Role of net-baryon density distribution on the rapidity dependent strangeness enhancement factor of the produced particles at FAIR energies

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Rapidity dependent strangeness enhancement factor of the identified particles have been studied with the help of a string based hadronic transport model UrQMD-3.3 (Ultra Relativistic Quantum Molecular Dynamics) at FAIR energies. A strong rapidity dependent strangeness enhancement could be observed with our generated data for Au + Au collision at the beam energy of 30A GeV. The strangeness enhancement is found to be maximum at mid-rapidity for the particles containing leading quarks while for particles having produced quarks only, the situation is seen to be otherwise. Such rapidity dependent strangeness enhancement could be traced back to the dependence of rapidity width on centrality or otherwise on the distribution of net-baryon density.

I. INTRODUCTION

In heavy ion collisions, the pattern of variation of net baryon density ($\mu_B$) in rapidity space is found to vary with beam energy. For example, for SIS18/AGS energies, the variation of net baryon density with rapidity is found to be of Gaussian shape with its peak at mid-rapidity \cite{1} whereas at RHIC/LHC energies, such variation of ($\mu_B$) shows bimodality with a minimum at mid-rapidity \cite{2–5}. It is therefore easily comprehensible that the rapidity distribution of a particle, the production of which is sensitive to net baryon density, or otherwise, the particles containing leading quarks (such as $k^+$, $\Lambda$, $\Xi^-$), might tend to follow the net baryon density. The rapidity dependence of other particles whose none of the constituents are $u$ or $d$ quarks might not exhibit any such dependencies on net baryon density. Our earlier work \cite{6} on variation of width of the rapidity distribution of various produced particles on beam rapidity, with special reference to $\Lambda$ and anti $\Lambda$ has vindicated such prediction. It may therefore be not completely out of context to believe that a number of other kinematic and dynamical properties of heavy ion collision might get coupled with this net baryon density effect.

Strange particles are produced only at the time of collisions and thus expected to carry important information of collision dynamics. Strangeness enhancement is considered to be one of the traditional signatures \cite{7, 8} of formation of Quark Gluon Plasma (QGP). Due to the limitation of the detector acceptance, the past and ongoing heavy ion experiments could measure the strangeness enhancement at midrapidity only. All such measurements assume a global conservation of strangeness. However, Steinheimer et al. \cite{9} from UrQMD calculation predicted that strangeness is not uniformly distributed over rapidity space leading to a local violation of strangeness conservation. Thus, the study of rapidity dependent strangeness enhancement is of considerable significance.

Considering the fact that with the large acceptance upcoming FAIR-CBM detector \cite{10–13} measurement of the rapidity dependent strangeness enhancement factor $E_S$ could be a possibility, strangeness enhancement factor at different rapidity bin has been estimated for various identified particles produced in Au + Au collisions at 30A GeV using a string based hadronic transport model UrQMD-3.3 (Ultra Relativistic Quantum Molecular Dynamics). A sum of 93 million minimum biased UrQMD events has been used for the present analysis.

II. THE URQMD MODEL

Ultra relativistic Quantum Molecular Dynamics (UrQMD) \cite{14, 15} is a microscopic model based on a phase space description of $p+p$, $p+A$ and $A+A$ collisions that remains successful in describing the observables of heavy ion collisions over an energy range $E_{lab} = 100$ AMeV to $\sqrt{s} = 200$ GeV \cite{16–19}. At low and intermediate energies ($\sqrt{s} < 5$ GeV), it describes the phenomenology of heavy ion collisions in terms of interactions between known hadrons and their resonances. At higher energies ($\sqrt{s} > 5$ GeV), the excitation of color strings and their subsequent fragmentation into hadrons are taken into account. In this model, strange hadrons in heavy ion collision may either be produced in the very early stage in the initial collisions among the incoming nucleons or in the later stage through secondary collisions among the produced particles \cite{20}. In low energy domain i.e., close to threshold energy, strangeness can either be produced in NN reaction channel directly e.g. $p+p \rightarrow p + \Lambda + K^+$ or in two steps reactions such as $p+p \rightarrow N + N_{1710}^*$ and finally $N_{1710}^* \rightarrow Y + K^+$. At

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higher incident beam energies, particle production in general is dominated by string excitation and fragmentation [20]. Other than string excitation and fragmentation, the multi-strange hyperons like Ω(sss) can also be produced via Ξ\(K^-\)→Ωπ channel.

III. STRANGENESS ENHANCEMENT

Strangeness enhancement factor \(E_S\) is quantified by measuring the ratio of yield of strange particles in \(A + A\) collision and respective yield in \(p + p\) collisions, where both the numerator and denominator are normalized by the number of participants (\(N_{\text{part}}\)). The conventional definition of strangeness enhancement factor is [21–23] –

\[
E_S = \frac{\langle \text{Yield}_{AA} \rangle}{\langle N_{\pi^-} \rangle} / \frac{\langle \text{Yield}_{pp} \rangle}{\langle N_{\pi^-} \rangle}
\]  

(1)

In this report, using reference [24], alternative definition of strangeness enhancement factor \(E_S\) is used where \(E_S\) is defined as -

\[
E_S = \left[ \frac{\langle \text{Yield}_{AA} \rangle}{\langle N_{\pi^-} \rangle} \right]_{\text{central}} / \left[ \frac{\langle \text{Yield}_{AA} \rangle}{\langle N_{\pi^-} \rangle} \right]_{\text{peripheral}}
\]  

(2)

The reason for taking the average number of produced pions \(\langle N_{\pi^-} \rangle\), instead of \(\langle N_{\text{part}} \rangle\), as a measure of centrality variable is described elsewhere [25, 26].

The strangeness enhancement factor \(E_S\) has been calculated and plotted as a function of rapidity for various identified particles for \(Au + Au\) collision at 30 A GeV and is shown in Fig.1. We choose \(Au + Au\) collision at 30 A GeV for the present study as the baryon density is reported to be maximum at this energy [27]. It is interesting to see from the figure that \(E_S\) depends strongly on rapidity and this dependence follow two distinctive patterns. While the enhancement factor at mid-rapidity is found to be maximum for the particles containing leading quarks (filled circle), the same is observed to be minimum at mid-rapidity for the particles containing produced quarks only (open circle). However, even though a rise and fall pattern is also visible for Ω\(^-\), consisting of three produced quarks only (sss), the existence of a slight dip at mid-rapidity can not be ruled out and is consistent with the general trend.
FIG. 2. (Color online) Normalized rapidity distribution of particles containing leading and produced quarks for central as well as peripheral Au + Au collision at 30A GeV.

To understand the underlying dynamics of such rapidity dependent strangeness enhancement, the normalized rapidity distributions (Fig. 2) as well as the width of the rapidity distribution as a function of centrality (Fig. 3) are plotted for various produced particles. It is readily evident from Fig. 2 and Fig. 3 that the different patterns of rapidity dependence of strangeness enhancement factor for particles containing and not containing leading quarks lie on the dependence of rapidity distribution or otherwise the variation of the width of the rapidity distribution on centrality. The width of the rapidity distribution increases as we go from central to peripheral collisions for the particles containing leading quarks, a feature that might be attributed to the variation of net-baryon density with impact parameter at the studied energy. In Fig. 4, we therefore plot the rapidity distribution of net-baryon number for different centrality for the studied Au + Au collision at 30A GeV. It is seen from this figure that as we go from central to peripheral collision, the width of the rapidity distribution of net-baryon number increases up to a certain impact parameter. As the impact parameter is further increased, as expected, the net-baryon number tends to populate the extreme rapidity spaces due to small overlap of the colliding partners. This increase in the population of baryon over antibaryon at larger rapidities causes the broadening of the width of the rapidity distribution of the particles containing leading quarks (since their production is dependent on the distribution of $u$ and $d$ quark). Further, from Fig. 3 (right panel) it is seen that for all but $\Omega^-$ particles, that contain produced quarks only, the rapidity width decreases with decreasing centrality. Such decrease in the width of the rapidity distribution of the particles containing produced quarks only could be due to the decrease in the size of the central fireball with the increase of impact parameter. For $\Omega^-$, whose all the constituent quarks are produced quarks only (sss), its production in UrQMD-3.3, in addition to string fragmentation is also influenced by $\Xi^-$ (dss), whose one of the constituent is a leading quark, via $\Xi^- \rightarrow \Omega^- \pi$. It is because of this influence of $\Xi^-$, being a leading particle whose width increases with decrease of centrality, $\Omega^-$ is found to exhibit a different pattern other than its species member (having no leading quarks). To prevent the production of $\Omega^-$ from $\Xi K^-$ in-
IV. SUMMARY

The strangeness enhancement factor of various produced particles containing and not containing leading quark as one of the constituents is studied at various rapidity bins for Au + Au collisions at 30A GeV. From this study it is seen for the first time that the pattern of rapidity dependent strangeness enhancement factor depends on the quark content of hadrons. At mid-rapidity, the strangeness enhancement factor is found to be maximum for the particles containing leading quarks while it shows a minimum at mid-rapidity for the particles containing produced quarks only. Such two distinctive pat-
terns of variation of strangeness enhancement with rapidity have been attributed to the fact that the width of the rapidity distribution of the produced particles follows two different patterns with centrality (impact parameter) for particles containing or not containing leading quarks.

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