Emergence of fragment spin bearing modes in fission: Remarks on a non-equilibrium thermodynamic treatment

Bency John
Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA
email: bjohn@barc.gov.in

Introduction

Spontaneous generation of angular momentum bearing modes in fission, that cause gamma ray emissions from fission fragments, is a barely understood aspect in nuclear fission theory. This aspect, however, is very important for the determination of prompt gamma spectra in low energy fission which are essential in high accuracy calculations of gamma ray heating and damage of nuclear reactor components. In a nucleus, rotation is a complicated interplay between collective and intrinsic degrees of freedom. This situation is further enriched in the fission process since the spontaneous thermal generation of rotational modes arise near the scission stage where the nucleus is transformed into an excited di-nucleus under non-equilibrium conditions. The intricate behavior of intrinsic degrees and collective rotational degrees can be treated under approximations by choosing a small set of collective variables, and surely the definition of right collective variables is a very important task. As excitation energy plays a major role in the evolution of scission configurations, a finite excitation-energy formalism that defines relevant collective space need to be used.

Emergence of spin bearing modes

Rotational motions in a progressively necking-in pre-scission nucleus can be understood on the basis of collective modes induced by the fast elementary nucleon transfer processes[1]. The exchange, back and forth, of nucleons in such a di-nucleus has been treated in the wall and window formulae for one-body dissipation in heavy ion collisions[2]. It has been pointed out, on the other hand, that pair drifts of nucleons from the neck region in pre-scission nucleus initiates a more organized form of motion as angular momentum bearing modes[3,4]. Justification for the pair-drift mechanism is simple. In the final non-equilibrium phases, the volume from which the nucleons finally recede to pre-fragments is spatially confined (on the average) to the neck region. Sum total of net linear momentum of the receding nucleons from the neck region is zero ($\Sigma\vec{p_i} = 0$) to keep the center of mass at rest. Nucleon recesses at this stage are thus not totally random but rather as pairs moving in opposite directions to balance momentum. It can be shown that this organised motion leads to the bulk phenomenon of shear stress between moving boundaries of the forming pre-fragments that will lead to a gradual build-up of spin bearing wriggling and twisting modes. This is beyond what is described by the window formula and thus a different theoretical toolset becomes necessary. One has at hand a situation where emergence of collective motion from among unstructured excitation occur under non-equilibrium conditions. Concepts that might explain the emergences in context of these nuclear processes are discussed in this work(see also [3]) for the first time.

The irreversible motion beyond the saddle (pre-scission motion) faces instability and increased fluctuations. Under certain conditions this type of motion may become a source of order, and may lead to a new type of dynamic states of matter called “dissipative structures”[5]. Required energy comes from the enthalpy change from the saddle to scission motion. This energy will feed the above discussed ‘pair drifts’ and eventually the rotational wriggling and twisting modes. The time-scale for the fission degree of freedom is slow whereas the rotational and intrinsic degrees are relatively very fast, fastest being the intrinsic degrees. As the fast degrees are far more numerous, their mutual equilibration allows an *isothermal* description for themselves at various points of evolution of the relatively slower degrees of freedom (Gibb's approach).

In the present work, the pre-scission nucleus is treated as a closed thermodynamic system, within which the thermodynamics of a (canonical) sub-system of spontaneous rotational modes that can exchange energy with its surrounding has been studied. For the rotational modes the model assumes a transient quasi-stationary process that is approaching to an equilibrium. Transient quasi-stationary processes can occur in a sub-system like the above. Entropy of this mesoscopic sub-system increases due to entropy generated in spontaneous processes and decreases when heat is expelled into the surrounding. It can be shown that the rate of change of entropy for the rotational modes is given by

$$\frac{d\tilde{S}^{rm}}{dt} = e_p^{rm} - \frac{\tilde{h}_d^{rm}}{T} \quad , \qquad (1)$$

where e_p^{rm} is the entropy production rate, $\tilde{h}_d^{rm}$ is the heat dissipation and T is the temperature defined in the Gibb's isothermal approach.

The entropy production rate e_p^{rm} is just the dissipation at the level of the associated free energy. The free energy, $F^{rm}(t)$, always decreases until it reaches its minimum at the equilibrium. The free energy dissipation rate is given by

$$-\frac{dF^{rm}(t)}{dt} = f_d = Te_p^{rm}. \qquad (2)$$

A generalized non-equilibrium free energy $F^{rm}(t)$ for the rotational modes ($k_BT = 1$) can be defined as follows.

$$F^{rm}(t) = \sum_j P(j,t) ln \frac{P(j,t)}{P_{eq}(j)} \qquad (3)$$

From this it can be seen that the entropy production rate e_p^{rm} is independent of the mechanical details of the environment; Whereas, the heat dissipation $\tilde{h}_d^{rm}$ is not. The latter involves the entropy change in the surrounding as a result of heat expelled into it and different formalisms [6] are available for the heat dissipation calculation.

Using the equation for $P(j,t)$ and $P_{eq}(j,t)$ given in[3], $F^{rm}(t)$ was calculated for a fragment from symmetric fission of ^{236}U nucleus as given in Fig.1. Values of heat dissipation $\tilde{h}_d^{rm}$ have been obtained using Ref.[6] . $\frac{d\tilde{S}^{rm}}{dt} = \Sigma_\rho J_\rho X_\rho \geq 0$ where J_ρ are the rates of various associated irreversible processes involved and X_ρ are the corresponding generalized forces [5]. Further work is in progress to include the relative translational motions of the fragments.

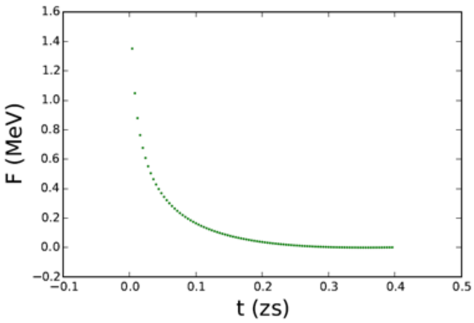

Fig.1 Free energy as a function of time

Discussion

For far from equilibrium systems, the free energy function assumes a leading role, and the entropy production in a non-equilibrium system is regarded as a matter of primary importance. The interest is not only focused on why the entropy increase as the non-equilibrium system evolves but also on how the entropy is produced. The present work probes some of these important points in context of nuclear processes.

Author is grateful to his colleagues from Nuclear Physics Division for useful comments and discussions.

References

[1] T. Dossing and J. Randrup, Nucl. Phys. **A433**, 215 (1985)
[2] J. Blocki et al., Ann. Phys. **113**, 330(1978)
[3] Bency John, Proc. DAE Symp. Nucl. Phys. **60**, p.402 (2015); ibid **61**, p402(2016)
[4] Bency John, Pramana-J. Phys. **85,** 267 (2015); Bency John and S. K. Kataria , Phys. Rev. C **57**, 1337(1998)
[5] I. Prigogine, Nobel Lecture, 8 Dec. 1977
[6] C. Simenel and A. S. Umer, Phys. Rev. C **89**, 031601(R) 2014