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Comparison of strangeness production between $A+A$ and $p+p$ reactions from 2 to 160 A GeV

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The measured K^+/π^+ ratios from heavy-ion reactions are compared with the K^+/π^+ ratios from $p+p$ reactions over the energy range $2-160A$ GeV. The K/π enhancement in heavy-ion reactions is largest at the lower energies, consistent with strangeness production in secondary scattering becoming relatively more important than initial collisions near the kaon production threshold. The enhancement decreases steadily from 4 to $160A$ GeV, suggesting that the same enhancement mechanism of hadronic rescattering and decay of strings may be applicable over this full energy range. Based on existing data, the midrapidity K^+/π^+ ratio is predicted to be 0.25 ± 0.02 for the forthcoming Pb+Pb reactions at $40A$ GeV/c.

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Strangeness enhancement has been extensively discussed as a possible signature for the quark-gluon plasma (QGP) [1]. A key question is, enhanced with respect to what [2]? Experiments with Si beams at $14.6A$ GeV/c [3] measured a K^+/π^+ ratio in heavy-ion reactions that is four to five times larger than the K^+/π^+ ratio from $p+p$ reactions at the same energy. However in heavy-ion reactions secondary collisions often occur between resonant states, and the excitation energy of the resonances is then available for particle production. When this mechanism is modeled in transport calculations of heavy-ion reactions [4–6] the measured strangeness yield can be qualitatively reproduced. This effectively established a new baseline: strangeness is a potential signature of the QGP if the measurements are above what one could reasonably produce from hadronic rescattering.

Strangeness enhancement has also been characterized within the context of thermal models [7,8]. One can predict the value of particle ratios, such as K/π, produced by a statistical system at temperature T and baryon chemical potential μ. The yields of particles from $p+p$ reactions can be well described by such a statistical model [9], but fitting the strangeness yields requires an extra strangeness suppression factor, γ_s. The factor γ_s scales the thermal yield of a strange hadron, with strangeness quantum number *s*, by $\gamma_s^{|s|}$. For $p+p$ reactions, $\gamma_s=0.2$ across a broad range of energies [9], and this small value has been interpreted as a canonical suppression due to the small volume of the system. The same statistical analysis of the measured yields from heavy-ion reactions at $160A$ GeV required less strangeness suppression ($\gamma_s=0.6$), and the analysis of the data at $10A$ GeV is consistent with no suppression ($\gamma_s=0.9-1.0$), i.e., the predicted strangeness yields are in full equilibrium with non-strange hadrons [9]. Therefore in the context of statistical models, strangeness enhancement in heavy-ion reactions has been reinterpreted as a reduction in canonical strangeness suppression from $p+p$ to $A+A$ reactions.

There are at least two explanations for this change in suppression. Either it is driven by hadronic rescattering in heavy-ion collisions that helps to populate the strange hadrons, or a ''prehadronic'' QGP-like phase possibly formed in the reaction [10] leads to rapid strangeness production. It is important to explore the beam energy evolution of these two scenarios. For example if the hadronic rescattering mechanism dominates strangeness enhancement at $10A$ GeV, how rapidly does this reduce as the beam energy is increased? In particular, does the rescattering mechanism provide sufficient enhancement to reproduce the measured strangeness data at $160A$ GeV? Or if a new mechanism is required to explain the high-energy data, then how does this mechanism turn off as the beam energy is reduced?

These questions are being addressed within transport models of heavy-ion reactions. In order to reproduce the strangeness data at $160A$ GeV, the transport models have had to move beyond the degrees of freedom of hadrons and strings [11], to either interacting strings [4], or new mechanisms to break diquarks at one end of a string [12]. We take a complementary approach and return to the original definition of strangeness enhancement based on experimental data, namely a comparison between the K^+/π^+ ratio in heavy-ion reactions and proton-proton reactions. By examining the evolution of the K/π enhancement from 2 to $160A$ GeV [13–15] we can address how rapidly the effects of hadronic rescattering change with beam energy. Interpolating between 10 and $160A$ GeV also provides a data-based prediction for the K/π ratio at the newly available beam energy of the SPS, $40A$ GeV/c.

There have been many critiques on the K^+/π^+ ratio as a QGP signature. If the K^+/π^+ ratio is set by the chemical properties of the system, then it could reach similar values for both long-lived hadronic and QGP systems. Theoretical work [10] has therefore focused on whether a hadronic system is large enough and lives long enough to reach its full level of strangeness production. Multistrange particles potentially offer more sensitivity to strangeness enhancement [16], however if chemical equilibrium is reached within the strangeness sector, then the yield of kaons contains the same information content as the yield of any strange hadron. Finally the K^+/π^+ ratio can be criticized because it is the ratio of two signatures: strangeness enhancement and a possible increase in pion multiplicity due to an increase in the system's entropy [17,18]. Despite these caveats, the K^+/π^+ ratio still provides a useful comparison between heavy-ion and $p+p$ data by removing to first order the increase in both kaon and pion yields due to system size.

Data for inclusive K^+ yields in $p+p$ reactions over a

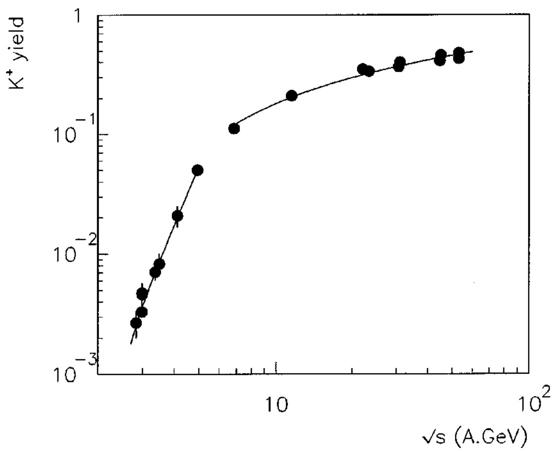

FIG. 1. A compilation of K^+ yields from $p+p$ reactions as a function of $s^{1/2}$ [19–22]. The lines are a piecewise parametrized fit to the data as described in the text.

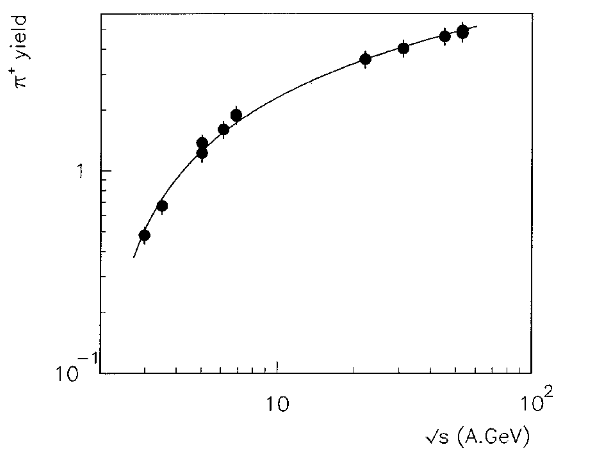

FIG. 2. A compilation of π^+ yields from $p+p$ reactions as a function of $s^{1/2}$ [24,22]. The line is a parametrized fit that is described in the text.

broad energy have been published in the literature [19–22] and are shown in Fig. 1. No single parametrization was found that could accurately describe these yields over the full energy range; instead a piecewise parametrization was used. The form of the low-energy part was proposed in Ref. [23] and the form of the high-energy portion has been used by, e.g., Rossi *et al.* [24]

$$Y_{K+}=c_l\times(s/s_0-1)^{a_l}\times(s/s_0)^{b_l} \quad \sqrt{s_0}<\sqrt{s}<6.0\text{ GeV}, \tag{1}$$

$$Y_{K+}=a_h+b_h\times\ln(s)+c_h/\sqrt{s} \quad 6.0<\sqrt{s}<20\text{ GeV}, \tag{2}$$

where $s_0=(m_p+m_K+m_\Lambda)^2$. The data for $\sqrt{s}<6.0$ GeV shown in Fig. 1 were fit to obtain the parameters $a_l=0.224$, $b_l=2.196$, and $c_l=0.00221$. The data from $\sqrt{s}>6.0$ GeV shown in Fig. 1 were fit to obtain the parameters $a_h=-0.242$, $b_h=0.089$, and $c_h=0.128$. These two parametrizations are within 10% of each other at $\sqrt{s}=6.0$ GeV. It is noted that even lower-energy $p+p$ data from COSY exists for kaon production, but only 6 MeV above the production threshold [25]. This data does not effectively constrain the parametrization close to $\sqrt{s}\sim 3$ GeV because the measured yield of kaons from COSY is three orders of magnitude below the yields of the lowest energy point shown in Fig. 1.

The π^+ yields from $p+p$ reactions shown in Fig. 2 have been fit by Rossi *et al.* [24] with

$$Y_{\pi+}=a+b\times\ln(s)+c/\sqrt{s} \quad 3<\sqrt{s}<20\text{ GeV}. \tag{3}$$

We use the parameters obtained by Rossi *et al.* [24]: $a=-1.55$, $b=0.82$, and $c=0.79$. It is estimated that the systematic uncertainty of both the parametrized kaon and pion yields is 10%, but becomes larger towards the ends of the fitted ranges.

The K^+ yield from $p+p$ reactions increases faster with beam energy than the π^+ yield, such that the K^+/π^+ ratio from $p+p$ reactions (hashed region in Fig. 3) increases steadily throughout the energy range. At higher energies the ratio tends towards a value of $K^+/\pi^+=0.08$.

In heavy-ion reactions, data on the K^+/π^+ ratio at midrapidity are available from central Au+Au reactions at 2, 4, 6, 8, and 10.7A GeV [14], and from central Pb+Pb reactions at 158A GeV [15]. These data are shown in Fig. 3. The K^+/π^+ ratio increases steadily from $0.0271\pm0.0015\pm0.0014$ at 2A GeV to $0.202\pm0.005\pm0.010$ at 10.7A GeV [14]. The measured ratio $K^+/\pi^+=0.19\pm0.01$ from Pb+Pb collisions at 157A GeV/c [15] is comparable to the ratio from Au+Au reactions at 10.7A GeV. This suggests that either the ratio saturates or that a maximum exists in the K^+/π^+ from heavy-ion reactions at energies between the AGS and SPS. At all beam energies the K^+/π^+ ratio from heavy-ion reactions is larger than in $p+p$ reactions. It is noted that the data from $A+A$ are measured at midrapidity whereas the $p+p$ results are integrated over the full phase

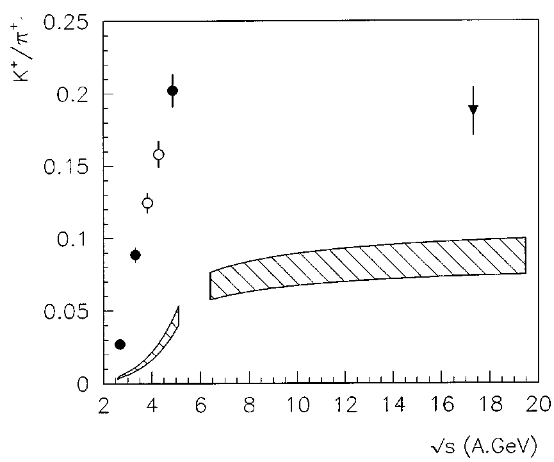

FIG. 3. The ratio of dN/dy for K^+/π^+ at midrapidity in central Au+Au and Pb+Pb reactions as a function of the initial available energy. The filled circles are from E866, the open circles are from E917, and the triangle is from NA49. The hashed region is the K^+/π^+ ratio from the parametrized K and π yields from $p+p$ reactions (see text for details). The hashed region covers $\pm1\sigma$ around the $p+p$ K^+/π^+ ratio.

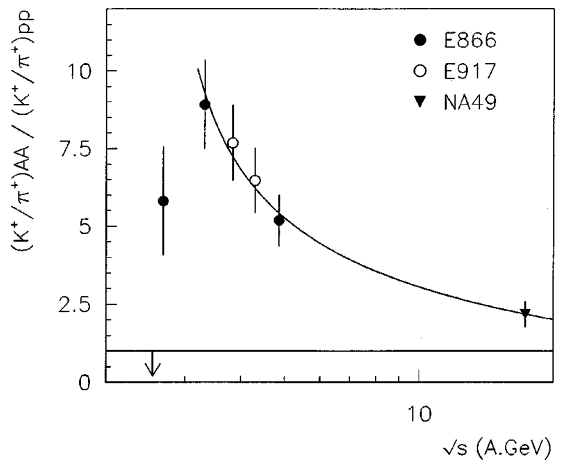

FIG. 4. The double ratio K^+/π^+ at midrapidity from central Au+Au reactions divided by K^+/π^+ of total yields from $p+p$ reactions as a function of the initial available energy. The errors include both statistics and a 10% systematic uncertainty in the parametrized kaon and pion yields from $p+p$ reactions. These systematic errors increase to 20% at the lowest beam energy ($2A$ GeV). The arrow indicates the threshold energy for producing K^+ in a $p+p$ reaction, the horizontal line is an enhancement of one, and the hyperbolic line is a fit to the data [Eq. (4)].

space. As an estimate of the level of the difficulties this might cause, in Au+Au reactions at $10.7A$ GeV the midrapidity K^+/π^+ ratio is $0.202\pm0.005\pm0.010$ [14] and is within a few percent of the value obtained by integrating over a broader rapidity range of $0.6<y<2.0$ where $K^+/\pi^+=0.197\pm0.003\pm0.010$ [13].

The measured heavy-ion K^+/π^+ ratio divided by the $p+p$ K^+/π^+ ratio calculated using Eqs. (1)–(3) is shown in Fig. 4. This double ratio is referred to in this work as the K^+/π^+ enhancement. The enhancement is smallest at the highest beam energy at the SPS. At low beam energies the K^+/π^+ enhancement in Au reactions is likely to be caused by secondary hadron collisions. The increase in enhancement at lower energies suggests that as the beam energy is reduced towards the threshold for kaon production, secondary collisions increase in relative importance compared to initial collisions. At beam energies below the kaon threshold the double ratio is, by definition, infinite.

Any increase in pion absorption in heavy-ion reactions as the beam energy decreases would also contribute to the enhancement of the K^+/π^+ ratio. At $10.7A$ GeV four-fifths of the K^+/π^+ enhancement is due to an increase in kaon yield, since K^+ production per collision participant in central Au+Au reactions was measured [13] to be four times larger than for nucleon-nucleon reactions. It is not clear why the enhancement apparently decreases from 4 to $2A$ GeV, though it is in this region that the parametrized pion yields from $p+p$ reactions are not well constrained.

The increase in importance of secondary collisions as the beam energy approaches a production threshold approaches is counterintuitive. Most of these secondary collisions occur at values of $\sqrt{s}$ that are lower than the $\sqrt{s}$ available in initial nucleon-nucleon collisions and hence the production of kaons in a single secondary collision is lower than the production of kaons in a single primary collision. However in heavy-ion reactions the large number of secondary reactions compensates for this and, in total, produce more kaons than the initial nucleon-nucleon collisions.

The decrease in the enhancement from 4 to $160A$ GeV provides a natural way to view the existence of a maximum in the heavy-ion K^+/π^+ ratio. The K^+/π^+ ratio from $p+p$ reactions increases in this energy range. If this is coupled with a heavy-ion reaction mechanism that causes the K^+/π^+ enhancement to fall, then the K^+/π^+ ratio in heavy-ion reactions must have a maximum as a function of beam energy.

There is a large gap in the data between $10A$ GeV and the SPS energy of $160A$ GeV. However the enhancement at the SPS is consistent with a smooth continuation of the decrease in enhancement from the AGS energies. To demonstrate this, the enhancement from $4-160A$ GeV can be fit with

$$\frac{(K^+/p^+)_{AA}}{(K^+/p^+)_{pp}}=\frac{a}{(\sqrt{s}-\sqrt{s_0})^b}, \tag{4}$$

with two free parameters $a=8.2$ and $b=0.49$ and three degrees of freedom ($\sqrt{s_0}$ is the threshold for K^+ production in $p+p$ reactions). This fit is shown as a solid line in Fig. 4. Because both the SPS and AGS enhancement data can be empirically fit with the same decreasing function, it is possible that a qualitatively similar reaction mechanism for strangeness enhancement is present at both AGS and SPS energies.

This argument is far from establishing that the same enhancement mechanism *is* at work over this full energy range. There are many examples of strong-interaction physics where particle production smoothly increases with beam energy, but the reaction mechanism evolves between two scenarios. For example, the charged particle multiplicity steadily increases as the beam energy is increased from a region where the data can be modeled by the excitation and breaking of strings to higher energies where a description of the data requires the fragmentation of mini-jets [26]. However in the case of heavy-ion reactions, there is the possibility of forming a QGP which might be observable as distinct changes in the characteristics of particle production with increasing beam energy.

Whether the smooth decrease of the K/π enhancement continues between AGS and SPS energies will be checked by forthcoming measurements of Pb+Pb collisions at $40A$ GeV/c ($\sqrt{s}=8.8A$ GeV). From Eq. (4), the interpolated K^+/π^+ enhancement at $40A$ GeV/c is 3.3 ± 0.2. Multiplying this enhancement by the parametrized K^+/π^+ from $p+p$ reactions [Eqs. (1)–(3)], we can make the prediction of a strikingly large $K^+/\pi^+=0.25\pm0.02$ for Pb+Pb reactions at $40A$ GeV/c.

If the measured K/π result is below the predicted value, then this would imply that the K/π enhancement decreases faster at intermediate energies than the current hyperbolic function. However if the measured K/π value is significantly lower than our prediction, then this could result in a mini-

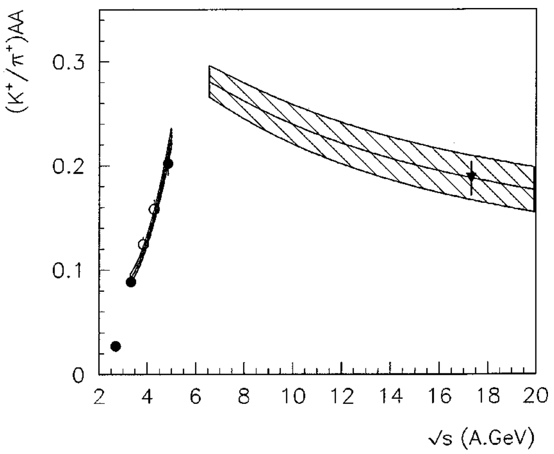

FIG. 5. The predicted ratio K^+/π^+ at midrapidity for central $A+A$ reactions as a function of the initial available energy. The two parametrizations that were used for the low- and high-energy portions of the kaon $p+p$ data lead to two different parts of this predicted excitation function. The hashed region covers $\pm 1\sigma$ around the predicted K^+/π^+ ratio.

mum in the strangeness enhancement. A minimum would logically require the existence of an additional mechanism for strangeness production at the highest SPS energy ($160A$ GeV). A similar speculation can be put forward for the forthcoming Relativistic Heavy Ion Collider (RHIC) results, which will measure an excitation function of Au+Au collisions between approximately $50<\sqrt{s}<200A$ GeV. An observation of a minimum in the combined AGS-SPS-RHIC excitation function of strangeness enhancement would lead to the model-independent conclusion of an additional source of strangeness production turning on at some beam energy, potentially driven by the quark-gluon plasma.

The full range of predicted K^+/π^+ ratio as a function of beam energy is shown in Fig. 5. The two parametrizations that were used for the low- and high-energy portions of the kaon $p+p$ data lead to two different parts of this predicted excitation function. Because the parametrizations have a discontinuity in slope at $\sqrt{s}=6.0A$ GeV, this region is omitted from Fig. 5. The new SPS energy of $40A$ GeV ($\sqrt{s}=8.8A$ GeV) is above this gap. Theoretical predictions for the excitation function of K/π have also been made. By fitting a thermal model to the measured data at the SIS, AGS, and SPS, Cleymans and Redlich [27] obtain chemical parameters as a function of beam energy. Interpolating produces a predicted K/π ratio that is approximately flat between the AGS and SPS and does not rise above $K^+/\pi^+=0.21$. In a different approach, the dynamical hadron-string transport model HSD has been used to calculate collisions between heavy nuclei as a function of beam energy [28]. The predicted K^+/π^+ ratio from HSD monotonically increases between $1A$ GeV and $160A$ GeV. The model reproduces both the data at $1A$ GeV and $160A$ GeV yet underpredicts the measured K/π ratios at $10A$ GeV by a factor of two.

In summary, the existing heavy-ion K^+/π^+ data have been compared with the data from $p+p$ reactions over the energy range $2-160A$ GeV. The K/π enhancement is largest at the lower energies, consistent with strangeness production in secondary scattering becoming relatively more important than initial collisions near the kaon production threshold. The enhancement decreases steadily from the AGS to the SPS. The AGS data sets the rate of decrease for the K/π enhancement due to the hadronic rescattering and the formation of strings. Since the AGS and SPS data can both be fitted with a smooth decrease in the strangeness enhancement, the data are consistent with the same enhancement mechanism at work over this full energy range. Key to confirming or excluding this possibility is the SPS measurement at $40A$ GeV/c and the forthcoming RHIC experiments at higher energies.

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