Emergence of fragment spin bearing modes in fission: Non-equilibrium thermodynamic approach

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A widely open problem in nuclear fission theory is the sizable spontaneous generation of angular momenta in fragments. The angular momenta thus generated in deformed fragments signify emergence of ordered collective motion from among unstructured excitations at a stage far away from equilibrium conditions. The influence of this emergence, i.e. , the increase in number of rotational degrees of freedom that have not yet equilibrated on the overall dynamics of the fissioning system is not yet understood[1]. Non-equilibrium may become a source of order, and irreversible processes may lead to a new type of dynamic states of matter called "dissipative structures"[2]. These structures are of special interest in a wide range of fields like chemistry and biology. Answer to whether such view-points prevail in case of the nuclear fission process is one of the objectives of the present study.

The intricate behavior of a large number of nucleons near the scission stage can only be described by general average properties of a few variables. One of the main hypotheses of non-equilibrium thermodynamics is that the thermodynamic variables defined in each sub-system of a conveniently partitioned system admit the same interpretation as in equilibrium. The other main hypothesis being the 'entropy production' of any isolated system is always non-negative. Partitioning of the near-scission nucleus in to subsystems for treating in the non-equilibrium thermodynamic-way naturally leads to the sub-systems of pre-fragments. The Two Centre Shell Model Parameterization (TCSMP) describes compact shapes, separated fragments and also in-between shapes that occur in the fission process[3]. At present it is the only parameterization having this facility, and for this reason, we have used TCSMP in our calculations.

A mechanism of pair-drifts from the neck-region as a reasonable description for the fission-process towards the final split has been proposed recently[4,5]. As the nucleus elongates and pre-fragments are formed, there arises an increase in number of rotational degrees of freedom that have not yet equilibrated. In the final phases, the volume from which the nucleons recede to pre-fragments is spatially confined (on average) to 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. This condition at the same time maximizes the thrust parameter defined as T = Maximum of $\vec{n_i}$ ($\Sigma_i |\vec{p_i}.\vec{n_i}| \ / \ \Sigma_i |\vec{p_i}|$) where $\vec{n_i}$ is a unit vector pointing in any direction. It can be shown that this leads to the bulk phenomenon of shear stress between moving boundaries of the forming pre-fragments. This in turn lead to a gradual build-up of spin bearing wriggling and twisting modes. With this as starting point, the initial non-equilibrium thermodynamic description of the phenomenon has been worked out.

Let $P(E_1^i, j, t)$be the probability density of finding one of the pre-fragment (indexed as '1') at time t with angular momentum j, and excitation energy buildup E_1^i, on its way to building-up of the spin-bearing modes and finally equilibration, as

$$P(E_1^i, j, t) = \frac{\rho(E_1^i, j)}{\Sigma_j \ \rho(E_1^i, j)} = \frac{\frac{(2j+1)}{2\sigma^2}\exp(-\frac{j(j+1)}{2\sigma^2})}{\Sigma_j \frac{(2j+1)}{2\sigma^2}\exp(-\frac{j(j+1)}{2\sigma^2})},$$

and let $P_{eq}(E_1^*, j)$ be the equilibrium distribution defined in the same form with a corresponding set of parameters. The spin cut-off parameter $\sigma^2 = \frac{IT}{\hbar^2}$ is calculated with moment of inertia and temperature calculated for various stages of the pre-fragment formation.

By using the Gibbs entropy postulate, the contribution to entropy that arises from deviations of the probability density $P(E_1^i, j, t)$ from its equilibrium value $P_{eq}(E_1^*, j)$ is given by

$$\delta S = -k_B \int \delta P(j,t) ln \frac{P(j,t)}{P_{eq}(j)} dj.$$

Entropy production per unit time is given by

$$\frac{dS}{dt} = \Sigma_\rho J_\rho X_\rho \geq 0 ,$$

where J_ρ are the rates of various irreversible processes involved and X_ρ the corresponding generalized forces [2] . For ^{236}U nucleus undergoing fission, values of δS has been calculated for various values of excitation energy build-ups in the pre-fragments. The equilibrium temperature for the selected fragment masses is assumed to be equal to 1.2 MeV which corresponds to 16.9, 21.6 and 25.6 MeV for A=94, 120 and 140, respectively, when the level density parameter is taken as $a=A/8$. The results are shown in Fig. 1. At the low excitation energies, the scope for addition to the entropy (δS) is large, and as the excitation reaches that of equilibrium temperature value, δS goes to zero. The same results apply for the complementary pre-fragment.

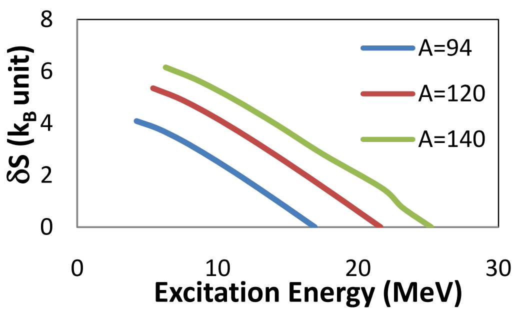

Fig. 1 Additions to the entropy that arises from deviations of the probability density from its equilibrium value in pre-fragments of mass A.

The time scale of the events near scission may become specific to the potential energy changes in this region. Within the TCSMP, the optimal shape that fissioning nuclei attain just before the scission has been described in detail in Ref.[6], considering also the mass asymmetry and elongation at scission point. The present work will be extended by taking these specificities into account. With these supplementary assumptions, the entropy production $\frac{dS}{dt} \geq 0$ can be established in pre-scission nucleus and this defines a region of local equilibrium in terms of an extended set of (angular momentum) degrees of freedom.

The exchange, back and forth, of nucleons between two nuclei connected by a narrow neck has been treated in the window formula for one-body dissipation in heavy ion collisions[7]. Pair drifts of nucleons from the neck region in pre-scission nucleus initiates a more organized form of motion, namely spin bearing wriggling and twisting modes, and these have not been treated before using the tools of dissipative structures. The approach we have presented here is a beginning in this direction. Further results obtained will be presented.

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