K/π Ratios in Relativistic Nuclear Collisions: A Signature for the Quark-Gluon Plasma?

R. Mattiello, H. Sorge, H. Stöcker, and W. Greiner
Institut für Theoretische Physik, Johann Wolfgang Goethe Universität, Frankfurt am Main, Germany
(Received 8 June 1989)

Collisions of Si(14.5A GeV)+Au are investigated in the relativistic-quantum-molecular-dynamics approach. The calculated pseudorapidity distributions for central collisions compare well with recent experimental data, indicating a large degree of nuclear stopping and thermalization. Nevertheless, nonequilibrium effects play an important role in such complex multihadron reactions: They lead to a strong enhancement of the total kaon production cross sections, in good agreement with the experimental data, without requiring the formation of a deconfined quark-gluon plasma.

PACS numbers: 25.70.Np, 12.38.Mh

The unique opportunity to create extended regions of superdense deconfined matter in the laboratory is one of the most fascinating motivations for relativistic heavy-ion collisions. Numerous experiments have been started recently to investigate whether such high-energy-density matter can actually be formed. It was predicted that abundant strangeness production should accompany the formation of the so-called quark-gluon plasma.[1,2] Therefore, the recent observation of strong nuclear stopping[3] and of strongly enhanced $K(\Lambda)/\pi$ ratios (as compared to pp data and FRITIOF calculations, respectively) in the first ultrarelativistic heavy-ion experiments at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) and the CERN Super Proton Synchrotron[4] has received much attention.

In the present Letter we demonstrate that the observed enhancement of the K/π ratios can be understood without requiring the formation of the quark-gluon plasma. A covariant microscopic approach, dubbed relativistic quantum molecular dynamics (RQMD), is employed to study the kaon production without the simplifying assumptions of thermal equilibrium or independent fragmentation. Details of the RQMD approach are described elsewhere;[5] here we sketch only briefly the main features. RQMD allows us to follow the time evolution of all hadrons (initially present and subsequently created). It combines classical propagation of the hadrons (molecular dynamics) with quantum effects (stochastic scattering and particle decay). The hadrons are propagated in a manifestly covariant framework of relativistic Hamiltonian constraint dynamics, including the interaction by quasipotentials.[6] Pions and other mesons (e.g., ρ,K,ω) are created via the decay of excited hadrons, which in turn are produced through inelastic collisions. The various resonance production probabilities for nucleon-nucleon, pion-nucleon, pion-pion, and kaon-nucleon scattering are taken from experimental data.[7,8]

Baryon resonances can decay into various channels, e.g., the nonstrange baryons Δ',N' with $m<2$ GeV/c^2 into $N+\pi$, $\Delta+\pi$, $N+\rho$, $N+\eta$, or $Y+K$ where $Y=\Lambda,\Sigma$. Their branching ratios and mean lifetimes are determined by inspection of the experimental data.[9] Baryon resonances with $m>2$ GeV/c^2 can also be produced in high-energy collisions. Their decay is incorporated into the present work via a phenomenological string model.[10] Only those hadrons which carry the valence quarks of the decaying string system can interact immediately. Their interaction probability is the same (in a simple constituent-quark model) before and after the jet decays. The other hadrons produced in the fragmenting jets need a proper formation time (here we assume $\tau=1$ fm/c) before they are on shell and can interact with other particles. This leads to the inside-outside picture for rapidly moving particles.

Kaons are produced either directly, i.e., in collisions, or via decay of resonances. The following measured elementary cross sections have been implemented:[8,11] $K+N\rightarrow K^*+N$, $\pi N\leftrightarrow YK$, $N\bar{K}\leftrightarrow\pi Y$, $NN\rightarrow NYK$, $NN\rightarrow NNK\bar{K}$, and $K^+n\leftrightarrow K^0p$. Other (unknown) cross sections for K production are related to these known reactions by simple hadron models (e.g., one-pion exchange, detailed balance, additive quark model). For instance a considerable fraction of the kaons are produced in interactions between the nonstrange mesons π, ρ, η, and ω. In these cases—lacking experimental information—we use a constant cross section ($\sqrt{2}>2m_K$), e.g., $\sigma(\pi^+\pi^0\rightarrow K^+\bar{K}^0)=2$ mb. To give a feeling for the influence of such input on the predictions of our approach we have checked that the use of a cross section of 3 mb in particular for this channel changes the final results for K^+ production by less than 5%.

The multiplicity and rapidity distributions as well as the transverse-momentum spectra of the different particle species are calculated in this approch. Also, other observables, e.g., two-body correlations (due to decay of resonances or scattering), fragment formation, baryon (p,n,Λ) rapidity distributions, energy densities, Hanbury-Brown–Twiss correlations, and so forth, can be directly taken as predictions of this model. The nonrelativistic QMD model has been extremely successful at LBL Bevalac and Dubna energies ($E_{\text{lab}}\sim 50A$ MeV–$4A$ GeV). Here the predicted stopping power, collective

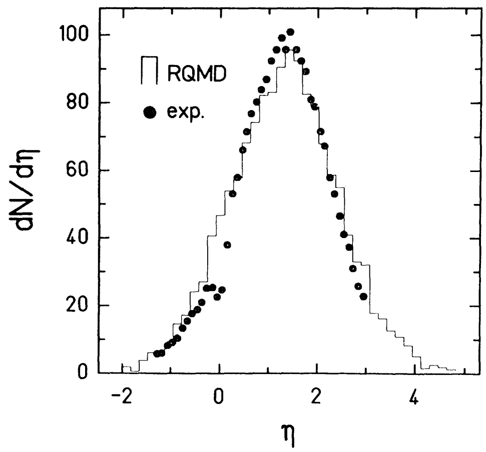

FIG. 1. Charged-particle pseudorapidity distribution in Si(14.5*A* GeV) on Au: comparison between the RQMD results (histogram) at impact parameter $b=1$ fm and the preliminary data from the E802 Collaboration (Ref. 4) for central events.

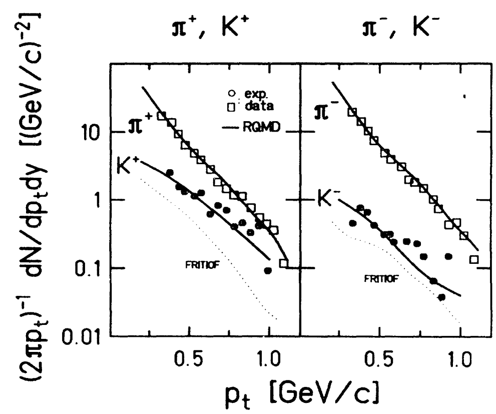

FIG. 2. Transverse-momentum spectra of π^+, K^+ (left-hand side) and π^-, K^- (right-hand side). The preliminary data from E802 Collaboration (Ref. 4) for the rapidity interval $1.2 < y_{\text{lab}} < 1.5$ are given by the open squares ($\pi^\pm$) and filled dots ($K^\pm$). The solid lines represent the RQMD results ($1.0 < y_{\text{lab}} < 1.5$) and the dotted lines the FRITIOF results. Absolute normalization of the cross section is to the π^+ spectra at $p_t = 300$ MeV/c.

flow, bounceoff of fragments, and squeezeout of the participant matter as well as the measured pion, kaon, photon, and fragment multiplicities and spectra agree remarkably well with the available 4π data.[12]

Let us first demonstrate that the RQMD approach does indeed reproduce important features of the available experimental data at AGS energies: The pseudorapidity distribution for charged particles in central collisions is compared in Fig. 1 with the RQMD results for an impact parameter of $b=1$ fm. We choose this value because the experimental trigger was to take the 7% of the highest-multiplicity events. In a simple geometric picture they correspond to nucleus-nucleus collisions with a maximum impact parameter of around 2.5 fm. In order to verify this procedure we checked that the results change by less than 15% if other impact parameters in the range $0 \leq b \leq 3$ fm are chosen. Note that the total multiplicities and the $dN/d\eta$ distribution predicted by the RQMD calculations agree well with the experimental data.

Let us now turn to the charged-kaon and -pion yields. The E802 group has measured them recently in the reaction Si(14.6 GeV)+Au over a limited region of phase space.[4] To compare our results directly with the unnormalized experimental data we fix the absolute normalization of all spectra to the π^+ spectra at $p_t = 300$ MeV/c. Acceptance cuts of the experiment have been included in the theoretical analysis by a cutoff in rapidity ($0.1 < y < 1.5$) and in transverse momentum ($p_t > 0.3$ GeV/c). The measured and calculated $\pi^\pm, K^\pm$ spectra are shown in Fig. 2. The integration of the calculated spectra over this rapidity range gives ratios $K^+/\pi^+ \approx 22\%$ and $K^-/\pi^- \approx 6\%$ in good agreement with the experimental values 20% and 5%, respectively.[4] We would like to point out that the kaon enhancement is not an effect due to the efficiency cuts employed, but that it has a physical origin: The kaon yields from the RQMD approach show factors of $2(K^+/\pi^+)$ and 1.5 (K^-/π^-) increase if the integration is performed over the whole phase space. The independent-hadron-fragmentation model FRITIOF (dotted lines in Fig. 2) predicts for the K/π ratios the same numbers as for *pp* collisions—in disagreement with the data.

The underlying physics for the enhancement of the K/π ratios is the following: The independent-fragmentation scheme FRITIOF[13] assumes that the projectile nucleons move on straight lines through the target. They hit those target nucleons which are within a tube of a cross section given by the inelastic nucleon-nucleon cross section. The excited projectile and target nucleons decay independently after the actual collision process has ceased. Therefore the *produced* hadrons do not interact—they have an infinite mean free path. In the FRITIOF model one thus obtains nearly the same K^+/π^+ and $K^-/\pi-$ ratios as in elementary nucleon-nucleon collisions at the same c.m. energy. In contrast, the space-time evolution of the complete system and, therefore, all interactions of the produced hadrons with any other hadron are explicitly taken into account in a manifest covariant manner in the RQMD approach.

Now let us discuss the question of whether the assumptions of the thermal model (instantaneous equilibrium) or of the independent-fragmentation schemes (no secondary collisions) are justified for relativistic heavy-ion collisions. At AGS energies there are two main sources of kaons (and other mesons) in the RQMD ap-

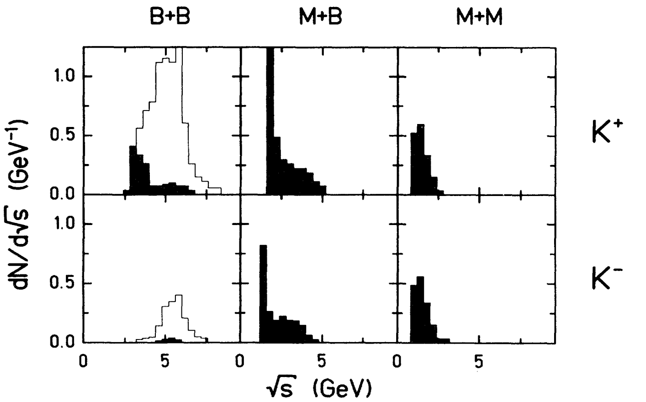

FIG. 3. The invariant-mass distribution for those collision types in which K^+ (first row) and K^- (second row) are produced. *B* and *M* denote baryon and meson, respectively. (Darkened histograms, secondary reactions; unshaded, primary reactions.)

proach which are of comparable magnitude. Let us denote the produced mesons as "primaries" if they stem from Glauber-type collisions of the projectile nucleons on their passage through the target nucleus. They roughly correspond to the particles produced in the independent-fragmentation schemes. "Secondaries" are produced in all other types of collisions and decays. The c.m. energy distribution of those primary and secondary collisions which produce the observed kaons are displayed in Fig. 3. We would like to emphasize that the difference between primary and secondary kaons corresponds roughly to two distinct c.m. energy regions: The primary kaons are produced in baryon-baryon reactions with $\sqrt{s} \approx \sqrt{s_{\text{init}}}$. However, secondary baryon-baryon scattering (with $\sqrt{s} < \sqrt{s_{\text{init}}}$), meson-baryon, and meson-meson channels all contribute to the final number of produced kaons. The invariant-mass distribution of the different channels also clearly explains why the nonequilibrium flavor kinetics model, which assumes a thermal heat bath of $T \sim 150$–200 MeV, drastically underestimates the kaon production.[14] There one assumes that the initial kinetic energy is transferred instantly into thermal energy of a participant fireball. Collision rates for kaon-producing channels are small in such a scenario.[2,15] This is due to the suppression of high relative momenta at these temperature values. Thus the time necessary to approach the observed K/π ratios in such a model is much longer than simple estimates of nucleus-nucleus collision times would suggest. However, the present studies clearly demonstrate that the c.m. energy distribution of the binary collisions is nonthermal (see Fig. 3).

We have also studied kaon production in $p+$Au collisions. Here only about one K^+ per five events is produced. Therefore we have not been able to acquire sufficient statistics to give a K/π ratio in the acceptance range of the E802 data. However, the K/π ratio in the lower p_t bins (<300 MeV/c) seems to be (with admittedly very large statistical error) enhanced to 15%–25%.

In conclusion, the experimentally observed K^+/π^+ and K^-/π^- enhancement in ultrarelativistic heavy-ion collisions does not require the formation of a quark-gluon plasma. Nonequilibrium multihadron dynamics as employed in the RQMD approach demonstrates that the use of thermal or—to the other extreme—independent-fragmentation models is highly questionable for these reactions. More generally spoken, the present studies demonstrate that the complex dynamical space-time evolution and nonequilibrium effects must be taken quite seriously in the discussion of any of the *quantitative* (factors of ~ 2) signatures for the creation of the quark-gluon plasma in relativistic nuclear collisions. We would like to emphasize that in our opinion *qualitatively* unique, possibly exotic signatures, like, e.g., the recently proposed s-$\bar{s}$ separation leading to the formation of metastable strange-quark-matter droplets[16] or the production of antimatter clusters ($\bar{d}$, $\overline{\text{He}}$, $\bar{\text{C}}$, etc.),[17] will have to receive much more attention in the near future.

We are most grateful to C. Chasman, O. Hansen, S. Nagamiya, and the members of the E802 Collaboration for many stimulating and fruitful discussions and for providing preliminary experimental data prior to publication.

[1]J. Rafelski and B. Müller, Phys. Rev. Lett. **48**, 1066 (1982); **56**, 2334 (1986); T. S. Biro and J. Zimanyi, Nucl. Phys. **A395**, 525 (1983); N. K. Glendenning and J. Rafelski, Phys. Rev. C **31**, 823 (1985); J. Kapusta and A. Makijan, Phys. Rev. D **33**, 1304 (1986); T. Matsui, B. Svetitsky, and L. D. McLerran, Phys. Rev. D **34**, 783 (1986); **34**, 2047 (1986); K. Kajantie, M. Kataja, and P. V. Ruuskanen, Phys. Lett. **B179**, 153 (1986).

[2]P. Koch, B. Müller, and J. Rafelski, Phys. Rep. **142**, 167 (1986); P. Koch, Z. Phys. C **38**, 269 (1988); C. M. Ko, Nucl. Phys. **A498**, 561 (1989).

[3]E814 Collaboration, P. Braun-Munzinger *et al.*, Z. Phys. C **38**, 45 (1988); E802 Collaboration, L. P. Remsberg, *et al.*, Z. Phys. C **38**, 35 (1988); NA35 Collaboration, A. Bamberger *et al.*, Phys. Lett. B **184**, 271 (1987).

[4]E802 Collaboration, Y. Miake, *et al.*, Z. Phys., C **38**, 135 (1988); P. Vincent *et al.*, Nucl. Phys. **A498**, 67 (1989); C. Chasman, O. Hansen, and S. Nagamiya (private communication). NA35 Collaboration, G. Vesztergombi *et al.*, Z. Phys. C **38**, 129 (1988); A. Bamberger *et al.*, Z. Phys. C **43**, 25 (1989).

[5]H. Sorge, H. Stöcker, and W. Greiner, Ann. Phys. (N.Y.) (to be published); Nucl. Phys. **A498**, 567 (1989).

[6]A. Komar, Phys. Rev. D **18**, 1881 (1978); J. Samuel, Phys. Rev. D **26**, 3475 (1982); **26**, 3482 (1982); H. Sorge, Ph.D. thesis, University of Bremen, 1987 (unpublished).

[7]J. Bystricky *et al.*, Départment de Physique des Particles Elémentaires, Centre d' Etudes Nucléaires de Saclay, Report No. DPhPE87-03, 1987 (unpublished); G. Bertsch, M. Gong, L. McLerran, V. Ruuskanen, and E. Sarkkinen, Phys. Rev. D **37**, 1202 (1987); C. B. Dover and G. E. Walker, Phys. Rep. **89**,

1 (1982).
[8]A. M. Rossi *et al.*, Nucl. Phys. **B84**, 269 (1975).
[9]Particle Data Group, Lawrence Berkeley Laboratory Report No. LBL-100 Revised UC-34d, 1982 (unpublished).
[10]B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrang, Phys. Rep. **141**, 31 (1983); X. Artru, Phys. Rep. **141**, 147 (1983).
[11]H. W. Barz and H. Iwe, Nucl. Phys. **A453**, 728 (1986); W. Zwermann, Mod. Phys. Lett. A **3**, 251 (1988); J. Randrup and C. M. Ko, Nucl. Phys. **A343**, 519 (1980); C. B. Dover and G. E. Walker, Phys. Rep. **89**, 1 (1982).
[12]H. Stöcker and W. Greiner, Phys. Rep. **137**, 277 (1986); J. Aichelin and H. Stöcker, Phys. Lett. B **176**, 14 (1986); A. Rosenhauer, J. Aichelin, H. Stöcker, and W. Greiner, J. Phys. C **4**, 395 (1986); J. Aichelin, A. Rosenhauer, G. Peilert, H. Stöcker, and W. Greiner, Phys. Rev. Lett. **58**, 1926 (1987); G. Peilert, H. Stöcker, and W. Greiner, Phys. Rev. C **39**, 1402 (1988); G. Peilert, A. Rosenhauer, J. Aichelin, H. Stöcker, and W. Greiner, Mod. Phys. Lett. A **3**, 459 (1988); K. H. Kampert, Ph.D. thesis, University of Münster, 1986 (unpublished).
[13]T. Sjostrand, Comput. Phys. Comm. **39**, 347 (1986); B., Andersson, G. Gustafson, and B. Nilsson-Almqvist, Nucl. Phys. **B281**, 289 (1987).
[14]B. Friman, Nucl. Phys. **A498**, 161 (1989).
[15]R. Mattiello, C. Greiner, D. H. Rischke, H. Sorge, H. Stöcker, and W. Greiner (to be published).
[16]C. Greiner, P. Koch, and H. Stöcker, Phys. Rev. Lett. **58**, 1825 (1987); C. Greiner, D. H. Rischke, H. Stöcker, and P. Koch, Phys. Rev. D **38**, 2797 (1988); Nucl. Phys. **A479**, 295 (1988); Z. Phys., C **38**, 283 (1988).
[17]U. Heinz, P. R. Subramanian, H. Stöcker, and W. Greiner, J. Phys. G **12**, 1237 (1986).