CAN DISSIPATIVE DYNAMICS WITH FLUCTUATIONS EXPLAIN FUSION OF HEAVY SYSTEMS? *

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A new method of calculating probabilities of rare events in the Langevin dynamics, based on importance sampling, has been used for analysis of the energy dependence of the fusion probability of a heavy nucleus-nucleus system, ^{86}Kr+^{136}Xe, recently studied experimentally at GSI Darmstadt. The calculations were done applying the importance sampling method to a realistic three dimensional dynamical model based on the concept of one-body dissipation and including shell effects. Comparisons with experimental results show that the fusion processes observed in experiments extend to significantly lower energies than expected theoretically.

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1. Introduction

Fusion excitation functions for nucleus-nucleus collisions seem to be reasonably understood in terms of macroscopic models based on classical Lagrange–Rayleigh equations of motion. For heavy systems, a strong dissipative force resulting from the assumed one-body dissipation mechanism [1] leads to a shift of the fusion energy threshold from the interaction barrier toward higher energies (the "extra-push" energy). On the other hand, experiments on the production of the transuranic elements show that the fusion excitation functions extend very far below the "extra-push" energies. In the present paper we investigate whether the near-threshold fusion of heavy systems can be explained as an effect of fluctuations in standard nuclear dynamics with one-body dissipation.

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2. Scheme of calculations

In order to investigate the role of fluctuations in the near-threshold fusion reactions we have to simulate very rare events of Langevin trajectories leading to fusion, while almost all other trajectories result in reseparation of the colliding nuclei. Therefore in the calculations we used a new method for computing probabilities of very rare events proposed in Ref. [2].

The main idea of the method is essentially based on a dynamical variant of *importance sampling* which is a tool for gaining information about one probability distribution (a "target" distribution) by choosing randomly from another (a "sampling" distribution defined on the same space) and then assigning weights to the points sampled. As proposed in Ref. [2], the probability of fusion is defined with respect to the "target" ensemble of Langevin trajectories calculated with the original Langevin equation. The "sampling" ensemble is the distribution of trajectories evolving from the same initial conditions but under a modified Langevin equation in which a fictitious (unphysical) term is added in order to "push" trajectories toward fusion. The effect of the modification of the Langevin equation can be compensated by biasing each trajectory with a corresponding weight which is assigned in such a way that in the limit of infinitely many simulations the result converges exactly to the fusion probability for the original Langevin process. (The biasing weights are determined by functionals of the trajectories, as prescribed in Ref. [2].) Thus the fusion probability for the original Langevin process is expressed in terms of information coming from simulations of the modified (fusion-enhancing) process.

As an illustration of the advantages of the new method, we show results of a numerical experiment [2] in which importance sampling was applied in conjunction with a simple model of heavy ion collisions proposed by Swiatecki [3]. Very fast calculations of dynamical trajectories can be done with the model [3] owing to simplified geometry of the colliding system. It was therefore possible to compare predictions of the fusion probability of the assumed symmetric ^{100}Zr + ^{100}Zr system in both standard Langevin trajectory calculations and calculations involving the importance sampling method. In the latter case an extra drift localized in the vicinity of the saddle point (where the ultimate fate of the interacting nuclei — either fusion or reseparation — is decided in the interplay of deterministic and stochastic forces) was added in order to increase the likelihood of fusion. In Fig. 1, fusion probability is plotted as a function of the excess of the center-of-mass energy above the barrier for both the standard direct simulation (top) and the importance sampling calculation (bottom). Each point was obtained using 1000 Langevin trajectories. It is seen that the importance sampling calculation leads to the same results as does the direct simulation, but considerably amplifies the statistics of rare events.

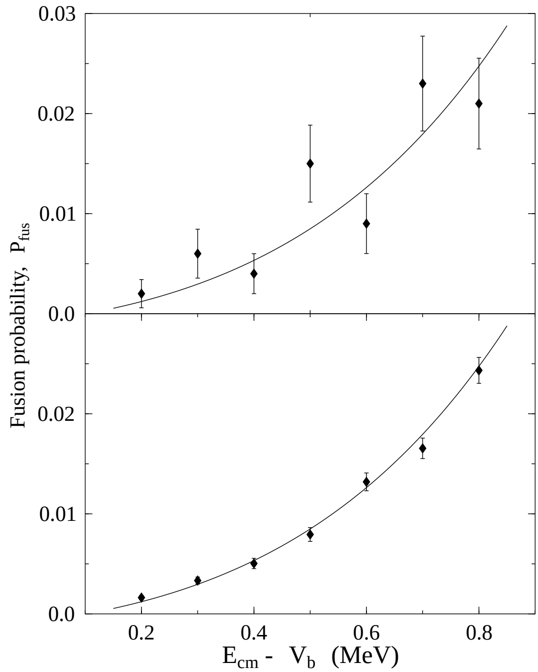

Fig. 1. Fusion probability for the assumed ^{100}Zr + ^{100}Zr system as a function of the excess of energy above the barrier in standard Langevin trajectory calculations (top) and importance sampling simulation (bottom), obtained from 1000 trajectories per point.

3. Calculation with a realistic model

Having demonstrated the advantages of the importance sampling method, we have implemented this method to a full-scale dynamical model in which Langevin trajectories are calculated in 3-dimensional configuration space of the relative distance, "neck", and mass asymmetry variables defined as proposed in Ref. [4]. (In addition, the charge asymmetry variable is included independently of the mass asymmetry.) The conservative driving forces are calculated along the trajectory from the Coulomb interaction energy and the "Yukawa-plus-exponential" potential [5] modulated by shell effects [6]. The dissipation forces assumed in the model are due to the one-body "wall-plus-window" formula [1]. The inertia tensor of the interacting system is calculated with the Werner–Wheeler method.

We have used the model outlined above for calculations of the near-threshold fusion probabilities for the ^{86}Kr + ^{136}Xe reaction studied recently at GSI Darmstadt by Stodel *et al.* [7]. Cross sections for different (fusion,xn) channels were measured for this system at near-threshold energies, as shown in Fig. 2 (top). From the combined compound-residue cross sections, the dependence of the fusion probability on the excitation energy of the compound nucleus was deduced by the authors of Ref. [7], see Fig. 2 (bottom). The deduced fusion probability increases from $P_{\rm fus} \approx 2\times10^{-4}$ at $E_{\rm cm} = 195$ MeV to $P_{\rm fus} \approx 1$ at $E_{\rm cm} \approx 230$ MeV, *i.e.*, in the range of energies extending far below the standard extra-push threshold, $E_{\rm extra-push} = 228.7$ MeV. To some extent, the lowering of the fusion threshold is due to the shell structure of the fusing system. (Our model, with the shell corrections included, predicts the extra-push threshold for the reaction in question to be lower, $E^{\rm shell}_{\rm extra-push} = 224.2$ MeV.)

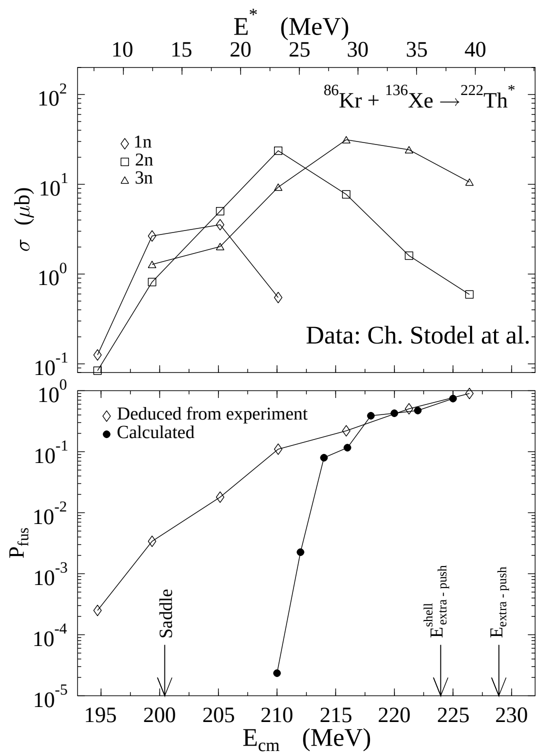

Fig. 2. Comparison of the theoretically predicted (see text) near-threshold fusion probability with experimental results for the ^{86}Kr + ^{136}Xe system obtained at GSI Darmstadt [7]. Only low-energy part of the experimental data is shown.

In our calculations we attempted to check whether the rise of fusion probability, observed already at quite low energies, can be explained in terms of the standard fusion dynamics with fluctuations determined by the dissipation-fluctuation theorem. In Fig. 2 results of our calculations for the ^{86}Kr + ^{136}Xe reaction are compared with the experimental data. By using the importance sampling method, we were able to carry out conclusive calculations even at the lowest energies and thus to verify the near-threshold part of the excitation function. The results of the calculations show that the observed near-threshold fusion probabilities in the ^{86}Kr + ^{136}Xe reaction cannot be explained with the standard fusion dynamics model based on one-body dissipation. Clearly, fusion extends to lower energies than expected by the theoretical calculation.

Since precise knowledge of the fusion excitation functions is essential for planning future experiments aimed at synthesizing new super-heavy elements, we are going to carefully investigate all possible effects which may be responsible for the observed discrepancy. Estimates of the magnitude of the penetrability through the barrier show that the contribution of the sub-barrier fusion is negligible for such heavy systems. Also the role of fluctuations caused by the exchange of particles, not accounted for in the present calculations, is presumably marginal because the velocity mismatch at near-threshold energies is small. (In the calculations we used only the temperature part of the diffusion tensor given by the Einstein relation.) Therefore we do not exclude that other constituents of the dynamical model, such as shape parametrization and/or energy dissipation, will need to be reconsidered in the adiabatic limit.

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