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学位論文題目	Unified Description of Dynamical Multifragmentation Reactions and Corresponding Equilibrium Systems by Antisymmetrized Molecular Dynamics（反対称化分子動力学による動的多重破砕反応と対応する平衡系の統一的記述）
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In medium energy heavy ion collisions at around the Fermi energy, intermediate mass fragments (IMFs) are copiously produced as well as a large number of nucleons and alpha particles. This phenomenon is called multifragmentation. It is a challenging problem to understand the complex but rich quantum many-body dynamics of multifragmentation. By using heavy-ion reactions, we want to explore the properties of nuclear matter. Especially, it is interesting to study the connection between multifragmentation and the nuclear liquid-gas phase transition.

There are shortcomings in conventional theoretical approaches to heavy ion collisions at intermediate energies. The dynamical approach by transport theories such as BUU, QMD and AMD simulates the time evolution of the reaction using nucleonic degrees of freedom. Some of them are able to describe the fragment formation in dynamical process. However, it is not straightforward to relate their results to statistical properties of nuclear matter, such as phase transition. On the other hand, it is questionable to directly relate the results of the statistical approach which assumes a complete equilibrium to the experimental data of multifragmentation reactions.

In this study, we establish a unified description of multifragmentation reactions and corresponding equilibrium systems by simulating both situations with Antisymmetrized Molecular Dynamics (AMD). Employing this unified description, we investigate whether the concept of equilibrium is relevant to the multifragmentation reactions, and if so, in what sense. This is the first work, to our knowledge, that directly compares a dynamical multifragmentation reaction and corresponding equilibrium systems by describing both with the same model.

We describe an equilibrated system with AMD by applying it to a many-nucleon system confined in a container. The AMD equation of motion is solved for a long time to construct a microcanonical equilibrium ensemble for a given energy and volume. The system with 18 protons and 18 neutrons is studied. The constant pressure caloric curves are then drawn by extracting temperature and pressure from the equilibrium ensembles. We demonstrate that the negative heat capacity, which has been discussed as a signal of the phase transition in finite systems, appears in the calculated result. We perform also the AMD simulation for central ^{40}Ca + ^{40}Ca collisions at 35 MeV/nucleon, to confirm that it reasonably well reproduces the experimental data of the fragment yields with the exactly same model parameters as those used in the above-mentioned equilibrium calculation. A reaction ensemble at time t is constructed by gathering the many-body states at the time t in each simulation.

We then investigate whether the concept of equilibrium is relevant in multifragmentation reactions. More specifically, the subject is to study whether the reaction ensemble at a given time t is equivalent to an equilibrium ensemble with appropriately chosen energy and volume. The comparison of reaction and equilibrium ensembles is performed for the average values of some selected observables. In this study, we choose the fragment charge distribution and the distribution of the excitation energy of each fragment as the observables. Our calculations show that there exists an equilibrium ensemble which well reproduces the reaction ensemble at each time t for the investigated period $80 < t < 300$ fm/c.

The surprising discovery is that the concept of equilibrium is relevant in the present multifragmentation reaction as long as the test observables mentioned above are concerned, even though no equilibrium hypothesis has been introduced in the reaction simulation. This study clarifies the evolution of the reaction system in terms of the properties of the equivalent equilibrated system. This enables to draw a reaction path in the phase diagram (or the E-T plane). Our unified approach will be useful also in relating the final observables in the simulation for multifragmentation reactions, which are closely related to the experimental observables, to the properties of equilibrated systems such as the liquid-gas phase transition.

論文審査の結果の要旨

本論文は、原子核の状態方程式、特に、液相・気相相転移の存在、及び核子あたり数十MeVの中高エネルギー重イオン反応における平衡化の概念の有効性とその意義について反対称化分子動力学(AMD:antisymmetrized molecular dynamics)に基づいて議論した論文である。原子核のような少数量子多体系で液相・気相相転移が起こるか否かは、基本的な問題であり、これまでにも多くの研究がなされてきた。一方、中高エネルギー重イオン衝突では、核破砕反応が起こり、様々な質量数をもった破砕片が生成されるが、それら破砕片の質量分布の入射エネルギー依存性と液相・気相相転移の関係が議論されてきた。また、破砕片の質量分布の解析には、統計模型や、BUU（Boltzmann-Uehling-Uhlenbeck）理論などの動的理論が用いられてきた。本論文は、まず、18個の陽子と18個の中性子を球に閉じ込めた平衡系を考え、様々な体積とエネルギーの組に対してsimulationを行う事によって定圧下の熱量曲線を描き、有限系の相転移の指標とされる負の比熱の存在を示した。また、同じ枠組みを、核子あたり35MeVでの^{40}Ca+^{40}Ca反応に適用し、核破砕反応の破砕片の質量分布に関する実験データが理論計算によって良く再現されることを示した。更に、破砕片の質量分布及び各破砕片の励起エネルギー分布を判定基準にとり、反応中の各時刻の状況と平衡系を比べ、遅くとも100fm/c を越すと、反応に於ける各時刻の状況を、適当に選んだ平衡系で対応させられること、更に、それらの対応する平衡系の体積は時間とともに大きくなり、温度は時間とともに低くなること、得られた温度や体積は、状態方程式の図で、液相・気相相転移が起こる領域に対応することを明らかにした。それら全ての結論は、本研究で初めて明らかにされたものであり、原子核系における液相・気相相転移、状態方程式、核破砕反応のダイナミックスの研究にとって極めて重要な知見である。計算が、原子核の結合エネルギーを良く再現する核子間力の一つであるGogny力を用いて行われたこと、また、核破砕反応における平衡化概念の検証を目的とした他の研究と比べた場合、平衡系の計算と重イオン反応の計算を同じAMDの枠組みで統一的に行ったことが本研究の重要な特徴である。本論文は、古田　琢哉が自立して研究活動を行うに必要な高度な研究能力と学識を有している事を示している。従って、古田　琢哉提出の博士論文は、博士（理学）の学位論文として合格と認める。