PRAMANA
— journal of
physics

Vol. 53, No. 3
September 1999
pp. 453–456

The simulations of Ca–Ca collisions: Binary break-up, onset of multifragmentation and vaporization

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Abstract. The incomplete fusion, onset of multifragmentation and vaporization is studied in Ca–Ca collisions at bombarding energies between 20–1000 A MeV and at impact parameters between $b = 0$ to $b_{\rm max}$ using quantum molecular dynamics model. We find incomplete fusion events at $E/A = 20$ MeV. The light mass fragment production at a given incident energy does not show any rise and fall with a change in the impact parameter. Whereas, the IMF production at higher energies (≥ 150 A MeV) has a clear rise and fall.

Keywords. Quantum molecular dynamics; multifragmentation; rapidity; flow.

PACS Nos 25.70Jj; 25.70 Mn; 25.70Pq

1. Introduction

The most interesting domain of the incident energy in heavy ion collisions is between 20 A MeV to 1000 A MeV where one can have incomplete fusion, fusion–fission, multifragmentation or a complete disassembly of the excited nuclear matter [1]. The new experimental studies of the multifragmentation have revealed that it is a very complicated phenomenon which depends crucially on the bombarding energy and on the impact parameter. Here we plan to understand the complex dependence of the light mass and intermediate mass fragments on bombarding energy and impact parameter by carrying a systematic study of the formation of fragments and their properties in Ca–Ca collision using quantum molecular dynamics (QMD) model [2].

2. The model

The simulations of Ca–Ca collisions are performed using QMD model [2], where each nucleon is described by a Gaussian in momentum and coordinate space and the centroid of each nucleon propagates using the Hamiltonian equations of motion:

$$\frac{\mathrm{d}\vec{r}_i}{\mathrm{d}t} = \frac{\partial H}{\partial \vec{p}_i}; \qquad \frac{\mathrm{d}\vec{p}_i}{\mathrm{d}t} = \frac{\partial H}{\partial \vec{r}_i} \tag{1}$$

with Hamiltonian

$$H = \sum_{i}^{A} \frac{\vec{p_i}^2}{2m} + \frac{1}{2} \sum_{i=1}^{A} \sum_{j \neq i}^{A} (u_{sk}^{ij} + u_{yk}^{ij} + u_{c}^{ij}). \tag{2}$$

The u_{yk}, u_{sk} and u_c appearing in eq. (2) are, respectively, the Yukawa, Skyrme and Coulomb interactions. For details, the reader is referred to ref. [2].

3. Results and discussion

In the present study, a hard equation of state with energy dependent cross-section is used. We follow the time evolution of nucleons till 200 fm/c and then construct the fragments using the minimum spanning tree method which allows two nucleons to share the same fragment if their centroids are closer than 4 fm.

In figure 1, we display the final multiplicities (at 200 fm/c) as a function of the scaled impact parameter $\hat{b} = b/b_{\mathrm{max}}$. The displayed quantities are: the largest fragment A^{max}, emitted nucleons, light mass fragments (LMFs) $(2 \leq A \leq 4)$ and intermediate mass fragments (IMF's) $(5 \leq A \leq 25)$. The A^{max} will give us possibility to look for fusion in Ca–Ca collisions. Whereas the emission of nucleons will show the disassembly (and hence the vaporization) of the matter. At low energies, few nucleons are emitted from the excited compound system which is followed by the emission of the LMFs. In some cases (specially at non-central collisions), the excited system decays in two steps: (i) it fissions into two parts (the binary break-up) and (ii) these fissioned products emit nucleons/LMFs. The A^{max} yields several interesting points: (i) One clearly sees a partial fusion at 20 A MeV for $\hat{b}$ $(= b/b_{\mathrm{max}}) =$ 0.45–0.75. (ii) The A^{max} at low energies is nearly independent of the impact parameter. Whereas a stronger impact parameter dependence is observed at higher energies. This can be understood on the ground that at low energies, the available phase-space is too small to allow the frequent nucleon–nucleon collisions. Therefore, the variation in the impact parameter at low energies has a least effect on A^{max}. At higher bombarding energies ($\geq$ 100 A MeV), the dynamics is dominated by the frequent nucleon–nucleon collisions which depend strongly on the impact parameter.

The emission of nucleons increases with increase in the bombarding energy for central and semi-central collisions. In central collisions at 1000 A MeV, nearly 90% of the nuclear matter ends emitted nucleons. If we label the phenomenon with $\approx$ 60% matter emitted nucleons as 'vaporization', we see the vaporization for central collisions above 200 A MeV.

The LMFs production in central collisions peaks around 150–200 A MeV. This peak vanishes for peripheral collisions. The IMFs show a clear transition from multifragmentation to complete disassembly of the nuclear matter at central collision. We notice a rise and fall in IMFs production with increase in the bombarding energy in central collisions. The peak/plateau in IMFs production has also been observed recently [1]. The variation of LMFs and IMFs with impact parameter yields different results: (i) There is no rise and fall in the LMFs production with a change in the impact parameter. (ii) The IMFs clearly show a rise and fall for bombarding energies $\geq$ 150 A MeV. The plateau of the peak in the multiplicity decreases with increase in the bombarding energy till 400 A MeV and remains the same for further change in the incident energy. This is simply due to the fact that the mass of the system is very small. Therefore, after certain excitation energy, the final structure will no longer change. We also see the onset of the multifragmentation around 60 A MeV where the IMF production is maximum.

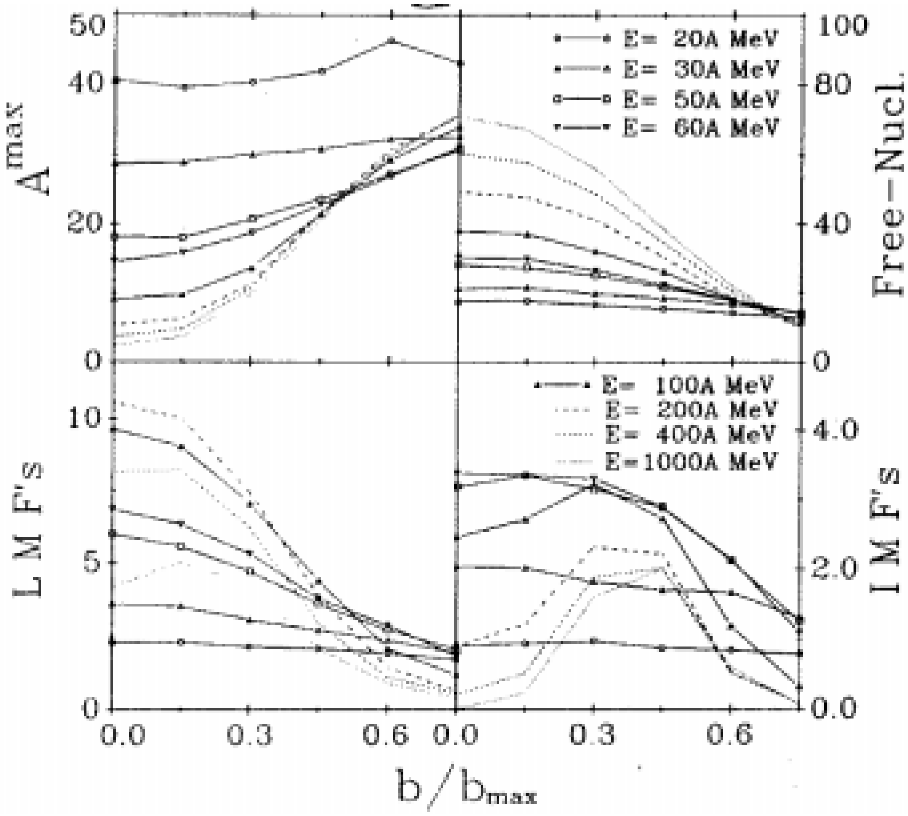

Figure 1. Different fragment multiplicities as a function of the scaled impact parameter $\hat{b} = b/b_{\max}$. Here we simulate Ca–Ca reaction for 500 events.

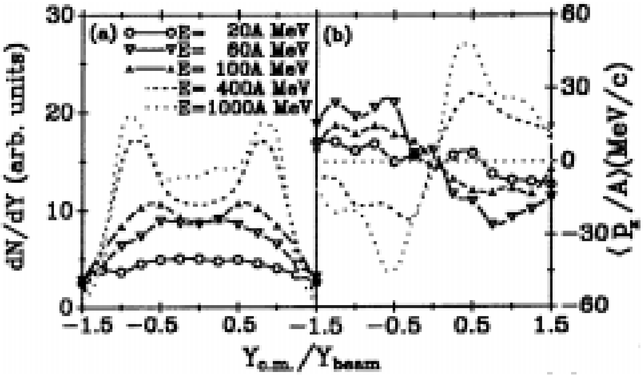

Figure 2. (**a**) The rapidity distribution of nucleons emitted in Ca–Ca collisions. (**b**) The nuclear flow as a function of rapidity.

In figure 2(a) and (b), we display the rapidity distribution ($\mathrm{d}N/\mathrm{d}Y$) and the flow (p_x/A) of nucleons at $b = 4.5$ fm. Here different curves display the results at various incident energies. We notice that at low energies ($\leq$ 60 MeV/A) nucleons overlap in momentum space and as a result one sees a peak at mid-rapidity region. On the other hand, peaks at target and projectile rapidities occur at higher incident energies indicating non-equilibrium situation. Note that the rapidity distribution depends strongly on the number of nucleons emitted. The flow (p_x/A) depicts well-known behavior. The nuclear flow is negative at lower incident energies which becomes repulsive (+ve) at higher incident energies.

We also see an increase in the slope of flow with increase in the incident energies. Note that at some incident energy, the nucleonic flow will disappear.

4. Summary

We have carried out a systematic study of the formation of fragments and their properties in Ca–Ca collisions. Our results clearly indicate that (i) the simulations at 20 A MeV show several events of partial fusion. (ii) A rise and fall in the fragment production in central collisions with an increase in the bombarding energy. (iii) The IMF multiplicity is maximum at central collision and it decreases with increase in the impact parameter at lower energies whereas it has a clear rise and fall at higher energies. The rapidity distribution of nucleons indicates non-equilibrium at higher incident energies. The nucleonic flow is negative at low incident energies which becomes positive at higher incident energies.

Acknowledgement

The work is supported by DAE research grant.

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