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STRANGE HYPERON PRODUCTION IN p + p AND p + Pb INTERACTIONS FROM NA49

TOME ANTIČIĆ, SANDRA HORVAT, KREŠO KADIJA and TATJANA ŠUŠA

Ruđer Bošković Institute, Zagreb, Croatia

Dedicated to Professor Kseno Ilakovac on the occasion of his 70$^{\mathbf{th}}$ birthday

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In the NA49 experiment, data on Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$ hyperons in minimum-bias p + p and centrality-selected p + Pb collisions at 158 GeV/c have been obtained. For the first time, p + p measurements have been done for Ξ^- and $\bar{\Xi}^+$ in the kinematic region around central rapidity. 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. 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.

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1. Introduction

In ultrarelativistic nucleus–nucleus interactions, one can study hadronic systems under extreme conditions of temperature and pressure [1]. The main goal of the present study is to learn some properties of such systems. The idea is to reach the conditions under which hadronic matter is expected to turn into a new state of strongly interacting matter, the quark gluon plasma (QGP). Whichever conclusion we make, either that QGP has been formed in A + A collision, or that the system stays in the hadronic phase, it should be based on our understanding of the formation and the space-time evolution of the partonic and/or hadronic source. Because of the complexity of the dynamical processes, we still can not claim a true understanding of the physics of heavy-ion collisions at ultrarelativistic energies.

A detailed study of p + p and p + A physics is one of the important prerequisites for a deeper understanding of A + A data. For example, we need to understand the failure of (microscopic) hadronic models in describing the p + p and p + A data in order to interpret the failure of these models in describing the A + A data. Another example is given by the statistical approach which describes the yields in elementary hadronic collisions even for those particles which did not lose the memory about the incident channel, like e.g. protons, single and double strange hyperons, K^+ mesons, etc [2]. Consequently, the success of the statistical model in describing particle yields in A + A collisions does not guarantee that this model is suitable for the description of all measured particles in A + A. To be able to distinguish particles according to their different production mechanisms, a detailed study of particle production in p + p and p + A interactions is needed. This is one of the goals of the NA49 experiment.

2. *Experimental method*

NA49 [3] is a fixed target, large acceptance experiment at the CERN SPS, designed to investigate p + p, p + A and A + A interactions. The experiment uses four large-volume time projection chambers (TPCs) which provide precise tracking of charged particles, as well as their identification using specific energy loss ($\mathrm{d}E/\mathrm{d}x$). Two TPCs (VTPC1 and VTPC2) are placed inside superconducting dipole magnets. They allow momentum determination from the track curvature ($\sigma(\mathrm{p})/p^2 = (0.3 - 7) \cdot 10^{-4}$ $(\mathrm{GeV}/c)^{-1}$). Two TPCs (MTPC-R and MTPC-L) are positioned downstream, outside of the magnetic field. The combined $\mathrm{d}E/\mathrm{d}x$ resolution is about 3%.

In this paper, the results on Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$ from inelastic p + p (2.5 M events), and centrality-selected p + Pb (800 K events) reactions are presented.

For p + Pb reactions, the centrality is determined by measuring the number of grey particles (recoiled target protons in the momentum range from 0.15 to 1 GeV/c) using a centrality detector [3] which surrounds the target. The Venus model is used as an input for the detailed simulation of the response of the centrality detector. The agreement with the experimentally observed grey-particle distributions allows us to use the model to calculate the relation between the number of grey tracks and the number of projectile collisions ν.

Using the number of grey particles as a trigger, the total p + Pb sample was divided into two centrality bins, each containing roughly equal number of events and characterized by the (calculated) mean number of collisions, $\langle\nu\rangle$, equal to 3.7 and 5.7.

The Λ ($\bar{\Lambda}$) analysis identifies the decay channel $\Lambda \to \mathrm{p} + \pi^-$ ($\bar{\Lambda} \to \bar{\mathrm{p}} + \pi^+$) ($BR = 63.9\%$) by locating 2-prong vertices (so called V^0s) downstream from the reconstructed primary vertex.

Ξ^- ($\bar{\Xi}^+$) are detected via the channel $\Xi^- \to \Lambda + \pi^-$ ($\bar{\Xi}^+ \to \bar{\Lambda} + \pi^+$) ($BR = 99.89\%$) by using the previously found Λ ($\bar{\Lambda}$) candidates. The daughter-particle candidates are selected using a $\mathrm{d}E/\mathrm{d}x$ cut of $3\,\sigma$ around the expected value of the Bethe-Bloch curve. The details of the procedure are described in Refs. [4, 5]. The final statistics in $\mathrm{p+p}$ and in the two centrality-selected $\mathrm{p+Pb}$ bins amount in each sample to a few hundreds of Ξ^- and $\bar{\Xi}^+$ and about 40k Λ and 10k $\bar{\Lambda}$.

In $\mathrm{p+p}$ and $\mathrm{p+Pb}$ interactions, the acceptance covers the full p_t range (0 - 2 GeV/c) and a rapidity range of more than ± 1 unit around mid-rapidity.

All data are corrected for geometrical acceptance, reconstruction efficiency and branching ratios. The yields of Λ and $\bar{\Lambda}$ are not corrected for feed-down from cascade and Ω decays. These corrections are expected to be less than 10%.

3. Results and discussion

3.1. p + p

Figure 1 shows the rapidity distributions of Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$ particles produced in $\mathrm{p+p}$ interactions [6]. The measurement of Ξ^- and $\bar{\Xi}^+$ hyperons is the first $\mathrm{p+p}$ measurement close to mid-rapidity ($y^* = 0$). The shape of the rapidity distributions for Ξ^- and Λ indicate a "leading particle effect", while $\bar{\Xi}^+$ and $\bar{\Lambda}$ are mostly produced around central rapidity.

The precise measurement of the ratio $\bar{\Lambda}/\Lambda$ at $y^* = 0$ is of particular interest, since it directly measures the net-baryon content in the central region. The observed ratio $\bar{\Lambda}/\Lambda = 0.39 \pm 0.01$ implies that the central region in $\mathrm{p+p}$ collisions at SPS is still net-baryon dominated, as a result of baryon stopping, e.g., the energy loss

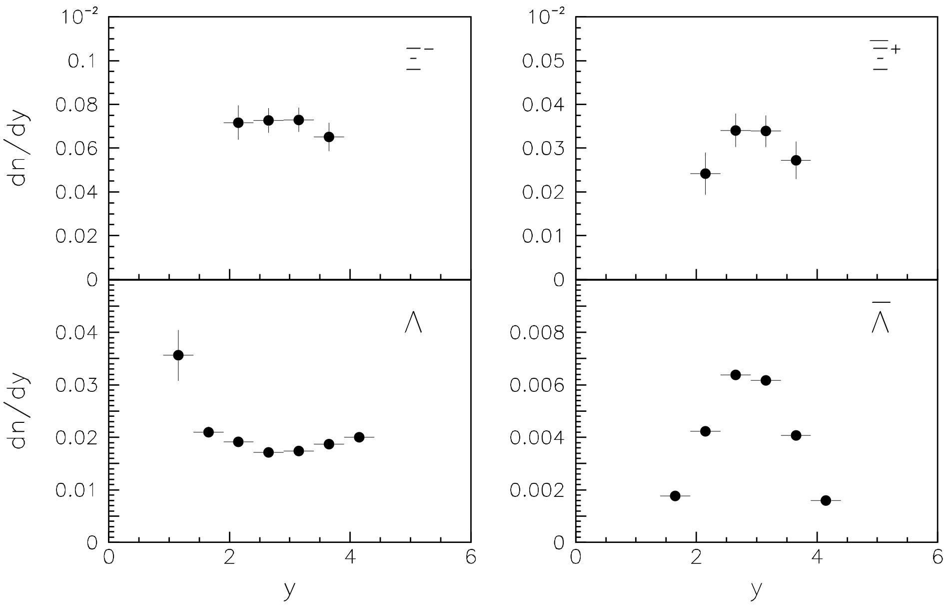

Fig. 1. NA49 preliminary $\mathrm{p+p}$ *rapidity distributions of* Λ, $\bar{\Lambda}$, Ξ^- *and* $\bar{\Xi}^+$ *at 158* GeV/*c*.

of the projectile nucleons and/or of the net-baryon transfer. On the quark level, the net-baryon transfer (from the projectile and target fragmentation regions to mid-rapidity) can generally be described as a transfer of the net-quarks (to be distinguished from the quarks produced in quark-antiquark pairs). From this point of view, the mechanism of net-baryon transfer in $\mathrm{p+p}$ and $\mathrm{A+A}$ collisions could be very similar.

It was mentioned above that Λ and $\bar{\Lambda}$ particles are a good measure for the net-baryon density at central rapidity, the reason being their charge and isospin

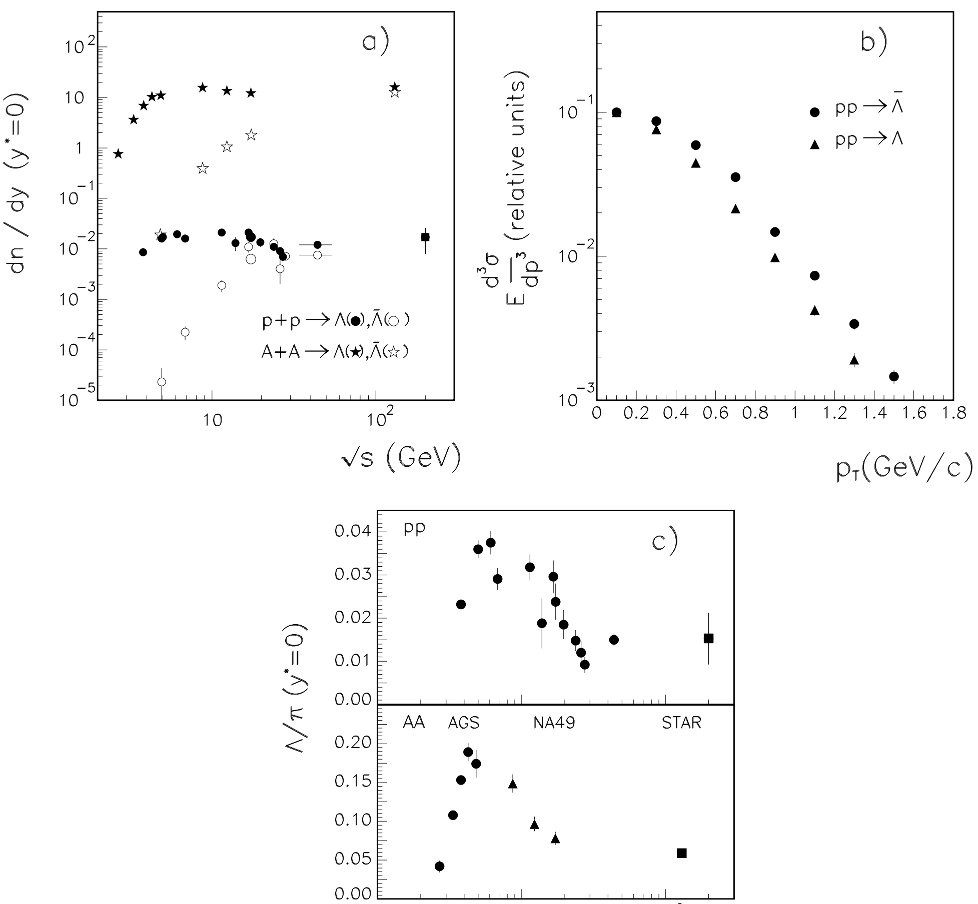

Fig. 2. a) Energy dependence of Λ *and* $\bar{\Lambda}$ *mid-rapidity multiplicities, including preliminary NA49 data, b) Normalized* p_T *distributions of* Λ *and* $\bar{\Lambda}$ *at mid-rapidity at 158* GeV/*c (NA49 preliminary), c) Energy dependence of* Λ/π *ratio at mid-rapidity in* $\mathrm{p+p}$ *(upper plot) and* $\mathrm{A+A}$ *(lower plot).*

neutrality. The energy dependence of the Λ and $\bar{\Lambda}$ multiplicities at mid-rapidity in $\mathrm{p+p}$ [7] and $\mathrm{A+A}$ [8] collisions is shown in Fig. 2a. The averaged yields of Λ and $\bar{\Lambda}$ particles from $\mathrm{p}+\bar{\mathrm{p}}$ collisions at $\sqrt{s} = 200$ GeV/c (full square), is shown to indicate the expected Λ and $\bar{\Lambda}$ yields at higher energy.

The $\mathrm{p+p}$ data for $\bar{\Lambda}$ shows a continuous rise with nucleon-nucleon centre-of-mass energy, $\sqrt{s}$. Due to the isospin arguments, the number of $\bar{\Lambda}$'s measures the number of pair-produced Λ's. The data are not conclusive enough, but there is an indication that pair-produced Λ's 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.

Owing to a high net-baryon density at mid-rapidity, at lower energies the Λ particles are singly produced (essentially through the associated production mechanism together with K^+ mesons). Available results on singly-produced Λ's suggest a very steep rise after passing the threshold energy. The yield levels off to an almost constant value at energies $\sqrt{s} = 5 - 10$ GeV, and still dominates the total Λ production. At higher $\sqrt{s}$, where the pair-produced lambdas start to contribute dominantly, the yield of singly produced Λ's is steeply falling off. 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.

NA49 data shows that approximately 40% of the Λ's at mid-rapidity are pair-produced, and 60% are singly-produced (in associated production with K^+). To demonstrate the correlation between the particle-production mechanism and particle p_T spectra, Fig. 2b shows the normalized p_T distributions of Λ and $\bar{\Lambda}$ hyperons measured at mid-rapidity. A steeper p_T slope observed for the $\bar{\Lambda}$'s (pair produced Λ's) than for the Λ's (singly and pair produced Λ's) demonstrates that the p_T spectra clearly depend on the particle production mechanism. An interesting question is, how this matches the physical assumptions of the statistical model, regardless of its success in describing particle yields from $\mathrm{p+p}$ interactions.

In Fig. 2a, we compare Λ and $\bar{\Lambda}$ production at mid-rapidity for $\mathrm{A+A}$ and $\mathrm{p+p}$ collisions. Although at the same energy, the $\mathrm{A+A}$ data show a higher degree of stopping than $\mathrm{p+p}$ data. It is interesting to note a striking similarity of the energy dependence of these two data sets. Both samples show that Λ production at mid-rapidity is strongly correlated with the energy change of the net-baryon density. Therefore, it is not unexpected that the energy dependence of Λ/π ratio at mid-rapidity in $\mathrm{p+p}$ and $\mathrm{A+A}$ shows a similar behaviour: non-monotonic, passing through a maximum around $\sqrt{s} = 4 - 7$ GeV (Fig. 2c).

We would like to emphasize that the K^+/π ratio should be affected similarly, due to the associated production of K^+ together with Λ particles at lower energies (where the net-baryon density is still high). Unfortunately, data in this energy range are still missing.

Consequently, any conclusion 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 may be premature.

From this point of view, the study of baryon and anti-baryon production in p + p and p + A collisions, from low energies, starting with AGS, all the way up to the top RHIC energy, will be extremly important for a better understanding of baryon propagation in rapidity and/or x_F space in A + A interactions. For this purpose, new and precise measurements of p + p, p + A (and of course A + A) are needed.

3.2. p + Pb

In addition to the similarity between p + p and A + A data, the energy dependence of the Λ/π ratio (Fig. 2c) 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 [9] has shown that the strange particle yields (Λ, $\bar{\Lambda}$, Ξ^-, $\bar{\Xi}^+$ and Ω^-+$\bar{\Omega}^+$) at central rapidity increase from p + Pb to Pb + Pb, under the assumption that the particle yields are proportional to the number of wounded nucleons N_W. Note that a p + A collision with a mean number of projectile collision $\langle\nu\rangle$, has $N_W = \langle\nu\rangle + 1$. Following the logic of the wounded-nucleon-model (WNM) [10], it is actually assumed that the number of produced particles depends only on the total number of nucleons, N_W, participating in the collisions, and not on the number of collisions per participating nucleon. The enhancement, relative to the prediction of the WNM, is found to be more

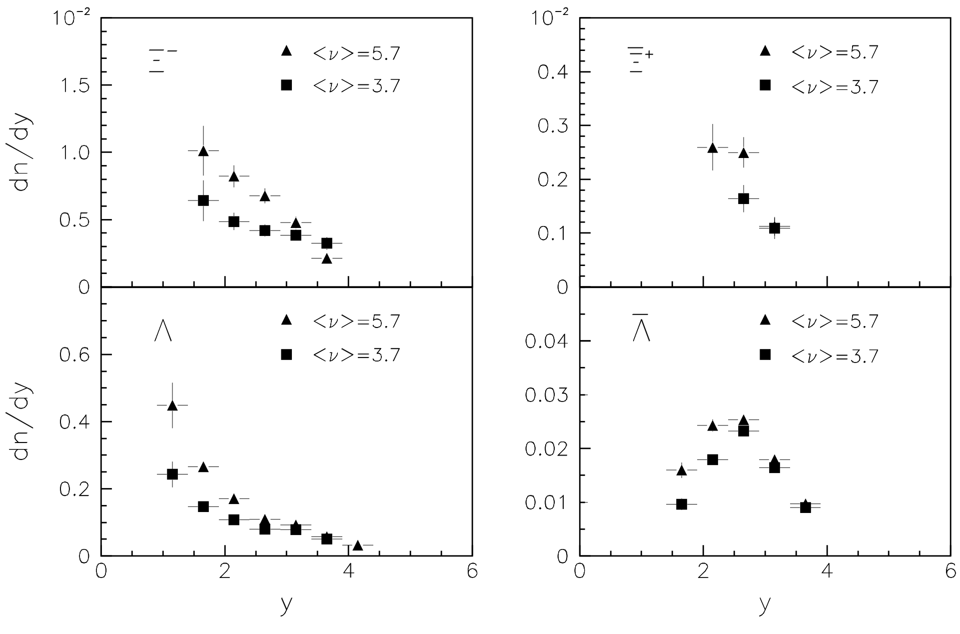

Fig. 3. Rapidity distributions of hyperons in two centrality bins ($\langle\nu\rangle$= 3.7 and $\langle\nu\rangle$= 5.7) in p + Pb *at 158* GeV/*c (NA49 preliminary).*

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

Figure 3 shows the rapidity distributions of hyperons in the two centrality bins of $\mathrm{p+Pb}$ reaction [6] (characterised by the mean number of projectile collisions $\langle\nu\rangle$). We compute for each particle species an enhancement E at mid-rapidity as the ratio between the measured data and the WNM prediction

$$E\,(\nu, y^* = 0) = \frac{\left(\dfrac{\mathrm{d}N}{\mathrm{d}y}\right)^{\mathrm{data}}_{\mathrm{pA}}(\nu)}{\left(\dfrac{\mathrm{d}N}{\mathrm{d}y}\right)^{\mathrm{WNM}}_{\mathrm{pA}}(\nu)}\,. \tag{1}$$

As already observed in $\mathrm{Pb+Pb}$ collisions [9], the excess in $\mathrm{p+Pb}$ is larger for particles of higher strangeness content and is larger for baryons than for antibaryons (Fig. 4). Although the yield of Ξ^-, $\bar{\Xi}^+$ and Λ hyperons scales approximately with ν, as predicted by the WNM, 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.

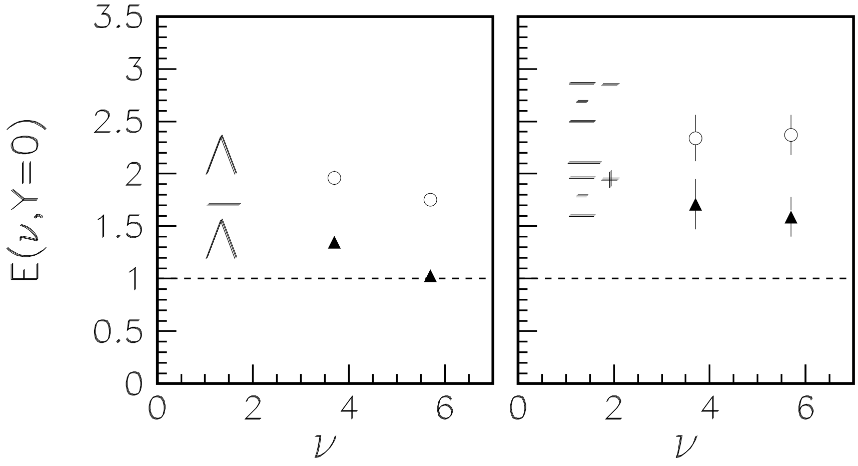

Fig. 4. Ratio E between the measured data and the WNM prediction at mid-rapidity versus mean number of projectile collisons $\langle\nu\rangle$.

In the backward rapidity region, we observe a similar effect. Figure 5 shows the ratios of hyperon multiplicities produced in $\mathrm{p+A}$ and $\mathrm{p+p}$ collisions versus rapidity. Solid and dashed lines show the prediction of the WNM for the first ($\langle\nu\rangle$= 3.7) and the second ($\langle\nu\rangle$= 5.7) centrality $\mathrm{p+Pb}$ bin, respectively. There is 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 (except for the $\bar{\Lambda}$ which shows a strong enhancement in the backward region also for the most central $\mathrm{p+Pb}$ bin).

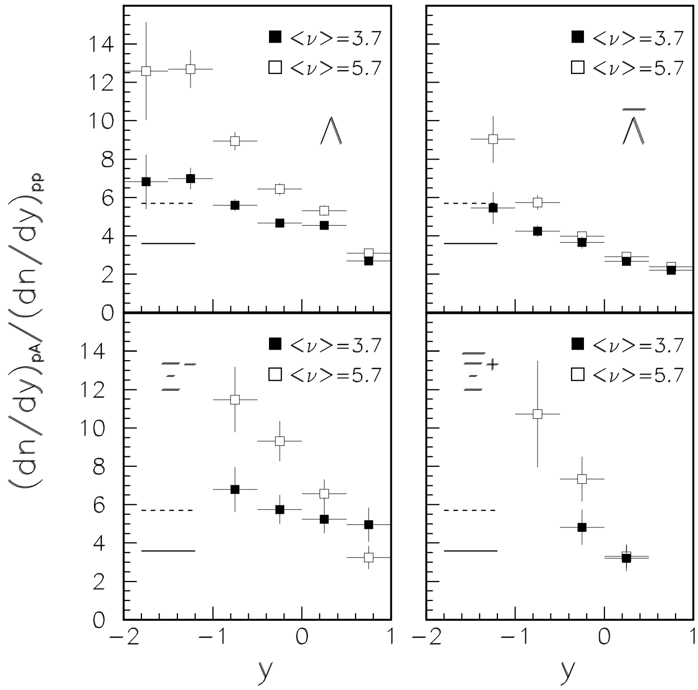

Fig. 5. Ratios of hyperon multiplicities in $\mathrm{p+A}$ *and* $\mathrm{p+p}$ *collisions versus rapidity. Solid and dashed lines show the prediction of the WNM for the first* ($\langle\nu\rangle$= 3.7) *and the second* ($\langle\nu\rangle$= 5.7) *centrality* $\mathrm{p+Pb}$ *bin, respectively.*

The observed enhancement of strange and multistrange baryons in $\mathrm{p+Pb}$ data shows a pattern similar to the one observed in $\mathrm{Pb+Pb}$ and 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 $\mathrm{A+A}$, is a sign for QGP formation [9], one has to study carefully the consequences of the multiple-collision mechanisms as they become accesible in $\mathrm{p+A}$ interactions.

4. *Conclusions*

The NA49 Collaboration at the CERN-SPS has measured Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$ hyperons in minimum-bias $\mathrm{p+p}$ and centrality-selected $\mathrm{p+Pb}$ reactions.

It is important to emphasize that the present measurement of Ξ^- and $\bar{\Xi}^+$ hyperons is the first $\mathrm{p+p}$ measurement close to $y^* = 0$. A steeper p_T slope observed for $\bar{\Lambda}$'s (pair produced Λ's) than for the Λ's (pair and non-pair produced Λ's) reflects their different production mechanisms. It should be critically considered how this matches the physical assumptions of the statistical model, regardless of its success in describing particle yields from $\mathrm{p+p}$ reactions. The same question concerns the applicability of the statistical model in describing the particle yields in the fragmentation region of $\mathrm{A+A}$ reactions.

By comparing the energy dependence of Λ and $\bar{\Lambda}$ production at mid-rapidity, a striking similarity is observed between $\mathrm{p+p}$ and $\mathrm{A+A}$ 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 might be affected similarly due to the associated production of K^+ together with Λ particles, particularly at the lower energies where the net-baryon density is still relatively high. From this we conclude that a rapid change of the energy dependence of strangeness to pion (entropy) ratio may not be a unique characteristic of the heavy-ion reactions (at least not at mid-rapidity).

Comparing the yields of produced hyperons in $\mathrm{p+p}$ and $\mathrm{p+Pb}$ reactions, an excess of Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$ is observed relative to the prediction of the WNM. This excess shows a similar pattern to that observed in $\mathrm{Pb+Pb}$ data: the enhancement is larger for multistrange baryons and larger for baryons than for anti-baryons. The observed enhancement in $\mathrm{p+A}$ shows that the extrapolation to $\mathrm{A+A}$ using WNM is questionable, as well as the conclusions based on this extrapolation.

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

References

[1] *Proc. 14th Int. Conf. Ultra-Relativistic Nucleus-Nucleus Collisions, Quark Matter 99*, eds: L. Riccati, M. Masera and V. Vercellin, Nucl. Phys. A **661** (1999) 1c.

[2] F. Becattini and U. Heinz, Z. Phys. C **76** (1997) 269.

[3] S. Afanasiev et al., NA49 Collaboration, Nucl. Instr. Meth. A **430** (1999) 210.

[4] L. S. Barnby et al., NA49 Collaboration, J. Phys. G **25** (1999) 469.

[5] R. A. Barton et al., NA49 Collaboration, J. Phys. G **27** (2001) 367.

[6] T. Šuša, for the NA49 Collaboration, *Cascade Production in p + p, p + A and A + A Interactions at 158 A·GeV*, to be published in *Proc. 15th Int. Conf. Ultra-Relativistic Nucleus-Nucleus Collisions (QM 2001)*, Long Island, New York, January 15–20, 2001.

[7] B. Y. Oh and G. A. Smith, Nucl. Phys. B **49** (1972) 13; V. Blobel et al., Nucl. Phys. B **69** (1974) 454; K. Jaeger et al., Phys. Rev. D **11** (1975) 1756; H. Boggild et al., Nucl. Phys. B **57** (1973) 77; W. Ammosov et al., Nucl. Phys. B **115** (1976) 269; J.W. Chapman et al., Phys. Lett. B **47** (1973) 465; D. Brick et al., Nucl. Phys. B **164** (1980) 1; K. Jaeger et al., Phys. Rev. D **11** (1975) 2405; F. LoPinto et al., Phys. Rev. D **22** (1980) 573; A. Sheng et al., Phys. Rev. D **11** (1980) 1733; F.T. Dao et al., Phys. Rev. Lett. **30** (1973) 1151; M.Asai et al., Z. Phys. C **27** (1985) 11; F. Kichimi et al., Phys. Rev. D **20** (1979) 37; F.W. Busseret al., Phys. Lett. B **61** (1976) 309; R.E. Ansorge et al., Nucl. Phys. B **328** (1989) 36.

[8] G. Rai, for the E895 Coll., shown at *14th Int. Conf. Ultra-Relativistic Nucleus-Nucleus Collisions*, QM99, Torino, Italy, 10–15 May, 1999; M. Gazdzicki, for the NA49 Collaboration, the same proceedings; P. Jones for the STAR Collaboration, the same proceedings.

[9] E. Andersen et al., WA97 Collaboration, Phys. Lett. B **449** (1999) 401.

[10] A. Białas, M. Bleszyński and W. Czyż, Nucl. Phys. B **111** (1976) 461.

TVORBA STRANIH HIPERONA U $p+p$ I $p+Pb$ SUDARIMA U MJERENJU NA49

U mjerenju eksperimenta NA49 dobiveni su podaci o tvorbi Λ, $\bar{\Lambda}$, Ξ^- i $\bar{\Xi}^+$ hiperona u neelastičnim $p+p$ sudarima i u $p+Pb$ sudarima odabranim prema centralnosti, na 158 GeV/c. Načinili smo prva mjerenja $p+p$ sudara s opažanjem Ξ^- i $\bar{\Xi}^+$ čestica u kinematičkom području oko središnjeg rapiditeta. Na osnovi usporedbe $p+Pb$ i $p+p$ reakcija, opaža se da prinosi stranih hiperona rastu brže nego broj udarenih nukleona. Kako se to ranije opazilo i u $A+A$ sudarima, povećanje je veće za višestruko strane nego za strane barione, i također za barione nego za antibarione. Usporedbom energijske ovisnosti tvorbe Λ i $\bar{\Lambda}$ za srednji rapiditet, nalazimo izraženu sličnost $p+p$ and $A+A$ podataka. To se također odnosi i na energijsku ovisnost omjera Λ/π.