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Excitation function of K^+ and π^+ production in Au + Au reactions at 2–10 AGeV

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Abstract

Positive pion and kaon production from Au + Au reactions have been measured as a function of beam energy over the range 2.0–10.7 AGeV. Both the kaon and the pion production cross-sections at mid-rapidity are observed to increase steadily with beam kinetic energy. The ratio of K^+ to π^+ mid-rapidity yields increases from $0.0271 \pm 0.0015 \pm 0.0014$ at 2.0 AGeV to $0.202 \pm 0.005 \pm 0.010$ at 10.7 AGeV and is larger than the K^+/π^+ ratio from p + p reactions over the same beam energy region. There is no indication of a strong onset of any new production mechanism in heavy-ion reactions in this energy range beyond rescattering of hadrons.

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This Letter presents the results of the first measurements of particle production in Au + Au reactions in the energy range from 2 to 10 AGeV. Recent results [1] for proton stopping in high energy nuclear collisions suggest that an extended region of dense nuclear matter is formed at beam energies near 10 AGeV. Increasing the beam energy from 2 A to 10 AGeV is expected to increase the maximum density achieved from approximately twice normal density at 2 AGeV [2–5] to an estimated eight times normal nuclear density at 10 AGeV [6].

The properties of such dense matter can be explored by measuring how the production of pions and kaons varies with beam energy. For example, secondary collisions may occur between resonant states, and the excitation energy of the resonances is then available for particle production. At a beam energy of 10.7 AGeV the kaon yield per participant in central Au + Au reactions [7] has been measured to be three to four times that for p + p reactions at the same energy, consistent with the majority of kaon production coming from secondary rather than primary hadronic collisions. At lower beam energies, a larger fraction of these secondary collisions will be below the threshold for producing a pair of strange hadrons. From models of nucleus-nucleus reactions at 1–2 AGeV [6,8], kaon production is dominated by the rare secondary collisions that are above threshold compared to production from primary collisions boosted by Fermi motion. An excitation function of

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heavy-ion reactions from 1 to 10 AGeV can be used to study how the role of secondary collisions in strangeness production evolves with increasing beam energy.

Secondary collisions can also change the production of pions. At beam energies near 1 AGeV, the measured yield of pions per participant in central Au + Au reactions is below the yield of pions in nucleon-nucleon collisions at the same energy [9,10]. Transport calculations of heavy-ion reactions at these beam energies [5] attempt to reproduce this reduction in pion yield through the production of Δ's and their subsequent rescattering $\Delta + N \rightarrow N + N$. Recent transport calculations overestimate the yield of pions and do not reproduce the measured system size dependence at beam energies near 1 AGeV [11]. At higher energies the effects of the rescattering of excited resonances may be reduced, since it has been observed that the mid-rapidity π yields in p + A reactions at 14.6 AGeV [12] are independent of A. In addition, the measured pion yield per participant from central Si + A reactions at 14.6 AGeV/c [13] is similar to that measured in peripheral reactions, in contrast to the reduction observed in Au + Au reactions at 1 AGeV [9,10]. The transverse spectra of pions may also provide information on the reaction dynamics. Spectra from Au + Au collisions at 10.7 AGeV have been observed to rise faster than an exponential function at low p_t [1], with π^- having a larger low-p_T rise than π^+. There have been many suggestions for the origin of this rise: pion emission from different stages of the reaction [14], the decay of resonances [15], and possible enhancement due to Bose-Einstein correlations [16]. To make progress on these topics, it is useful to measure the evolution of the mid-rapidity pion spectra and yields as a function of beam energy from 1 to 10 AGeV.

It is also possible that a small region of baryon-rich quark-gluon plasma might be formed in heavy-ion reactions near 10 AGeV. Whether this is observable as changes in the characteristics of pion and kaon production as the beam energy increases is an open question. For each beam energy there are likely to be fluctuations from event to event in the energy density. Even if some critical density is reached these fluctuations will act to smooth out possible changes in particle production. Despite these caveats, it is important to make the experimental measurements, and use the evolution of particle production with beam energy to confront models that either assume only hadronic scattering, and those that include the formation of the plasma.

The data in this Letter come from two separate AGS collaborations, E866 and E917; each of which used much the same apparatus. The E866 collaboration measured Au + Au collisions at 1.96, 4.00, and 10.7 AGeV kinetic energy. The E917 collaboration measured Au + Au reactions at 5.93 and 7.94 AGeV kinetic energy. The beam energies quoted and used in this Letter correspond to the energy half-way through the target. For shorthand these will be referred to as 2, 4, 6, 8 and 10.7 AGeV in the text. The pion and kaon spectra at 10.7 AGeV have already been published by E866 [1,7].

The new data presented in this Letter (Au + Au at 2, 4, 6, and 8 AGeV) were measured with the Henry Higgins spectrometer used by experiments E802, E859, E866 and E917. For more details on the equipment and data analysis the reader is referred to Refs. [1,7,17]; a brief description is provided here. A Au target of 1960 mg/cm^2 was used for each data set. This thickness corresponds to approximately a 3% interaction probability for Au. The Au beam loses approximately 0.06 AGeV as it passes through the target. The rotatable spectrometer has an acceptance of 25 msr with an opening angle of $\Delta\theta \sim 14°$, and consists of drift and multi-wire chambers on either side of a dipole magnet. Similar track reconstruction, efficiency corrections, acceptance and decay algorithms were used for the data at each beam energy. The average tracking inefficiency ranged from 40% at 10.7 AGeV to 10% at 2 AGeV. Particle identification was performed using a wall of time-of-flight detectors with a timing resolution (σ) of 130 ps. The detectors for global event characterization were a multiplicity array surrounding the target, and a calorimeter placed at zero degrees with a 1.5° opening angle. For the 2, 4, 6, and 8 AGeV Au + Au data, central collisions were selected with the multiplicity array. The data at 10.7 AGeV were measured prior to installation of the multiplicity detector, so central collisions at this beam energy were selected using the zero-degree calorimeter. A comparison of event selection using these two devices has been published [18]. Based on similar analyses fully described in Refs. [1,7] the total systematic uncertainty in the normalization of the particle yields is 15% and is dominated by the uncertainty in the acceptance, tracking efficiency, and extrapolation to low transverse mass required to obtain particle yields. The systematic uncertainty on the mean transverse mass extracted from the spectra is estimated to be 10%. The relative beam-energy-to-beam-energy systematic uncertainty in both the yields and mean transverse mass is 5% because, while the systematic uncertainty from the geometrical acceptance is common to all the measurements, the dependence of the tracking efficiency on the occupancy of the spectrometer [7] and the uncertainty involved in extrapolating to obtain particle yields and mean transverse mass are not.

The invariant yields of K^+ are shown in the left panel of Fig. 1 as a function of transverse mass, $m_t = \sqrt{p_t^2 + m_0^2}$, for Au + Au central collisions at 2, 4, 6, 8, and 10.7 AGeV [7] beam kinetic energy. The centrality selection at each beam energy is the most central 5% of the total interaction cross-section ($\sigma_{\mathrm{int}} = 6.8$b). For each beam energy there are two m_t spectra shown in Fig. 1. In each of the 2, 4, 6, and 8 AGeV data sets, one of these spectra corresponds to a rapidity slice just backwards of mid-rapidity, $-0.25 < \frac{y-y_{nn}}{y_{nn}} < 0$ (shown as circles in Fig. 1) and the other is symmetrically forward of mid-rapidity, $0 < \frac{y-y_{nn}}{y_{nn}} < 0.25$ (shown as triangles), where y_{nn} is mid-rapidity in the laboratory frame. For the 10.7 AGeV reactions the rapidity slice is narrower, $|\frac{y-y_{nn}}{y_{nn}}| < 0.125$ to match the bin-width of the published pion spectra [1]. A single exponential function in m_t was fit simultaneously to the two kaon spectra at each beam energy

$$\frac{1}{2\pi m_t}\frac{d^2N}{dm_t dy} = \frac{dN/dy}{2\pi\left(Tm_0 + T^2\right)} e^{-(m_t - m_0)/T}. \quad (1)$$

The fits reproduce the spectra well with two free parameters, the inverse slope parameter T and the rapidity density, dN/dy, in that rapidity slice. These parameters are tabulated in Table 1 for each beam energy, as well as the mean value of the transverse mass, $\langle m_t \rangle$, calculated from the inverse slope parameter. The mean transverse mass values at 6 and 8 AGeV are slightly but not significantly higher than at 10.7 AGeV. The m_t range at 6 and 8 AGeV is smaller than at 10.7 AGeV which included data from the forward spectrometer of E866. The variation in $\langle m_t \rangle$ with fitting range is included in the quoted 5% point-to-point systematic uncertainty. The kaon spec-

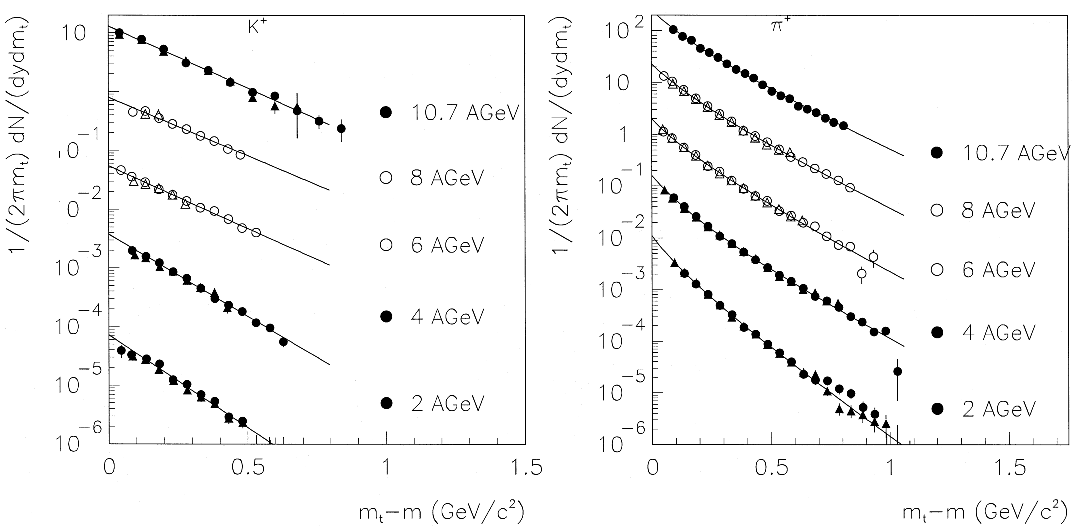

Fig. 1. The invariant yield of K^+ (left panel) and π^+ (right panel) as a function of m_t at mid-rapidity from Au + Au collisions for the different beam energies. For each energy the spectrum just back of mid-rapidity is shown with circles, the spectrum just forward of mid-rapidity is shown with triangles. The data from E866 are shown as filled symbols and the data from E917 are shown as open symbols. The data at 10.7 AGeV are shown at the correct scale, the data at each lower energy are divided by successive powers of ten for clarity. The errors are statistical only.

Table 1
Excitation function of K^+ spectral characteristics at mid-rapidity from central Au + Au reactions. The mid-rapidity range for 2, 4, 6, 8 AGeV is $|\frac{y-y_{nn}}{y_{nn}}| < 0.25$, for 10.7 AGeV the width is $|\frac{y-y_{nn}}{y_{nn}}| < 0.125$, where y_{nn} is mid-rapidity in the laboratory frame. The errors are statistical only

Collaboration	E_{kin} (AGeV)	y_{nn}	dN/dy	T (GeV/c^2)	$\langle m_t \rangle - m_0$ (GeV/c^2)
E866	1.96	0.90	0.381 ± 0.015	0.138 ± 0.004	0.168 ± 0.005
E866	4.00	1.17	2.34 ± 0.05	0.158 ± 0.003	0.197 ± 0.005
E917	5.93	1.34	4.84 ± 0.09	0.208 ± 0.006	0.270 ± 0.009
E917	7.94	1.47	7.85 ± 0.21	0.219 ± 0.011	0.287 ± 0.017
E866	10.74	1.60	11.55 ± 0.24	0.204 ± 0.006	0.264 ± 0.008

tra were also fit by the scaled exponential given in Eq. (2) below. For all energies except 8.0 AGeV, these fits produced dN/dy and $\langle m_t \rangle$ values within 5% of the values extracted from the exponential fits. The yields from the scaled exponential fits at 8.0 AGeV were 10% smaller than the exponential fits. This is consistent with the estimated systematic uncertainty.

The right panel of Fig. 1 shows invariant spectra for π^+ from Au + Au reactions at each of the five beam energies. The 10.7 AGeV data have already been published [1]. The spectra cover the same rapidity ranges as for the kaons. These spectra rise above an exponential at low m_t, and were therefore fit with a scaled exponential,

$$\frac{1}{2\pi m_t}\frac{d^2N}{dm_t dy} = \frac{dN/dy}{2\pi T_s^{2-\lambda}\Gamma(2-\lambda, m_0/T_s)} m_t^{-\lambda} e^{-m_t/T_s}. \quad (2)$$

$\Gamma(2-\lambda, m_0/T_s)$, the complementary incomplete gamma function, is introduced in the normalization so that dN/dy is a fitted parameter. The yields and the other free parameters, λ and T_s, are tabulated in Table 2 along with $\langle m_t \rangle$ calculated from the fit parameters in Eq. (2)

$$\langle m_t \rangle = \frac{T_s \Gamma(3-\lambda, m_0/T_s)}{\Gamma(2-\lambda, m_0/T_s)}. \quad (3)$$

The uncertainty in $\langle m_t \rangle$ for pions includes the covariance between the fitted parameters λ and T_s.

The pion invariant yields could also be fit with a sum of two exponentials in m_t. These fits produced dN/dy and $\langle m_t \rangle$ values which are within 5% of the values obtained from the scaled exponential fits. Scaled exponential fits to the pion transverse spectra are used throughout this paper.

The mid-rapidity yields of π^+ and K^+ are shown in the upper panels of Fig. 2 plotted as a function of the c.m. energy of initial nucleon-nucleon collisions, $\sqrt{s}$. Both the π and the K yields increase steadily with beam energy. In the lower panels of Fig. 2, the values of $\langle m_t \rangle$ minus the rest mass (m_0) for π^+ and K^+ are plotted versus $\sqrt{s}$. Compared to the increase

Table 2
Excitation function of π^+ spectral characteristics at mid-rapidity from central Au + Au reactions. The mid-rapidity range for 2, 4, 6, and 8 AGeV beam energy is $|\frac{y-y_{nn}}{y_{nn}}| < 0.25$, for 10.7 AGeV is $|\frac{y-y_{nn}}{y_{nn}}| < 0.125$, where y_{nn} is the mid-rapidity in the laboratory frame. The errors are statistical only

Collaboration	E_{kin} (AGeV)	dN/dy	T_s (GeV/c^2)	λ	$\langle m_t \rangle - m_0$ (GeV/c^2)
E866	1.96	14.1 ± 0.5	0.149 ± 0.008	1.06 ± 0.18	0.145 ± 0.004
E866	4.00	26.4 ± 0.4	0.205 ± 0.009	1.14 ± 0.10	0.192 ± 0.002
E917	5.93	38.9 ± 0.5	0.205 ± 0.010	0.91 ± 0.11	0.214 ± 0.003
E917	7.94	49.7 ± 0.7	0.215 ± 0.012	0.84 ± 0.11	0.233 ± 0.003
E866	10.74	57.1 ± 0.8	0.230 ± 0.008	0.87 ± 0.09	0.246 ± 0.003

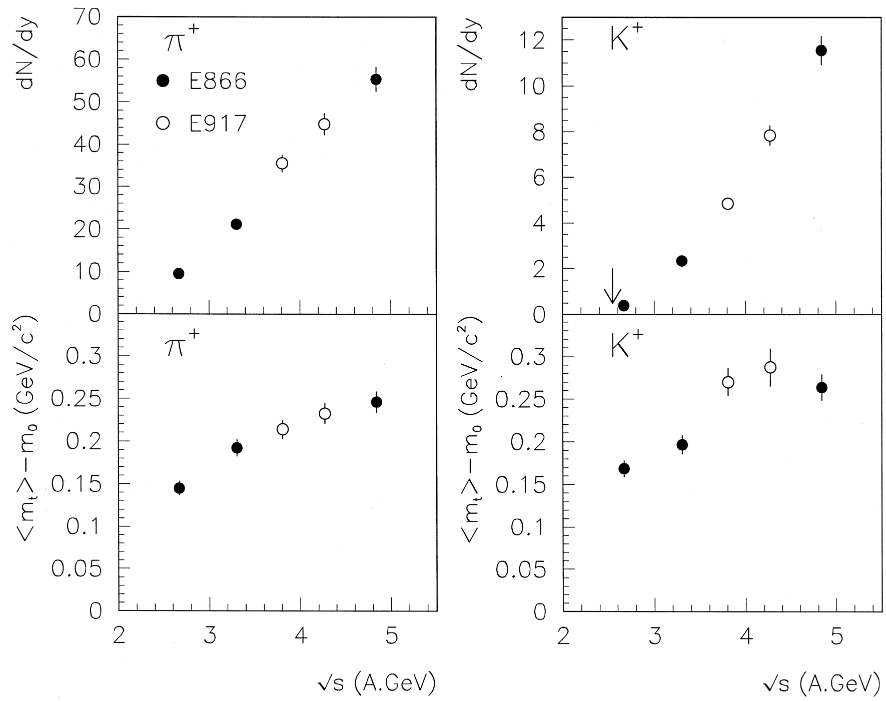

Fig. 2. The yield of π^+ and K^+ at mid-rapidity (top-panels) for central Au + Au reactions as a function of the initial available beam energy. The data from E866 are shown as filled circles and the data from E917 are shown as open circles. The lower panels show the mean m_t minus the rest mass for π^+ and K^+ at the same rapidity. The errors include both statistical and a 5% (dN/dy), 5% (mean m_t) point-to-point systematic uncertainty. The arrow indicates the threshold energy for producing K^+ in a p + p reaction.

of particle production, $\langle m_t \rangle$ is observed to increase more slowly with beam energy. Within the statistical and systematic errors the changes in $\langle m_t \rangle - m_0$ for pions and kaons with beam energy are similar. The λ parameter from the scaled exponential fits to pions (Eq. (2) and Table 2) slightly decreases as the beam energy increases, i.e. the m_t spectrum is tending towards a pure exponential with increasing beam energy.

The increase in K yield with beam energy shown in Fig. 2 is more rapid than the increase of π yield. This is emphasized in Fig. 3, where the ratio of dN/dy for K^+ to π^+ is plotted versus $\sqrt{s}$. There is a 5% point-to-point systematic uncertainty in this quantity. The measured K^+/π^+ ratio increases steadily from $0.0271 \pm 0.0015 \pm 0.0014$ at 2 AGeV to $0.202 \pm 0.005 \pm 0.010$ at 10.7 AGeV. The smooth increase of the measured K^+/π^+ ratio suggests that there is no large onset of a production mechanism different than hadronic scattering as the beam energy is increased. It is noted that ratios can be difficult to interpret because changes could occur in both the numerator and denominator. The measured ratio $K^+/\pi^+ = 0.19 \pm 0.01$ from Pb + Pb collisions at 157 AGeV/c [19] is comparable to the ratio $K^+/\pi^+ = 0.202 \pm 0.025 \pm 0.010$ from Au + Au reactions at 10.7 AGeV of the present work. 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. Decreasing the beam energy further to 1 AGeV, the mid-rapidity K^+/π^+ ratio from central Au + Au reactions measured by the KaoS collaboration [8] is $K^+/\pi^+ = (3 \pm 1) \times 10^{-3}$. This is one order of magnitude below the K^+/π^+ ratio at 2 AGeV, which is approximately consistent with the rate of decrease observed from the data in this Letter.

Data for inclusive K^+ yields in p + p reactions in the same energy range as the Au data in this Letter (3 to 12 GeV/c) are available [20–23]. A suitable

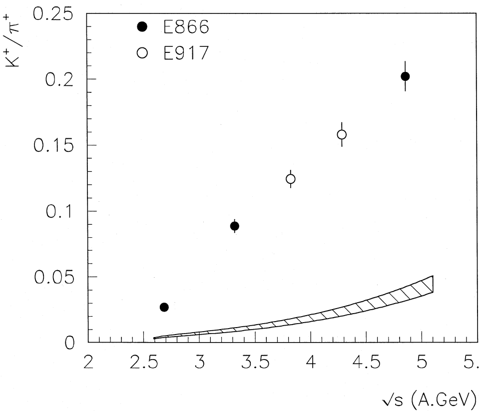

Fig. 3. The ratio of dN/dy for K^+/π^+ at mid-rapidity in central Au + Au reactions as a function of the initial available energy. The data from E866 are shown as filled circles and the data from E917 are shown as open circles. The errors include a 5% systematic uncertainty. The hashed region is the K^+/π^+ ratio from the parameterized K and π yields from p + p reactions (see text for details). The hashed region covers $\pm 1\sigma$ around the p + p K^+/π^+ ratio.

parameterization of these yields was suggested in Ref. [24]

$$Y_{K^+} = c \times (s/s_0 - 1)^a \times (s/s_0)^b,$$
$$\sqrt{s_0} < \sqrt{s} < 20\,\text{GeV}, \tag{4}$$

where $s_0 = (m_p + m_K + m_\Lambda)^2$. The p + p data were fit to obtain the parameters $a = 0.223$, $b = 2.196$, and $c = 0.00221$. From the errors of the data points it is estimated that there is a 10% systematic uncertainty in the parameterized kaon yield from $3 < \sqrt{s} < 5$ GeV. The π^+ yields from p + p reactions have been fit by Rossi et al. [25] with

$$Y_{\pi^+} = a + b \times ln(s) + c/\sqrt{s}, \quad 3 < \sqrt{s} < 20\,\text{GeV}. \tag{5}$$

We use the parameters obtained by Rossi et al. [25]; $a = -1.55$, $b = 0.82$, and $c = 0.79$. From the errors on the data points it is estimated that the systematic uncertainty of the parameterized pion yield is 10%.

In this energy range, the K^+ yield from p + p reactions increases faster with beam energy than the π^+ yield, as is shown in Fig. 3 where the ratio of the p + p K^+ and π^+ yields is shown as a hashed region. The measured K^+/π^+ ratio in Au + Au reactions is significantly larger than the ratio from p + p reactions. The data from Au + Au are measured at mid-rapidity whereas the p + p results are integrated over the full phase space. As an estimate of the level of the difficulties this might cause, in Au + Au reactions at 10.7 AGeV the mid-rapidity K^+/π^+ ratio is $0.202 \pm 0.005 \pm 0.010$ and is within a few percent of the value obtained by integrating over a broader rapidity range of $0.6 < y < 2.0$ where $K^+/\pi^+ = 0.197 \pm 0.003 \pm 0.010$ [7]. Also the production data from p + p reactions are used in this comparison instead of estimating n + p, n + n and then averaging over the initial isospin. The isospin-averaged K^+/π^+ ratio for N + N reactions is within 20% of the K^+/π^+ ratio for p + p reactions at 10.7 AGeV [26].

To summarize, particle production in central Au + Au reactions has been measured at 2, 4, 6, 8 and 10.7 AGeV beam kinetic energy. This data set bridges the gap between experiments at the AGS and BEVALAC/SIS accelerators, and as such provides a strong test for hadronic models that have been developed and applied only at one or the other end of this excitation function. The mid-rapidity yields of both pions and kaons from central Au + Au reactions steadily increase with beam energy. Over this energy range the mean m_t of the transverse spectra of pions and kaons increases by less than 75%. A larger fraction of the extra available energy therefore goes into particle production rather than into increasing the transverse energy per particle. The shape of the pion transverse spectrum has a low m_t rise above an exponential function. This rise is slightly smaller at the higher energies. The K^+/π^+ ratio increases steadily with beam energy from nearly 3% at 2 AGeV to 20% at 10.7 AGeV. The K^+/π^+ ratio is larger in Au + Au reactions than in p + p reactions. The smooth increase of the K^+/π^+ ratio in Au + Au suggests that there is no evidence for a large onset of a production mechanism other than hadronic scattering as the beam energy is increased.

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