Dissipation-fluctuation dynamics of fusion-fission reactions and synthesis of superheavy elements

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Dynamical treatments of fission processes are briefly reviewed with an emphasis on the strong dissipation or friction for collective motions of nuclei in high excitation. The theories are applied to synthesis of superheavy elements. Characteristic features of formation and surviving are discussed with reference to possible incident channels. Theoretical prediction are presented on favorable incident channels and on optimum energies for synthesis of the element $Z = 114$.

Why Langevin equation or dissipation-fluctuation?

Atomic nuclei in high excitation can be seen as Fermion systems at finite temperature, as supported by evaporation spectra of neutrons. How do the collective motions known in low excitation become in high excitation? They, of course, interact with intrinsic nucleonic degrees of freedom, and thereby could be described in analogy with a Brownian particle interacting with heat bath particles. This viewpoint was employed in so-called deep-inelastic collisions of heavy ions, and naturally applied to nuclear fission processes later, though H. A. Kramers already proposed it in 1950 in order to understand Bohr-Wheeler(B-H) formula for fission from the dynamical point of view.$^{1)}$ Recent revival of Kramers equation or equivalent Langevin equation in nuclear fission processes clarified that fission life is far longer than that predicted by B-H formula. Time scale of fission in high excitation can be evaluated by how many neutrons are emitted before scission, i.e., by measurements of pre-scission neutron multiplicities. Canberra group observed anomalous neutron multiplicities which increase almost linearly as initial excitation energy of compound nuclei increases. This is not explained by the standard statistical code, even if level density parameters are adjusted.$^{2)}$ Another anomally is on post-scission neutron multiplicities which do not increase so much as the excitation energy increases. These mean that energy deposited initially in compound nuclei is mostly released by neutron evaporation before the systems reach the scission point, and therefore fission life time should be long enough for that. Quantitative analyses were made on neutron multiplicities and kinetic energies distributions of fission fragments; the formers bear information on total time scales from the spherical shape to the scission point, while the latters bear that on dynamics only from the saddle to the scission point.$^{3)}$ Figure 1 shows time dependence of the fission width for ^{200}Pb with initial excitation energy $E^* = 80.7$ MeV. Solid lines are the widths calculated at scission while dotted lines those at saddle. Dashed lines denote quasistationary fission widths corresponding to Kramers limit. It is worth to notice here that the widths are time-dependent with dead or transient time at the beginning. Gradual decreases of the dashed lines and the calculated re-

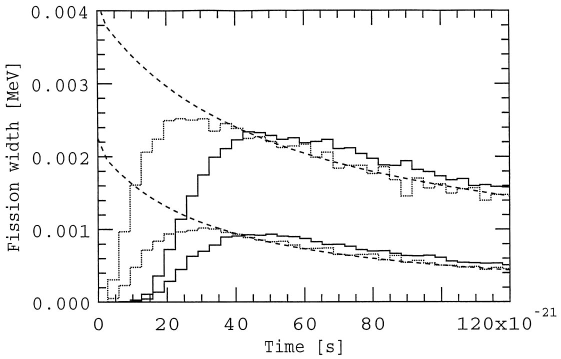

Fig. 1. Time dependence of the fission width for ^{200}Pb with initial excitation energy $E^* = 80.7$ MeV.

Table 1. Calculated results with the one-body wall-and-window formula for the friction.

E^* (MeV)	ζ (MeV^{-2})	σ_{fus} (mb)	σ_{fiss} (mb)	σ_{ev} (mb)	ν_{pre}	π_{pre}	α_{pre}	TKE (MeV)	σ_{TKE} (MeV)
	0.014	1150	790	360	2.93	0.0092	0.0037	135.1	8.46
80.7	0.009	1150	758	392	3.08	0.0091	0.0036	135.5	8.33
	exp.	1150	767	383	3.2±0.3	…	…	…	…
	0.014	1400	1244	156	7.33	0.363	0.140	137.0	10.2
195.8	0.009	1400	1223	177	7.64	0.385	0.140	137.5	9.82
	exp.	1400	…	…	7.7±0.3	…	…	139	16.5

sults are due to the cooling by neutron evaporation. As is well known, Kramers limit is smaller than B-H value due to the friction by so-called Kramers factor (< 1). The factor and the transient time make fission life to be much longer than B-H. Then, more neutrons are evaporated before scission. Table 1 shows the calculated results with the one-body wall-and-window formula for the friction. We can see that the calculated neutron multiplicity ν_{pre} increases in accord with the experimental one from $E^* = 80.7$ to 195.8 MeV. And the average kinetic energy TKE is also in agreement with the experiment (see Refs. 3 and 4 for the details). The success of the one-body friction means that fission life is much longer than being believed. The unexpectedly long life of fission is now known in other reaction processes such as decays of giant resonances etc.[4] Therefore, it is interesting and important to take into account the effect of the strong friction in dynamical evolutions of nuclear systems leading to the superheavy elements, where the speed of cooling which restores the shell correction energy, or slowness of fissioning motion is crucial. As a matter of course, under action of strong friction we can expect more residue cross sections than being conceived in hot or warm fusion reactions.

Theoretical predictions of SHE residue cross sections

Superheavy elements (SHE) around $Z = 114$ (or 126) and $N = 184$ have been believed to exist according to theoretical predictions of stability given by the shell correction energy in addition to average nuclear binding energy.[5] This means that heavy atomic nuclei with fissility parameter $x \geq 1$ could be stabilized against fission by a huge barrier which is resulted in by the additional binding of the shell correction energy around the spherical shape. In other words, if superheavy compound nuclei (C.N.) are formed in such high excitation that the closed shell structure is mostly destroyed, they have no barrier against fission and thus are inferred to decay very quickly, though time scales of fission are now believed to be much longer than that of B-H formula due to a strong friction for the collective motion.[3] Therefore, the point is how to reach the ground state of the superheavy nuclei, or how to make a soft-landing at them. In order to minimize fission decays of C.N. or maximize their survival probabilities, so-called cold fusion reactions have been used, which succeeded in synthesizing SHEs up to $Z = 112$.[6] They have the merit of large survival probabilities, but suffer from the demerit of small formation probabilities because of the sub-barrier fusion. On the other hand, so-called hot(warm) fusion reactions have the merit of expected large formation probabilities and the demerit of small survival probabilities due to relatively high excitation of C.N. formed. Anyway, an optimum condition for large residue cross sections of SHEs is a balance or a compromise between formation and survival probabilities as a function of incident energy or excitation energy of C.N. formed over possible combinations of projectiles and targets.[7]

Formation and surviving (decay) are not always independent, especially in so-called massive systems, but for simplicity we briefly discuss them separately. Formation of C.N. is by the fusion reaction. Fig. 2 reminds us of its characteristic features, depending on the system. In lighter systems, i.e., those with $Z_1 \cdot Z_2 \leq 1800$, they undergo fusion if they have enough energy to overcome the Coulomb barrier (say, Bass barrier,[8] while in heavier systems, they have to overcome so-called conditional saddle to get fused even after overcoming the Coulomb barrier. Since the systems are under the action of strong nuclear interactions, their incident kinetic energies are quickly transformed into internal motions, and thereby much more energy than the difference between the barrier and the saddle point is required for formation of C.N., which corresponds to the extra-push or extra-extra-push energy.[9] One more point to notice is that the potential energy surface for SHE has almost no pocket schematically shown in Fig. 2 if the C.N. are formed in rather high excitation. This would be the reason why a simple practical formula is not available for SHE formation probability. A dynamical framework had been called for so long untill the recent works appeared.[7] It is also worth to mention that Fig. 2 is just a one-dimensional schematization. Real processes are in many dimensions including mass asymmetry degree of freedom etc. in addition to the elongation or the separation between two fragments. An important case that we will discuss below is that the incident channel is with $Z_1 \cdot Z_2 \simeq 1200$ and the compound nucleus is with $Z = 114$. The potential energy surface for the compound nucleus has almost no minimum like that shown in Fig. 2 due to excitation, while the Bass barrier is high, but quite inner close to the point where the energy surface becomes flat.

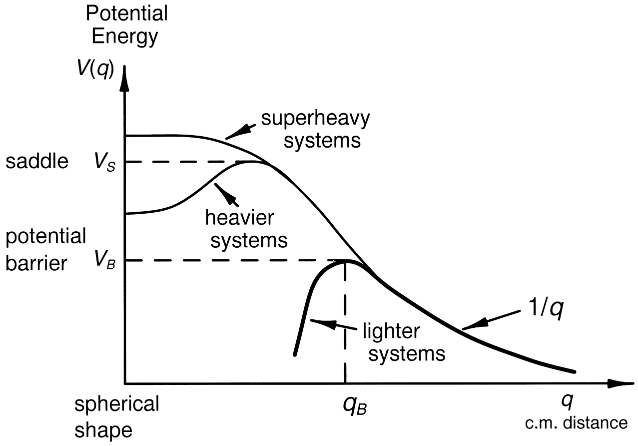

Fig. 2. Characteristic features of formation of compound nuclei by fusion reactions.

We have calculated formation probabilities in the following way.[10] If an incident energy is below the barrier, we take into account the barrier penetration factor using WKB approximation. The potential (barrier) is calculated with the Coulomb and the nuclear proximity potentials[11] between the incident ions, where effects of deformations etc. are not taken into account in order to see simply a general trend. After the incident ions reach the contact point, evolutions of shapes of the total system are under the dissipation-fluctuation dynamics, as mentioned above. We have employed a multi-dimensional Langevin equation to describe trajectories in three-dimensional space where the mass-asymmetry and the fragment deformation are taken into account as well as the distance (or elongation) degree of freedom. Some trajectories go to the spherical shape of the compound nucleus and its around, while some others, or say most of them to re-separations after random walks in the space. Examples of calculated formation probabilities are shown in Fig. 3 for

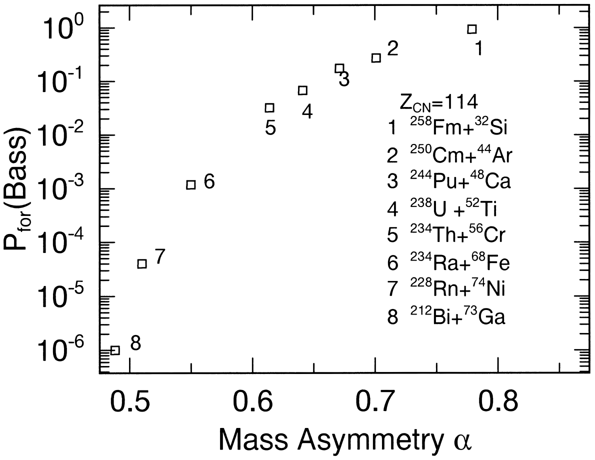

Fig. 3. Formation probability at E^*_{bass}.

$Z = 114$ C.N. with the possible incident channels at the incident energies corresponding to their Bass barriers. We can readily see that the larger the mass asymmetry (α) is, the larger the formation probability (P_{for}) is. This is just consistent to the feature in $Z_1 \cdot Z_2$ dependence of fusion reactions mentioned above. The smalll P_{for}'s in small mass- asymmetric cases correspond qualitatively to the "heavier systems" in Fig. 2, i.e. are due to the strong friction for the collective motions. What is noticeable here is the great increase of several orders of magnitude as a function of α. This indicates that mass asymmetric incident channels do not suffer much from the dissipation and are extremely favorable in formation of C.N., but on the other hand, as shown in Fig. 4, C.N. formed with mass asymmetric channels have higher excitation energies than those with less asymmetries, due to Q-values, which means that asymmetric channels are unfavorable for surviving. In order to know more precisely about excitation-energy dependence of survival probability (P_{sur}) in SHEs, we have to take into account effects of cooling speeds which are essential for SHEs, because superheavy C.N. can be stabilized only by the restoration of the shell correction energy which is determined by the cooling, i.e., mainly by neutron evaporation. For particle evaporations we have used the statistical theory as usual. One more crucial factor in determining P_{sur} is the time scale of fission. Since we know fission of excited nuclei is a dynamical process under strong friction, we have employed one-dimensional Smoluchowski equation for describing the evolution of fissioning degree of freedom, which is known to be correct enough for the present purpose.[4)] Results of P_{sur} for $Z = 114$ are shown in Fig. 5 as a function of excitation energy(E^*) over several mass numbers A. It is surprising that (1) P_{sur}'s decrease very quickly as E^* increases and (2) mass number dependence of the decrease is enormous. This means that C.N. with large mass numbers are favorable for surviving. This is essentially due to quick coolings in neutron-rich C.N. where the separation energy B_n's are small. Thus, unfavorable large E^*s could be somehow compensated by the quick coolings if C.N. are of small B_n, of course, with the aid of the long time scales of fission. On the other hand, if we initially form neutron-deficient isotopes, cooling speeds are slow and thereby their survival probabilities drop very rapidly as E^* increases. In such cases, we have to form C.N. in as low excitation as possible in order to obtain large residue cross sections, which is qualitatively consistent with GSI experiments.[6)] It should be mentioned here that change of friction strength gives rise to the same tendency of P_{sur} as that of neutron number.

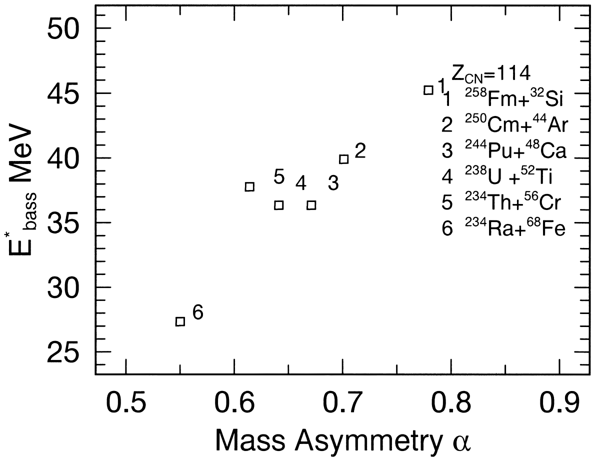

Fig. 4. Excitation energy at bass barrier top.

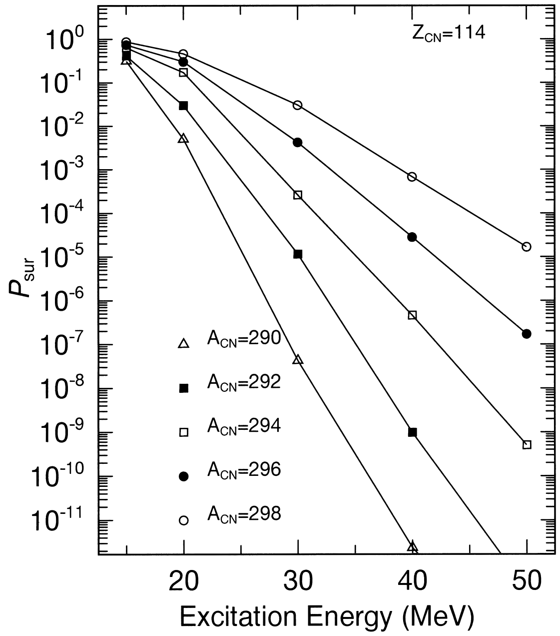

Fig. 5. Survival probability.

We have calculated excitation functions of evaporation residue cross sections by combining the two reaction processes; formation and surviving. Results for possible incident channels to form $Z = 114$ isotopes are shown in Fig. 6 as a function of E^*. The left-hand side increases toward the peaks are due to formation probabilities, i.e., the barrier penetration and the dynamical evolution for fusion, while the right-hand decreases due to E^* dependence of survival probabilities. The arrows with the numbers show the positions of the Bass barriers in the channels, respectively. The incident channels ^{250}Cm + ^{44}Ar and ^{244}Pu + ^{48}Ca are predicted to have cross sections more than 1 pb which is thought to be a limit in measurements. The importance of larger neutron numbers is readily understoood. It is extremely interesting that Dubna group has recently observed an event which could be related to a synthesis of $Z = 114$ with the latter channel.[12)]

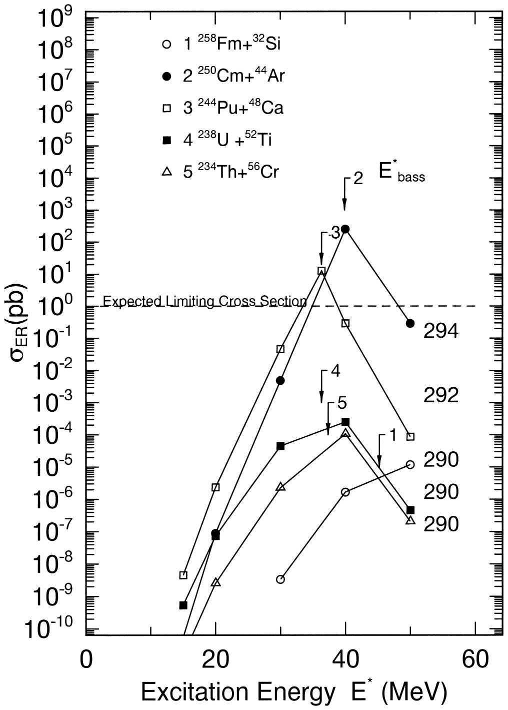

Fig. 6. Evaporation residue cross section.

Remarks

Summarizing, our framework gives a comprehensive treatment of the whole reaction process leading to SHE residues, which later on undergo spontaneous α-particle decay and/or fission decay. It would be worth to mention again (1) that the important point is a balance between formation and surviving and (2) that the strong friction which determines fission time scale and the neutron separation energy Bn's which determine cooling speeds are another important quantities in addition to the magnitudes of the shell correction energy. The second point encourages us to explore exotic targets and projectiles with more neutron excess. For more precise quantitative prediction of residue cross sections, one-dimensional WKB approximation for the penetration factor should be improved so as to accomodate effects of the deformations of the incident ions etc. The last remark is on more mass-symmetric incident channels which are not shown here. They generally suffer more from the effects of dissipation which unfavor fusion probabilities but on the other hand, if neutron-rich C.N. could be formed, again there is a hope to obtain rather large residue cross sections of the order of pb.$^{7)}$

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