Present Status of the Theory of Fission of hot Nuclei

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Recent progress in the theory of fission of hot nuclei is reported. We discuss in particular the properties of the friction form factor as function of the deformation (and possibly of the temperature) which are necessary to reproduce data concerning fission of hot nuclei and its accompanying light particle and γ-ray emission. Recent theoretical work gives support to a phenomenological friction form factor (proposed some time ago[1)]), which is weak for compact shapes and increases on the way to scission.

1.Introduction

Fission is one of the main decay channels after fusion of two heavy ions. The following discussion is restricted mainly to systems for which Bohr's hypothesis is valid, which states that the formation and decay of the compound nucleus are independent processes, i. e. fission starts only after a completely equilibrated compound nucleus has been formed. We do not deal with systems having a considerable fast fission component or with systems where the dynamics from capture to the formation of the compound nucleus plays a role. These topics are elsewhere discussed in these conference proceedings, see the contributions of Hinde, Trotta, Hannape, Abe, Aritomo and Rummel.

In the following, we report on progress made since the the review article[2)] appeared in our understanding of fission of hot nuclei and its acompanying processes (light particle and γ-ray emission). Whereas there is no doubt that a Langevin description plus a Monte Carlo treatment of the evaporation processes provides the most adequate dynamical description (one obtains physical insight by e.g. sampling distributions which tell which particle with a particular energy and position is emitted along the fission path at a particular time), there is less agreement on the input quantities which enter the description. (i) A fusion model has to be applied in order to obtain the initial spin distribution for fission. (ii) A choice of the relevant variables has to be made for the shape parametrization with which the driving force is constructed (it is not yet common practice to use the free energy or the entropy). (iii) An evaporation model has to be coupled to the dynamics. (iv) After reaching a stationary value for the fission width, a modified statistical model has to be added for computational reasons. (v) Most controversial is the choice of the friction form factor, the discussion of which is the main topic of this article. We start in

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Section 2 with reporting on multi-dimensional Langevin calculations,[3] which solve a long-standing problem concerning the width of the kinetic energy distribution of the fission fragments. In Section 3 we discuss a chaos-weighted wall formula which supports the phenomenological friction form factor proposed in Ref.[1] (see also[2,4]) in order to reproduce simultaneously data for fission probabilities and pre-scission neutron multiplicities, which was not possible within a statistical model. This friction form factor was subsequently used extensively to analyse experimental data on pre-scission neutron multiplicities and fission (respectively survival) probabilities, pre-scission neutron energy spectra, pre-scission charged particle (p,α) and giant-dipole γ multiplicities and spectra, evaporation residue cross sections, fission times, temperatures at scission, and the fission angular distribution; see the review article.[2] In Section 4 we turn to a discussion of a possible temperature dependence of the friction form factor, and make some remarks on quantal corrections in Section 5 before concluding.

2. The kinetic energy distribution of fission fragments

There have been attempts to explain the measured correlation between the kinetic energy distribution of fission fragments and pre-scission neutron multiplicities with two dimensional (elongation and constriction) Langevin dynamics by Wada et al.,[5] who use one-body dissipation (wall friction) and by Tillack et al.,[6] who use two-body viscosity. In both investigations the width of the kinetic energy distri-
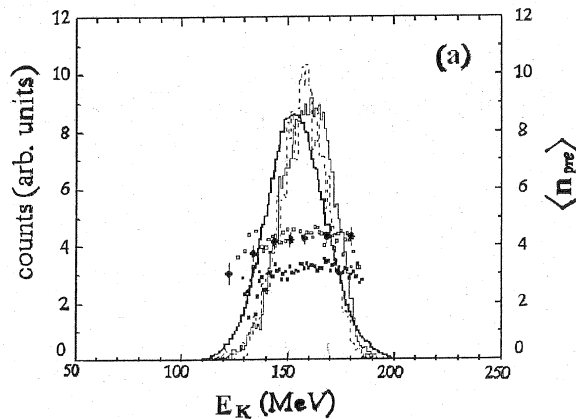

Fig. 1. The measured kinetic energy distribution (fat solid histogram) in coincidence with the pre-scission neutron multiplicities (filled circles) are compared with the corresponding calculated quantities with reduced widow friction: $K_s = 0.25$ (dashed histogram, open squares), and $K_s = 0.5$ (thin solid histogram, filled squares), from Ref.[3]

bution came out by about a factor of two too narrow. This was attributed to the neglect of the mass asymmetry degree of freedom in some schematic calculations.[8] Systematic multi-dimensional Langevin calculations[3] showed that the recoupling of

the mass asymmetry degree of freedom to the kinetic energy distribution of the fission fragments leads to agreement with the measured widths. For an example see figure 1. There is agreement for 'light' systems ($^{172}Y,^{205,215}Fr,^{224}Th$) with the data for the TKE-widths and also for the pre-scission neutron multiplicities. However, in order to find agreement with experiment one has to reduce the strength of the wall friction by a factor $K_s \simeq 0.25 - 0.5$. For very heavy systems with 100% fission probability such as $^{252,256}Fm$, the pre-scission neutron multiplicities cannot be reproduced. For systems with a long saddle to scission path, one seems to need a stronger friction at large deformations. See the discussion in Section 3.

A reduction of the strength of the wall formula is also necessary for reproducing experimental fission times in a multi-dimensional Langevin description.[7]

The findings above are <u>in contradiction</u> to the work of Abe and collaborators,[5],[9] who apply the wall formula without reducing its strength.

3. The chaos-weighted wall formula

One of the essential assumptions in deriving the wall formula is that the single-particle collisions with the wall are completely randomized. This corresponds to chaotic motion. However the amount of chaos depends on the deformation of the fissioning nucleus: in a spherical container one has regular motion, with increasing deformation the fraction of chaotic motion increases. This leads to a reduction of the wall formula due to incomplete randomization. Pal and coworkers[10] have calculated a factor taking into account the amount of chaos. This reduces the strength of the wall formula as a function of the deformation. This chaos-weighted wall friction form factor is shown in Fig.2 as function of the elongation coordinate in comparison to
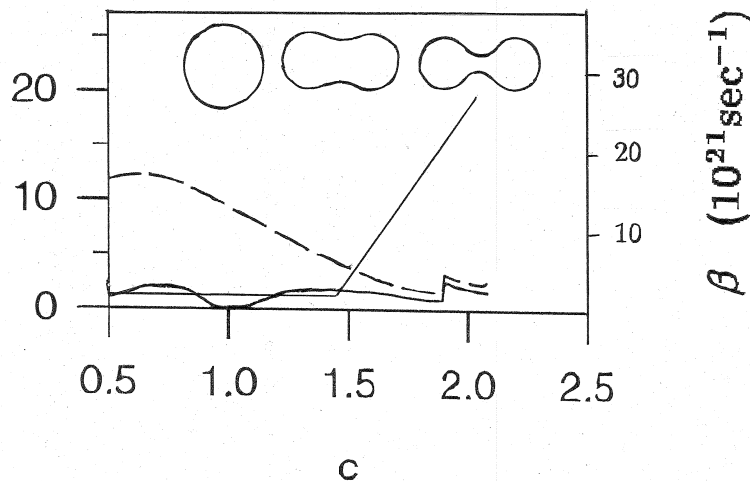

Fig. 2. Comparison of the wall friction (dashed line), the chaos-weighted wall friction[10] (solid curve), and the universal phenomenological friction form factor of Fröbrich and Gontchar[1],[2] (straight lines).

the full wall friction. A comparison is also made with the phenomenological form

factor of Fröbrich et al.[1] Using this form factor in an overdamped one-dimensional Langevin equation reproduces in a systematic way the data on fission (respectively survival) probabilities and pre-scission neutron multiplicities for light and heavy systems: $^{178}W, ^{188}Pt, ^{200}Pb, ^{213}Fr, ^{224}Th$ and ^{251}Es. For compact shapes, both form factors are of the same order of magnitude. For light systems, it is essential to have this relatively weak friction in order to reproduce the data. This has been confirmed by Pal et al.[10] by performing Langevin calculations with their input for the systems above. However, they cannot reproduce the neutron multiplicities for ^{251}Es, because their form factor does not increase for large deformations. In Ref.[1] this rise was introduced in order to reproduce the pre-scission neutron multiplicities for very heavy systems with a long saddle to scission path, whereas the rise turns out to be insensitive to the neutron multiplicities of light systems with a short saddle to scission path. The strength at scission ($\beta = 30 * 10^{21} sec^{-1}$) is comparable to the value of the surface friction model in the exit channel of a deep-inelastic collision which looks similar to the final stage of fission.

4. On the temperature dependence of the friction form factor

A reduction of the wall friction is also obtained by Aleshin,[11] who derived a modification of the wall formula by relaxing the randomization assumption and taking into account interactions of the single-particle motion in dressing[12] the single-particle propagator by introducing the spreading width as in linear response theory. In this way, a temperature dependence of the friction form factor is introduced. This form factor is calculated for ^{208}Pb in the temperature range of $T = 2.1 - 3.3 MeV$ and compared in Fig.3, again with the wall friction and the phenomenological form factor of Fröbrich et al.[1,2] The temperature dependent form factor behaves similarly to the phenomenological one. It is weak at compact shapes and rises with increasing deformation but not as strong as the phenomenological one.

For a comparable temperature range, the form factor of Aleshin looks similar to that of Ivanyuk et al.,[13] which is also weaker than the wall friction for compact shapes and also does not show a steep rise for large elongation. It would be desirable to perform Langevin calculations coupled to an evaporation procedure using the temperature- and deformation-dependent form factors of Refs.[11,13] A first step in this direction was done in Ref.[14]

The necessity for clarifying the role of the deformation and temperature dependence is exemplified in a recent paper by Dioszegi et al.[15] who were able to reproduce their data with a modified statistical model (containing a number of uncertain parameters) by applying either a temperature dependent friction form factor (with a stronger temperature dependence than that discussed above) or with a deformation-dependent form factor which is in accordance with the phenomenological form factor weak at compact shapes and stronger at large deformations.

A side remark: The temperature dependence of the friction form factor seems to be clearer in the decay of metallic clusters, where the viscosity of the bulk materials is measured. There, one is in the hydrodynamical regime (two-body viscosity), and friction becomes weaker with increasing temperature.[16]
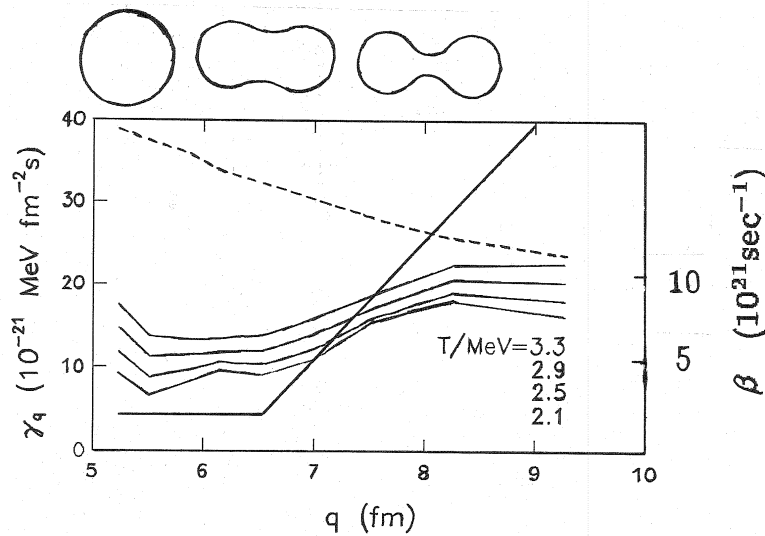
Fig. 3. Comparison of the wall friction (dashed line), the temperature dependent friction[11] (solid curves), and the phenomenological friction form factor of Fröbrich and Gontchar[1,2](straight lines).

5. Remarks on quantal corrections

In principle, one should use quantum mechanically calculated transport coefficients instead of phenomenological input. Quantum mechanics is not only hidden in the phenomenological parameters, but also influences e.g. the fission rates beyond the classical Langevin results up to quite high temperatures. A fission rate calculated with an influence functional path integral technique gives e.g. a 20% enhancement as compared to a Kramers rate for fission of ^{224}Th at a temperature of $1.57 MeV$.[17] At lower temperatures, e.g. when dealing with Langevin models for superheavy element formation, quantum effects are even more important. For instance, when calculating rates around the so called cross over temperature, one has to apply more complicated techniques, e.g. those of Ref.[18]

6. Conclusions

The main purpose of the present contribution was to discuss properties of the friction form factor necessary to describe data concerning fission of hot nuclei. Arguments for a modification of the wall formula were collected. To be consistent with a large variety of data friction needs to be comparably weak at compact configurations and stronger for elongated shapes. The role of the temperature dependence of the friction form factor predicted by microscopic theory has still to be clarified by using it in Langevin calculations and confronting the results with experimental data. In the present paper, we discussed only systems where fission follows the formation of an equilibrated compound system. However, there is an increasing amount of data in which contributions of fast fission are identified; i.e. there is a need for modelling

the fast fission process. A systematic analysis of as many data as possible should be done with the same model, if possible within a multi-dimensional Langevin dynamics to which an evaporation procedure for light-particle emission is coupled. In this way it may be possible to decide upon the friction formfactor with respect to its deformation (and temperature) dependence, and finally to arrive at a unified picture for fission of hot nuclei.

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