Entropy production in heavy-ion collisions: Confrontation of model calculations with experimental data

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Introduction

The motivation for studying the heavy-ion collisions at intermediate energies is to investigate the properties of nuclear matter at high temperature and high density. However, intermediate nuclear system formed during the course of nucleus-nucleus collisions, remains hot and dense for a very short time. One, therefore, needs the observable that can preserve the signatures of the early hot and dense phase of nuclear matter. In Ref. [1], it has been argued that entropy is produced at maximum temperature and density during nn collisions. The entropy grows rapidly during the initial stage of the reaction and does not change much during the expansion phase. Thus, the entropy per nucleon produced in a collision is one of the observables that preserves the memory of the early phase. During nucleus-nucleus collisions at sufficiently high energies, the fire ball formation takes place and a large share of kinetic energy is converted into thermal excitation and fragment formation. Siemens and Kapusta [1] had suggested that the entropy can be estimated from the ratio of the deutron to proton yield. But later on, Doss *et al.* [2] discussed that light fragments such as d, t, ^{3}He, ^{4}He also contribute significantly towards the entropy production. The entropy can be estimated by the following generalized formula [3]:

$$S_N = 3.945 - \ell n(d_{like}/p_{like}). \qquad (1)$$

Stöcker *et al.* [4] has also discussed the importance of contributions from heavier fragments ($A > 4$). With the increase in the bombarding energy, the formation of heavy fragments goes on decreasing. Therefore, heavy fragments make a significant contribution at low energies only, while at high energies the contribution of these fragments is negligible.

In the present paper, we try to estimate the entropy S_N from the yield ratio of deuteron-like to proton-like clusters. Here, our aim is to see whether an isospin-dependent quantum molecular dynamics (IQMD) model can explain the entropy production in heavy-ion collisions as reported in the experimental studies.

The Model

The present study is carried out within the framework of the isospin-dependent quantum molecular dynamics (IQMD) model [5]. The IQMD model is an extension of quantum molecular dynamics (QMD) model [6], which includes isospin degrees of freedom explicitly. The model consists of isospin-dependent Coulomb potential, symmetry potential, and nn cross sections. The total interaction potential is given by

$$V^{total} = \sum_{i}^{A}(V_i^{Sky} + V_i^{Yuk} + V_i^{Coul} + V_i^{sym}). \qquad (2)$$

The V_i^{Sky}, V_i^{Coul}, V_i^{Yuk} and V_i^{sym} are, respectively, the Skyrme, Yukawa, Coulomb, and symmetry potentials.

The phase space generated within IQMD model is analyzed using the minimum spanning tree (MST) method with clusterization range 2.8 fm.

Results and Discussion

We simulated the central collisions of ^{40}Ca $+^{40}$Ca (at 400 and 1050 MeV/nucleon) and ^{93}Nb $+^{93}$Nb (at 400 and 650 MeV/nucleon). We, here, used a soft equation of state along with standard isospin- and energy-dependent

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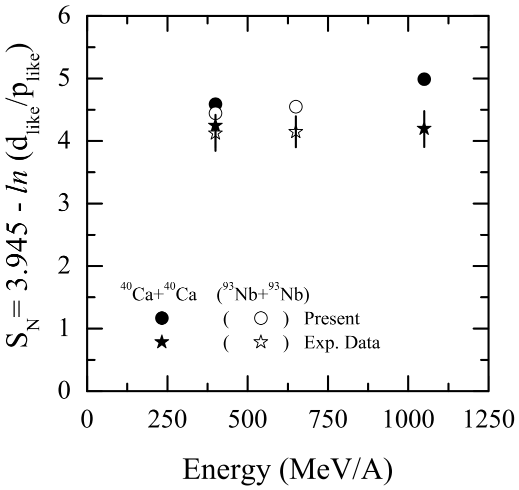

FIG. 1: The baryonic entropy S_N as a function of incident beam energy for the central collisions of ^{40}Ca $+^{40}$Ca and ^{93}Nb $+^{93}$Nb (preliminary results). Also shown are entropy values extracted by the Plastic Ball group [2].

cross section. The entropy is then estimated via Eq.(1). The d_{like}/p_{like} ratios and entropy are calculated typically after 40 fm/c, when average nucleonic density saturates and nn collisions practically cease. At this time, the comparison with the experimental data can be made as yields of the composite particles are well settled.

In Fig. 1, we display the model calculations for entropy S_N along with experimental data taken with Plastic Ball detector [2]. From the figure, we see that our calculations are in good agreement with experimental data. Also, the entropy is found to be independent of the mass of the colliding pairs. There is only slight increase in the entropy with increase in the incident beam energy. These results show that the IQMD model contains essential features to explain the underlying physics of the entropy production. As a next course, we plan to extend this study for neutron-rich matter.

Acknowledgments

This work is supported by a research grant from Council of Scientific and Industrial Research (CSIR), Government of India vide sanction No. 03(1263)/12/EMR-II. S. K. acknowledges fellowship from Department of Science and Technology (DST), Government of India.

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