Rapidity dependence of the produced particles at FAIR energies

Kalyan Dey* and B. Bhattacharjee†

Nuclear and Radiation Physics Research Laboratory
Department of Physics, Gauhati University
Guwahati - 781014, India
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Evolution of width of the rapidity distribution on beam rapidity and the rapidity distribution of strangeness enhancement factor have been studied for a number of produced particles with UrQMD-3.3p1 generated events at various FAIR energies. The results on the width of the rapidity distribution on beam rapidity, thus obtained with our UrQMD generated events, have been compared with the existing experimental data (E877, E891, E896, NA49). For both experimental and UrQMD data, the width of the rapidity distribution is found to bear a power law with beam rapidity for all the studied hadrons. Such power law behavior follows a mass ordering separately for mesons and baryons which is observed to be violated at Λ baryon if the studied hadrons are taken together. From the study of variation of strangeness enhancement factor $E_S$ with rapidity, two distinct patterns could be seen for the studied mesons and baryons.

Keywords: Rapidity, strangeness enhancement, UrQMD.

I. INTRODUCTION

The upcoming Compressed Baryonic Matter (CBM) experiment at the future Facility for Antiproton and Ion Research (FAIR) will be a dedicated heavy ion experiment operating in fixed target mode (Au+Au collision up to 35 AGeV) and is planned to explore the properties of nuclear matter at moderate temperature and high baryon density [1–3]. One of the characteristic features of FAIR is its high luminosity beam which would be suitable to study rare probes of such hot and dense medium. The state of art large acceptance detectors of CBM experiment will give it access to almost the entire forward rapidity hemisphere. Thus, the evolution of the width of the rapidity distribution with beam energy and centrality will be experimentally addressed. Due to different scattering cross-sections of hadrons, this evolution is believed to be sensitive to the final state re-scattering of the produced particles [4, 5]. Moreover, different kinetic behavior at late hadronic stage of various hadronic species [6] are also expected to influence the evolution of the width of the rapidity distribution on beam energy and centrality.

Strange particles are produced only at the time of collisions and are thus expected to carry important information of collision dynamics. Strangeness enhancement is considered to be one of the traditional signatures [7, 8] of formation of Quark Gluon Plasma (QGP). However, such an enhancement was challenged by an alternate idea of canonical suppression [9] of strangeness in small systems like p+p or p+Λ collisions. Further, there are a number of other mechanisms that might also result in enhancement of strange and multi-strange baryons [10–13]. Strangeness enhancement is found to be strongly dependent on the number of strange quark content of various strange baryons. Any study of strangeness enhancement, in general, assumes global as well as local strangeness conservation. However, from a study of strangeness to anti-strangeness ratio with UrQMD model that does not have any intermediate hydrodynamic phase, Steinheimer et al. [14] observed that strangeness is not uniformly distributed over rapidity space leading to a local violation of strangeness conservation.

In this work, an attempt has been made, with UrQMD-3.3p1 [15–17] generated Au+Au events at 10, 20, 30 and 40 AGeV, to investigate the evolution of the width of the rapidity distribution with beam rapidity and the rapidity dependence of strangeness enhancement factor of a few mesons and baryons. The event statistics of our generated data (for central collisions only) is presented in Table I. It may be worth mentioning that even though there exist experimental results on the evolution of width of rapidity distribution on beam rapidity for a number of hadrons [18, 19], no such result has been reported inclusive of Λ baryon, whose mass is in close proximity with φ meson. Such a study with UrQMD generated Λ is also important because of the fact that Λ, resulting from the decay of Σ°, can not be separated from the directly produced one via a secondary vertex measurement [20] and hence the experimentally measured value of Λ is an over-estimation of the number of Λ actually produced in the collision. Although due to nearly equal mass and identical quark content, Σ° and Λ are expected to exhibit same rapidity width, yet it is desirable that one should study the rapidity width of the produced Λ alone using an appropriate event generator. Furthermore, the differential strangeness enhancement results are not available from any experiment yet. Thus, it would be desirable to cross-check these findings using UrQMD with experimental results, which will be possible when CBM comes into operation.
TABLE I. Event statistics of the present investigation (for central collisions only).

| Energy (AGeV) | Events (Million) | $\pi^- \times 10^8$ | $K^- \times 10^7$ | $\Lambda \times 10^6$ | $\phi \times 10^5$ | $\Xi^- \times 10^4$ | $\Omega^- \times 10^4$ |
|---------------|-----------------|---------------------|-------------------|-------------------|------------------|-------------------|-------------------|
| 10            | 4.6             | 7.37                | 1.74              | 6.70              | 9.76             | 7.68              | 2.73              |
| 20            | 3.1             | 7.66                | 2.72              | 6.40              | 17.81            | 11.80             | 6.30              |
| 30            | 4.9             | 14.28               | 6.55              | 15.15             | 42.36            | 24.20             | 20.07             |
| 40            | 1.1             | 3.47                | 1.82              | 3.51              | 11.02            | 6.31              | 6.12              |

FIG. 1. (Color online) Rapidity distribution of produced particles ($\pi^-, K^-, \Lambda, \phi$) for four different beam energies $E_{lab} = 10, 20, 30$ and 40 AGeV is compared with the existing SPS (NA49) [18] and AGS (E877, E891, E896) [22, 23] data.

II. WIDTH OF RAPIDITY DISTRIBUTION OF MESONS AND BARYONS

In heavy ion collision, rapidity ($Y$) or pseudorapidity ($\eta$) distribution is found to be quite informative of particle production mechanism [4, 21]. In Fig. 1, the rapidity distributions of a few hadrons such as $\pi^-$, $K^-$, $\phi$ and $\Lambda$ produced in UrQMD generated Au+Au collisions at 10, 20, 30 and 40 AGeV are plotted and compared with the existing SPS (NA49) [18] and AGS (E877, E891, E896) [22, 23] data at the same energies. It is seen from this figure that, with UrQMD generated events, due to the reason mentioned earlier, the rapidity distribution of ($\Lambda + \Sigma^0$) and not $\Lambda$ alone gives a better agreement with the experimental data on $\Lambda$.

From this figure it is also seen that lighter mesons like $\pi^-$ and $K^-$ show a fair agreement between experimental data [18, 22, 23] and UrQMD prediction at all energies. However, for heavier meson like $\phi$, as the energy of collision increases, there is a considerable disagreement between the observed and UrQMD predicted values. This may be because of the fact that at low energies, $E_{lab} \leq 10$ AGeV, the $\phi$ production mechanism is predominantly via hadronic channels; at higher energies there might be significant contribution from non-hadronic processes [24]. In UrQMD, with regard to the production of $\phi$ meson, the hadronic processes mostly refer to KK coalescence whereas other non-hadronic contributions mostly come from string excitation and fragmentation.

The rapidity spectra of all the studied hadrons from UrQMD generated and experimental data [18, 22, 23] are parameterized by a Gaussian distribution and the resulting values of $\sigma$ are listed in Table II.

Fig. 2 represents the width of the rapidity distributions as a function of beam rapidity for studied mesons and baryons for UrQMD generated central Au+Au collision. As expected, the lighter particles have larger width. From this plot, a scaling behavior of the type $\sigma \propto (Y_{beam})^\tau$ of the width of the rapidity distribution on beam rapidity is readily evident. Friese et al. [19] have reported similar results for Pb+Pb collision with NA49 data. The values of the exponent for the studied mesons and baryons for UrQMD generated data are listed in Ta-
TABLE II. The parameter $\sigma$ resulting from the Gaussian fits of the rapidity spectra of all the studied hadrons of UrQMD generated and experimental data (within brackets).

| Width     | 10 AGeV | 20 AGeV | 30 AGeV | 40 AGeV |
|-----------|---------|---------|---------|---------|
| $\sigma(\pi^-)$ | $0.959 \pm 0.003$ | $1.064 \pm 0.003$ | $1.128 \pm 0.003$ | $1.172 \pm 0.003$ |
|           | $(0.857 \pm 0.021)$ | $(1.060 \pm 0.009)$ | $(1.098 \pm 0.016)$ | $(1.140 \pm 0.014)$ |
| $\sigma(K^-)$ | $0.718 \pm 0.016$ | $0.807 \pm 0.012$ | $0.861 \pm 0.010$ | $0.899 \pm 0.009$ |
|           | $(0.661 \pm 0.017)$ | $(0.727 \pm 0.009)$ | $(0.832 \pm 0.010)$ | $(0.935 \pm 0.017)$ |
| $\sigma(\phi)$ | $0.560 \pm 0.054$ | $0.664 \pm 0.039$ | $0.728 \pm 0.035$ | $0.773 \pm 0.033$ |
|           | $(0.518 \pm 0.001)$ | $(0.620 \pm 0.026)$ | $(0.787 \pm 0.043)$ | $(0.866 \pm 0.026)$ |
| $\sigma(\Lambda)$ | $0.637 \pm 0.007$ | $0.757 \pm 0.007$ | $0.843 \pm 0.006$ | $0.903 \pm 0.007$ |
|           | $(0.648 \pm 0.028)$ | $(0.731 \pm 0.028)$ | $(0.968 \pm 0.028)$ | $(1.193 \pm 0.076)$ |
| $\sigma(\Xi^-)$ | $0.520 \pm 0.057$ | $0.619 \pm 0.045$ | $0.692 \pm 0.044$ | $0.744 \pm 0.043$ |
|           | — | $(0.634 \pm 0.033)$ | $(0.779 \pm 0.035)$ | $(0.887 \pm 0.062)$ |
| $\sigma(\Omega^-)$ | $0.451$ | $0.540$ | $0.597$ | $0.693$ |

FIG. 2. (Color online) Variation of width of the rapidity distribution with UrQMD generated data of (a) mesons (b) baryons (c) all studied hadrons as a function of beam rapidity in the lab system. In the panel (d) the same has been plotted separately for $\Lambda$ and $\phi$. In the panel (e) the power law exponent ($\tau$) is plotted as a function of mass of the produced particles. The solid lines correspond to the best fitted lines. The error bars shown here correspond to the statistical errors. For $\Omega^-$ the error bars are large and hence not shown in this figure.

Table III and the variation of this exponent with the mass of the produced particles is shown in plot (e) of Fig.2. The exponent values are found to increase linearly with the mass of the produced particles, indicating the mass dependent nature of the exponent. It is interesting to note from Fig.2 (plots a and b) that though mesons and baryons separately follow mass ordering, such mass ordering is violated at $\Lambda$ if the studied hadrons are taken together (plot c). The mass ordering of the width of the rapidity distribution is believed to be due to the build-up of some collective flow, which in a hadronic model like UrQMD is considered to be due to individual particle thermal scattering, a property, which may be considered as microscopic analog of pressure [25]. The observed violation of mass ordering at $\Lambda$ may be due to the fact that the kinetic behavior during the late hadronic stage may not be similar for all hadronic species [6]. Moreover, it has been pointed out by NA49 collaboration [26–28] that since $\Lambda(uds)$ hyperons carry a significant fraction of the total net baryon number, their rapidity distribution is influenced by the overall net baryon number distribution.

Fig.3 represents the same plots of Fig.2, but with the experimental data (of ref. [18, 22, 23] and [26]) of Fig.1 of this article. It is interesting to note that though there is quantitative difference between the two plots, which is not unexpected, the general trend agrees well for experimental data and UrQMD prediction. For the experimental data also the mesons and baryons separately follow mass ordering, but taken together, the mass ordering is violated at $\Lambda$. To see the possible effect
FIG. 3. (Color online) Variation of width of the rapidity distribution (calculated from data [18, 22, 23, 26]) of (a) mesons (b) baryons as a function of beam rapidity in the lab system (c) the same has been plotted separately for Λ and φ. In panel (d) the power law exponents has been plotted as a function of mass of the produced particles and is compared with the UrQMD calculation. The solid lines (and the dashed line as shown in panel d) correspond to the best fitted lines. The error bars shown here correspond to the statistical error.

TABLE III. Exponent values for particles of various masses for UrQMD generated data.

| Particle Mass [GeV/c^2] | Exponent (τ) |
|-------------------------|--------------|
| π^-                     | 0.140 ± 0.011 |
| K^-                     | 0.493 ± 0.068 |
| φ^+                     | 1.020 ± 0.292 |
| Λ^-                     | 1.115 ± 0.038 |
| Λ^+                     | 1.321 ± 0.354 |
| Ω^-                     | 1.072 ± 0.076 |

FIG. 4. (color online) The width of the rapidity distribution as a function of beam rapidity for φ both from UrQMD and experimental data (AGS+SPS) and Λ(UrQMD).

of underestimation of the φ meson yield in UrQMD model on the mass ordering of the width of rapidity distribution, the width of the rapidity distribution of φ meson, both from UrQMD and experimental data, are plotted in Fig.4 and compared with the result obtained for Λ with UrQMD generated data. It can be readily seen from this figure that the difference between experimental and UrQMD estimated φ - rapidity width for most of the studied energies lie within the error bars. Such observation implies that even though the experimental values of the rapidity distribution of φ differ from UrQMD prediction, such differences do not have any significant effect on our result on the mass ordering violation of the width of the rapidity distribution on beam rapidity for the studied hadrons.

In order to have a more clear picture of mass ordering violation, the variations of the width of the rapidity distribution as a function of mass of the produced particles at a particular energy are plotted in Fig.5. It is readily seen from this figure that at each energy, for UrQMD generated data, the width of the rapidity distribution of all but Λ hadrons follow a mass ordering. The mass ordering is violated at Λ. A similar behavior could be seen with the experimental data as well. The effect of mass ordering is seen to be more prominent at low \( p_T \) (Fig.6) suggesting that the observed mass ordering effect has been developed mostly at the later stage of the collision.

III. STRANGENESS ENHANCEMENT

Strangeness enhancement factor \( E_S \) is quantified by measuring the ratio of yield of strange particles in \( A + A \)
FIG. 5. (Color online) Variation of rapidity width as a function of mass of the produced particles in central Au+Au collision at FAIR energies. The errors seen in both the figures correspond to the statistical error. For Ω− the error bars are large and hence not shown in the figure for UrQMD calculation.

FIG. 6. (Color online) Variation of rapidity width as a function of transverse momentum ($p_T$) using UrQMD-3.3p1 generated central Au+Au collision at 30 AGeV. The error bars shown here correspond to the statistical error. For φ, Ξ− and Ω− the error bars are large and hence not shown in this figure.

collision and respective yield in $p + p$ collisions, where both the numerator and denominator are normalized by the number of participants ($N_{part}$). The conventional definition of strangeness enhancement factor is [29].

$$E_s = \frac{(Yield)_{AA}}{<N_{part}>} \left( \frac{Yield}_{pp} \right) / 2 \right)$$

In this report, following reference [30], the strangeness enhancement factor $E_S$ is re-defined as -

$$E_S = \left[ \frac{(Yield)_{AA}}{<N_{\pi^-}>}_\text{central} / \left( \frac{Yield)_{AA}}{<N_{\pi^-}>}_\text{peripheral} \right) \right]$$

where the number of produced pions $N_{\pi^-}$, instead of $N_{part}$, is chosen as a centrality variable as the later exhibits a nonlinear behavior with the volume of the participant zone [31].

However, such enhancement depends strongly on the kinematical restrictions. Soff et al.[30] have reported a strong rapidity dependent strangeness enhancement factor. While they observed $E_S$ less than 1 at target and projectile rapidities for Λ hyperon, the same is found to be greater than 1 at all other rapidities for Λ, Ξ− and Ω− hyperons with maximum at mid-rapidity. In this work, using UrQMD generated events, $E_S$ has been estimated as a function of rapidity for both strange mesons ($k^−$ and φ) and strange baryons (Λ, Ξ− and Ω−) at the incident beam energy 30 AGeV and is shown in the top panel of Fig. 7. From this figure, it is interesting to note that even though the enhancement factor $E_S > 1$ almost at all rapidities for both mesons and baryons, the patterns of variation of enhancement factor $E_S$ for the studied mesons and baryons are completely different. For Λ, Ξ− and Ω−, as observed in ref. [10, 30], $E_S$ is found to be maximum at mid-rapidity and minimum at beam and target rapidities while for $k^-$ and φ, the trend is otherwise. Similar behavior has been observed at other FAIR energies viz. 10, 20 and 40 AGeV as well. Such observation of $E_S > 1$ for all the studied strange particles may be attributed to the fact that in a hadronic scenario, strangeness enhancement is mainly due to hadronic rescattering [30] and as such more strange particles are produced in central than peripheral collisions. It is readily evident from the bottom panel of
FIG. 7. (Color online) Top panel: Strangeness enhancement factor $E_S$ as a function of rapidity for $\Omega^-$, $\Xi^-$, $\phi$, $\Lambda$ and $k^-$ at 30 AGeV. The red dashed curves correspond to Gaussian fits while solid blue curves corresponds to a polynomial fit of 3rd order. Bottom panel: Rapidity width as a function of impact parameter for $\Omega^-$, $\Xi^-$, $\phi$, $\Lambda$ and $k^-$ at 30 AGeV.

Fig. 7 that such different patterns of variation of $E_S$ with $Y$ for the studied mesons and baryons are due to different pattern of evolution of rapidity width with centrality. Moreover, in heavy ion collision, the baryochemical potential is dependent on rapidity [32, 33]. At FAIR energies, due to baryon stopping the baryochemical potential is expected to be high at mid-rapidity and depending on $\mu_B$ there is a preference for baryon production over meson production, resulting in more strange baryons at mid-rapidity. At forward rapidity the strangeness ends up in more production of mesons like kaons and $\phi$.

IV. SUMMARY

The present study on the width of the rapidity distribution of mesons and baryons produced in central Au+Au collisions at 10, 20, 30 and 40 AGeV using both UrQMD generated and experimental data reveals a power law behavior of width of the rapidity distribution on beam rapidity. The values of the exponent in both the cases are found to be dependent on the mass of the particles. Moreover, the variation of the width of the rapidity distribution on beam rapidity follows a mass ordering separately for mesons and baryons. If the studied hadrons are taken together, the mass ordering is violated at $\Lambda$. Further, from this work it is seen that for $k^-$ and $\phi$ the variation of rapidity dependence of strangeness enhancement factor $E_S$ is completely different than that of $\Lambda$, $\Xi^-$ and $\Omega^-$. For strange baryons the enhancement is found to be maximum at mid rapidity while for strange mesons maximum enhancement is found to be at beam and target rapidities.

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