Effects of Quantum Fluctuations in Antisymmetrized Molecular Dynamics

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We incorporate the recently developed Quantal Langevin treatment into Antisymmetrized Molecular Dynamics. The effects of refined microscopic transport model, AMD-QL, in the statistical property of fermions in the harmonic oscillator potential and Ξ^- absorption at rest on ^{12}C are shown in this study.

1 Introduction

Microscopic transport models in nuclear physics have been successfully applied to nuclear reactions. Among them, Antisymmetrized Molecular Dynamics (AMD) [1] takes account both of the anti-symmetrization of A-body wave functions and two-body collision processes, which enable us to describe fragmentation processes due to cluster and nuclear shell effects. However, it has been pointed out recently that additional fluctuations may be necessary to describe fragmentation processes, even if anti-symmetrized wave packets are employed.[2,3] For example, the inherent finite energy fluctuation within a wave packet, $\sigma^2 = <\Psi|\hat{H}^2|\Psi> - <\Psi|\hat{H}|\Psi>^2 \neq 0$, has been shown to affect the statistical properties of nuclei and fragmentation reactions in heavy-ion collisions significantly, within the context of the recently developed Quantal Langevin Model (QLM).[2]

In this study, we extend AMD to incorporate quantum energy fluctuations in the manner of the QLM, whose application to nuclear reactions have been limited to the case without anti-symmetrization until now. Then, we apply this resulting model (AMD-QL) to the double- and twin-hyperfragment formation from Ξ^- absorption.[4]

2 Models

In AMD, quantum states are constructed by the Slater determinant of Gaussian wave packets parametrized by $\{\boldsymbol{z}_i\}$ vector, which represent the mean position $\boldsymbol{d}_i$ and the mean momentum $\boldsymbol{k}_i$. Applying the time-dependent variational principle, the equation of motion (EOM) is then derived to be $\dot{\boldsymbol{z}}_i = \frac{i}{\hbar}\boldsymbol{F}_{\boldsymbol{i}}$. In

addition to the mean field evolution described by this EOM, This two body collsion term partially describes the fluctuations from the mean field evolution.

Since the above EOM gives the average path and the two-body collision is not effective at low excitations, the effects of inherent energy fluctuations in wave packet wave functions on the dynamics is expected to play an important role. Here we incorporate the energy fluctuations into AMD following the QLM procedures. (a)We calculate the statistical weight ($\mathcal{W}$) at available equilibrium (canonical,microcanonical) which contains the information of energy fluctuations. (b)We derive tha Master equation of probability distribution which has the above $\mathcal{W}$ as the equilibrium solution. (c)We derive the following Langevin type AMD-QL equation of motion of $\{\boldsymbol{z}_i\}$ vector which is equivalent to above Master equation.

$$\dot{\boldsymbol{z}}_i = \frac{i}{\hbar}\boldsymbol{F_i} + \beta'_{\mathcal{H}} \sum_{kl} g_{ik} g_{kl} \boldsymbol{F'_l} + \sum_k g_{ik} \boldsymbol{\zeta_k} \ , \qquad \beta'_{\mathcal{H}} = \frac{\mathcal{H} - E}{\sigma'^2_E} \ .$$

The stochastic term which includes white noise ζ appearing here is referred to as the *Quantal Langevin* force and this gives the energy fluctuations for the system. Here, we remove the energy fluctuations related to the fragment CM motion and we employ the matrix $\boldsymbol{g}$ that contains off-diagonal parts reflecting single-particle overlaps so that the energy is unaffected by the fluctuation for fragments close to their ground states.

3 Results

First, we apply AMD-QL to the analysis of the fermions moving in the harmonic oscillator potential. As can be seen in Fig.1, the AMD-QL well reproduces the quantal statistical property of the system which is composed by fermions moving in the one-dimensional harmonic oscillator potential. On the contraty, the AMD results coincide with classical relation. Since the relative kinetic energy among fragments is well described by $3T/2$ in a static situation, the smaller temperature estimated in AMD than that of quantal statistics (dashed lines) at a fixed mean excitation energy suggests the suppression of fragment kinetic energies and consequent suppression of fragment emissions.

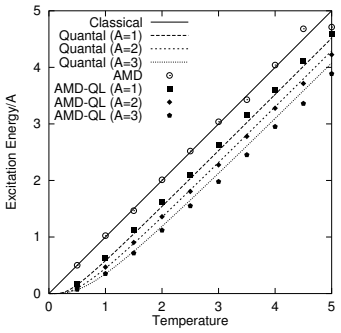

Figure 1: Temperature-Energy relation in Harmonic Oscillator Potential

Next, we apply AMD-QL to Ξ^- absorption at rest on ^{12}C in order to investigate the effects of energy fluctuations in the nuclear reaction. In the Ξ^- absorption reaction, various hyperfragments including double hypernuclei [5], single hypernuclei and twin hypernuclei are observed, from the primary elementary process $\Xi^- p \to \Lambda\Lambda$. In the AMD simulation, two Λ particles are easily absorbed into the compound nucleus and double hyperon compound nucleus formation becomes dominant (80.3 %). On the other hand, due to the energy fluctuation present in AMD-QL, the Λ emission probability is drastically enhanced and the probability of double hypernuclear formation decreases (to 11.4%) in the dynamical process. A remarkable result of the dynamical AMD-QL simulation is the appearance of twin hyperfragments (0.48%), while no twin hyperfragment formation has been seen in the dynamical stage of AMD. We found that AMD-QL suppress the formation probability of double hyperfragments to around 10%, which is comparable to the experimental data, and the dynamical formation of twin hyperfragment can be described qualitatively, althogh formation probability of twin hyperfragment is largely underestimated (Exp.$\approx 6 \sim 20$ %). These results are summarized in Table I.

	Compound [6]	DWIA [7]	AMD	AMD-QL	Exp.
Double Hyp.	66.0	4.75	46.4(80.3)	11.1(11.4)	$3 \sim 10$
Twin Hyp.	14.0	0.11	2.1 (0.0)	0.53(0.48)	$6 \sim 20$

Table 1: Formation probabilities of double and twin hypernuclei.

It should be kept in mind that there are still ambiguities in AMD-QL. The key quantity concerning fluctuations, the matrix $\boldsymbol{g}$, is taken somewhat arbitrarily. Therefore, in the future, it would be of interest to determine $\boldsymbol{g}$ from a more fundamental point of view.

References

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