}O+^{194,198}Pt and ^{12}C+^{194,198}Pt systems. Finally a brief conclusion is presented.

2. The statistical model

The experimentally obtained neutron multiplicities are compared with the statistical model predictions. In these calculations, emission of neutrons, protons, αs and giant dipole resonance (GDR) γ-rays are considered along with fission as the possible decay channels of a CN. The light particles and the γ decay widths are obtained from the Weisskopf formula.

The fission width in this work is taken from [14] where the effect of dissipation is included. Considering fission as a diffusive process of a Brownian particle across the fission barrier in a viscous medium, Kramers solved the relevant Fokker–Planck equation and obtained the following expression for fission width [14]:

$$\Gamma_{\mathrm{K}} = \frac{\hbar\omega_{\mathrm{gs}}}{2\pi} \mathrm{e}^{-V_{\mathrm{B}}/T} \left[\sqrt{1 + \left(\frac{\beta}{2\omega_{\mathrm{sad}}}\right)^2} - \frac{\beta}{2\omega_{\mathrm{sad}}} \right], \tag{1}$$

where β is the reduced dissipation coefficient, ω_{gs} and ω_{sad} are the local frequencies of the harmonic oscillator potentials which have the same curvatures as the liquid-drop model (LDM) nuclear potential at the ground-state and the saddle configuration, respectively. The fission barrier and the nuclear temperature are denoted by V_{B} and T, respectively. The nuclear potential is obtained as a function of elongation using the finte-range liquid-drop model (FRLDM) [18]. As the potential profile depends on the spin of the CN, the frequencies ω_{gs} and ω_{sad} should have spin dependences [15,16]. Accordingly, spin dependence of frequencies is considered in the present calculation.

The fission width reaches its stationary value (eq. (6)) after the elapse of a build-up or transient time τ_f and the dynamical fission width is given as

$$\Gamma_f(t) = \Gamma_{\mathrm{K}}[1 - \mathrm{e}^{-2.3t/\tau_f}] \tag{2}$$

which is used in the time evolution of the CN in the present calculation.

The particle and γ-decay widths and the compound nuclear temperature are calculated using the level density parameter taken from the work of Ignatyuk *et al* [17] which takes into account the effect of nuclear shell structure at low excitation energies and is given as

$$a(E^*) = \bar{a}\left(1 + \frac{f(E^*)}{E^*}\delta W\right) \tag{3}$$

with

$$f(E^*) = 1 - \mathrm{e}^{-E^*/E_{\mathrm{D}}}, \tag{4}$$

where $\bar{a}$ is the asymptotic value to which the level density parameter approaches with increase in excitation energy (E^*) of the CN, δW is the shell correction obtained from the difference between the experimental and LDM masses and E_{D} is a damping term which accounts for the washing out of shell effect with increasing excitation energy. The value of E_{D} is taken to be 18.5 MeV.

Shell correction can also be added to the fission barrier as follows [17]. The parametrized form of the shell-corrected temperature-dependent barrier is given by

$$V_{\mathrm{B}}(T) = V_{\mathrm{LDM}} - \delta W \mathrm{e}^{-(E^*/E_{\mathrm{D}})}, \tag{5}$$

where V_{LDM} is the fission barrier from the finite-range rotating LDM potential [18], E^* is the CN excitation energy and E_{D} is the shell damping term.

In the Monte-Carlo simulation of compound nuclear decay using various decay widths, the number of neutrons emitted during the transition from the saddle to the scission configuration is also calculated for fission events. The time interval for the transition of CN from saddle to scission is given as

$$\tau_{\rm ss} = \tau_{\rm ss}^{0}\left(\sqrt{1+\left(\frac{\beta}{2\omega_{\rm sad}}\right)^{2}}+\frac{\beta}{2\omega_{\rm sad}}\right), \tag{6}$$

where $\tau_{\rm ss}^{0}$ is the non-dissipative time interval for the transition from saddle to scission. The neutrons emitted during the saddle to scission journey of a CN contribute to the pre-scission neutron multiplicity. The post-scission neutron multiplicities from the fission fragments are also calculated assuming symmetric fission.

3. Results from the ^{19}F+^{194,196,198}Pt systems

Considering the shell effects in the level densities and the fission barriers, the pre-scission and the total neutron multiplicities were calculated. It is observed that the pre-scission neutron multiplicities are underestimated for all the cases except the one at the lowest excitation energy of ^{213}Fr. It may be pointed out that the statistical model predictions with $\beta = 0$ for $M_{\rm pre}$ should not be larger than the experimental values, though the input level density parameters can be adjusted to bring down the calculated $M_{\rm pre}$ value for ^{213}Fr at 50 MeV excitation. Use of standard parameter set for level density was preferred in our calculation because the deviation concerns only one data point by a marginal amount. It may further be noted that though the $M_{\rm pre}$ values are underpredicted, the multiplicities of the total number of neutrons are reasonably well reproduced. This is a consequence of the balance between the excitation energies taken away by the pre- and post-scission neutrons because together they account for most of the initial excitation energy of the CN. Next, we fitted the experimental $M_{\rm pre}$ value at each excitation energy with the statistical model result using β as a free parameter. Figure 1a shows the fitted values of $M_{\rm pre}$ along with the experimental numbers. The corresponding values of β are given in figure 1b. In this plot, the shaded area for each nucleus corresponds to the uncertainty in the fitted β values due to the error in the experimental $M_{\rm pre}$. It is observed that β values for ^{215}Fr and ^{217}Fr are remarkably close within the limits of uncertainty over the entire range of excitation energy. The shell structures of these two isotopes of Fr are also very similar, each having a partially occupied $1g_{9/2}$ neutron shell after the shell gap at neutron number 126. On the other hand, the dissipation strength required for ^{213}Fr is clearly smaller than those for ^{215}Fr and ^{217}Fr at lower excitation energies though all the three become close at higher excitation energies. With a major shell closure with 126 neutrons, the shell structure of ^{213}Fr is very distinct from those of ^{215,217}Fr. Recalling that shell structure can influence level density, fission barrier as well as the strength of dissipation, these observations regarding smaller dissipation for ^{213}Fr can solely be attributed to its shell structure, because shell effects in the level density and the fission barrier are already included in the calculation. We thus arrive at the following interpretation regarding shell effect on dissipation. While the reduced dissipation strength varies marginally among

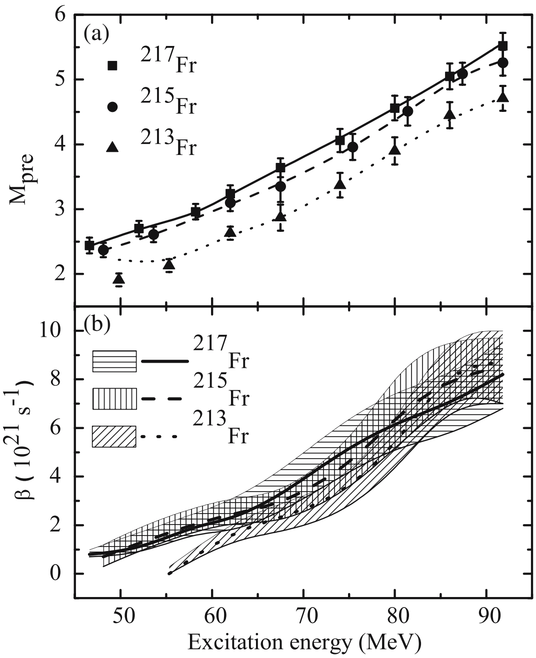

Figure 1. (**a**) Experimental pre-scission neutron multiplicity (symbols) for different systems with statistical model fits (lines) when shell effects are included in the calculation. (**b**) Best-fit values (lines) of β. The shaded areas in (**b**) represent the uncertainty in β associated with the experimental error in M_{pre}.

nuclei which are away from shell closure, it is suppressed for shell closure nuclei at low excitations.

Next we performed statistical model calculations without considering shell effects and figure 2 shows the best-fit M_{pre} and the corresponding β values. It is surprising to observe that M_{pre} cannot be fitted at all at low excitation energies for all the three Fr isotopes. It is further observed that the best-fit β values for different isotopes are quite different in contrast to those obtained with shell effects as given in figure 1.

We then performed statistical model calculations using LDM nuclear masses to obtain the neutron binding energies and the FRLDM for the fission barrier. Shell corrections were not applied either to the neutron binding energies or to the fission barrier. The pre-scission neutron multiplicity at each excitation energy was fitted by adjusting the strength of the reduced dissipation coefficient β. It is observed that the experimental data cannot be fitted with a constant value of β. Figure 3 shows the best-fit β values for different isotopes of Fr. It is observed that the dissipation coefficients for ^{217}Fr and ^{215}Fr isotopes increase rapidly with increasing excitation energy over its entire range, whereas the dissipation strength remains nearly zero till 70 MeV of excitation energy followed by a slower rate of increase for ^{213}Fr. The overall magnitude of the dissipation strength also remains much smaller for ^{213}Fr compared to the other two isotopes of Fr.

We next incorporated the ground-state shell corrections [19] in the LDM masses in the statistical model calculations. Figure 4 shows the dissipation strengths required to

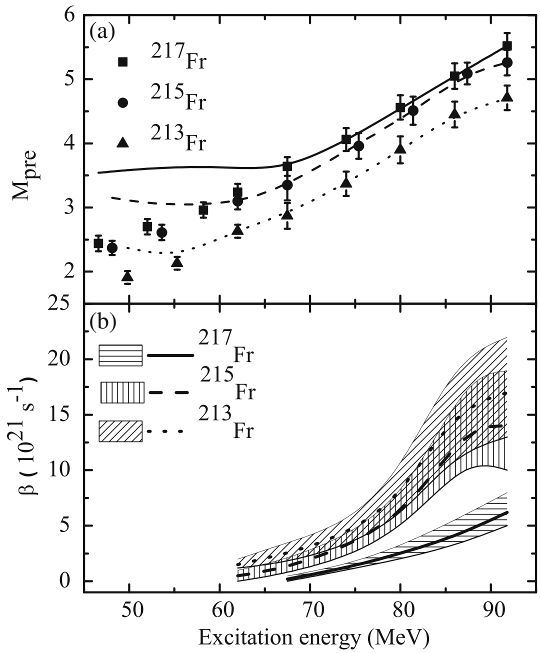

Figure 2. Same as figure 1 except that the statistical model calculations were performed after excluding the shell effects.

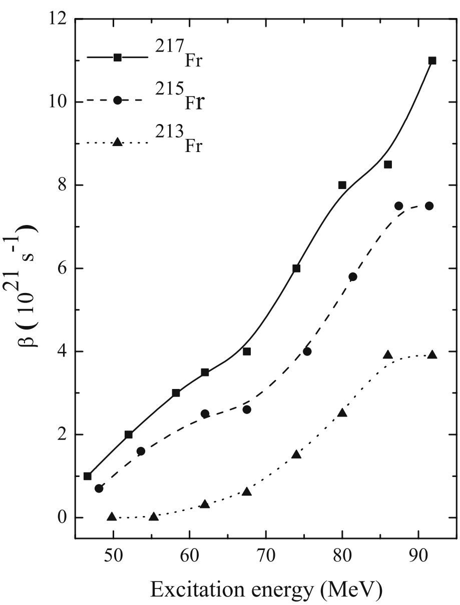

Figure 3. Excitation energy dependence of β required to fit the experimentally obtained M_{pre} for different systems using LDM masses and without shell corrections in fission barrier. The lines are drawn to guide the eye.

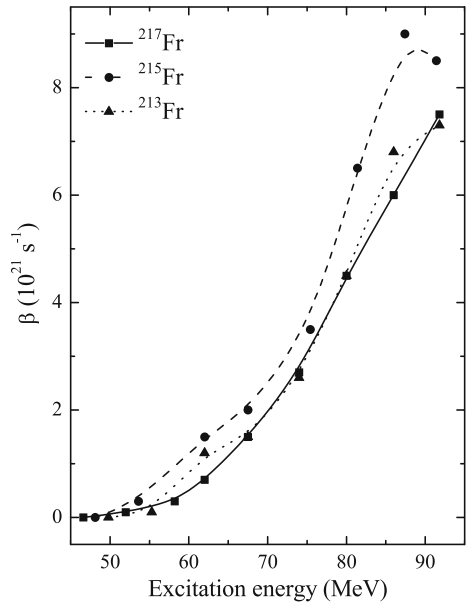

Figure 4. Excitation function of β values required to fit the experimentally obtained M_{pre} using the shell-corrected LDM and without shell correction in fission barrier for different isotopes of Fr. The lines are drawn to guide the eye.

fit the experimental multiplicities for all the three Fr isotopes. It is clearly observed in figure 4 that the anomalous lowering of dissipation strength for ^{213}Fr disappears and all the isotopes require nearly the same dissipation strength to fit the experimental results. This observation can be explained as follows. As the masses are taken to be the sum of the LDM masses and the shell corrections, the neutron separation energy obtained from the shell-corrected LDM masses increases for ^{213}Fr compared to that from the LDM masses while it decreases for the other two isotopes. This reduces the M_{pre} values for ^{213}Fr, but increases the same for ^{217}Fr and ^{215}Fr for a given value of the dissipation strength in the statistical model calculation. Consequently, higher values of dissipation strength are required to fit M_{pre} for ^{213}Fr, whereas lower values of dissipation are required for the other two isotopes, in comparison to the calculations without shell correction in masses. The dissipation strengths of the different isotopes therefore converge.

Comparing the results given in figures 3 and 4 an interesting observation can be made. When shell correction is not applied to the ground-state nuclear masses, the fitted β values for the different Fr isotopes are quite different (figure 3). However, the best-fit β values for the three Fr isotopes converge to a common value at each excitation energy when either of the shell-corrected (figure 4) nuclear masses are used in the statistical model calculation. Though it is expected that the calculated M_{pre} values (and hence fitted β values) will change when the input masses are changed in the statistical model calculation for a given compound nucleus, the observation of the convergence of the fitted β values is made possible only because the present experimental measurements are made for an isotopic sequence of the CN.

We now investigate the effect of shell correction to the fission barrier on the fitted values of dissipation strength. It is observed that inclusion of shell effect in fission barrier affects the fitted β values differently for shell-closed and non-shell-closed nuclei at low excitation energies. However, the effect of the inclusion of shell correction in fission barrier is not as severe as the effect of shell correction in LDM masses (figures 3 and 4) or the effect of shell correction in the level density formula [6].

4. Results from the ^{16,18}O+^{194,198}Pt systems

We first plot the pre-scission neutron multiplicities at each compound nuclear excitation energy as a function of N/Z in figure 5. While M_{pre} increases with N/Z at the three higher excitation energies, a minimum is observed for ^{212}Rn at the lowest excitation energy. As the number of neutrons in the ^{210,212,214,216}Rn nuclei are 124, 126, 128 and 130, respectively, one might expect that the appearance of the above minimum is due to the shell-closure effects at $N = 126$ for ^{212}Rn. If we assume that M_{pre} is simply proportional to the neutron decay width, which in turn is approximately proportional to $\exp(-B_n/T)$, and use the experimental nuclear masses to obtain the last neutron binding energies (B_n) of ^{210,212,214,216}Rn as 8.74, 7.98, 6.69 and 6.65 MeV, respectively, a monotonic increase of M_{pre} with N/Z is predicted. The trend remains the same when emission of the second neutron is also considered. Though the experimental M_{pre} values at the higher excitation energies agree with the prediction, the appearance of the minimum at the lowest excitation energy remains to be explained. We therefore perform statistical model calculations to study the detailed nature of the experimental data.

The best-fit β values at each excitation energy for each compound nucleus are given as a function of N/Z in figure 6. In this plot, the shaded area corresponds to the uncertainty in the fitted β values due to the experimental error in M_{pre}. It is noted from this figure that the best-fit β has a minimum at ^{212}Rn for the lowest excitation energy though at higher excitation energies, N/Z dependence of β does not show any specific trend. It is of further interest to note that the N/Z dependence of β is similar to the N/Z dependence of M_{pre} (figure 5) at the lowest excitation energy. The minimum in M_{pre} at ^{212}Rn

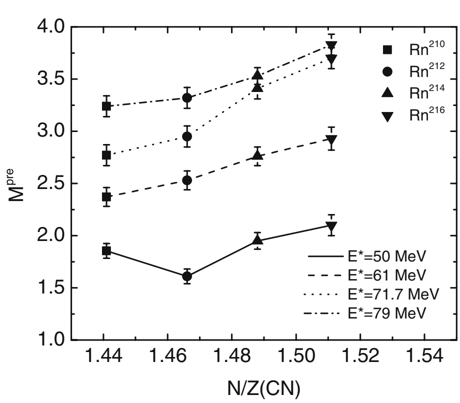

Figure 5. Variation of M_{pre} with N/Z (CN) for different systems. The experimental values are also shown.

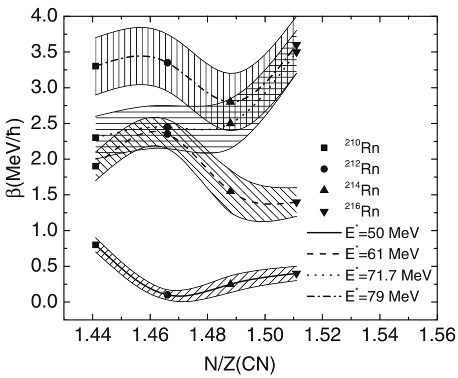

Figure 6. Variation of the best-fit values of β with N/Z (CN) of the CN at different excitation energies. The shaded areas represent the uncertainty in β associated with the experimental error in M_{pre}.

cannot be understood in terms of neutron partial widths alone as we have discussed in the previous section. It indicates a shorter fission half-life for ^{212}Rn compared to the neighbouring isotopes. Consequently, a minimum in β with respect to N/Z appears at ^{212}Rn. As ^{212}Rn has a closed neutron shell at $N = 126$, this N/Z dependence of β is also expected from the microscopic theory of one-body dissipation [6], where incoherent particle–hole excitations cause dissipation. In an isotopic chain with a closed shell nucleus, particle–hole excitation is easier for the non-closed nuclei than for the closed shell one and consequently, the former is expected to be more dissipative than the latter. Evidently, this concept is valid only at excitation energies where the shell structure persists. The present results thus suggest the presence of shell effects at the lowest excitation energy. Similar observation is also made in the ^{19}F+$^{194.196,198}$Pt systems as reported in the previous section of this paper [6–8], where measurement of pre-scission neutron multiplicities from Fr isotopes are reported. At higher excitation energies, however, the

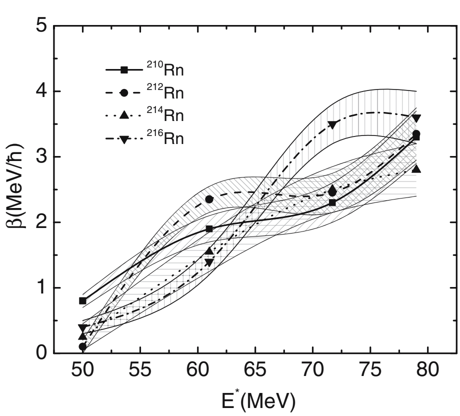

Figure 7. Variation of the best-fit values of β with excitation energy for different CN. The shaded areas represent the uncertainty in β associated with the experimental error in M_{pre}.

particle spectrum becomes more complex and the N/Z dependence of β does not present a clear picture. The excitation energy dependence of the best-fit β values is shown in figure 7. A strong (initial) excitation energy dependence of β can be observed here. Several factors not considered in the present statistical model calculations possibly contribute to the observed energy dependence [9].

5. Results from the ^{12}C+^{194,198}Pt systems

Here the pre-scission neutron multiplicities for the ^{12}C+^{194}Pt (forming ^{206}Po) and ^{12}C+^{198}Pt (forming the shell closed $N_C = 126$ compound nucleus ^{206}Po) systems were measured. Measurements were carried out at low excitation energies (49–62 MeV) to look specifically for the role of shell correction at the saddle point. The measured pre-scission neutron multiplicities for the ^{12}C+^{194}Pt system are larger than that for the ^{12}C+^{198}Pt system at all energies. The statistical model parametres were varied to fit simultaneously the measured neutron multiplicity data along with the available evaporation residue and fission cross-section data. The pre-scission neutron multiplicity data were found to play major role in constraining the statistical model parameters. It has also been observed that a considerable amount of shell correction at the saddle point is required to fit the experimental data [12].

6. Summary and conclusions

Results from some of the recent experiments carried out at NAND [13] facility, IUAC, New Delhi were reviewed. Pre-scission neutron excitation functions have been measured for the compound nuclei ^{213,215,217}Fr and analysed using the statistical model. We found the strengths of the reduced dissipation coefficient for nuclei which are away from shell closure to be very similar, though it is suppressed for closed-shell nuclei at low excitations. The experimental neutron multiplicities were compared with the statistical model predictions using the fission width due to Kramers. The best-fit β values of different nuclei are found to be quite different when shell effects are not included in the nuclear masses or fission barriers (figure 3). In particular, the β values for the closed shell ^{213}Fr nucleus are much smaller than those of the other two non-closed shell nuclei. However, when the shell-corrected nuclear masses or the experimental nuclear masses are used in calculations, the divergence among the β values of the three nuclei disappears to a large extent (figure 4). This clearly demonstrates the importance of using the correct neutron binding energy in neutron width calculation to extract the dissipation strength from fitting experimental neutron multiplicity.

A difference between the magnitudes of β-values of closed shell and non-closed shell nuclei however appears at low excitation energies, when a shell correction is incorporated in the fission barrier. Shell correction in fission barrier however does not affect the fitted values of the dissipation coefficient as strongly as is found when including shell effects in nuclear masses or in the level density parameters.

The measured pre-scission neutron multiplicities from ^{210,212,214,216}Rn compound nuclei increase with the increase of N/Z of the compound nuclei at all the excitation energies except the lowest one.

In the pre-scission neutron multiplicity analysis of $^{12}C+^{194,198}Pt$ (forming non-shell-closed ^{206}Po and shell-closed ^{210}Po compound nucleus), it is shown that considerable amount of shell correction at the saddle point is required to fit the measured experimental data.

Acknowledgements

This work was carried out at the NAND [13] facility of IUAC, New Delhi. This talk comprises a part of the Ph.D. thesis work of Varinderjit Singh and Rohit Sandal from Panjab University, Chandigarh and K S Golda (IUAC and Punjabi University, Patiala). The author is thankful to P Sugarhan, Akhil Jhingan, K S Golda, R P Singh, Varinderjit Singh, Rohit Sandal, Maninder Kaur, Savi Goyal, N Madhavan, S Mandal, A Saxena, S Kailas, K Mahata, S Santra, M B Chatterjee, R K Bhowmik, A Kumar, H Singh, N M Badigar, Santanu Pal, Jhilam Sadhukhan and Amit Roy for helping in various aspects of this project. NAND facility is a collaborative project of Panjab University, Chandigarh; Delhi University, Delhi; Karnataka University, Dharwad and IUAC, New Delhi and is supported through the DST, Govt. of India project no. IR/S2/PF-02/2007.

References

[1] K T R Davies *et al*, *Phys. Rev. C* **13**, 2385 (1976)
[2] M Thoennessen and G F Bertsch, *Phys. Rev. Lett.* **71**, 4303 (1993)
[3] T Schafer and D Teaney, *Rep. Prog. Phys.* **72**, 126001 (2009)
[4] N Auerbach and S Shlomo, *Phys. Rev. Lett.* **103**, 172501 (2009)
[5] V Singh *et al*, *EPJ Web Conf.* **17**, 16014 (2011)
[6] V Singh *et al*, *Phys. Rev. C* **86**, 014609 (2012)
[7] V Singh *et al*, *Phys. Rev.C* **87**, 064601 (2013)
[8] V Singh *et al*, *EPJ Web Conf.* **66**, 03080 (2014)
[9] R Sandal *et al*, *Phys. Rev. C* **87**, 014604 (2013)
[10] R Sandal *et al*, *AIP Conf. Proc.* **1524**, 167 (2013)
[11] R Sandal *et al*, *EPJ Web Conf.* **66**, 03006 (2014)
[12] K S Golda *et al*, *Nucl. Phys. A* **913**, 157 (2013)
[13] K S Golda *et al*, *Proc. DAE Symp. Nucl. Phys.* **51**, 626 (2006)
[14] H A Kramers, *Physica (Amsterdam)* **7**, 284 (1940)
[15] J Sadhukhan and S Pal, *Phys. Rev. C* **78**, 011603(R) (2008)
[16] J P Lestone and S G McCalla, *Phys. Rev. C* **79**, 044611 (2009)
[17] A V Ignatyuk *et al*, *Yad. Fiz.*, **21**, 485 (1975) [*Sov. J. Nucl. Phys.* **21**, 255 (1975)]
[18] A J Sierk, *Phys. Rev. C* **33**, 2039 (1986)
[19] W D Myers and W J Swiatecki, *Nucl. Phys. A* **601**, 141 (1996)