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Thesis Outline:

Study on mechanisms of nuclear fission by Langevin equation

（ランジュバン方程式による核分裂機構の研究）

Chapter 1: Introduction

In the introduction we highlighted the interconnections between the few characters involved in the early developments of nuclear calculations. Some of these early calculations later turns out to be of major importance. One of the early works include the use of a liquid like model to estimate the gross contribution to nuclear deformation energy. This work by Neils Bohr later eventually evolved to the liquid drop deformation that we now use in the current work for constructing the potential energy surface. At around the same time, developments were also being made on the description of Brownian motion by Paul Langevin. In that scheme, the Langevin equation are able to describe the random forces in Brownian motion. Thus, it can easily include the balance of forces due to conservative and non-conservative forces. This technique pioneered by Langevin was eventually applied to describe the changes in the shape of the nucleus as it evolved from a single compound nucleus into two fragments as it fission. We do this by describing the shape of the nucleus in terms of generalized coordinates. In the later portion of the introduction, we give a general overview of the work and objective of the study.

Chapter 2: Theory

In this chapter, we try to describe the theories involved in our work. The Langevin equation used in the current work describes the evolution of collective variables on the potential energy surface while subject to the influence of friction and the resultant random force. Thus, the first matter naturally concerns the collective variables inspired from the shape parameterizations that we have chosen. The shape parameterizations are based on the Two-Center Shell Model where we can describe the shape of the nucleus using the elongations between two potential energy surface, the shape of the fragment tips and the mass asymmetry of the fragments. In the 3-D Langevin, the shape of the two fragment tips are fixed to always be equal to each other but in our 4-D Langevin work, the shape of the fragment tips are allowed to evolve independently from each other. With the shape resolved, we began to describe the potential energy surface used in our calculations. The potential energy surface arises from the sum of liquid drop deformation energy and the shell corrections. In order to calculate the liquid drop deformation energy, we also need to calculate the liquid drop energy for both the spherical shape and for the deformed shape characterized by the collective variables. Afterwards we explain how the liquid drop energy is calculated from the surface energy of the nucleus and its Coulomb energy. The energy released in fission from the estimates of liquid drop energy is sufficiently correct, but it cannot account for the two peak fission fragment yield that we saw in experiments. This is resolved by the introduction of shell correction energy. It is calculated by subtracting the average energy of the single particle energies from the sum of the single particle energies. By introducing the quasiparticle energies in BCS calculations, the contribution of pairing to the shell correction can also be added. Then we multiply the contribution of the shell correction with a factor called the shell correction factor to approximate the potential energy surface at a higher temperature. Only afterwards can discuss the transport coefficients used. Here the transport coefficients meant the mass and friction tensor in the Langevin equation. We have used both the macroscopic and microscopic approaches to calculate these transport coefficients. The macroscopic approach attempts to describe the mass and friction tensor exclusively by the shape of the nucleus. In the microscopic approach we began with the mean field Hamiltonian for a many body system (nucleus) to describe the linear response of the Hamiltonian when it was subjected to some perturbation in the shape of the nucleus. Then we show how the random force rose from the presence of friction. Finally, we demonstrated on how the Langevin equation is derived.

Chapter 3: Results and Discussion

In this chapter, the results that we have achieved in the past three years are examined. We begin describing how the potential energy surface affects the predictions of fission observables. Discussion on the potential energy surface began with 1-D potential energy surface towards 2-D potential energy surface. In this we discuss that while reducing the potential energy surface to a lower dimension helps in furthering our understanding on the evolution of nuclear shapes, we also show how it was inevitable that by doing so, some information are lost. This made it necessary to expand the potential energy surface to the 3-dimensional surface that we often use and now to 4-dimensional surface. In the 1-D case, we may plot the potential energy surface with regards to elongation and in 2-D case, the potential energy surface is expanded to include mass-asymmetry. In both 3-D and 4-D potential energy surface, the shape of the fission fragment tips is incorporated. In 3-D potential energy surface, the two fission fragment tip are fixed to always be the same but in 4-D potential energy surface, the fission fragment tip are allowed to evolve independently. If we also have transport coefficients to accommodate the increase of dimensionality, we can easily implement Langevin equation at the same dimensionality. However, to derive transport coefficients at ever higher dimension is not an easy endeavor and each increase in dimension of the transport coefficients require an increasingly longer time to calculate. This problem of computational cost is even more acute if we wish to calculate microscopic transport coefficients.

Then the behaviors of the transport coefficients are also explored. We are able to see that while macroscopic and microscopic transport coefficients occasionally coincide with each other, those circumstances only happen at very low temperature in the case of mass tensors and at high temperature in the case of the friction tensor. The role of pairing in the transport coefficients are also explored. Finally, we begin to discuss the fission observables such as TKE and fission yield and how the dynamics induced by Langevin equation affects them. In these respect, we first explore the use of microscopic transport coefficients in 3-D Langevin equation and compare them to results from 3-D Langevin equation with macroscopic transport coefficients that are often used traditionally. We find that the use both transport coefficients with 3-D Langevin equation gave an equally good fission fragment yield when compared with fission product yield from JENDL. The advantage of microscopic transport coefficients is only revealed when we study the fission fragment total kinetic energy (TKE), especially with the increase of excitation energy. The extension to 4-D Langevin however allowed us to observe the natural twin transition phenomena from Fm256 to Fm258 in terms of fission fragment yield and TKE. Then we explore the trajectory that allowed such transitions to happen.

Chapter 4: Conclusions

In the conclusions, we summarize our journey in discovering the physics involved in fission. We now have some glimpses on the possible refinements that we could make on the theory for further development beyond the submission of this thesis.