Inclusion of internal kinetic energy in classical frozen configurations of nuclei for heavy-ion collision simulations

I. B. Desai, S.S. Godre*
Department of Physics, Veer Narmad South Gujarat University, Surat – 395007, India
** email: ssgodre@yahoo.com*

Introduction

A proper ground-state configuration of the colliding nuclei and the form of NN-potential are important inputs in the heavy-ion collision studies [1-4]. Such configurations can be obtained by the "STATIC" method which is a potential energy minimization program [1,2]. The ground-state configurations of nuclei are obtained using "STATIC" program by taking randomly generated initial configurations of nucleon positions. This program gives a final configuration which is frozen with no internal motion. When such frozen configurations are used in collision simulations they correspond to absence of possible nucleon-transfer degrees of freedom. It has been reported that inclusion of internal kinetic energy and nucleon motion can result in particle evaporations which can affect fusion cross sections [1, 2].

In the present paper we report a successful attempt to include internal motion in the frozen configurations generated using the "STATIC" method without evaporation. We study the dynamical evolution of the most bound frozen configuration of ^{24}Mg, e.g., by assigning initially random velocities to the nucleons [5].

Calculational Details

Dynamical evolution of a system of many particles is carried out by solving the coupled classical equations of motion,

$$m\frac{d^2\vec{r}_i}{dt^2} = -\vec{\nabla}_i\left(\sum_{j\neq i} V_{ij}\right)$$

with given initial conditions of particle coordinates and velocities [1]. Above equations are solved numerically by using 4th order Runge-Kutta Method with a sufficiently small time step of ?t = 0.02 × 10^{-22} sec which gives good conservation of the total energy.

For the present study we choose the frozen configuration of ^{24}Mg corresponding to the maximum binding energy of all the configurations generated by "STATIC" with a soft-core Gaussian form of the NN-potential with potential parameter set P4 (V_o = 1155 MeV, C= 2.07 fm, r_o= 1.2 fm) [3]. Dynamical evolution of this system is carried out by assigning random velocities to all the particles up to a given maximum value V_{max}.

The effect of choosing different values of V_{max} corresponding to different values of internal kinetic energy on dynamical evolution of the above system is studied as the system evolves dynamically for $T_{max} = 100 \times 10^{-22}$ sec. This time scale is long enough for attaining equilibrium and evaporation of nucleons from the system, if any. As the system evolves in time, total potential energy, total kinetic energy (KE), rms radius (R_{rms}) and deformation parameter ($ß_2$) are calculated at regular intervals. These parameters change from their initial values and after some time fluctuate around their respective mean values which are different from the initial values.

Results and Discussion

We have studied dynamical evolution of ^{24}Mg with various initial random velocities (V_{max}). As we increases the value of V_{max} the initial value of internal kinetic energy increases suddenly as system evolves and within a few time-intervals it suddenly drops and fluctuates around a decreased mean value as shown in fig. 1(a) & 2(a). We also observe an increase in R_{rms} from fig 1(b) & 2(b) as internal kinetic energy (V_{max}) is increased initially.

An increase in V_{max} beyond a certain value leads to evaporation of a few particles from the system. In the present case we find the critical value is V_{max} = 2.7 fm/10^{-22} sec corresponding to initial total kinetic energy = 82.36 MeV. After the dynamic evolution it results in an equilibrium value of the total kinetic energy = 32 MeV (fig. 1(a)) which is less than the initial value.

Therefore, artificially imparted internal kinetic energy to the system, by way of random velocities, result in rearrangement of the particle configuration leading to enhanced separation between the nucleons giving rise to increased value of the rms radius. The difference in the initial and final equilibrium value of the kinetic energy appears as a reduction in the attractive parts of the total potential energy.

Beyond the value of V_{max} = 2.7 fm/10^{-22} sec, an increase in V_{max} does lead to an increase in the initial value of the kinetic energy but it also results in more violent collisions and separation between nucleons. In such cases some nucleons acquire enough kinetic energy to escape by evaporation from the nucleus by overcoming the attraction of the remaining nucleons in the nucleus. For V_{max} = 2.8 fm/10^{-22} sec, dynamic evolution leads to evaporation of one nucleon which is evident from fig. 2(b) as R_{rms} increases for t > 25 x 10^{-22} sec. For V_{max} = 6.2 fm/10^{-22} sec the nucleus is disintegrated by evaporation of all the nucleons [5].

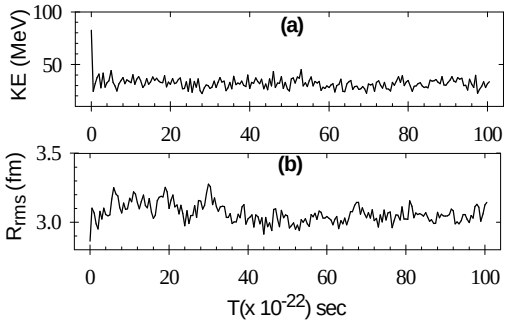

Fig. 1 Time evolution for configurations with initial velocity V_{max} = 2.7(fm/10^{-22} sec).

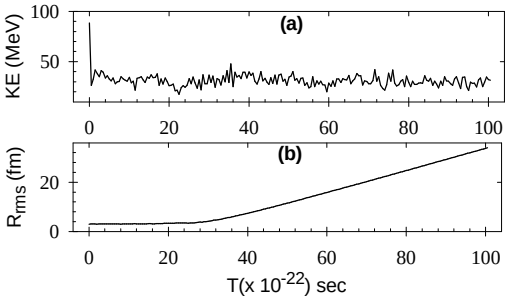

Fig. 2 Time evolution for configurations with initial velocity V_{max} = 2.8(fm/10^{-22} sec).

The problem of the evaporation of nucleons arises because of the very short range and the large repulsive-core in the shallow and narrow potential P4. In order to overcome the problem of evaporation of nucleons for the case of V_{max} = 6.2 fm/10^{-22} sec, we adjust the potential parameters such that no evaporation takes place in t = T_{max}. (potential Pev: V_0=245 MeV, C=2.07 fm, r_0=2.2 fm). This potential Pev is compared with the potential P4 in fig. 3. Potential Pev is very deep and wide as compared to potential P4.

In this case a higher equilibrium value of the total kinetic energy = 226.8 MeV is obtained; although with much higher value of the attractive potential energy as well. However, the rms radius is 3.28 fm which is close to the value for this system with the potential P4.

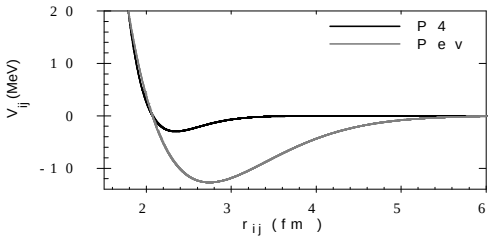

Fig 3 Comparisons of NN-potential P4 and Pev.

Dynamical simulations with even larger value of V_{max} show no particle evaporation. Therefore, with a careful choice of the potential parameters it may be possible to obtain suitable non-frozen nuclei for heavy-ion collisions where internal energy is not neglected. This will also be important in simulations of heavy-ion collisions where nucleon exchange is a significant channel.

References

[1] S. S. Godre, Ph.D. Thesis, *'Classical and semi classical microscopic approaches for heavy-ion fusion reactions*', Indian Institute of Technology, Kanpur (1989).

[2] S. S. Godre and Y. R. Waghmare, Phys. Rev. **C** 36, 1632 (1987).

[3] S. S. Godre, Nucl. Phys. A**734** (2004) E17.

[4] S. S. Godre and P. R. Desai, Nucl. Phys. **A834**, 195 (2010)

[5] I. B. Desai, M.Phil. Dissertation, *'A study of construction of ground-state nuclei with various NN-potentials in "STATIC" and "DYNAMIC" methods'*, Veer Narmad South Gujarat University, Surat (2009).