Systematic study of isospin effects in the $d_{\rm like}/p_{\rm like}$ ratio and entropy production

Sukhjit Kaur and Rajeev K. Puri*

Department of Physics, Panjab University, Chandigarh 160014, India

(Received 16 December 2013; revised manuscript received 4 March 2014; published 14 May 2014)

We report our analysis of $d_{\rm like}/p_{\rm like}$ ratio and entropy production in heavy-ion collisions using an isospin-dependent quantum molecular dynamics model. The entropy is estimated using the method proposed by Siemens and Kapusta [P. J. Siemens and J. I. Kapusta, Phys. Rev. Lett. **43**, 1486 (1979)]. Our calculations are in good agreement with experimental data. We also study the role of the neutron content of colliding pairs on the production of $d_{\rm like}/p_{\rm like}$ ratio and entropy. Our findings reveal that entropy decreases with an increase in the isospin asymmetry for both isotopic and isobaric pairs.

DOI: 10.1103/PhysRevC.89.057603 PACS number(s): 25.70.Pq, 24.10.Cn, 21.65.Cd

The motivation behind accelerating heavy ions to ultrahigh energies is to study the properties of hot and dense nuclear matter. The hot and dense phase of nuclear matter, however, remains for a short interval of time. Therefore, to study the nuclear matter at high densities and temperature, one needs those observables that contain traces of the early hot and dense phase. As evident from the literature, entropy production is one of the observables that preserves the memory of the early hot and dense phase of nuclear matter [1–7] and, hence, can shed light on the properties of the hot and dense phase of nuclear matter. The entropy production in a collision can be estimated via a number of different prescriptions. For example, Siemens and Kapusta [1] suggested that the entropy can be estimated from the ratio of the deutrons to the protons. On the other hand, Bertsch and Cugnon [2] also took light clusters like t, ^{3}He, and ^{4}He into account apart from deutrons and protons. Later on, Stöcker *et al.* [3] proposed that heavier fragments ($A > 4$) should also be taken into account for studying the entropy production at low energies. Their contribution, however, turned out to be insignificant at higher energies.

In another study, Doss *et al.* [4,5] measured the production of composite particles and entropy for the reactions of ^{40}Ca + ^{40}Ca (400 and 1050 MeV/nucleon) and ^{93}Nb + ^{93}Nb (400 and 650 MeV/nucleon). They computed entropy within both methods proposed by Siemens and Kapusta [1] and Stöcker *et al.* [3]. The main conclusion of their study was that entropy production is nearly independent of the mass of the reacting partners. A detailed review of the deutron/proton ratio and entropy production can be found in Ref. [8]. Recently, the CHIC Collaboration [9] measured the yields of d/p and t/p in asymmetric collisions of p + Kr, O + Kr, and Ne + Ar. The statistical evaporation models were reported to fail to reproduce these ratios [9]. The microscopic and mean-field calculations, on the other hand, could explain the data nicely. Recently, one of us and a collaborator [10] and, earlier, others also [11] studied the entropy production in heavy-ion collisions within a quantum molecular dynamics (QMD) model and found good agreement with the 4π Plastic Ball data. Here, entropy was calculated using the method proposed by Siemens and Kapusta [1].

*rkpuri@pu.ac.in

Among all the studies reported in the literature, none of them has ever dealt with the question of how neutron content affects the $d_{\rm like}/p_{\rm like}$ ratio and hence entropy production. The availability of second generation radioactive-ion beam (RIB) facilities has made it possible to study the collision of highly isospin asymmetric systems. As evident from the above, entropy is closely related to the fragment production that is affected by the neutron content of a colliding pair [12–19]. It would, therefore, be of interest to study the behavior of entropy production with the neutron content of the reacting partners. Our present aim, therefore, is at least twofold: (i) to compare our calculations using isospin-dependent quantum molecular dynamics (IQMD) with 4π Plastic Ball data [4] and (ii) to analyze the role of the neutron content of reacting partners on the $d_{\rm like}/p_{\rm like}$ ratio and hence entropy production.

As stated, present analysis is made within the framework of the IQMD model [20]. The details can be found in Ref. [20]. Once phase space is generated and clusterized using the minimum spanning tree (MST) method [21], the entropy can be calculated using the method proposed by Siemens and Kapusta [1]. Here, entropy is calculated by the following formula:

$$S_N = 3.945 - \ell n(R_{dp}), \qquad (1)$$

where R_{dp} is the ratio of deutrons to protons. Bertsch and Cugnon [2] generalized the above relation by incorporating lighter clusters as well:

$$S_N = 3.945 - \ell n(\widetilde{R}_{dp}), \qquad (2)$$

where $\widetilde{R}_{dp}$ is the ratio of deutronlike clusters to protonlike clusters and is given by

$$\widetilde{R}_{dp} = \frac{d_{\rm like}}{p_{\rm like}} = \frac{d + \frac{3}{2}(t + {}^3{\rm He}) + 3\,{}^4{\rm He}}{p + d + t + 2\,{}^3{\rm He} + 2\,{}^4{\rm He}}. \qquad (3)$$

In Refs. [10,11], the yield ratio of $d_{\rm like}$ and $p_{\rm like}$ clusters is simplified in the following way:

$$\widetilde{R}_{dp} = \frac{d_{\rm like}}{p_{\rm like}} = \frac{Y(A=2) + \frac{3}{2}Y(A=3) + 3Y(A=4)}{N_p}, \qquad (4)$$

where $Y(A = n)$ stands for the number of fragments with mass n in one event. The participant proton multiplicity is calculated as

$$N_p = \frac{Z_P + Z_T}{A_P + A_T}[Y(A = 1) + 2Y(A = 2) + 3Y(A = 3) + 4Y(A = 4)], \quad (5)$$

where $Z_P + Z_T$ and $A_P + A_T$, respectively, define the total charge and mass of the colliding pair.

First of all, we simulated those reactions for which experimental data are available. In particular, we simulated the reactions of ^{40}Ca + ^{40}Ca (at 400 and 1050 MeV/nucleon) and ^{93}Nb + ^{93}Nb (at 400 and 650 MeV/nucleon) over the whole range of impact parameters. The choice of projectile-target combination and incident energy is guided by the experimental data. We here used a soft equation of state along with energy- and isospin-dependent *nn* cross sections. The simulations were carried out with reduced Fermi momentum (by 30%). All reactions were followed till 300 fm/c. The yield ratios were extracted after the compression phase was over and the nucleonic density got saturated (∼40 fm/c) as described in Ref. [10].

In Fig. 1, we display the ratio of deutronlike to protonlike ($d_{\rm like}/p_{\rm like}$) clusters as a function of participant proton multiplicity, N_p. The solid circles (solid stars) represent our calculations (experimental data). From the figure, we see that the $d_{\rm like}/p_{\rm like}$ ratio increases with N_p (or decreases with impact parameter). It implies that the production of light clusters is maximal in central collisions compared to peripheral ones. It has also been supported by Ref. [22], where Puri and co-workers studied the impact parameter dependence of the multiplicity of light-charged particles (LCPs) and found that the multiplicity of LCPs goes on decreasing with impact parameter. They also correlated the multiplicity of LCPs to the degree of stopping in heavy-ion collisions. From the figure,

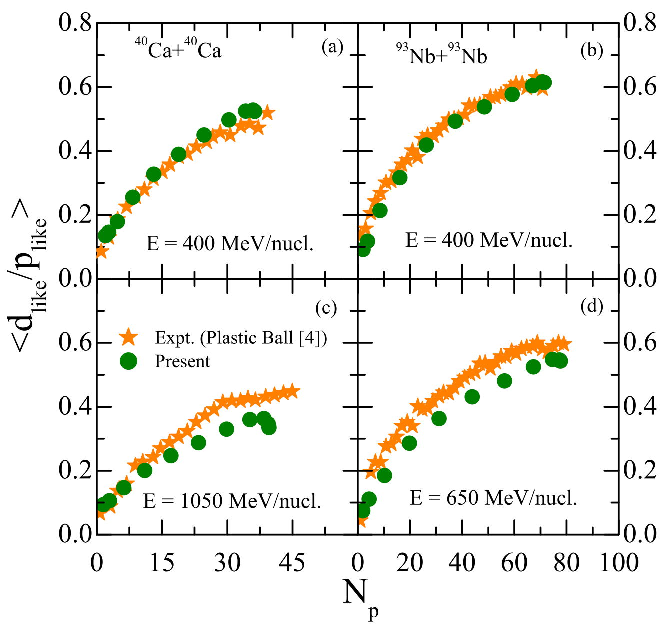

FIG. 1. (Color online) The $d_{\rm like}/p_{\rm like}$ ratio as a function of participant proton multiplicity, N_p. The model calculations (solid circles) are compared with the experimental data (solid stars) [4].

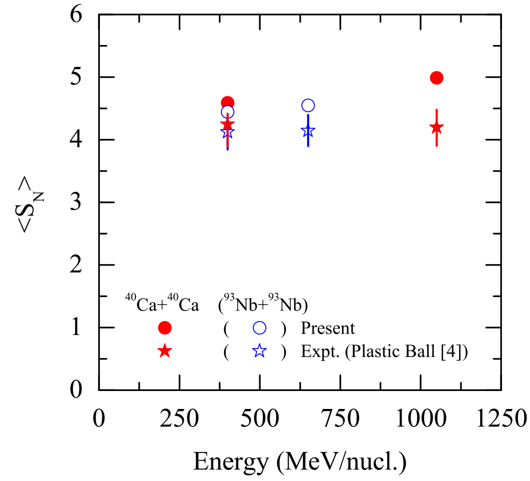

FIG. 2. (Color online) The entropy S_N per nucleon as a function of the incident beam energy for the central collisions of ^{40}Ca + ^{40}Ca and ^{93}Nb + ^{93}Nb. Also shown are the entropy values extracted by the Plastic Ball group [4].

we also see that our calculations are in good agreement with the experimental data in most of the cases. This shows that the IQMD model can be used reliably to study the production of the $d_{\rm like}/p_{\rm like}$ ratio and hence entropy produced in heavy-ion collisions.

In Fig. 2, we display the entropy per nucleon [calculated using Eq. (2)] as a function of the incident beam energy. We also compared our calculations with the 4π Plastic Ball data [4]. Our calculations are in good agreement with the experimental data (within 10%) except for the reaction of ^{40}Ca + ^{40}Ca at 1050 MeV/nucleon. It has been shown in Ref. [23] that about 10 to 18% of the nucleons are excited to Δ resonances at incident energies between 1 and 2 GeV/nucleon that further decay to pions. As noted from Fig. 2, our calculations at 1050 MeV/nucleon deviate by about 20% from the experimental data. This difference, therefore, could be due to the contribution coming from the pions that are not taken into account in the present calculations. From both Figs. 1 and 2, it is evident that the IQMD model can reproduce the $d_{\rm like}/p_{\rm like}$ ratio as well as the entropy production reasonably well.

We now extend the above study for the neutron-rich/neutron-deficient colliding pairs. To see the role of the neutron content of a colliding pair, we simulated the reactions of $^{52}_{32}$Ge + $^{52}_{32}$Ge (at 400 and 1050 MeV/nucleon), $^{52}_{26}$Fe + $^{52}_{26}$Fe (at 400 and 1050 MeV/nucleon), $^{40-60}_{20}$Ca + $^{40-60}_{20}$Ca (at 400 and 1050 MeV/nucleon), and $^{83-123}_{41}$Nb + $^{83-123}_{41}$Nb (at 400 and 650 MeV/nucleon), which covers the N/Z ratios between 0.63 and 2.0 over the whole range of impact parameters. In Figs. 3(a) and 3(b), we display the N/Z dependence of the $d_{\rm like}/p_{\rm like}$ ratio and the entropy per nucleon, respectively, for the isotopic series of $^{40-60}$Ca and $^{83-123}$Nb. The solid circles and squares represent the calculations for the reactions of Ca + Ca at incident energies of 400 and 1050 MeV/nucleon, respectively. Open circles and squares represent the calculations for the reactions of Nb + Nb at incident energies of 400 and 650 MeV/nucleon, respectively. From the figure, we

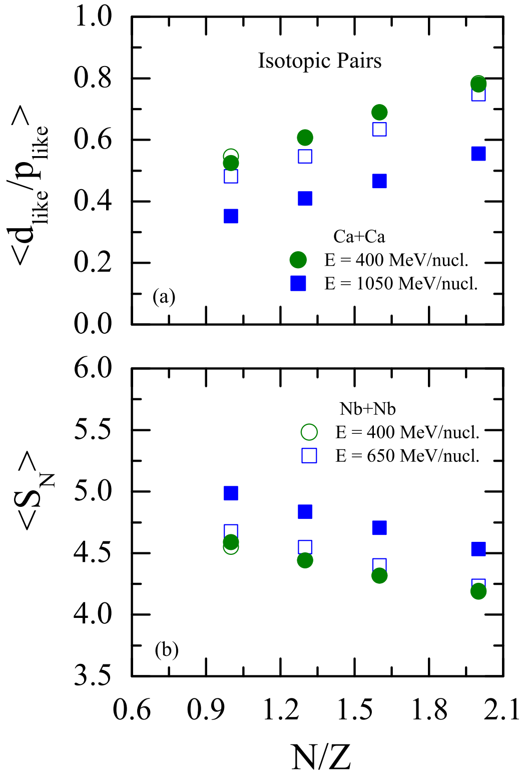

FIG. 3. (Color online) N/Z dependence of the $d_{\text{like}}/p_{\text{like}}$ ratio (upper panel) and entropy per nucleon (lower panel) for isotopic pairs of Ca and Nb. Various symbols are explained in the text.

see that the $d_{\text{like}}/p_{\text{like}}$ ratio increases and hence the entropy decreases with isospin asymmetry. Because entropy represents the degree of randomness, therefore, the decrease in the entropy production with isospin asymmetry shows that, with an increase in the neutron content, the nuclear system gets more and more ordered. Along the isotopic series, the system mass increases due to the increase in the number of neutrons, whereas the number of protons remains the same. As a result, the increase in the $d_{\text{like}}/p_{\text{like}}$ ratio along the isotopic series could be due to the contribution coming from the d_{like} clusters. We will examine this aspect later on. For a particular value of the isospin ratio (N/Z), the entropy is found to be independent of the mass of the reacting partners, but depends on the incident beam energy.

We have also checked the N/Z dependence of the $d_{\text{like}}/p_{\text{like}}$ ratio and entropy per nucleon for isobaric pairs having total mass of 104 units. In particular, we simulated the reactions of ${}^{52}_{32}\text{Ge} + {}^{52}_{32}\text{Ge}$, ${}^{26}_{26}\text{Fe} + {}^{52}_{32}\text{Fe}$, and ${}^{52}_{20}\text{Ca} + {}^{52}_{20}\text{Ca}$ at incident energies of 400 and 1050 MeV/nucleon. The results are displayed in Figs. 4(a) and 4(b). The solid diamonds and triangles represent the calculations for incident energies of 400 and 1050 MeV/nucleon, respectively. From the figure, it is evident that again the $d_{\text{like}}/p_{\text{like}}$ ratio increases, whereas the entropy decreases with the increase in the neutron content for isobaric pairs. For isobaric pairs, the total mass of the system remains fixed, whereas the numbers of neutrons and protons vary. It is well known that the isospin effects constitute the contributions from the symmetry potential, the isospin-dependent cross

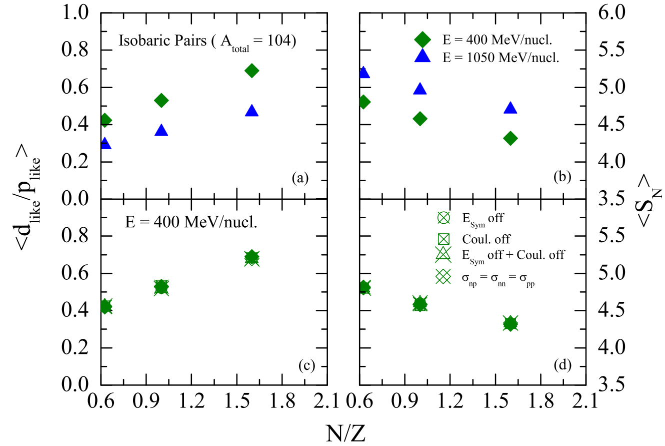

FIG. 4. (Color online) N/Z dependence of the $d_{\text{like}}/p_{\text{like}}$ ratio (left panels) and entropy per nucleon (right panels) for isobaric pairs. Crossed circles represent calculations without symmetry energy and crossed squares denote results without Coulomb potential, whereas crossed triangles represent calculations when both symmetry energy and Coulomb potential are turned off. Calculations of isospin-independent cross sections are denoted by crossed diamonds.

section, and the Coulomb potential. Therefore, to find the cause behind this behavior, we checked the relative contribution of all three factors at 400 MeV/nucleon. These results are displayed in Figs. 4(c) and 4(d). From the figure, we see that the variation in the strength of the symmetry energy and the Coulomb potential do not alter the results. Similarly by taking the isospin-independent nn cross section, the results remain the same. In other words, factors governing the isospin degree of freedom do not affect the $d_{\text{like}}/p_{\text{like}}$ ratio and hence entropy production at a fixed N/Z ratio.

As noted above, entropy decreases with the N/Z ratio for both isotopic and isobaric colliding pairs. To see the relative contribution of the yields of p_{like} and d_{like} clusters towards entropy production, in Fig. 5, we display the impact parameter dependence of the yields of protonlike and deutronlike clusters separately. The short-dotted, solid, dashed, and dash-dotted lines represent yields for the reactions of ${}^{40}_{20}\text{Ca} + {}^{40}_{20}\text{Ca}$, ${}^{52}_{32}\text{Ge} + {}^{52}_{32}\text{Ge}$, ${}^{52}_{26}\text{Fe} + {}^{52}_{26}\text{Fe}$, and ${}^{52}_{20}\text{Ca} + {}^{52}_{20}\text{Ca}$, respectively. We find that the variation in the system mass (neutron content) does not change the yield of the protonlike clusters for isotopic pairs. The number of deutronlike clusters, however, keeps increasing with the mass of the colliding pair. This enhances the production of the $d_{\text{like}}/p_{\text{like}}$ ratio and hence reduction in the net entropy. The variation in the neutron content does not change the yield of deutronlike clusters in isobaric pairs, whereas the yield of the protonlike clusters is affected significantly by the neutron content of the colliding pairs. A neutron-rich system (like ${}^{52}_{20}\text{Ca}$) yields less protonlike clusters than a neutron-deficient system (like ${}^{52}_{32}\text{Ge}$). From Eq. (5), we see that the yield of protonlike clusters has a factor of $\frac{Z_P+Z_T}{A_P+A_T}$. For isobaric pairs, while the total system mass $(A_P + A_T)$ remains fixed, the total system charge $(Z_P + Z_T)$ increases monotonically and therefore affects the net production of the protonlike clusters. Therefore, there will be a net increase in the $d_{\text{like}}/p_{\text{like}}$ ratio with neutron content. This will subsequently

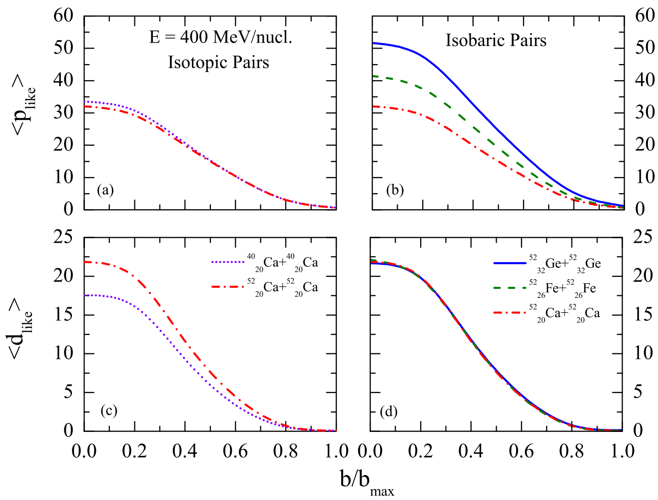

FIG. 5. (Color online) The yields of $p_{\rm like}$ (upper panels) and $d_{\rm like}$ (lower panels) clusters as a function of the impact parameter for isotopic (left panels) and isobaric (right panels) pairs for an incident energy of 400 MeV/nucleon. Various lines are explained in the text.

decrease the entropy production [as per Eq. (2)] with neutron content. It is worth mentioning that one of us and co-workers [24] reported the dominance of the Coulomb potential towards the isospin effects in balance energy for isobaric pairs. In the case of isotopic pairs, balance energy (at which the collective flow disappears and has an inverse relation with the collective flow) is also found to decrease with the isospin asymmetry [25]. Such a correlation, however, does not exist for the isobaric pairs [24].

Summarizing, here we studied the $d_{\rm like}/p_{\rm like}$ ratio and hence entropy production using the method proposed by Siemens and Kapusta [1] within the framework of the IQMD model. We compared our calculated yield ratios as well as entropy with the 4π Plastic Ball data. Our calculations are in good agreement with the experimental data. This motivated us to analyze the role of the neutron content of the colliding pair on the production of the $d_{\rm like}/p_{\rm like}$ ratio and entropy. We checked the effect of the neutron content on the production of the $d_{\rm like}/p_{\rm like}$ ratio and entropy for isotopic as well as for isobaric colliding pairs. We found that the entropy decreases with an increase in the N/Z ratio for both isotopic and isobaric colliding pairs. This change can be attributed to the altered production of the $d_{\rm like}$ and $p_{\rm like}$ clusters with neutron content.

This work is supported by a research grant from the Council of Scientific and Industrial Research (CSIR), GOI Vide Sanction No. 03(1263)/12/EMR-II. S.K. acknowledges support from DST, GOI.

[1] P. J. Siemens and J. I. Kapusta, Phys. Rev. Lett. **43**, 1486 (1979).
[2] G. Bertsch and J. Cugnon, Phys. Rev. C **24**, 2514 (1981); G. Bertsch, Nucl. Phys. A **400**, 221 (1983).
[3] H. Stöcker *et al.*, Nucl. Phys. A **400**, 63 (1983); B. V. Jacak *et al.*, Phys. Rev. Lett. **51**, 1846 (1983); B. V. Jacak, H. Stöcker, and G. D. Westfall, Phys. Rev. C **29**, 1744 (1984).
[4] K. G. R. Doss *et al.*, Phys. Rev. C **32**, 116 (1985).
[5] K. G. R. Doss *et al.*, Phys. Rev. C **37**, 163 (1988).
[6] J. Aichelin and E. A. Remler, Phys. Rev. C **35**, 1291 (1987).
[7] K. K. Gudima, V. D. Toneev, G. Röpke, and H. Schulz, Phys. Rev. C **32**, 1605 (1985).
[8] K. H. Kampert, J. Phys. G: Nucl. Part. Phys. **15**, 691 (1989).
[9] A. Fokin *et al.* (CHIC Collaboration), Phys. Rev. C **60**, 024601 (1999).
[10] Y. K. Vermani and R. K. Puri, Nucl. Phys. A **847**, 243 (2010).
[11] G. Peilert *et al.*, Phys. Rev. C **39**, 1402 (1989).
[12] R. Ogul *et al.*, Phys. Rev. C **83**, 024608 (2011); W. Trautmann *et al.*, Int. J. Mod. Phys. E **17**, 1838 (2008); C. Sfienti *et al.*, Phys. Rev. Lett. **102**, 152701 (2009).
[13] V. Baran *et al.*, Nucl. Phys. A **703**, 603 (2002); F. Gagnon-Moisan *et al.*, Phys. Rev. C **86**, 044617 (2012).
[14] L. W. Chen, C. M. Ko, and B. A. Li, Phys. Rev. C **68**, 017601 (2003).
[15] G. J. Kunde *et al.*, Phys. Rev. Lett. **77**, 2897 (1996).
[16] F.-S. Zhang, L.-W. Chen, Z.-Y. Ming, and Z.-Y. Zhu, Phys. Rev. C **60**, 064604 (1999).
[17] R. Płaneta *et al.*, Phys. Rev. C **77**, 014610 (2008).
[18] M. L. Miller *et al.*, Phys. Rev. Lett. **82**, 1399 (1999).
[19] S. Kaur and R. K. Puri, Phys. Rev. C **87**, 014620 (2013).
[20] C. Hartnack *et al.*, Eur. Phys. J. A **1**, 151 (1998); S. Kumar, S. Kumar, and R. K. Puri, Phys. Rev. C **81**, 014601 (2010); R. Bansal, S. Gautam, R. K. Puri, and J. Aichelin, *ibid.* **87**, 061602(R) (2013); R. Bansal, S. Gautam, and R. K. Puri, J. Phys. G: Nucl. Part. Phys. **41**, 035103 (2014).
[21] S. Goyal and R. K. Puri, Phys. Rev. C **83**, 047601 (2011); Y. K. Vermani and R. K. Puri, J. Phys. G: Nucl. Part. Phys. **36**, 105103 (2009); **37**, 015105 (2010).
[22] J. K. Dhawan, N. Dhiman, A. D. Sood, and R. K. Puri, Phys. Rev. C **74**, 057901 (2006).
[23] B. Hong *et al.*, Phys. Lett. B **407**, 115 (1997).
[24] S. Gautam *et al.*, J. Phys. G: Nucl. Part. Phys. **37**, 085102 (2010); S. Gautam, A. D. Sood, R. K. Puri, and J. Aichelin, Phys. Rev. C **83**, 014603 (2011).
[25] A. D. Sood, Phys. Rev. C **84**, 014611 (2011).