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Strangeness enhancement in p–A collisions: Consequences for the interpretation of strangeness production in A–A collisions

B.A. Cole [b], X.H. Yang [b], V. Cianciolo [f], A. Frawley [c], E.P. Hartouni [e], H. Hiejima [b], A. Lebedev [d], N. Maeda [c], S. Mioduszewski [a,*], K. Read [g], M. Rosati [d], R.A. Soltz [e], S. Sorensen [g], J.H. Thomas [e], Y. Torun [a], D. Winter [b], W.A. Zajc [b]

[a] *Brookhaven National Laboratory, Upton, NY 11973, USA*
[b] *Columbia University, New York, NY 10027, USA*
[c] *Florida State University, Tallahassee, FL 32306, USA*
[d] *Iowa State University, Ames, IA 50010, USA*
[e] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[f] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[g] *University of Tennessee, Knoxville, TN 37996, USA*

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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) formation [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 enhancement of strange mesons in central heavy ion collisions at the AGS but are unable to reproduce the enhancements observed at the SPS without the introduction of "exotic" processes. Furthermore, inclusive measurements of kaon production in proton–nucleus (p–A) collisions at the AGS have shown an enhancement 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 cascade 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 Experiment 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

* Corresponding author.
E-mail address: mio@comp.tamu.edu (S. Mioduszewski).

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of the proton in the Au nucleus and demonstrated enhanced Λ production over a wounded-nucleon (N_{part}) scaling of p–p data. In this Letter 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 collisions 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. The total Λ multiplicity was reported to be consistent with a binary collision scaling for the first three collisions. It then follows the wounded-nucleon slope until saturating at $\nu > 5$ collisions, presumably due the stopping of the projectile [19].

$$N_\Lambda(\nu) = N_\Lambda^{pp}\nu, \quad \nu \leqslant 3,$$
$$N_\Lambda(\nu) = \frac{1}{2}N_\Lambda^{pp}(\nu+3), \quad \nu > 3. \tag{1}$$

Based upon the observed scaling of Eq. (1) we construct a simple model for singly strange particle production in p–A collisions. The contribution from the projectile is given by Eq. (2) for $\nu \leqslant 3$,

$$N_\Lambda^{proj}(\nu) = \frac{1}{2}N_\Lambda^{pp}\nu, \quad \nu \leqslant 3, \tag{2}$$

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_Λ^{pp} replaced by the estimated yield in isospin averaged nucleon–nucleon (N–N) collisions, N^{NN}. The total multiplicity in an A–B collision is then given by Eq. (3),

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

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

$$N_{part}^{AB} = \sum_{\nu\geqslant 1} AP_p(\nu) + BP_t(\nu), \tag{4}$$

we can directly obtain the relationship between N^{AB} and N_{part}.

In our analysis the $P_{p/t}(\nu)$ distributions were calculated using both a Glauber model [20] and the Lund Monte Carlo [21]. The results are presented and compared in Fig. 1 in terms of $R_{part} \equiv 2N^{AB}/(N_{part}N^{NN})$, i.e., the factor by which the A–A yield per participant is enhanced relative to N–N collisions. In the Glauber calculation, the $P_{p/t}(\nu)$ distributions were evaluated at fixed values of collision impact parameter b, and the simultaneous dependence of N^{AB} and N_{part} on b was used to obtain $N^{AB}(N_{part})$. This procedure, while calculationally simple, potentially introduces errors by averaging over fluctuations that might differently affect N^{AB} and N_{part}. The slight differences between the two calculations at large b are consistent with the expectation that the Monte Carlo calculation would better account for these fluctuations. The two calculations give very similar results for the N_{part} dependence of R_{part}, though the Monte Carlo result has a slightly slower growth in R_{part} with N_{part}. To evaluate the importance of the stopping effects at AGS energies implied by the E910 data, we additionally imposed in the Glauber calculations a maximum 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. In this model we adopt the Wood–Saxon nuclear parameters and an inelastic nucleon–nucleon cross-section of 30 mb for the AGS systems and 32 mb for the SPS systems.

We now compare our calculations to experimental data starting with K^+ multiplicities 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 ν dependence as the Λ (excluding $K^+\bar{K}$ contributions). Previously estimated 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 re-

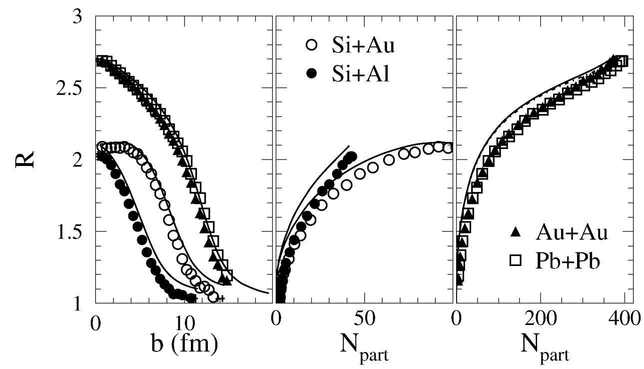

Fig. 1. Calculated enhancement factor R_{part} (see text for details) vs. b and N_{part} for various colliding systems, solid lines—Glauber geometry, points—Lund geometry.

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

Beam p (GeV/c)	System	Part.	Mult.	Error	Ref.
14.6	Si + Al/Au	K^+	0.049	0.008	[4]
14.6	Si + Al/Au	$K^+\bar{K}$	0.007	0.002	[22]
11.1	Au + Au	K^+	0.033	0.005	[4]
11.1	Au + Au	$K^+\bar{K}$	0.005	0.002	[22]
200	S + S/Ag	Λ	0.10	0.01	[30]
200	S + S/Ag	$\bar{\Lambda}$	0.013	0.005	[30]
158	Pb + Pb	Λ	0.0334	0.0005	[31]
158	Pb + Pb	$\bar{\Lambda}$	0.0111	0.0002	[31]

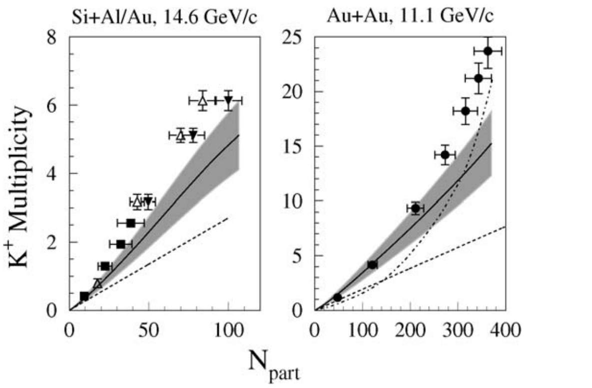

Fig. 2. Comparison between measured K^+ yields in Si–Al and Si–Au (left) and Au–Au collisions (right) at the AGS and extrapolations, ■—Si–Al, △—Si–Au, ●—Au–Au, ▼—Si–Au with adjusted N_{part}, solid line—extrapolations, dashed—N_{part} scaling of N–N, dot-dashed—RQMD calculation for Au–Au. Shaded regions indicate 1σ systematic errors due to uncertainties in N–N yields.

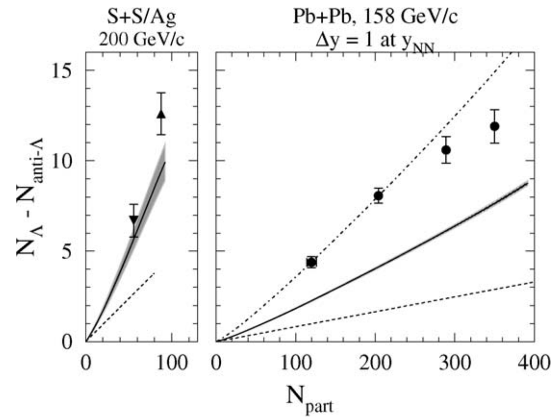

Fig. 3. Comparison of net Λ ($\Lambda - \bar{\Lambda}$) yields from (left) S–S and S–Ag and (right) Pb–Pb collisions at the SPS and calculations, ■—S–S, ▲—S–Ag, ●—Pb–Pb. Lines, solid—extrapolations, dashed—N_{part} scaling of N–N, dot-dashed (right) extrapolation corrected for stopping (see text for details).

sults 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 proportionally to N_{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. Fig. 2 shows a comparison between the results of our calculation and the experimentally measured K^+ yields. Two sets of points are shown for the Si–Au data because the experimentally quoted N_{part} values were found to be inconsistent with calculated values of N_{part} for the quoted centrality fractions [4], though nowhere by more than twice the stated error on the N_{part} values. Since the two calculations give results that differ by less than 2%, we attribute the discrepancy with the data to a systematic error in the method used by the experiment to estimate N_{part} in asymmetric collisions. The shaded region in Fig. 2 indicates 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 A GeV/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_{part} for very central collisions that may be due to rescattering processes, which would be expected to grow roughly like N_{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–antibaryon ($B\bar{B}$) production which is negligible at AGS energies but important at SPS energies, comparisons with SPS data are done using the "net" ($N_\Lambda - N_{\bar{\Lambda}}$) yields. Fig. 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 158 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 mid-rapidity 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 Λx_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 Pb–Pb [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

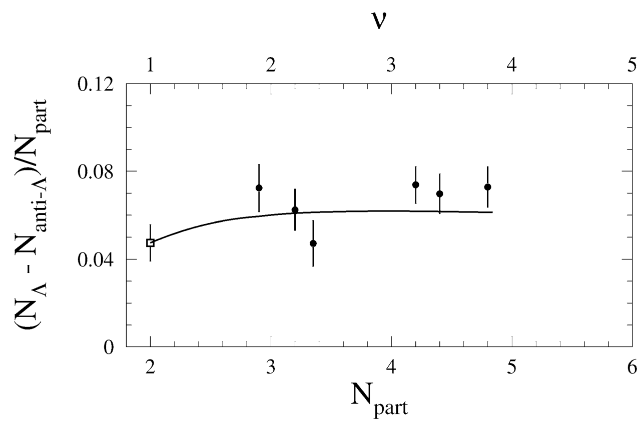

Fig. 4. Comparison of average net Λ yield per participant in inclusive p–A collisions 200 GeV/c and extrapolation of E910 data, ●—p–A, □—p–p, solid line—extrapolation.

Λ yield per participant for $\nu > 3$. Fig. 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.

We do not extrapolate to RHIC energies where contributions from hard scattering are significant. A similar analysis could be performed by extrapolating strange particle yields from d–Au with a proper accounting of contributions from soft and hard processes. A detailed study of strangeness vs. centrality in d–Au and Au–Au has not yet been published, but we note that the rapid rise in particle production observed in peripheral Au–Au collisions [29] is qualitatively consistent with the ideas presented here concerning strange particle production.

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.

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