New Physics: Sae Mulli,
Vol. 69, No. 6, June 2019, pp. 622∼624
http://dx.doi.org/10.3938/NPSM.69.622

Stability and Oscillation of Nucleus in QMD Simulation

SungMin Cho
Department of Physics, GIST, Gwangju 61005, Korea

Kang Seog Lee*
Department of Physics, Chonnam National University, Gwangju 61186, Korea

(Received 15 April 2019 : revised 2 May 2019 : accepted 3 May 2019)

In simulations of nuclear collisions using quantum molecular dynamics, a stable nucleus, which usually becomes unstable by emitting at least one nucleon in a few hundred fm/c, is needed. In this research, using a frictional cooling method, we obtain very stable nuclei with lifetimes up to 5000 fm/c. However, those nuclei are neither static nor in the ground; rather they show an oscillatory behavior. The frequencies of oscillation are studied and compared with the frequency of the giant monopole oscillation.

PACS numbers: 24.10.Cn, 24.10.Lx, 25.70.-z, 25.70.Mn, 25.70.Pq
Keywords: Transport model, Quantum molecular dynamics, Nuclear physics

I. Introduction

RAON, a rare isotope accelerator which is under construction in Korea [1] will accelerate unstable heavy-ions and collide them to stable ions to investigate important physical properties such as nuclear symmetry energy. The energy is up to a few hundred MeV per nucleon which is a little above the threshold energy for pion production and thus the description of nuclear collisions is not easy and possible way is to use the transport simulation methods [2,3] such as Blasov-Uhling-Uhlenbeck method(BUU) or Quantum molecular Dynamics(QMD). Aiming to simulate nuclear collisions at RAON, both BUU [4] and QMD [5] codes have been developed and actively studied.

In this article we report some results obtained from the study to improve the QMD simulation. After brief explanation of the QMD simulation for nuclear collisions in next section, friction cooling method is explained and applied in Sec. III, showing great improvement on the stability. In Sec. 4, the oscillation of the root-mean-squared radius of nucleaus simulated is explained, which is found during the propagation stage and generic in QMD simulations. We close with summary.

*E-mail: kslee@jnu.ac.kr

II. Quantum Molecular Dynamic simulation of nuclear collisions

QMD simulations of nucleus or nuclear collisions need nuclei which are groups of neutrons and protons interacting with certain nuclear potential energies such as Skyrme-type parametrization, which we use and are sum of two-body, three-body, Coulomb and symmetry terms. Each nucleon's position and momentum operators evolve through Hamilton's equation of motion and once those operators are known, the wavefunction of the nucleon is determined. In principle, any physical properties can be calculated from the wavefunction. Please refer to Ref. [5] for the details of the QMD code used in this work.

The first step of the QMD simulation of nuclear collisions is called initialization, which is the procedure preparing a certain nucleus with z protons and N neutrons in the state close to the real ground state. The positions of nucleons are determined by a Monte Carlo method according to the probability distribution of Wood-Saxon type, which approximately describes the spatial distribution of nucleus in the ground state. Momentums of protons and neutrons are also determined in a Monte Carlo way such that they lie uniformly below the Fermi momentum. The total energy or the binding energy per nucleon should be close to the measured value. Another important ingredient to add is the Pauli blocking: One needs to calculate the phase space density and if it exceeds 1, that nucleon is prohibited, and thus one has to choose the position and momentum of the nucleon again. The second step of QMD simulation is the time evolution using Hamilton's equations of motion. During the time evolution, stability of nucleus in simulation can be checked. One way is to check whether at least one nucleon is emitted from the remaining nucleons. If one nucleon escapes within a lifetime limit, e.g. 200 MeV/fm, the nucleus is considered as a unstable one and discarded. If the nucleus stays beyond the lifetime limit, the configuration, namely the positions and momenta, are recorded and will be used for further study. Interesting thing is that a nucleus is more stable and bound as one tries to closely follow the ground configuration together with the Pauli blocking.

One big difference with the simulated nucleus and the real one is the antisymmetrization of nuclear wave function [6], which needs enormous computation time and memory. Without antisymmetrization of wavefunctions the only thing one can do is to add a phenomenological Pauli blocking potential , which is a subject of a further study.

III. Frictional Cooling

Frictional cooling method [7] has been used to cool gas or liquid in classical MD by appliying frictional force which is proportional to the velocity difference of two particles

$$\vec{F}^n_{ij} = \mu \left|F^n_{ij}\right| \left|\frac{\vec{v}_1 - \vec{v}_2}{\vec{v}_1 - \vec{v}_2}\right| \tag{1}$$

where

$$\vec{F}^n_{ij}(r) = -\Delta V(r)$$

is the normal force applied by particle i to particle j, which can be calculated from the nuclear potential energy used in propagation stage. Applying the frictional cooling, the binding energy per nucleon reduces gradually as time goes on. Thus, in order not to make the

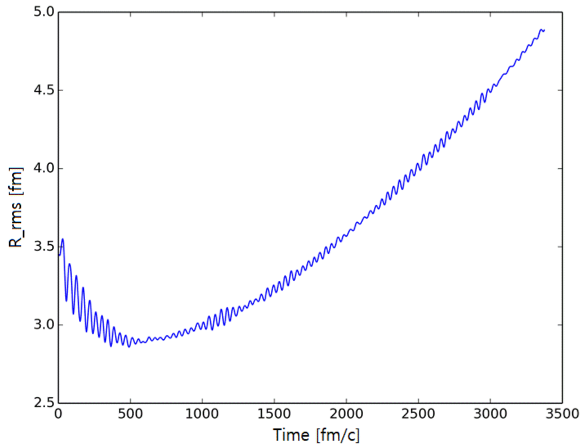

Fig. 1. (Color online) R_{rms} of Ca40 during propagation in unit of fm/c. Up to 500 fm/c frictional cooling is turned on and for $t > 500$ fm/c, it is turned off.

binding energy too small, the frictional cooling needs to be cut at a certain time step and later the nucleus prapagates without cooling. In this way, for a certain value for μ, we get a nucleus with extremely long lifetime, longer than 5000 fm/c, as shown in Fig. 1. In this figure, frictional cooling is turned on during the time $0 < t < 500$ fm/c, and the total energy is decreasing and R_{rms} gets reduced and saturates. In this figure, frictional cooling is turned off at $t = 500$ fm/c. The total energy stays constant for $t > 500$ fm/c and R_{rms} increases. It is amazing that the group of 40 nucleons clings together for such a long time up to 5000 fm/c, even though the radius is increasing slowly and the system is not static and even the radius oscillates. In the next section the nuclear oscillation will be studied.

IV. Nuclear Oscillation

Nucleus in QMD simulation shows oscillating behavior. When the lifetime is less than 200 fm/c, the number of oscillations is less than 3 and it is hard to measure the frequency of the oscillation. However, as the cooling is turned on and off, the lifetime is over a thousand fm/c and the number of oscillation is so big, as shown in Fig. 1, that we can measure the frequency of occurrence as a function of the period or the energy of oscillations, $E = \hbar\omega = 2\pi\hbar/T$, as shown in Fig. 2. The frequency of occurrence looks similar to the giant monopole resonance(GMR) oscillation [8–10], which is measured in the

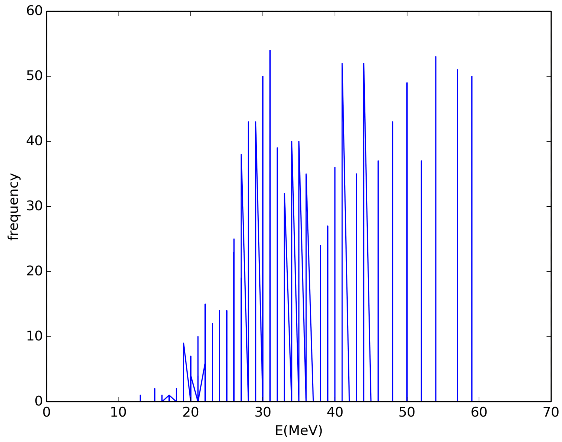

Fig. 2. (Color online) The strength of nuclear oscillation of R_{rms} as a function of energy $E = \hbar\omega = 2\pi\hbar/T$.

scattering of alpha particles from nuclei. However, the energy of oscillation ranges from 20 MeV to 60 MeV and larger than GMR oscillation, which is smaller.

V. Summary

In order to increase the lifetime of a nucleus in simulation, frictional cooling method has been applied and indeed the lifetime has increased enormously up to thousands of fm/c, making the nucleus in simulation good candidate for nuclear collision study. The root-mean-squared radius of nucleus shows oscillating behavior and the frequency of occurrence has been studied as a function of the oscillation energy. The oscillation looks similar to the giant monopole resonance oscillation. However, the oscillation energy is different from GMR. Further study to identify the nature of the oscillation is needed.

ACKNOWLEDGEMENTS

This work is financially supported by NRF2017R1D1A1B03034392.

REFERENCES

[1] S. Jeong, New Phys.: Sae Mulli **66**, 1458 (2016).
[2] C. J. Horowictz, E. F. Brown, Y. Kim, W. G. Lynoh and R. Michaels **et al.**, J. Phys. G: Nucl. Part. Phys. **41**, 0933001 (2014).
[3] J. Xu **et al.**, Phys. Rev. C **93**, 044609 (2016).
[4] M. K. Kim, C. H. Lee and S. Y. Jeon, New Phys.: Sae Mulli **66**, 1563 (2016).
[5] K. Kim, Y. Kim and K. S. Lee, J. Korean Phys. Soc. **71**, 628 (2017).
[6] A. Ono, H. Horiuchi, T. Maruyama and A. Ohnishi, Phys. Rev. C **47**, 2652 (1993).
[7] P. Das, M. Schwartz and S. Puri, J. Phys.: Conf. Ser. **905**, 012035 (2017).
[8] J. R. Stone, N. J. Stone and S. A. Moszkowski, Phys. Rev. C **89**, 044316 (2014).
[9] Y. -W. Lui, D. H. Youngblood, Y. Tokimoto, H. L. Clark and B. John, Phys. Rev. C **70**, 014307 (2004).
[10] T. Gaitanos, A. B. Larionov, H. Lenske and U. Mosel, Phys. Rev. C **81**, 054316 (2010).