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Abstract.
The microscopic origin of the strangeness enhancement observed in PbPb collisions at the SPS is studied by testing the effects of three types of strangeness enhancement mechanisms. First, the enhancements from the junction stopping and junction loop mechanisms found in the HIJING/BB event generator are reviewed showing that they can account for only part of the observed hyperon enhancements. Including the efficient final state chemical changing processes (e.g. \(\Lambda + K \leftrightarrow \Xi + \pi\)) by coupling the General Cascade Program (GCP) to HIJING/BB are also only able to account for part of the hyperon enhancements. In addition, it is shown that HIJING/BB+GCP can not reproduce the enhancement of the \(K^+/\pi^+\) ratio. The inclusion of transient field fluctuations or ropes to HIJING/BB+GCP is therefore shown to be needed to account for the observed enhancements.
1. Introduction

Striking enhancements of multistrange baryons have been recently observed in PbPb collisions at the SPS. In fact, when comparing the hyperons produced per number of participant, a factor of 20 enhancement is observed for the $\Omega$ in central PbPb collisions\[1, 2\] over that found in $pPb$ and $pBe$ collisions. In addition, the $K^+ / \pi^+$ in central PbPb collisions is found to be twice the value observed in $pp$ collisions \[3\].

These large enhancements are of particular interest since they have been proposed as one of the signatures of the formation of the quark-gluon plasma\[4, 5, 6\]. Several different approaches which assume a plasma initial condition are able to describe the observed yields. Different statistical fireball models (see \[7\] and \[8\]) are successful at demonstrating the statistical nature of the ratios of the hadrons. The ALCOR model which assumes the formation of a constituent quark plasma followed by a coalescence of the quarks into hadrons has also been able to successfully describe the hadronic yields and ratios\[9\]. In addition, a more elaborate model which begins with a system initially in a plasma which then freezes out by undergoing a first order phase transition followed by the final state rescattering of the produced particles is able to describe both the yields and the transverse momentum spectra of the hyperons\[10\].

A different approach is taken in this report, where an initial plasma state is not assumed and where different microscopic hadronic mechanisms are studied. Here, it is found that three hadronic mechanisms can provide large strangeness enhancements which can effectively describe the data.

The first mechanism is the baryon junction stopping\[11, 12\] and baryon junction pair production\[13\] processes. These Regge-motivated processes enhance baryon production at mid-rapidity since they produce baryons in the mid-rapidity region which are completely composed of sea quarks. The second is final state interactions or the scattering of the newly produced hadrons\[14\]. Here, the most efficient interaction is the exothermic, strangeness exchange interaction (e.g. $N + K^* \rightarrow \Lambda + \pi$) which produces a hyperon with one greater net strangeness. While the above mechanisms enhance the hyperons, they do not describe the total strangeness enhancement of the system as observed in the $K^+ / \pi^+$ ratio. Thus, a third mechanism is needed. Transient fluctuating fields or ropes\[15\] are therefore introduced. The ropes result from the geometrical overlap of wounded nucleons. In the region of the overlapping wounded nucleons, a larger energy-density is felt during their fragmentation. This leads to an increase in both $s - \bar{s}$ pair production and $qq - \bar{q}\bar{q}$ pair production. This mechanism naturally enhances strange meson and multistrange baryon production. These mechanisms will now be reviewed in more detail.

2. Baryon Junction Stopping and Junction Loop Pair Production

The baryon junction was first proposed in the 70’s in order to understand baryon-antibaryon annihilation\[16\]. Recently, the baryon junction was resurrected to provide an efficient mechanism for baryon stopping\[11\].

The baryon junction is motivated from writing the QCD gauge invariant operator of the baryon. It is the vertex which links the three color flux (Wilson) lines flowing from the valence quarks. Since the junction is a gluonic configuration, it can be easily transported into the mid-rapidity region in hadronic reactions. At mid-rapidity, a baryon which is composed of three sea quarks is produced from the fragmentation of the strings which connect the junction to the three valence quarks. This gluonic
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mechanism is able to explain a striking, preliminary measured baryon asymmetry observed approximately 8 units of rapidity away from the proton’s fragmentation region in ep collisions at HERA.

Using this Regge motivated mechanism, event generator calculations were able to reproduce the baryon stopping at the SPS. However, since this baryon stopping mechanism depleted the available phase space in the central rapidity region for antibaryon production, a mechanism for antibaryon production was needed. The valence baryon junction mechanism was then extended and a new mechanism for antibaryon production was proposed. Like the valence baryon junction mechanism, this junction-anti-junction loop (JJ) mechanism is also derived from the topological gluon structure of the baryon and originates in the context of Regge phenomenology. The (JJ) mechanism was shown to strongly enhance the anti-hyperon yields in nuclear collisions and to provide reasonable anti-hyperon to hyperon ratios. Both of these processes were implemented in HIJING/B, a modified version of the HIJING event generator.

The ratio of hyperon yields per number of participants in PbPb collisions to the hyperon yields per number of participants in pPb are plotted for Λ, Ξ and Ω production in figures 1a-c. Comparing the calculations of HIJING (solid line) and HIJING/B (dashed line) shows that the junction processes in HIJING/B provide a slight enhancement between the pPb and PbPb systems. However, it should be noted that the junctions have already strongly enhanced the Ω production in pPb by a factor of 10. The antihyperon to hyperon ratios are shown in figure 1d, where the junction mechanisms are shown to provide more reasonable values.

3. Final State Interactions

In collisions between large nuclei, the hadrons which are produced from direct production mechanisms such as string fragmentation are able interact with one another as they flow outward. At SPS energies, these interactions have typically low center of mass energies (\(\sqrt{s} \leq 3\) GeV) and have been shown to influence the observed particle yields. The effects of the final states interactions, in particular the strangeness changing processes, are explored by coupling the Genera Cascade Program (GCP) to the HIJING/B model.

The GCP models the evolution of the produced hadrons by solving the relativistic Boltzmann equation with two body collisions:

\[
p^\mu \partial_\mu W_a(x, p, t) = \sum_{b_1, b_2} \int \left[ \prod_{i=1,2} \frac{d^3 \vec{p}_{b_i}}{(2\pi)^3 2E_{b_i}} W_{b_i}(x, \vec{p}, t) \right] |\vec{v}_1 - \vec{v}_2| \sigma_{b_1 + b_2} \delta^4(p - \vec{p}_{b_1}) - \delta_{ab_1} \delta^3(\vec{p} - \vec{p}_{b_1}) - \delta_{ab_2} \delta^3(\vec{p} - \vec{p}_{b_2}) + \sum_{j=1}^m \delta_{ac_j} \delta^3(\vec{p} - \vec{p}_{c_j}),
\]

(1)

where \(W_a\) is the particle phase space distribution and \(\sigma_{b_1, b_2}\) is the cross section for the interaction of particles \(b_1\) and \(b_2\). A point particle distribution is assumed for the
Figure 1. The Hyperon yields per number of participant for PbPb collisions divided by the hyperon yields per number of participant in pPb are plotted in parts (a-c). The ratios of the anti-hyperons to hyperons are shown in part (d). Calculations from HIJING (solid), HIJING/BB (dashed), HIJING/BB+GCP (dotted) and HIJING/BB+GCP+Ropes (dash-dotted) are compared with measurements from WA97 Collaboration.**

\[
W_a(\vec{x}, \vec{p}, t) = \frac{N_a}{M_a} \sum_{i=1}^{M_a} \delta^3(\vec{x} - \vec{x}_i(t)) \delta^3(\vec{p} - \vec{p}_i(t)),
\]

where \(M_a\) is the number of test partons (\(M_a = 1\) is assumed for the present calculation).

In the GCP simulation, collisions between the hadrons occur when their distance of closest approach, \(d\), is less than their interaction range \(r = \sqrt{\sigma/\pi}\), which is determined from their interaction cross section, \(\sigma\). As the system evolves, all possible future collisions are time ordered in the global center of mass frame. As a collision occurs, the branching ratios of the possible channels give the final state spectrum and
all future possible collisions in the system are again determined. Between collisions, the particles are assumed to travel along straight lines. The cross sections for the interactions are determined by fitting available data or are assumed from general arguments. The inverse of these processes is obtained by modifying the cross section with the appropriate spin and momentum dependent factors (see reference [20]).

When coupling GCP to HIJING/BB[14], the phase space distribution of the hadrons produced from the string fragmentation is obtained using the strong assumption that the pseudo-rapidity \( \eta = \frac{1}{2} \ln \left( \frac{t + z}{t - z} \right) \) equals the rapidity \( y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \), or \( \eta = y \).

Three categories of final state interactions influence hyperon yields. The first is the strangeness exchange interactions,

\[
N + K \leftrightarrow \Lambda + \pi, \quad N + K \leftrightarrow \Sigma + \pi,
\]

\[
\Lambda + K \leftrightarrow \Xi + \pi, \quad \Sigma + K \leftrightarrow \Xi + \pi,
\]

\[
\Xi + K \leftrightarrow \Omega + \pi.
\] (3)

Channels which include the \( K^* \) and \( \Delta \) resonances are also included. For the \( K^- + p \) and \( K^- + n \) interactions, the cross sections are obtained by fitting the data[23]. For the other reactions, a general strangeness exchange cross section, \( \sigma_{\text{exchange}} = \sigma_{K^- + p} - \sigma_{K^+ + p} - \sigma_{K^- + p + K^0 + n} \), is used (see figure 2a). The strangeness exchange interactions are exothermic and are efficient mechanisms for enhancing the hyperons.

The most effective of these reactions is the \( K^* \) interacting with the \( N, \Lambda \) and \( \Xi \).

The second set of interactions are the strangeness creation reactions,

\[
N + \pi \leftrightarrow \Lambda + K, \quad N + \pi \leftrightarrow \Sigma + K,
\]

\[
\Lambda + \pi \leftrightarrow \Xi + K, \quad \Sigma + \pi \leftrightarrow \Xi + K,
\]

\[
\Xi + \pi \leftrightarrow \Omega + K.
\] (4)

The cross sections for the \( \pi^+ + p \) and \( \pi^- + p \) interactions are obtained from fitting data[23] while the cross section used for the other channels is assumed to be \( \sigma_{\text{creation}} = \sigma_{\pi^+ p \rightarrow \Sigma^+ K^+} \) (see figure 3b). Unlike the strong enhancements found in reference [21], the strangeness creation interactions in our simulation appears to have little effect in enhancing hyperon production.

The third type of interactions is baryon-antibaryon annihilation

\[
B + \bar{B} \rightarrow X,
\] (5)

which depletes both the net baryon and antibaryon yields. The cross section used for this interaction is taken from reference [24].

Calculations of HIJING/BB+GCP (dotted line) are shown in figure 1. The final state strangeness exchange interactions dramatically enhance the \( \Omega \). However, the baryon-antibaryon annihilation decrease the total yields. More striking is the comparison between HIJING/BB + GCP calculations of the \( K^+ / \pi^+ \) ratio (ratio of the total 4\( \pi \) yields) with the preliminary data[3] as shown in figure 5. Here, HIJING/BB + GCP gives a dependence of this ratio on the number of participants which is flat, underestimating by a factor of 2 the value in the most central collisions. The junction and final state interactions mechanisms most strongly influence hyperon production while only slightly enhancing the \( K \) yields. Additional strangeness enhancements mechanisms are therefore needed.
Figure 2. The general strangeness exchange cross section and the general strangeness creation cross section are shown in parts (a) and (b), respectively.

Figure 3. Calculations of the $K^+/\pi^+$ ratio as a function of the number of participants from HIJING/BB+GCP (solid line) and HIJING/BB+GCP+Ropes (dashed line) are compared with preliminary NA49 measurements for PbPb collisions at the SPS.
4. Ropes or Transient Field Fluctuations

Another efficient strangeness production mechanism is transient field fluctuations or ropes. Ropes occur when wounded nucleons physically overlap during their fragmentation. When the wounded nucleons overlap, the chromo electric field strength or string tension, $\kappa$, is increased, allowing for enhanced production of $s-\bar{s}$ and $qq-\bar{q}\bar{q}$ pairs during fragmentation. For example, using the Schwinger particle production mechanism, the probability for producing an $s-\bar{s}$ pair to a $u-\bar{u}$ pair is given as

$$P_{s/u} = e^{-\pi(m_s^2 - m_u^2)/\kappa}.$$  \hspace{1cm} (6)

In $pp$ interactions, $\kappa \simeq 1$ GeV/fm $= 0.2$ GeV$^2$, and when using the constituent masses for the quarks (i.e. $m_s = 0.45$ GeV and $m_u = 0.325$ GeV), $P_{s/u} \sim 0.3$. As $\kappa$ increases, the $P_{s/u}$ probability also increases and thus more strange hadrons are produced. This mechanism has been shown to increase hyperon production.

When adding the ropes to HIJING/BB+GCP, the string tension grows as the square-root of the number of overlapping wounded nucleons, $\kappa = \sqrt{n}$ GeV/fm. The number of overlapping wounded nucleons is determined by counting those which lie within a radius of $r = 0.25$ fm. The addition of ropes to HIJING/BB+GCP will be denoted by HIJING/BB+GCP+Ropes.

Using HIJING/BB+GCP+Ropes, calculations of the hyperon yields and the $K^+/\pi^+$ ratios are shown in figures 1 and 3, respectively. As seen in figure 1a-c, the ropes enhance the hyperon production. As seen in figure 3, the ropes also reproduce the smooth increase of the $K^+/\pi^+$ ratio with the increased number of participants.

5. Conclusion

The junction baryon stopping and junction loop baryon pair production mechanisms are important in describing the baryon stopping, hyperon production and the ratio of antihyperons to hyperons at the SPS. In addition, final state interactions, whose effects are most dominantly observed through the $p_T$ distributions of the particles, are also important in changing the hyperon yields. Here, the most dominant processes are the strangeness exchange channel and baryon-antibaryon annihilation. However, even with these two mechanisms, the overall net strangeness enhancement is under-produced as seen most strikingly through the $K^+/\pi^+$ ratio. Another mechanism is therefore needed and the initial state rope mechanism is used. This rope mechanism depends upon the number of overlapping strings and thus is able to produce more strange particles in denser systems as consistent with the observed $K^+/\pi^+$ ratio. When combined, the three mechanisms are able to describe both the large strangeness enhancement in the dense $PbPb$ collisions and the smooth dependence of the enhancement on the number of participants as seen at the SPS.

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