Strangeness Enhancement in p-A Collisions: Consequences for the Interpretation of Strangeness Production in A-A Collisions

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Abstract

Published measurements of semi-inclusive Λ production in p-Au collisions at the AGS are used to estimate the yields of singly strange hadrons in nucleus-nucleus (A-A) collisions. Results of a described extrapolation technique are shown and compared to measurements of K⁺ production in Si-Al, Si-Au, and Au-Au collisions at the AGS and net Λ production in S-S, S-Ag, Pb-Pb, and inclusive p-A collisions at the SPS. The extrapolations can account for more than 75% of the measured strange particle yields in all of the studied systems except for very central Au+Au collisions at the AGS where RQMD comparisons suggest large re-scattering contributions.

Strange particle production has long been considered an important experimental probe of heavy ion collisions due to the possibility that strange particle
yields may be significantly enhanced by quark-gluon plasma (QGP) for ma-
tion [1,2]. Heavy ion experiments at the Brookhaven National Laboratory
AGS and CERN SPS accelerators have observed factors of 3-4 enhancements
in the yield per participant of strange mesons and singly strange baryons [3–
10] and, at the SPS, larger enhancements in the production of multiply strange
baryons [11–13]. Cascade models can quantitatively reproduce the enhance-
ment of strange mesons in central heavy ion collisions at the AGS but are
unable to reproduce the enhancements observed at the SPS without the intro-
duction of “exotic” processes. Furthermore, inclusive measurements of kaon
production in proton-nucleus (p-A) collisions at the AGS have shown an en-
hancement with target size [14,15], while no such enhancement was seen at
the SPS [16]. The strong enhancements in nucleus-nucleus (A-A) collisions at
the SPS, combined with the lack of enhancement in p-A and the failure of cas-
cade models, have been cited as experimental evidence for QGP formation at
the SPS [17,18], while the enhancements at the AGS are typically attributed
to rescattering of produced hadrons. Then, the similarity in magnitude and
pattern of enhancements of singly strange hadrons at the AGS and SPS must
be attributed to coincidence.

However, previous measurements of semi-inclusive Λ production by Experi-
ment 910 at the AGS [19] suggest an alternative, common explanation for
the enhancement of singly strange hadron production in A-A collisions at the
AGS and SPS. E910 has measured the dependence of the total Λ yield in
17.5 GeV/c p-Au collisions on the number of scatterings ν of the proton in
the Au nucleus and demonstrated enhanced Λ production over a number of
participant (N_{part}) scaling of p-p data. In this paper we present the results of
an analysis that extrapolates the effect observed by E910 to A-A collisions and
predicts the hyperon-associated K^+ yields in Si-Al, Si-Au, and Au-Au collis-
sions at the AGS and the net Λ yields in S-S, S-Ag, and Pb-Pb collisions at
the SPS. We show that the extrapolation of the effect observed in p-A collisions
can account for most of the observed enhancements in hyperon-associated K^+
production at the AGS and Λ production at SPS in both light and heavy ion
induced reactions. With the same analysis we also explain the lack of observed
enhancement in inclusive p-A measurements at the SPS.

E910 reported [19] that the Λ excess in p-Au collisions over a simple N_{part}
or wounded-nucleon scaling of p-p data increased proportionally to ν for the first
three collisions with a slope equal to one half of the p-p Λ multiplicity,

\[ \Delta N_\Lambda(\nu) = (\nu - 1)\frac{1}{2}N_{pp}^{\Lambda}. \]  

(1)

Since the projectile contributes \( \frac{1}{2}N_{pp}^{\Lambda} \) to the total Λ multiplicity in the first
collision, the E910 excess is consistent with a projectile contribution to the
total $\Lambda$ multiplicity that grows with $\nu$, as [19]

$$N_{\Lambda}^{\text{proj}} = \frac{1}{2} N_{\Lambda}^{pp} \nu, \nu \leq 3,$$

and remains constant for $\nu > 3$. To extrapolate to A-A collisions we assume that Eq. 2 is valid for all relevant beam energies and that it applies equally to all participating nucleons with $N_{\Lambda}^{pp}$ replaced by the estimated yield in isospin averaged nucleon-nucleon (N-N) collisions, $N_{NN}$. Then, the total multiplicity in an A-B collision is

$$N_{AB} = \frac{1}{2} N_{NN} \sum_{\nu=1}^{3} [AP_p(\nu) + BP_t(\nu)] \nu + \frac{3}{2} N_{NN} \sum_{\nu>3} AP_p(\nu) + BP_t(\nu).$$

$P_{p/t}(\nu)$ represents the probability distribution for the projectile and target nucleons to undergo $\nu$ primary scatterings during the collision. Since the number of participants can also be calculated from the $P_{p/t}(\nu)$,

$$N_{\text{part}}^{AB} = \sum_{\nu \geq 1} AP_p(\nu) + BP_t(\nu),$$

we can directly obtain the relationship between $N_{AB}$ and $N_{\text{part}}$. We note that Eq. 3 applied to p-A collisions reduces to

$$N_{pA} = N_{NN} \nu, \nu \leq 3 ; N_{pA} = \frac{1}{2} N_{NN}(\nu + 3), \nu > 3.$$
evaluate the importance of the stopping effects at AGS energies implied by
the E910 data, we additionally imposed in the Glauber calculations a max-
imum thickness to the nuclei corresponding to 5 nucleon interaction lengths
with the result shown in Fig. 1 by the dashed lines. Hereafter we will use the
Monte-Carlo results when presenting the calculation results.

We now compare our calculations to experimental data starting with $K^+$ mul-
tiplicities measured by Experiments 859 and 866 in Si-Al, Si-Au, and Au-Au
collisions at the AGS [4]. At AGS energies, the $K^+$ is predominantly produced
in association with hyperons, so the total $K^+$ multiplicity should have the
same $\nu$ dependence as the $\Lambda$ (excluding $K^+\bar{K}$ contributions). Previously esti-
mated production rates for $K^+$ production in isospin-averaged N-N collisions
are listed in Table 1 for the three different colliding systems [4]. At comparable
energies p-p measurements [22] suggest that 15% of the $K^+$ yield results from
$K^+\bar{K}$ processes. Lacking clear knowledge of how these processes grow in p-A
collisions we conservatively assumed that $K^+\bar{K}$ production increases propor-
tionally to $N_{\text{part}}$. Thus, the N-N $K^+$ rates used in Eq. 2 were reduced by 15%,
and the $K^+\bar{K}$ contribution to the $K^+$ yield was added separately. Figure 2
shows a comparison between the results of our calculation and the experimen-
tally measured $K^+$ yields. Two sets of points are shown for the Si-Au data
because the experimentally quoted $N_{\text{part}}$ values were found to be inconsistent
with calculated values of $N_{\text{part}}$ for the quoted centrality fractions [4], though
nowhere by more than twice the stated error on the $N_{\text{part}}$ values. Since the two
calculations give results that differ by less than 2%, we attribute the discrep-
ancy with the data to a systematic error in the method used by the ex-
periment to estimate $N_{\text{part}}$ in asymmetric collisions. The shaded region in Fig. 2 indi-
cates the uncertainties in our extrapolation due to the systematic errors on
the N-N yields shown in Table 1 and the uncertainty in the $K^+\bar{K}$ rate in p-p
collisions. Our calculations account for more than 75% of the measured $K^+$
yields everywhere except in the most central Au-Au collisions where the data
exceeds our extrapolation by 50%. We also show in Fig. 2 the results from
the cascade model RQMD [23] simulating 11.1 AGeV/c Au+Au collisions.
Although RQMD significantly under-predicts the E866 $K^+$ yield over most of
the centrality range, it shows a rapid increase in $K^+$ yield with $N_{\text{part}}$ for very
central collisions that may be due to rescattering processes, which would be
expected to grow roughly like $N_{\text{part}}^2$. The rapid rise in the RQMD calculation
is qualitatively similar in shape to the observed excess of the central Au-Au
data over our calculation suggesting that this excess may, in fact, be due to
rescattering processes not present in p-A data.

We also apply our extrapolation procedure to SPS energies to determine
whether the strangeness enhancements there may also be accounted for by the
effect observed in the E910 data. Since Eq. 2 may not describe baryon-anti-
baryon (BB) production which is negligible at AGS energies but important at
SPS energies, comparisons with SPS data are done using the “net” $(N_A - N_\bar{A})$
yields. Figure 3 shows measurements of total net Λ production from NA35 in central S-S [8] and S-Ag [10] collisions at 200 A-GeV/c and net Λ production at mid-rapidity in Pb-Pb collisions at 160 A-GeV/c from WA97 [12]. The input N-N rates required for the extrapolation are listed in Table 1. For the Pb-Pb extrapolation we reduced the p-Be Λ yields of WA97 by a factor of 0.87 to remove the enhancement that would result from multiple collisions of the proton according to our method. The extrapolations, shown in Fig. 3 by solid lines, reproduce the observed Λ enhancement in S-A collisions but fall well below the Pb-Pb data. However, the problem with the latter comparison is that the WA97 measurements are limited to an acceptance of unit rapidity about the N-N center of mass. The p-p Λ rapidity distribution is strongly peaked at forward/backward rapidity and suppressed near mid-rapidity [24,25]. The increased stopping of the baryons in Pb-Pb collisions [26] will strongly shift the peaks toward mid-rapidity, so that an enhancement would be observed by WA97 even if there were no enhancement in the total Λ yield. From parameterizations of the Λ $x_F$ distribution in p-Be collisions [27] we estimate that 11% of the total p-Be Λ yield is contained within the central unit of rapidity. Using recent measurements and extrapolations for Λ and $\bar{\Lambda}$ $dn/dy$ for 158 A-GeV/c Au-Au [28] we estimate that 21% of the total net Λ yield is contained in the central unit of rapidity. If we multiply our extrapolation by a factor of $0.21/0.11 = 1.9$ to account for the effects of the $dn/dy$ shape change, we then obtain the dashed line shown in Fig. 3. The excellent agreement between this result and the Pb-Pb data may be partially accidental since we have not included an $N_{part}$ dependence to the correction factor. Nonetheless, we can conclude that our extrapolation accounts for more than 75% of the net hyperon yields in light and heavy ion collisions at the SPS.

The large enhancements at SPS energies predicted by the E910 extrapolation appear to contradict the lack of enhancement noted by previous p-A measurements at the SPS [16]. However, the effect observed by E910 may be substantially obscured in inclusive collisions due to the large contributions from peripheral collisions and due to the saturation of the projectile enhancement at $\nu = 3$, which will result in a decreasing Λ yield per participant for $\nu > 3$. Figure 4 shows results of our calculations for inclusive collisions compared with a variety of inclusive measurements [16]. Our calculation reproduces the nearly constant Λ yield per participant observed in the experimental data in spite of the enhanced projectile contribution.

In conclusion, we have performed a set of calculations intended to quantitatively evaluate the significance of the observed enhancement of Λ production in p-Au collisions [19] in the interpretation of strangeness enhancement in heavy ion collisions. Our extrapolation is based on applying the enhancement observed by E910 to all participant nucleons in A-A collisions assuming that it results directly from the multiple interactions of the proton. We show that our extrapolation can account for more than 75% of the total hyperon or hyperon
associated kaon yield in light and heavy ion induced collisions at the AGS and SPS except for K+ production in central Au-Au collisions. Here, comparisons with RQMD suggests that the discrepancy is due to rescattering processes that contribute most importantly in central collisions. The analysis presented here suggests that a dynamical mechanism and not QGP formation may be responsible for enhancing the yields of (at least) singly strange hadrons. Our analysis also suggests that the similar enhancements observed at the AGS and SPS result from a common mechanism in spite of the difference in beam energies.

References

[1] P. Koch, J. Rafelski, and W. Greiner, Phys. Lett. B123, 151 (1983).
[2] P. Koch, B. Müller, and J. Rafelski, Phys. Rep. 142, 167 (1986).
[3] T. Abbott et al., Phys. Rev. Lett. 64, 847 (1990).
[4] L. Ahle et al., Phys. Rev. C60, 044904 (1999).
[5] L. Ahle et al., Phys. Rev. C58, 3523 (1998).
[6] S. Eisman et al., Phys. Lett. B297, 44 (1992).
[7] S. Ahmad et al., Phys. Lett. B382, 35 (1996).
[8] J. Bartke et al., C48, 191 (1990).
[9] J. Bachler et al., Z. Phys. C58, 367 (1993).
[10] T. Alber et al., Z. Phys. C64, 195 (1994).
[11] F. Antinori et al., Phys. Lett. B447, 178 (1999).
[12] E. Andersen et al., Phys. Lett. B449, 401 (1999).
[13] H. Appelshäuser et al., Phys. Lett. B444, 523 (1998).
[14] T. Abbott et al., Phys. Rev. Lett. 66, (1991).
[15] T. Abbott et al., Phys. Rev. D 45, 3906 (1992).
[16] H. Bialkowska et al., Z. Phys. C55, 491 (1992), and references therein.
[17] U. Heinz, hep-ph/0009170 (2000).
[18] U. Heinz and M. Jacob, nucl-th/0002042 (2000).
[19] I. Chemakin et al., Phys. Rev. Lett. 85, 4868 (2000).
[20] R. J. Glauber and G. Matthiae, Nucl. Phys. B21, 135 (1970).
| Beam p (GeV/c) | System | Part. | Mult. | Error | Ref. |
|---------------|--------|-------|-------|-------|------|
| 14.6          | Si+A   | K⁺    | 0.049 | 0.008 | [4]  |
| 14.6          | Si+A   | K⁺\bar{K} | 0.007 | 0.002 | [22] |
| 11.1          | Au+Au  | K⁺    | 0.033 | 0.005 | [4]  |
| 11.1          | Au+Au  | K⁺\bar{K} | 0.055 | 0.002 | [22] |
| 200           | S+A    | Λ     | 0.10  | 0.01  | [29] |
| 200           | S+A    | \bar{Λ} | 0.013 | 0.005 | [29] |
| 160           | Pb+Pb  | Λ     | 0.0334| 0.0005| [30] |
| 160           | Pb+Pb  | \bar{Λ} | 0.0111| 0.0002| [30] |

Table 1
Measured or estimated rates for K⁺, K⁺\bar{K}, Λ, and \bar{Λ} production in nucleon-nucleon collisions used to extrapolate to corresponding measurements in indicated light/heavy ion collisions.

[21] B. Andersson, G. Gustafson, and B. Nilsson-Almqvist, Phys. Lett. B 281, 289 (1986).
[22] H. Fesefeldt et al., Nucl. Phys. B147, 317 (1979).
[23] H. Sorge et al., Phys. Rev. C 52, 3291 (1995).
[24] D. Brick et al., Nucl. Phys. B164, 1 (1980).
[25] J. Allday et al., Z. Phys. C40, 29 (1988).
[26] H. Appelshäuser et al., Phys. Rev. Lett. 82, 2471 (1999).
[27] T. Kachelhoeffer and W. M. Geist, Phys. Lett. B394, 225 (1997).
[28] T. Anticic et al., PRL 93, 022302 (2004).
[29] M. Gazdzicki and D. Rohrich, Z. Phys. C71, 55 (1996).
[30] F. Antinori et al., Nucl. Phys. A661, 476 (1999).

Fig. 1. Calculated enhancement factor R_{part} (see text for details) vs b and N_{part} for various colliding systems, solid lines - Glauber geometry, points - Lund geometry.

Fig. 2. Comparison between measured K⁺ yields in Si-A (left) and Au-Au collisions (right) at the AGS and extrapolations, ■ - Si-Al, △ - Si-Au, ● - Au-Au, ▼ - Si-Au with adjusted N_{part}, solid line - extrapolations, dashed - N_{part} scaling of N-N, dot-dashed - RQMD calculation for Au-Au. Shaded regions indicate 1σ systematic errors due to uncertainties in N-N yields.
Fig. 3. Comparison of net $\Lambda$ ($\Lambda - \bar{\Lambda}$) yields from (left) S-A and (right) Pb-Pb collisions at the SPS and calculations, ▼ - S-S, ▲ - S-Ag, ● - Pb-Pb. Lines, solid - extrapolations, dashed - $N_{\text{part}}$ scaling of N-N, dot-dashed (right) extrapolation corrected for stopping (see text for details).

Fig. 4. Comparison of average net $\Lambda$ yield per participant in inclusive p-A collisions 200 GeV/c and extrapolation of E910 data, ● - p-A, □ - p-p, solid line - extrapolation.
S+A
200 GeV/c

Pb+Pb, 160 GeV/c
Δy = 1 at y_{NN}

N_{Λ} - N_{anti-Λ}

N_{part}

ν

\frac{(N_{Λ} - N_{anti-Λ})}{N_{part}}

N_{part}