PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 85, No. 2
August 2015
pp. 357–365

Fission hindrance and nuclear viscosity

INDRANIL MAZUMDAR
Tata Institute of Fundamental Research, Mumbai 400 005, India
E-mail: indra@tifr.res.in

DOI: 10.1007/s12043-015-1050-4; ***e*Publication:** 29 July 2015

Abstract. We discuss the role of nuclear viscosity in hindering the fission of heavy nuclei as observed in the experimental measurements of GDR γ-ray spectra from the fissioning nuclei. We review a set of experiments carried out and reported by us previously [see Dioszegi *et al*, *Phys. Rev. C* **61**, 024613 (2000); Shaw *et al*, *Phys. Rev. C* **61**, 044612 (2000)] and argue that the nuclear viscosity parameter has no apparent dependence on temperature. However, it may depend upon the deformation of the nucleus.

Keywords. Fission; dissipation; level density.

PACS Nos 25.70.Jj; 25.70.Gh; 24.30.Cz

1. Introduction

The theory of rate equations concerning myriad processes in physics, chemistry, biology and engineering has a very rich history going back to the works of Van't Hoff and Arrhenius [1]. The subject has since been enriched by the seminal works of many pioneers to understand the processes of diffusion and transport through potential barriers in viscous media [2]. Most of these theories have been developed to address classical processes. One of the most important quantum mechanical processes of large-scale mass transfer across a barrier in a dissipative medium is that of the nuclear fission. The phenomenon of nuclear fission is nearly as old as the modern nuclear physics. It provides a fascinating example of nuclear collective motion where a correlated quantum many-body system splits into two or more fragments. The first and by far the most famous theory of nuclear fission was put forth by Bohr and Wheeler immediately on the heel of the discovery of nuclear fission [3]. The transition-state model of Bohr and Wheeler determines the probability of fission in terms of the ratio of transition states at the saddle point to the level density of the compound nucleus (CN) at an excitation energy E. The transition-state model met with great success in understanding the fission phenomenon and established itself as one of the landmark models in nuclear physics. The work of Bohr and Wheeler was closely followed by a seminal paper by Kramers that treated the problem dynamically using a model based on Fokker–Planck approach [4]. Kramers' work addressed the phenomenon of large-scale mass flow across a barrier in a dissipative medium. He studied the role of viscosity in slowing down the diffusion rate in comparison to the decay rate without viscosity predicted by Bohr and Wheeler. It is of great historical significance that Kramers' path-breaking work went nearly unnoticed in nuclear physics for the next several decades.

The advent of heavy-ion-induced fusion–evaporation and fusion–fission reactions have generated a very rich body of experimental observations over the last four decades. These experiments have rejuvenated the interest in nuclear dissipative processes and have revived Kramers' dynamical approach to understand nuclear fission at finite temperature and angular momentum. It has been nearly three decades since the observation of unexpectedly large yield of pre-scission charged particles and neutrons in heavy-ion-induced fusion–fission reactions [5,6]. These observations were followed by other measurements that showed excess yield of giant dipole resonance (GDR) γ-rays from heavy compound nuclei over what is expected from the statistical model of Bohr and Wheeler [7]. The early results of neutron and GDR γ measurements were summarized by Hilscher and Rossner and Paul and Thoennessen, respectively [8,9].

The measurements of GDR γ-rays from fissioning heavy nuclei were started by the Stony Brook group who studied systems like $^{16}O + {}^{208}Pb$, $^{32}S + {}^{nat}W$ and $^{32}S + {}^{208}Pb$. In all these systems GDR γ-rays were measured in coincidence with the fission fragments ensuring the detection of GDR γ-rays from the excited fission fragments and also the CN that would eventually undergo fission. The most important finding of these measurements was an excess yield of γ-rays from the fissioning compound systems over what is expected from the standard statistical model of Bohr and Wheeler. This excess yield was interpreted as a signature of the slowing down of the fission process due to nuclear viscosity leading to higher yield of GDR γ-rays from the compound system [10–12]. The analysis of these measurements also hinted at a rapid rise of viscosity parameter γ with temperature, favouring a rather strong temperature dependence (T^2) [13]. Such a strong temperature dependence of the viscosity parameter can be understood in terms of a two-body process as the underlying mechanism [14]. This conclusion is, however, at variance with the one-body mechanism of nuclear viscosity [15]. A better understanding of the exact dependence of the viscosity parameter on temperature (T^2 or linear T dependence) and angular momentum prompted revisiting the problem and carrying out systematic measurements over a wider range of excitation energy and angular momentum than reported in the previous papers. It was also intended to probe any turning over or reduction of γ at higher excitation energy as might be expected for a Fermi liquid [16]. As a part of this endeavour, absolute γ-ray/fission multiplicity was measured for two compound systems, namely, ^{224}Th and ^{240}Cf. It is worth noting that since the discovery of GDR decay from hot-rotating nuclei, the experimentally measured γ-ray spectra are always compared with the theoretical calculations by normalizing in the low-energy region of around 4–5 MeV. An absolute scale measurement of GDR γ/fission multiplicity significantly reduced the uncertainties associated with the extraction of statistical model parameters used in the calculations to reproduce the data. In this brief review, we recall these measurements and the primary conclusions that emerged. We also touch upon a series of more recent theoretical results which lead to similar conclusion regarding the temperature/angular momentum dependence of the nuclear viscosity paratmeter γ. We argue that the topic of viscosity hindering nuclear fission is as alive as it was more than a decade ago and should be pursued with renewed vigour.

2. Nuclear viscosity of hot rotating ^{224}Th

The ^{224}Th CN was populated at five different beam energies from 100 to 177 MeV by bombarding a 99.9% isotopically enriched, 980 μg/cm^2 thick self-supporting ^{208}Pb target with pulsed ^{16}O beam from the Stony Brook Tandem-LINAC Facility. The initial excitation energy of the CN, so formed, varied from 46 to 118 MeV. The details of the reactions, namely, fusion cross-section, average fission barrier, temperature, etc., of the CN are provided in [17]. The high-energy GDR γ-rays were measured in coincidence with the fission fragments in two different γ-ray spectrometers: (1) a large NaI(Tl) detector and (2) a compact seven-element array of BaF_2 detectors. The fission fragments were detected in four multiwire avalance counters arranged in a lamp-shade geometry. The experimental set-up was similar for the subsequent measurement to study GDR decay from the fissioning ^{240}Cf. The experimental details are provided in [17,18] and will not be discussed in this study. The fission-gated γ-ray spectra [17] are shown in figure 1. Figure 1a shows the spectra recorded in the BaF_2 array and the NaI(Tl) data are shown in figure 1b. The γ-ray spectra contain GDR γ-rays from both the CN and the fission fragments. The GDR centroids for the CN and the fission fragments are centred around 11 and 15.5 MeV, respectively. The solid lines are the calculated γ-ray/fission multiplicity using the statistical model code CASCADE considering γ decays from the CN and fission fragments. The excess yield of γ-rays, over what is expected from the statistical model calculations, in the region of the CN GDR for both the detectors is rather prominent and is in exact conformity with all the previous measurements [7,10–13]. The CASCADE calculations (solid lines in figure 1) used in this first level of analysis do not include any viscosity or temperature-dependent nuclear level density parameter a. The γ and particle decay are calculated using the standard prescriptions as provided in [17]. The fission of the CN is calculated using the Bohr–Wheeler formula based on the saddle-point transition state model [3,17]. The fission rate is determined by integrating over all available states at the saddle point. This can be reduced to a simpler form of $\Gamma_{\mathrm{f}}^{\mathrm{BW}} = T/2\pi[\exp(-E_{\mathrm{f}}/T]$ [19]. It is to be noted that in all our analyses [17,18] the exact integrals were calculated instead of using the simplified form. The second level of analysis involved a series of CASCADE calculations involving viscosity and temperature-dependent nuclear level density. The presence of nuclear viscosity reduces the Bohr–Wheeler fission width and prolongs the survival of CN against fission. An additional effect of nuclear viscosity is the transient build-up of the fission flux moving over the barrier [20]. The relevant expressions and details of the Kramers' formalism plus the dynamical transient effect, as implemented in our CASCADE calculations are provided in [17,18]. The temperature dependence of nuclear level density was implemented by following the Ignatyuk–Reisdorf formalism [17,18]. We also considered another ansatz for a stronger temperature dependence of nuclear level density parameter a [21]. A series of calculations were carried out to get the best reproduction of the experimental spectra. Here, we summarize the result of the calculations and the primary conclusions. It was observed that the CASCADE calculations with Ignatyuk–Reisdorf formalism for nuclear level density and a fixed value

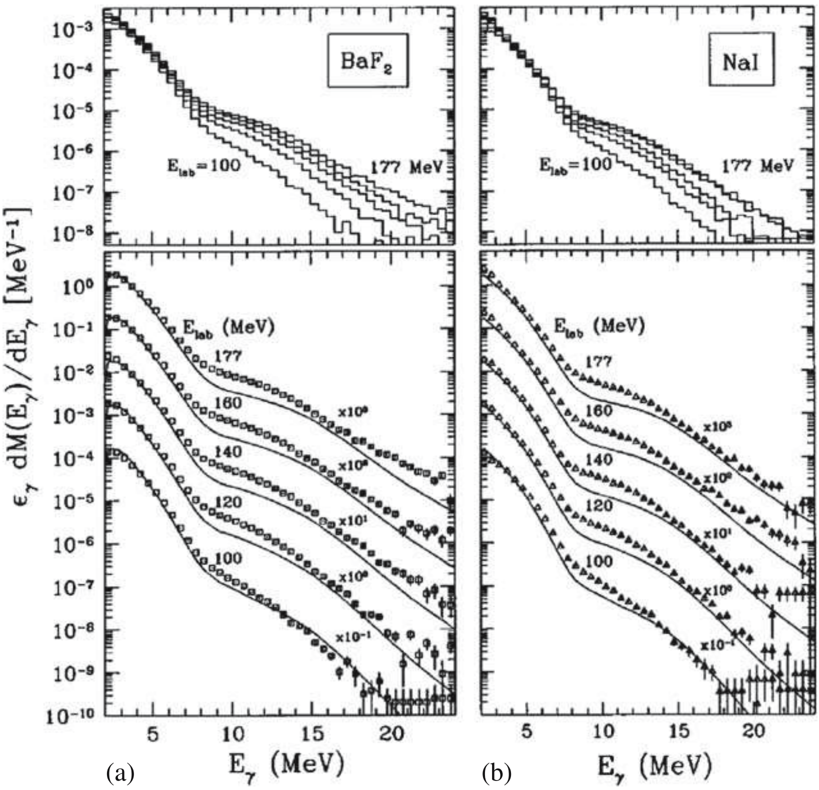

Figure 1. Absolute γ-ray/fission multiplicities for the ^{16}O + ^{208}Pb reaction measured in BaF_2 array (**a**) and large volume NaI(Tl) detector (**b**). The solid lines are CASCADE calculations without viscosity.

of Kramers' viscosity parameter γ failed to reproduce the spectra. However, excellent agreement between the data and CASCADE calculations could be obtained by considering a temperature-dependent viscosity parameter γ ($\gamma = 0.2 + 1.7T^2$) and a rather strong temperature dependence of nuclear level density parameter [21]. The top panels of figure 2 show the best reproduction of the γ-ray spectra [17] both in the full and linearized forms. The experimental γ-ray spectrum was linearized by fitting it with CASCADE calculation without any GDR strength and then dividing the experimental spectrum by the fitted spectrum. The same method was applied to get the linearized form of the calculated spectrum. The lower panels of figure 2 compare the CASCADE-generated spectra for neutron multiplicities, evaporation residue (ER) and fission cross-sections with the experimental data obtained from literature. In summary, a temperature-dependent viscosity parameter γ and a strong temperature-dependent level density ansatz could consistently reproduce GDR γ and neutron multiplicity along with ER and fission cross-sections for the fissioning ^{224}Th system. However, the increase in bombarding energy simultaneously increases the temperature and average angular momentum of the ^{224}Th system. This prohibits unambiguous determination of the exact dependence of viscosity parameter γ on temperature or on the deformation of the system. To investigate the possibility of any

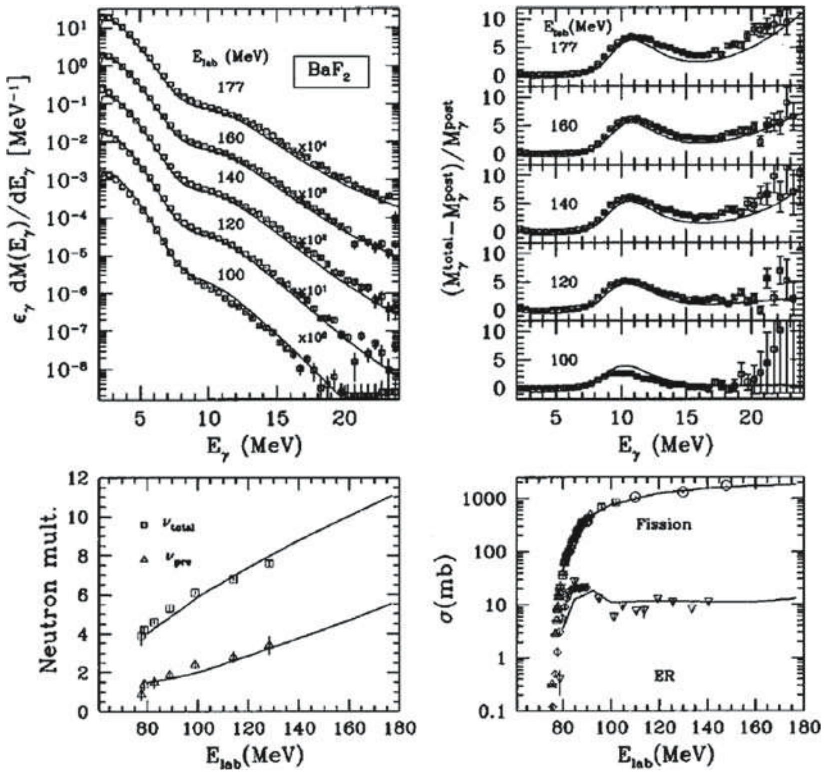

Figure 2. γ, neutron multiplicities and ER cross-sections for the $^{16}O + ^{208}Pb$ reaction compared with the calculations including temperature-dependent (T^2) viscosity parameter γ and a strong temperature-dependent nuclear level density.

deformation dependence the spectra from ^{224}Th for all the beam energies were fitted with constant (temperature independent) $\gamma = 2$ for decay from inside the saddle and constant γ =10 for the saddle-to-scission motion. This kind of deformation dependence would suggest one-body dissipation mechanism. It is to be noted that the compound system inside the saddle is expected to be compact and highly deformed during the saddle-to-scission path. The calculations with deformation-dependent viscosity parameter resulted in equally good reproduction of the data (γ, neutron multiplicities, ER and fission cross-sections) as with the temperature-dependent viscosity parameter (figure 2). The viscosity affects both the pre-saddle and saddle-to-scission motion of the compound system. In case of ^{224}Th both pre-saddle and saddle-to-scission emissions contribute to the spectra. If the viscosity (parameter) depends upon deformation it will be much higher for saddle-to-scission than for the pre-saddle stage. If larger saddle-to-scission viscosity has increasingly higher contribution with beam energy to the average viscosity, it will be impossible to uniquely determine the exact dependence of γ on temperature and deformation. It is therefore imperative to choose a system where the emissions from the pre-saddle and saddle-to-scission stages can be decoupled. Here, we were guided by the predictions of Weidenmuller and collaborators who predicted a very strong temperature dependence of the transient phenomenon associated with the temporal evolution of fission width Γ [20,22]. According to these researchers, as the temperature of the CN increases or the ratio of barrier height to temperature (E_{barrier}/T) decreases, the flux of the compound nucleus assaults the barrier rapidly, eventually leading to the motion of the flux to the saddle point in a swoop. Such a scenario would lead to very little or no contribution to the overall emission from the pre-saddle stage. This led us to the selection of a much heavier system of ^{240}Cf with much diminished barrier height compared to ^{224}Th for a given temperature and angular momentum. It is expected that compared to ^{224}Th, in ^{240}Cf, the emission will be dominated by the saddle-to-scission contribution.

3. Nuclear viscosity of hot rotating ^{240}Cf

The ^{240}Cf CN was populated by bombarding a 870 μg/cm^2 ^{208}Pb target by ^{32}S beam at seven energies from 180 to 285 MeV. The reaction parameters are summarized in [18]. Figure 3 presents the spectra for all the beam energies along with the CASCADE

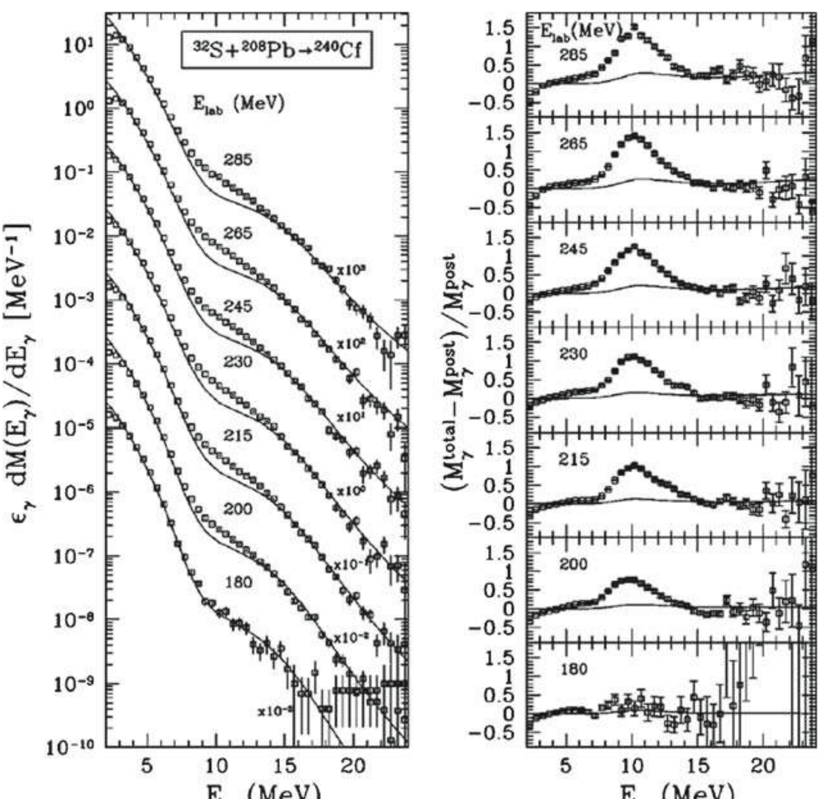

Figure 3. Absolute γ-ray/fission multiplicity measured from ^{240}Cf. The solid lines are CASCADE calculations without viscosity.

calculations without viscosity ($\gamma = 0$ for both inside and outside the saddle). Clearly, the statistical model fails to reproduce the yield of GDR γ from the compound system. The analysis including viscosity was carried out in two steps. In the first step, CASCADE calculations were done for the spectra at each energy by varying the viscosity parameter γ from 0.1 to 40 to obtain the best reproduction of the data. It was observed that the data could not be reproduced in the CN region for the viscosity parameter $\gamma < 5.0$. Much better fits were obtained for γ varying between 5 and 10. However, for γ greater than 15 the high-energy tails were underpredicted. In the next step, the spectra were fitted using a fixed value of the viscosity parameter $\gamma = 2$ for inside the saddle and $\gamma = 10$ for the saddle-to-scission motion. These calculations resulted in excellent agreement with the data (figure 4). At this stage it is necessary to point out the important differences between ^{240}Cf and ^{224}Th. The fission barrier for ^{240}Cf is only 1.6 MeV at $J = 0\hbar$ compared to 5.7 MeV for ^{224}Th. Furthermore, the ^{32}S + ^{208}Pb reaction has considerable quasifission cross-section. Therefore, the contribution of γ and particle emission from inside the saddle is rather small and the measured GDR γ-rays are emitted primarily during the saddle-to-scission motion. Thus, one can conclude that the measured nuclear viscosity in ^{240}Cf characterizes the viscosity of the saddle-to-scission motion. A deformation-dependent

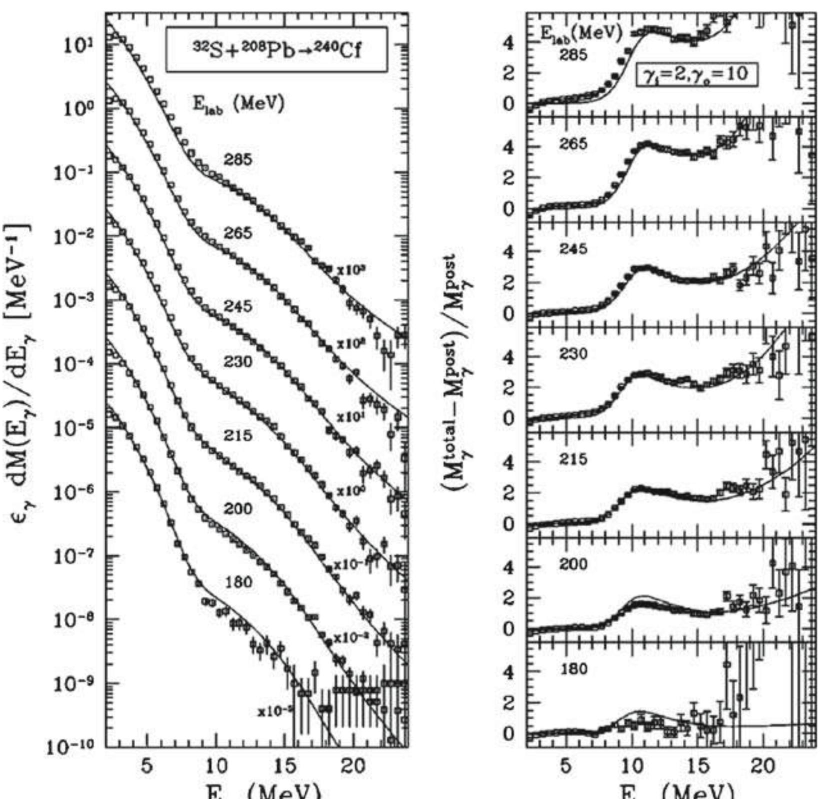

Figure 4. Experimental spectra from ^{240}Cf compared with CASCADE calculations using viscosity parameter $\gamma = 2$ inside the saddle and $\gamma = 10$ outside the saddle.

nuclear viscosity modelled here by a small constant dissipation ($\gamma = 2$) inside the saddle and a large constant dissipation ($\gamma = 10$) outside the saddle combined with a temperature-dependent level density ansatz provided the best fit to the data. It is also important to note that the same value of $\gamma = 10$ fitted all the spectra up to the highest beam energy. This is also understandable from the fact that the overall deformation of the compound system from the saddle to scission path does not vary significantly with higher beam energies. One can, therefore, conclude that the extracted nuclear viscosity parameter γ does not depend on temperature.

4. Summary and discussion

In this contribution we have reviewed our measurements which were carried out to investigate the dependence of nuclear viscosity parameter γ on temperature and deformation. Absolute γ/fission multiplicities were measured for ^{224}Th and ^{240}Cf. A systematic study of both the systems over a wide range of excitation energies does not reveal any temperature dependence of the viscosity parameter γ. However, γ may have a deformation dependence. It is inferred that one-body dissipation is very likely the underlying mechanism that reduces the fission width and increases the lifetime of the compound system.

Our analysis is carried out by incorporating the Kramers' model within a statistical model formalism. We are also guided by the predictions of Weidenmuller and collaborators regarding an increasing transient effect that brings the fission flux very rapidly to the saddle point with increasing temperature and diminishing fission barrier in our interpretation of the data. It is important to compare our analysis with the full-fledged dynamical calculations of nuclear fission involving viscosity. It is encouraging to note that in the intervening period since the publication of our results, a series of dynamical calculations based on Langevin analysis discuss the shape or deformation dependence of nuclear viscosity [23–25]. In fact, a specific calculation for the ^{16}O + ^{208}Pb system [23] show that the energy dependence of the dissipation strength extracted from fitting experimental data gets substantially reduced when spin dependence is taken into account.

It has been pointed out by McCalla and Lestone that they do not find any temperature dependence of the reduced nuclear dissipation parameter from their analysis and conclude a shape dependence of nuclear level density parameter in the range of the theoretical estimates [26]. They also conclude that the conclusion arrived in our work [17] of apparent temperature dependence of viscosity parameter is incorrect. We emphasize that there is no contradiction in the general conclusions arrived by McCalla and Lestone and our analysis. In [17] we did conclude, as discussed in this paper, that the GDR spectra from fission ^{224}Th can be fitted by considering both temperature and shape dependence of the viscosity parameter γ. This ambiguity arises primarily because of the emission from both pre-saddle and saddle-to-scission stages. An unambiguous dependence of viscosity parameter on temperature was never concluded in [17]. In fact, this was resolved by carrying out the measurements from a heavier system of ^{240}Cf where the emission is primarily from the saddle-to-scission stage and the contribution from the pre-saddle stage becomes very minimal. This effectively separates or decouples the γ-ray contributions from pre-saddle and saddle-to-scission stages. The deformation of the nucleus from saddle-to-scission remains more or less similar for all the beam energies and one can, therefore, study the effect of temperature on the viscosity parameter. The analysis of the ^{240}Cf data led us to conclude that there is no apparent dependence of viscosity parameter γ on temperature. We had also, like McCalla and Lestone, discussed at length the importance of shape dependence of nuclear level density and incorporated the Reisdorf formalism in our analysis.

We may conclude that the role of viscosity in the fission of hot and rotating nucleus and its dependence on temperature, angular momentum, isospin, etc., continues to be both deeply fascinating and challenging with wider ramifications beyond the immediate topic of nuclear fission. It is essential to carry out more precision and exclusive measurements backed by sophisticated theoretical analysis. It is to be noted that all the analysis and theoretical calculations mentioned in this paper are primarily classical while dealing with the atomic nucleus that is primarily quantum mechanical. A fuller understanding of the nuclear dissipation process within the framework of quantum mechanics continues to be a daunting challenge.

Acknowledgements

The experiments presented in this paper were carried out at the Stony Brook University, in close collaboration with P Paul, I Dioszegi, N P Shaw and A Hatzikoutelis.

References

[1] S Arrhenius, *Z. Phys. Chem.* **4**, 226 (1889)
[2] P Hanggi *et al*, *Rev. Mod. Phys.* **62**, 251 (1990)
[3] N Bohr and J A Wheeler, *Phys. Rev. C* **56**, 426 (1939)
[4] H A Kramers, *Physica* **7**, 284 (1940)
[5] L C Vaz *et al*, *Z. Phys. A* **315**, 169 (1984)
N N Ajitanand *et al*, *ibid.* **316**, 169 (1984)
[6] D J Hinde *et al*, *Phys. Rev. Lett.* **52**, 986 (1984)
[7] M Thoennessen *et al*, *Phys. Rev. Lett.* **59**, 2860 (1987)
[8] D Hilscher and H Rossner, *Ann. Phys.* **17**, 471 (1992)
[9] P Paul and M Thoennessen, *Ann. Rev. Nucl. Part. Sci.* **44**, 65 (1994)
[10] R Butsch *et al*, *Phys. Rev. C* **44**, 1515 (1991)
[11] I Dioszegi *et al*, *Phys. Rev. C* **46**, 627 (1992)
[12] D J Hofman *et al*, *Phys. Rev. Lett.* **72**, 470 (1994)
[13] D J Hofman *et al*, *Phys. Rev. C* **51**, 2597 (1995)
[14] K T R Davies *et al*, *Phys. Rev. C* **13**, 2385 (1976)
[15] J Blocki *et al*, *Ann. Phys.* **113**, 330 (1978)
[16] W R Abel *et al*, *Phys. Rev. Lett.* **17**, 74 (1966)
[17] I Dioszegi *et al*, *Phys. Rev. C* **61**, 024613 (2000)
[18] N P Shaw *et al*, *Phys. Rev. C* **61**, 044612 (2000)
[19] R Vandenbosch and J R Huizenga, *Nuclear fission* (Academic Press, 1974)
[20] P Grange and H A Weidenmuller, *Phys. Lett. B* **96**, 26 (1980)
[21] S Shlomo and J B Natowitz, *Phys. Rev. C* **44**, 2878 (1991)
[22] H A Weidenmuller and Zhang Jing-Shang, *Phys. Rev. C* **29**, 879 (1984)
[23] J Sadhukhan and S Pal, *Phys. Rev. C* **78**, 011603(R) (2008)
[24] J Sadhukhan and S Pal, *Phys. Rev. C* **79**, 064606 (2009)
[25] J Sadhukhan and S Pal, *Phys. Rev. C* **81**, 031602 (2010)
[26] S G McCalla and J P Lestone, *Phys. Rev. Lett.* **101**, 032702 (2008)