Strange Particle Production in p+p, p+Pb and Pb+Pb Interactions from NA49

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Abstract. Recent NA49 results on Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$ production in minimum bias p+p and centrality selected p+Pb collisions at 158 GeV/c, and the results on Λ, $\bar{\Lambda}$, K^+ and K^- production in central Pb+Pb collisions at 40, 80 and 158 A·GeV are discussed and compared with other available data. By comparing the energy dependence of Λ and $\bar{\Lambda}$ production at mid-rapidity a striking similarity is observed between p+p and A+A data. This is also seen in the energy dependence of the Λ/π ratio. K^+/π at mid-rapidity is affected in a similar way, due to the associated production of K^+ together with Λ particles. The observed yields increase faster than the number of wounded nucleons when comparing p+Pb to p+p. As already observed in A+A collisions, the increase is larger for multistrange than for strange baryons and for baryons than for anti-baryons.

1. Introduction

The NA49 experiment [1] offers a unique opportunity of collecting − with the same detector − data on the full set of available hadronic interactions. The processes studied range from hadron-nucleon and centrality selected hadron-nucleus interactions to nucleus-nucleus collisions covering a wide range of energies and system sizes.

In the context of this conference preliminary results concerning strange and multistrange baryon production in p+p, centrality selected p+Pb at 158 GeV/c [2], as well as the results on strange baryon [3] and meson [4] production from central Pb+Pb collisions at 40, 80 and 158 A·GeV, will be presented. A critical discussion - including whenever possible results from other experiments - will attempt to establish common features and differences between elementary and more complex hadronic collisions. The importance of maintaining a broad view on the totality of hadronic processes for the correct interpretation of the observables in specific systems will be emphasized.

2. Results and discussion

Λ and $\bar{\Lambda}$ particles are a good measure of the net-baryon density at mid-rapidity due to their charge and isospin neutrality. An observed ratio $\frac{\bar{\Lambda}}{\Lambda} \ll 1$ would imply that the central region is still net-baryon dominated. This is due to baryon stopping, as refering to the transport of baryon number away from the nuclear fragmentation regions. On the quark level the net-baryon transfer from the projectile and target fragmentation

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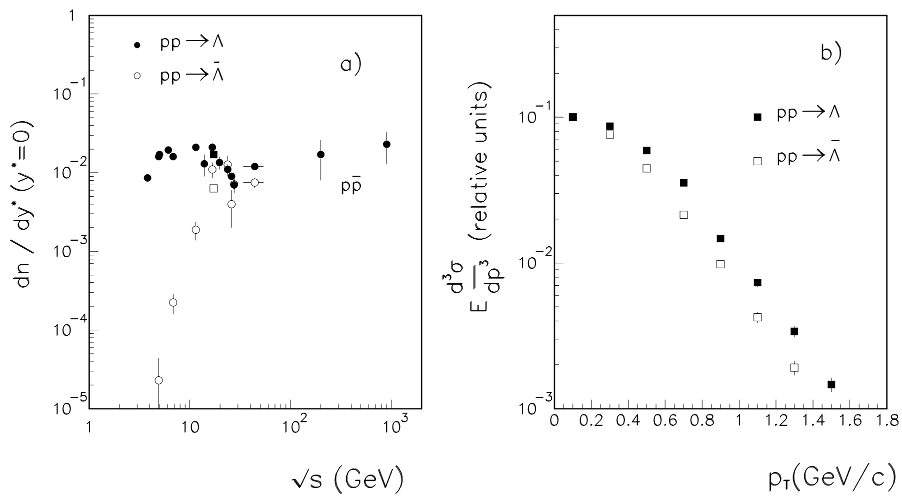

Figure 1. a) Energy dependence of Λ and $\bar{\Lambda}$ mid-rapidity multiplicities, including preliminary NA49 data (shown by squares), b) Normalized p_T distributions of Λ and $\bar{\Lambda}$ at mid-rapidity at 158 GeV/c (NA49 preliminary).

regions to mid-rapidity, can generally be described as a transfer of net-quarks (to be distinguished from the quarks produced in quark-antiquark pairs). From this point of view, the basic mechanism of net-baryon transfer in p+p, p+A and A+A collisions could be very similar, emphasizing the necessity of a more detailed study of particle production in p+p and p+A collisions.

The energy dependence of the Λ and $\bar{\Lambda}$ multiplicities at mid-rapidity in p+p [5] collisions is shown in Fig. 1a. The averaged yields of Λ and $\bar{\Lambda}$ particles from $p{+}\bar{p}$ collisions at $\sqrt{s}$=200 and $\sqrt{s}$=900 GeV are shown to indicate the expected Λ and $\bar{\Lambda}$ yields at higher energy. The p+p data for $\bar{\Lambda}$ shows a continuous rise with nucleon-nucleon center-of-mass energy, $\sqrt{s}$. Due to the isospin arguments the number of $\bar{\Lambda}$s measures the number of pair-produced Λs. The data is not conclusive enough, but there is an indication that pair-produced Λs dominate the mid-rapidity yield at energies above $\sqrt{s}$=20−30 GeV, as a consequence of the very low net-baryon density in this kinematic region. In contrast to the $\frac{\bar{\Lambda}}{\Lambda}$ ratio, which is expected to be 1 if the zero net-baryon density is reached, the ratios of particles which are not charge and isospin neutral (e.g. $\frac{\bar{p}}{p}$, $\frac{K^-}{K^+}$) are expected to be less than 1. This is due to the asymmetric pair production: for example $p\bar{n}$, $K^+\bar{K^0}$, etc.

The high net-baryon density at mid-rapidity at lower energies causes the Λ particles to be singly produced, essentially through the associated production mechanism together with K^+ mesons. Available results on singly produced Λs suggest a very steep rise after passing the threshold energy. At higher $\sqrt{s}$, where the pair-produced lambdas start to contribute dominantly, the yield of singly produced Λs is steeply falling. The sum of these two contributions shows a minimum arround $\sqrt{s}$= 25 GeV, as a border between the regions of high and low net-baryon density (see Fig. 1a).

Preliminary NA49 data [2] (squares in Fig. 1a) shows that approximately 40% of the Λs at mid-rapidity are pair-produced, and 60% singly-produced, in associated production with K^+.

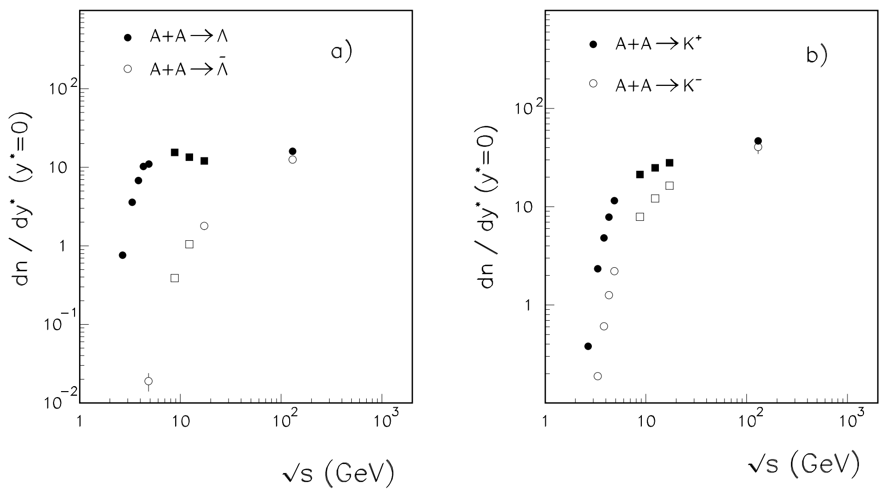

Figure 2. a) Energy dependence of Λ and $\bar{\Lambda}$, and b) K^+ and K^- mid-rapidity multiplicities in central A+A collisons. Preliminary NA49 data are indicated by the squares.

Different particle p_T spectra are expected for different production mechanisms. This correlation is demonstrated in Fig. 1b which shows the normalized p_T distributions of Λ and $\bar{\Lambda}$ hyperons measured at mid-rapidity. The steeper p_T slope observed for the $\bar{\Lambda}$s (pair produced Λs) than for the Λs (singly and pair produced Λs) suggests that the p_T spectra clearly depend on the particle production mechanism. An interesting question is how this matches the physics assumptions of the statistical model, regardless of its success in describing particle yields from p+p interactions. Results from A+A collisions are ploted in Fig. 2a. Preliminary NA49 data [3] on Λ and $\bar{\Lambda}$ production at mid-rapidity (squares) are compared to other experiments [6] [7] (circles). Although at the same energy A+A data shows a higher degree of stopping than p+p data, it is interesting to note a striking similarity in the energy dependence of these two data sets. Both samples show that Λ production at mid-rapidity is strongly correlated with the change with $\sqrt{s}$ of the net-baryon density. For a better understanding of the physical origin of the net-baryon transfer and its correlation to particle production, the precise p+p and A+A RHIC data, from the lowest up to top accesible energies, are needed. It is not excluded that the mid-rapidity Λ yield in A+A collisions will show a minimum, like it was observed in p+p. A different origin of this minimum is also not excluded. In p+p this could indicate the energy region with (almost) zero net-baryon density, and in A+A the region where the net-baryon density at mid-rapidity starts to saturate towards a non-zero value.

The energy dependence of K^+ and K^- mid-rapidity multiplicities in central A+A collisions is shown in Fig. 2b (preliminary NA49 data [4] are indicated by squares). Due to the associated production of K^+ with Λ particles at lower energies one would expect a similar behaviour of singly produced Λ baryons and singly produced K^+ mesons. The results on the energy dependence of the $K^+ - K^-$ and $\Lambda - \bar{\Lambda}$ yields at mid-rapidity, shown in Fig. 3a, confirm this expectation. We want to emphasize that the energy dependence of the $\Lambda - \bar{\Lambda}$ yield at mid-rapidity in p+p (see Fig. 1a)

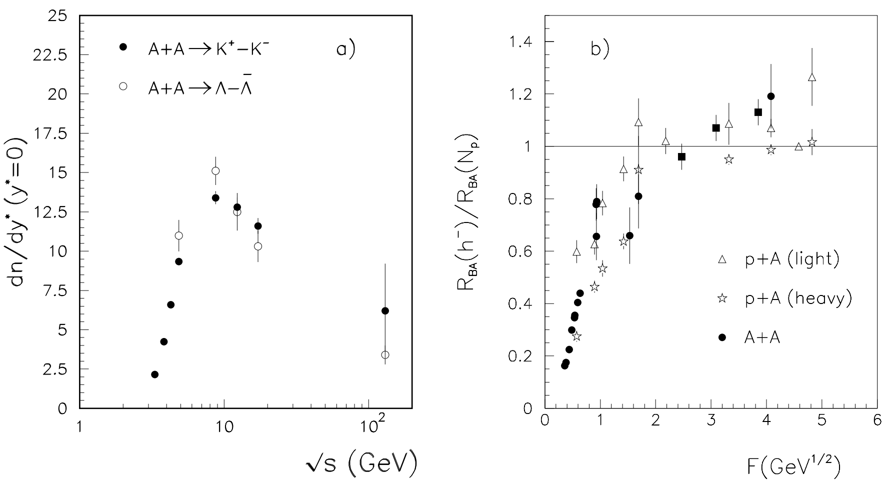

Figure 3. a) Energy dependence of Λ–$\bar{\Lambda}$ and K^+–K^- mid-rapidity multiplicities b) The ratio $R_{BA}(h^-)/\ R_{BA}(N_p)$ for p+A and A+A reactions versus Fermi energy F (for the explanation see text)

shows a similar pattern. Unfortunately, the corresponding K^+ and K^- data at lower energies are still missing.

Before we proceed with the results on the strangeness to pion multiplicity ratios, we would like to comment on the energy dependence of pion multiplicities observed in A+A and p+A collisions. In order to study this dependence, we define the double ratio of multiplicities per wounded nucleon

$$\frac{R_{BA}(h^-)}{R_{BA}(N_p)} = \frac{\langle h^-\rangle_{BA}}{\langle h^-\rangle_{NN}} / \frac{\langle N_W\rangle_{BA}}{\langle N_W\rangle_{NN}} \quad (1)$$

where $\langle h^-\rangle_{BA}$ ($\langle h^-\rangle_{NN}$) is the mean number of negative particles and $\langle N_W\rangle_{BA}$ ($\langle N_W\rangle_{NN}$) is the mean number of wounded nucleons in B+A (N+N) collisions. Fig. 3b shows the dependence of the double ratio $R_{BA}(h^-)/\ R_{BA}(N_p)$ on the Fermi energy F=$(\sqrt{s}-2\cdot m_p)^{\frac{3}{4}})/\sqrt{s}^{\frac{1}{4}}$ for the protons on light (A≤64) (triangles) and heavy (A≥108) (stars) nuclei, together with the results from A+A collisions (circles) [8]. Preliminary NA49 data are indicated by squares. In the Wounded-Nucleon-Model (WNM) [11] it is assumed that the number of produced particles depends only on the total number of wounded nucleons N_W participating in the collisions, and not on the number of collisions per participating nucleon. Under this assumption the ratio $R_{BA}(h^-)/\ R_{BA}(N_p) = 1$. The A+A results from Fig. 3b show that the WNM overpredicts the h^- yield at lower energies ($R_{BA}(h^-)/\ R_{BA}(N_p) < 1$) and underpredicts at higher energies ($R_{BA}(h^-)/\ R_{BA}(N_p) > 1$). Before we interpret this h^- enhancement, relative to the WNM, as an entropy enhancement and a phase transition indication a similar behaviour in p+A has to be critically considered (see Fig. 3b). It is interesting to note that the observed $R_{BA}(h^-)/\ R_{BA}(N_p)$ ratio is larger for the p reactions on light nuclei than on heavy nuclei. This may indicate that the WNM overestimates the number of the participating nucleons in the proton collisions on heavy nuclei. Because of the similarity in the production of Λ particles at mid-rapidity in p+p and

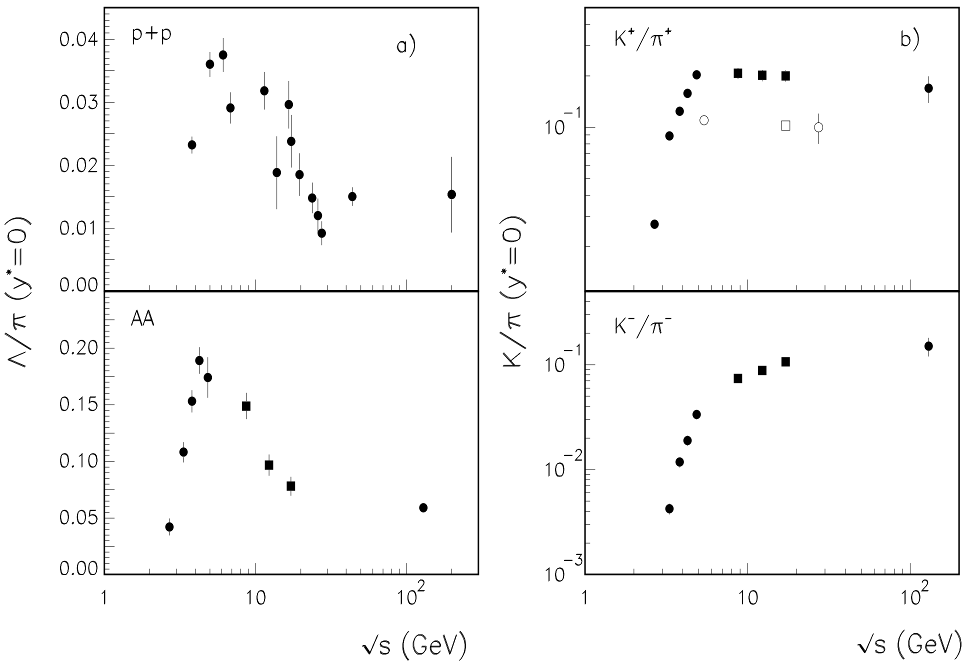

Figure 4. a) Energy dependence of Λ/π ratio at mid-rapidity in p+p (upper plot) and A+A (lower plot). b) Energy dependence of K^+/π^+ (upper plot) and K^-/π^- (lower plot) at mid-rapidity in A+A (full symbols) and p+A [9] (open symbols). Preliminary NA49 results are indicated by squares.

A+A collisions, it is not surprising that the energy dependence of the Λ/π ratio at mid-rapidity in p+p and A+A shows a similar behaviour: non-monotonic, passing through a maximum around $\sqrt{s}$=4−7 GeV (Fig. 4a).

The p+A and A+A data show (upper part of Fig. 4b) that the K^+/π^+ ratio is affected similarly, due to the associated production of K^+ together with Λ particles at lower energies, where the net-baryon density is still high. While a continuous rise in K^-/π^- from AGS over SPS to RHIC energies is observed in A+A data (lower part of Fig. 4b), the K^+/π^+ ratio in p+A and A+A data reaches a maximum approximately at the energy where the maximum in the Λ/π ratio is observed. Consequently, it may be premature to conclude that a rapid change of the energy dependence of strangeness to pion (entropy) ratio is a unique signal for the transition from confined to deconfined matter. From this point of view the study of baryon and anti-baryon production in p+p and p+A collisions, starting with the low AGS energies, and going up to the top RHIC energy, will be extremely important for a better understanding of baryon propagation in rapidity and/or x_F space in A+A interactions.

In addition to the similarity between p+p and A+A data, the energy dependence of the Λ/π ratio (Fig. 4a) also shows an important difference. The Λ/π ratio in A+A collisions is several times larger than the corresponding ratio in minimum bias p+p collisions. The WA97 experiment [10] has found that the strange particle yields (Λ, $\bar{\Lambda}$, Ξ^-, $\bar{\Xi}^+$ and Ω^-+ $\bar{\Omega}^+$) per wounded nucleon N_W at central rapidity increase from p+Pb to Pb+Pb. The enhancement, relative to the prediction of the WNM is found

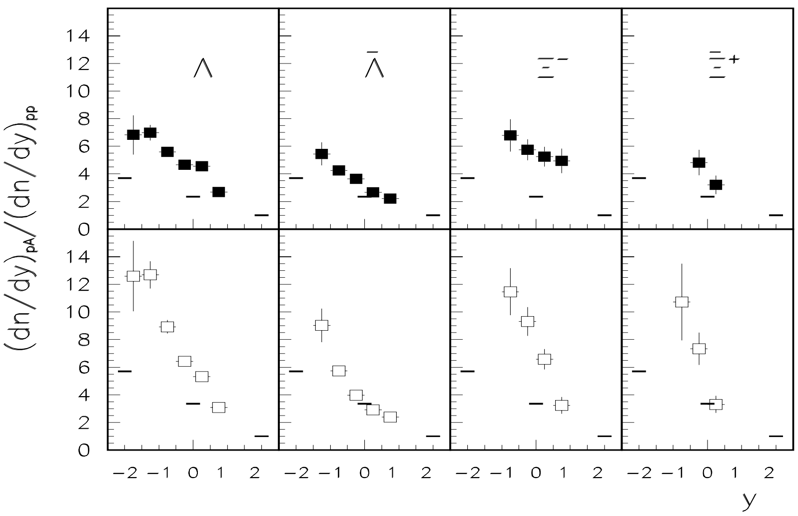

Figure 5. Ratios of hyperon multiplicities in centrality selected p+Pb and minimum bias p+p collisions. The experimental results for the first ($\langle\nu\rangle$= 3.7) and the second ($\langle\nu\rangle$= 5.7) centrality bin, are shown by full and open squares, respectively. The predictions of the WNM at backward, central and forward rapidities are indicated by the solid lines.

to be more pronounced for multistrange particles, and more pronounced for particles than for anti-particles. The relevant question is: does the simple WNM scaling hold between p+p and p+A interactions?

Fig. 5 shows the ratios of hyperon multiplicities produced in centrality selected p+Pb and minimum bias p+p collisions versus rapidity [2]. The centrality of p+Pb reactions is characterized by the mean number of projectile collisions $\nu = N_W - 1$. The experimental results for the first ($\langle\nu\rangle$= 3.7) and the second ($\langle\nu\rangle$= 5.7) centrality bin are shown by full and open squares, respectively. The predictions of the WNM at backward ($\frac{(dn/dy)_{pA}}{(dn/dy)_{pp}}=\nu$), central ($\frac{(dn/dy)_{pA}}{(dn/dy)_{pp}}=\frac{\nu+1}{2}$) and forward ($\frac{(dn/dy)_{pA}}{(dn/dy)_{pp}}=1$) rapidities are indicated by solid lines. As already observed in Pb+Pb collisions [10], the mid-rapidity enhancement in p+Pb, relative to the WNM prediction, is larger for particles of higher strangeness content and is larger for baryons than for antibaryons. Although the yield of Ξ^-, $\bar{\Xi}^+$ and Λ hyperons scales approximately with ν as predicted by the WNM (not shown here), it is important to emphasize that their absolute yield is enhanced. The yield of $\bar{\Lambda}$ is close to the WNM for the most central sample.

In the backward rapidity region there is also a clear indication for the enhanced production of Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$ particles relative to the WNM model, similar to the effect observed at the mid-rapidity region.

The observed enhancement of strange and multistrange baryons in p+Pb suggests that any extrapolation from elementary to nucleus-nucleus collisions using the simple WNM is questionable, as well as the conclusions based on the result of this extrapolation. Before one can conclude that the enhancement with respect to the WNM seen in A+A is a sign for QGP formation [10], one has to study carefully the consequences of the multiple collision mechanisms as they become accesible in p+A

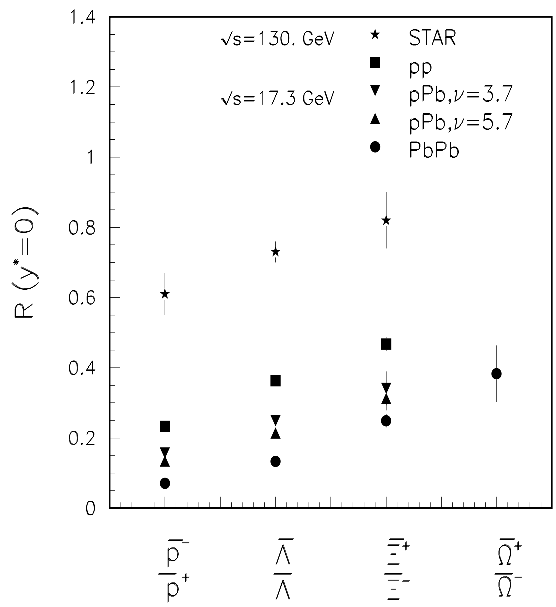

Figure 6. Antibaryon to baryon ratios at mid-rapidity. Preliminary NA49 results from p+p, p+A and A+A at $\sqrt{s}$ =17.2 GeV are compared with $\frac{\bar{\Omega}}{\Omega}$ ratio at $\sqrt{s}$ =17.2 [10] and the STAR results [7]

interactions.

A short summary of presented data, to emphasize again the importance of energy and system size dependence study, is shown in Fig. 6 in the form of antibaryon to baryon ratios at mid-rapidity for p+p, centrality selected p+Pb, central Pb+Pb at $\sqrt{s}$ =17.2 GeV, as well as central Au+Au at $\sqrt{s}$ =130 GeV. The "slope" of the antibaryon to baryon ratios at a given energy becomes flatter (going from $\frac{\bar{p}}{p}$ to $\frac{\bar{\Xi}}{\Xi}$ or $\frac{\bar{\Omega}}{\Omega}$) as the size of the colliding system (going from A+A to p+p), and consequently the net-baryon density at mid-rapidity, decreases. A similar effect is obtained by increasing the energy and keeping (approximately) the same system size (compare particle ratios from the central Pb+Pb and Au+Au collisions at SPS and RHIC energies, respectively). The ratios of $\frac{K^-}{K^+}$ will be affected in a similar way since the production of the K^+ mesons is strongly correlated with change of the net-baryon density, as it was discussed before. It would be very interesting to compare the antibaryon to baryon ratios in p+p and A+A at the different energies at which they have approximately the same $\frac{K^-}{K^+}$ ratio. In doing so the isospin effect should be carefully taken into account.

3. Conclusions

The NA49 Collaboration at the CERN SPS has measured strange hyperons in minimum bias p+p and centrality selected p+Pb reactions at 158 GeV/c, and Λ, $\bar{\Lambda}$, K^+ and K^- particles in central Pb+Pb collisions at 40, 80 and 158 A·GeV. A steeper p_T slope is observed in p+p reactions for $\bar{\Lambda}$s (pair produced Λs) than for the

Λs (pair and non-pair produced Λs) reflecting their different production mechanisms. It should be critically considered how this matches the physics assumptions of the statistical model regardless of its success in describing particle yields in p+p reactions. The same question concerns the applicability of the statistical model in describing the particle yields in the fragmentation region of A+A reactions.

By comparing the energy dependence of Λ and $\bar{\Lambda}$ production at mid-rapidity, a striking similarity is observed between p+p and A+A data. This is also seen in the energy dependence of the Λ/π ratio − non-monotonic, passing through a maximum around $\sqrt{s}$=4−7 GeV. The K^+/π ratio at mid-rapidity is affected similarly in p+A and A+A interactions due to the associated production of K^+ together with Λ particles, in particular at the lower energies where the net-baryon density is still relatively high. From this we conclude that a rapid change of energy dependence of strangeness to pion (entropy) ratio may not be a unique characteristic of heavy-ion reactions.

Comparing the yields of produced hyperons in p+p and p+Pb reactions an excess of Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$ is observed relative to the prediction of the Wounded-Nucleon-Model. This excess shows a similar pattern to the one observed in Pb+Pb data, indicating that the extrapolation to A+A using the WNM is questionable, as well as the conclusions based on this extrapolation.

We would like to stress that the observed similarity between p+p, p+A and A+A reactions does not prove that A+A is a simple superposition of p+p and/or p+A. It shows however, that a deeper understanding of p+p and p+A data is necessary for any interpretation of A+A reactions.

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