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FREEZE-OUT CONDITIONS IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS

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Abstract. We present recent results on single particle transverse momentum distributions of pions, kaons, and protons, measured in CERN Experiment NA44, of 200A·GeV/c S+S and 158A·GeV/c Pb+Pb central collisions. By comparing these data with thermal and transport models, freeze-out parameters like the temperature T_{fo} and the chemical potentials (μ_q, μ_s) are extracted and discussed.

1. Introduction

The physics motivation of ultrarelativistic heavy-ion collisions is to prepare nuclear matter with high baryon and energy densities, and hope to reach a new form of matter called quark-gluon plasma. By studying the decay of the system, we will gain knowledge of strong interactions under these extreme conditions and shed light on the puzzle of quark confinement.

The fireball created in these collisions contains a finite number of particles and its life time and spatial size are also limited. Furthermore, due to the finite interaction cross section among hadrons, statistically the freeze-out occurs from the outside toward the inside of the fireball. One may imagine that free streaming hadrons are evaporated from the fireball surface. Therefore it is important to understand if the final hadron spectra are those of a thermalized system, and if the u, d, and s quark distributions follow the statistical weights. This has been a subject of interest for many years, see refs. [1]-[7]. In this paper, after a brief description of the NA44 experiment, we will discuss the transverse momentum distributions of pions, kaons, and protons from 200 A·GeV/c S+S and 158 A·GeV/c Pb+Pb central collisions. From this study, the freeze-out temperature parameter T_{fo} for ultrarelativistic heavy-ion collisions is established. In order to gain insight into the chemical properties and the possible medium effects [8] in the produced fireball, we then study particle ratios to extract the $u(d)$ and s quark chemical potential parameters (μ_q, μ_s).

2. CERN Experiment NA44

The NA44 spectrometer is designed to measure one- and two-particle distributions of charged hadrons near the center of mass rapidity ($y_{mid} \approx 3$) over a transverse momentum range of $0 \leq p_T \leq 1.6$ GeV/c. Threshold Cherenkov counters and time-of-flight (TOF) scintillator hodoscopes are used for particle identification and momentum reconstruction. The TOF resolution is about $100ps$ and momentum spread is about $\delta p/p \leq 0.5\%$. The interaction trigger is provided by two scintillator paddles placed downstream of the target. For AA collisions, the trigger cross section is approximately $\sigma_{trig}/\sigma_{geom} \approx 10\%$, while for pA collisions a minimum bias trigger was used. More details of the spectrometer can be found elsewhere [9, 10].

The energy of the proton beam is 450 GeV, $y_{NN} = 3.44$; for the Sulphur beam, it is 200 A·GeV with $y_{NN} = 3.03$; and for the lead beam 158 A·GeV with $y_{NN} = 2.91$. In the following discussions, we will focus on the 8 GeV/c momentum setting. Here the spectrometer have rapidity span of (2.5 - 3.4) and (2.3 - 2.9) for kaons and protons, respectively. In order to use pions from the mid-rapidity region, low p_T part of pion data was taken from the 4 GeV/c setting and high p_T part was taken from the 8 GeV/c setting.

3. Results and Discussion

In heavy-ion physics, particle distributions are often shown in two directions: the longitudinal direction which is along the beam (z) direction and the transverse direction, perpendicular to the beam direction. The variable used for the longitudinal distribution is rapidity $y = 0.5log(E+p_z)/(E-p_z)$ and the variable used for transverse distributions is either the transverse momentum $p_T = (p_x^2 + p_y^2)^{1/2}$ or transverse kinetic energy $k_T = m_T -$ mass.[1]

Proton rapidity distributions [11] from the Pb+Pb collisions show a rather large number of protons piled up around mid-rapidity, implying, that even at the CERN energy, a high degree of stopping is achieved. The strong Coulomb effect [12, 13] observed in the Pb+Pb collisions provides additional evidence of high nuclear stopping.

At the high p_T limit, a transverse kinetic energy distribution can be represented by a simple exponential function: $exp(-m_T/T)$. [2] Here T is the slope parameter. The magnitude of the slope parameter can provide information about collective transverse flow, and deviations from the exponential distribution may signal new physics like the low p_T enhancement, medium effects [8] *etc.*

[1] Unless otherwise noted $\hbar$ = c = 1.

[2] Note that the exponential shape is only consistent with a thermal distribution, but not necessarily a proof of thermalization.

3.1. Transverse Momentum Distributions

Figure 1 shows the transverse kinetic energy distributions of charged pions, kaons, and protons. The dashed lines represent an exponential fit to the distributions and the fitted slope parameters are indicated in the figure. [3] First of all, the exponential functions fit the data well except for pions in the low p_T region, where the contributions of resonance decays become important. Secondly, the slope parameters increase as particle mass increases and this is independent of the sign of the particles. To make this point clearer, we summarize the slope parameters of pions, kaons, and protons from three collision systems: p+p [14] ($\sqrt{s} \approx$ 23GeV), S+S ($\sqrt{s} \approx$ 19.4A·GeV), and Pb+Pb ($\sqrt{s} \approx$ 17.3A·GeV) in Fig. 2 where the slope parameters T are plotted against particle mass.

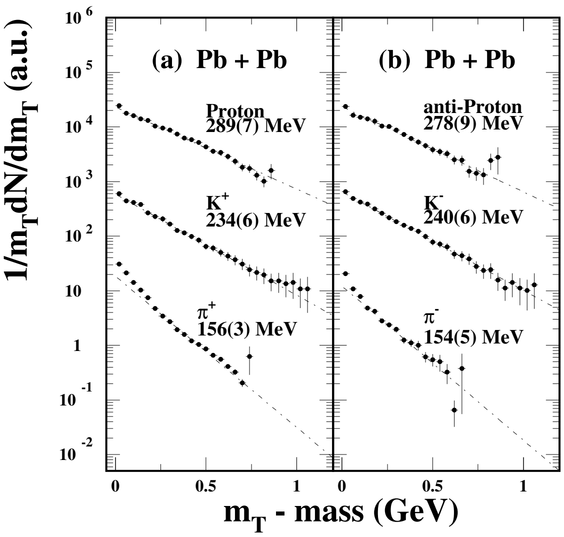

Figure 1. *NA44 preliminary transverse momentum distributions for pions, kaons, and protons.*

A distinct difference between the elementary p+p collision and heavy-ion collisions can be seen in the slope parameters. It is also interesting to observe that all curves converge to a point about $T_{fo} \approx 145 \pm 15$MeV at the limit mass $\rightarrow 0$ as indicated by the shaded bars in the plot. In hydrodynamics, matter flows, *i.e.*, all particles flow at a same collective velocity. Classically, the collective kinetic energy will then depend on the particle mass: particles with higher mass will carry higher energy. Therefore the slope parameter is a measure of the energy of the transverse motion. The transverse motion contains both thermal (random) and collective modes. The intrinsic freeze-out temperature is only determined by the thermal motion.

For p+p collisions, due to the saturation of the phase-space, the final hadron distributions show characteristic of thermalization [1, 15, 16]. Thus the slope pa-

[3] To avoid the distortion caused by high mass resonances in the pion spectra, the fit is for k_T $\geq$0.2 GeV.

rameter may reflects the true freeze-out temperature. This is supported by the fact that the slope parameters of pion, kaon and proton are very similar, around 150 MeV. However, for heavy-ion collisions, rescattering becomes more and more important and a collective transverse motion gradually develops. The slopes in the T-mass plot indeed demonstrate such characteristic hydrodynamic behavior. Furthermore, as one can see from the figure, the heavier the colliding system, the steeper the slope in the plot.

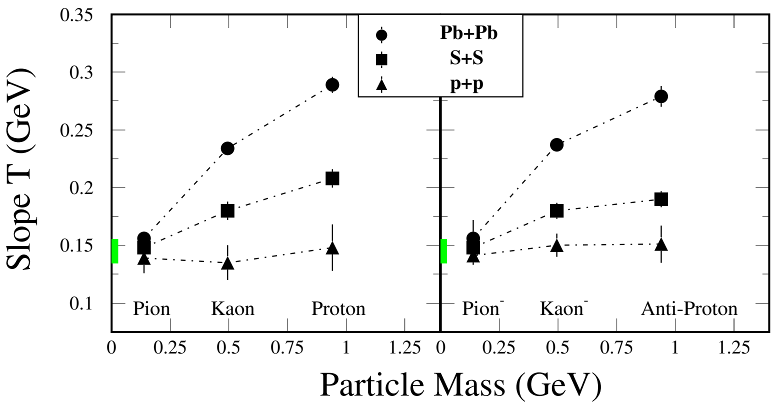

Figure 2. *Slope parameter T as a function of particle mass for p+p [14], S+S, and Pb+Pb central collisions. The AA data are preliminary.*

It is worth noting that very similar behavior can be found at the AGS energies ($E_{beam} \approx 10 - 15$A·GeV). The characteristic freeze-out temperature T_{fo} is also about 150 MeV! On the other hand, at lower energies, $E_{beam} \approx 0.2 - 5$A·GeV, one finds that T_{fo} decreases dramatically as the beam energy decreases. This observation implies that the freeze-out temperature T_{fo} saturates around 150 MeV at a beam energy of about 10 GeV as already discussed in ref. [2, 3, 17].

3.2. Particle Ratios

Having fixed the freeze-out temperature parameter T_{fo}, we now turn to the issue of chemical potentials. Assuming chemical equilibrium, this information can be extracted from the measured particle ratios. The NA44 spectrometer can measure particles of both signs at the same p_T and y window. It is therefore an unique advantage for studying the particle production ratios since many systematic errors will cancel out. In Fig. 3, the preliminary K^-/K^+ and $\bar{p}/p$ ratios are shown as a function of rapidity for both S+S and Pb+Pb central collisions. Model predictions[4] of RQMD(v1.08) [18] and VENUS(v4.12) [19] are represented by dashed and solid lines, respectively. The systematic errors on the ratios for Pb+Pb collisions are

[4] The calculations were performed with the similar centrality cut as done in the experiment.

estimated to be about 15%. The main contributors to the rather large error bars are centrality determination and particle identification efficiency corrections. For the S+S collisions, the systematic errors are about 11%.

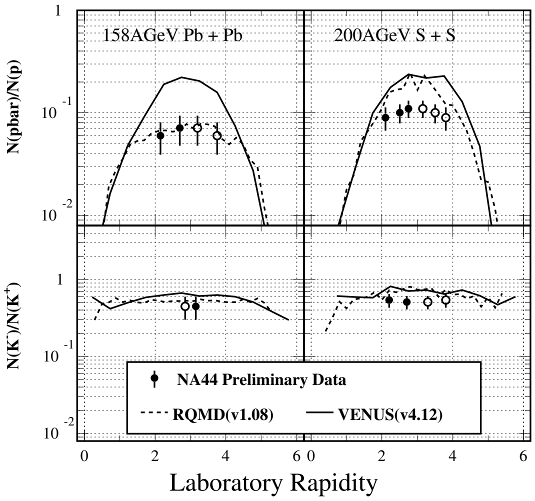

Figure 3. *NA44 preliminary K^-/K^+ and $\bar{p}/p$ ratios. Open circles are mirrored about the central rapidity of 3.0 and 2.9 for S+S and Pb+Pb central collisions, respectively. RQMD(v1.08) and VENUS(v4.12) predictions are shown in dashed and solid lines.*

In the case of $\bar{p}/p$ ratio, both model predictions deviate from the data by a factor of 3 for the light colliding system S+S. For the Pb+Pb collisions, RQMD seems to give a better results. However, for kaons, both model always overpredict the ratios. It is clear here that much work has to be done in order to understand the details of the particle production in heavy-ion collisions.

Particle density ratios determine the quantity: μ_i/T_{fo}^{ch}.[5] At the quark level, there are two chemical potentials μ_q and μ_s for light and strange quarks, respectively. The relationship between the bayonic and quark chemical potentials can be found in several references, for example, ref. [7, 21]. Assuming the condition of chemical equilibrium, the values of (μ_q,μ_s) and temperature parameter can be extracted from the measured particle ratios. The results of this analysis from the $\bar{p}$/p and K^-/K^+ ratios around mid-rapidity are listed in Table I.

Table I. *Light and strang quark chemical potentials (μ_q, μ_s) extracted from S+S and Pb+Pb central collisions. (All results are obtained from the mid-rapidity region.)*

	μ_q (MeV)	μ_s (MeV)
200A·GeV S+S	53±8	~0
158A·GeV Pb+Pb	71±15	9±2

Within the model considered here, the results are not dependent on how one

[5] Here T_{fo}^{ch} is the chemical freeze-out temperature parameter which is determined by the particle ratio study. See below for more detailed discussion.

treats the collective flow because only particle ratios are used. On the one hand, within the experimental error bars, the values of the chemical potentials are consistent with the values found in ref. [5, 22], even though particle mass up to 2 GeV and strange quantum number of S=2 were included in those studies. On the other hand, from the ratio analysis of 200A·GeV/c S-beam induced collisions S+Pb (W), the chemical freeze-out temperature parameter T_{fo}^{ch} is found consistently higher than 150 MeV, *i.e.*, $T_{fo}^{ch} \approx 170 \sim 200$ MeV. Since the fireball produced in heavy-ion collisions is an open thermodynamic system and the inelastic process requires more energy than elastic one, it is conceivable that the chemical freeze-out may occur earlier than thermal one [21].

Because of their large interaction cross section, antiprotons provide a unique probe of the hadronic environment. By studying the antiproton distribution, one gains information on dynamic processes such as pair production, annihilation, and mean-field-effects of the fireball. As has been noted by Gavin *et al.* [23] the $\bar{p}/p$ ratios are useful to understand the spacetime evolution of baryons in heavy-ion collisions. Experiment NA44 [24, 25] has measured proton and antiproton spectra with high statistics and has compared results of p+p, p+A, and A+A collisions in the same spectrometer. Fig. 4 shows the mid-rapidity $\bar{p}/p$ ratios all the way from the elementary collision p+p to the truly heavy-ion Pb+Pb collisions.

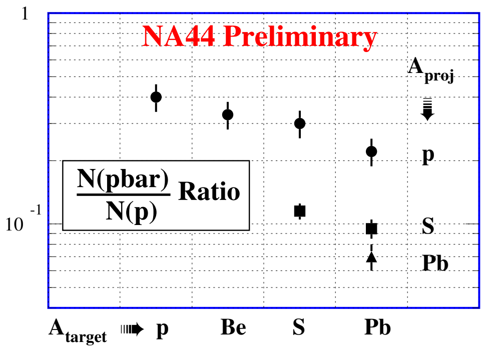

Figure 4. *NA44 preliminary $\bar{p}$ to p ratios for several projectile and target combinations. pp results is taken from ref. [14].*

In high energy p+p collisions [20], pair creation is the largest source of central p and $\bar{p}$. This implies that antiprotons are always produced with accompanying protons. In the case of heavy-ion collisions where a large number of protons are also shifted from the target and projectile into the mid-rapidity region, the $\bar{p}/p$ ratio will further decrease compared to that of proton induced collisions. This is consistent with the observed systematic trends. However, the measured ratios are the combined results of particle production at the earlier collision stage and later annihilation.

4. Summary

We have discussed the results of mid-rapidity transverse momentum distributions of pions, kaons, and protons from p+p, S+S and Pb+Pb central collisions. The systematics of the data strongly suggests a freeze-out temperature of $T_{fo} \approx 145 \pm 15$ MeV for collisions above beam energy $\sim$10 A$\cdot$GeV. Current results of cascade models RQMD(v1.08) and VENUS(v4.12) cannot fully reproduce the observed particle ratios. Systematic results of $\bar{p}/p$ ratios, from p+p to Pb+Pb central collisions, studied with the NA44 spectrometer were also presented. Such long awaited information should help to understand the collision dynamics.

All of our discussions were based on the measured light hadrons at the freeze-out stage. If thermal and chemical equilibria are indeed reached, information on the earlier stages of the collision is lost. In order to get insight into the initial condition of heavy ion collisions, we need to investigate the distributions and yields of leptons and photons and possibly high mass multi-strange resonances.

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