Collective expansion in high energy heavy ion collisions

I.G. Bearden[1], H. Bøggild[1], J. Boissevain[2], J. Dodd[3], B. Erazmus[4], S. Esumi[5], C.W. Fabjan[6], D. Ferenc[7], D.E. Fields[2], A. Franz[6], J.J. Gaardhøje[1], A.G. Hansen[1], O. Hansen[1], D. Hardtke[8], H. van Hecke[2], E.B. Holzer[9], T.J. Humanic[8], P. Hummel[9], B.V. Jacak[2], R. Jayanti[8], H. Kalechofsky[8], M. Kaneta[5], M. Kopytine[2], Y.Y. Lee[8], M. Leltchouk[3], T. Ljubicic[7], B. Lörstad[10], N. Maeda[5], R. Malina[9], A. Medvedev[3], M. Murray[11], S. Nishimura[5], H. Ohnishi[5], G. Paic[4], S.U. Pandey[8], F. Piuz[6], J. Pluta[4], V. Polychronakos[12], M. Potekhin[3], G. Poulard[6], D. Reichhold[8], A. Sakaguchi[5], J. Simon-Gillo[2], J. Schmidt-Sørensen[10], W. Sondheim[2], M. Spegel[6], T. Sugitate[5], J.P. Sullivan[2], Y. Sumi[5], W.J. Willis[3], K. Wolf[11], N. Xu[2], and D.S. Zachary[8]

1 Niels Bohr Institute, DK-2100 Copenhagen, Denmark.

2 Los Alamos National Laboratory, Los Alamos, NM 87545, USA.

3 Department of Physics, Columbia University, New York, NY 10027, USA.

4 Nuclear Physics Laboratory of Nantes, 44072 Nantes, France.

5 Hiroshima University, Higashi-Hiroshima 739, Japan.

6 CERN, CH-1211 Geneva 23, Switzerland.

7 Rudjer Boskovic Institute, Zagreb, Croatia.

8 Department of Physics, The Ohio State University, Columbus, OH 43210, USA.

9 Technical University, A-1040, Vienna, Austria.

10 Department of Physics, University of Lund, S-22362 Lund, Sweden.

11 Texas A&M University, College Station, TX 77843, USA.

12 Brookhaven National Laboratory, Upton, NY 11973, USA.

(The NA44 Collaboration)

Abstract

Transverse mass spectra of pions, kaons, and protons from the symmetric heavy-ion collisions 200A·GeV S+S and 158A·GeV Pb+Pb, measured in the NA44 focusing spectrometer at CERN, are presented. The mass dependence of the slope parameters provides evidence of collective transverse flow from expansion of the system in heavy–ion induced central collisions.

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The purpose of studying ultra-relativistic heavy-ion collisions is to understand the nature of hadronic matter under extreme conditions. Specifically, we are interested in a new form of matter, quark-gluon plasma, which may be produced in such collisions. Transverse momentum distributions are one of the most common tools used in studying high energy collisions. This is because the transverse motion is generated during the collision and hence is sensitive to the dynamics. More than 45 years ago, Fermi proposed a statistical method [1] to understand the results of high energy hadron-hadron collisions. Due to saturation of the phase space, the multiparticle production resulting from the high energy elementary collisions is consistent with a thermal description [1–3]. In heavy-ion collisions hydrodynamical behaviour, that is, local thermal equilibrium and collective motion, may be expected because of the large number of secondary scatterings.

It is now possible to identify and quantitatively measure the collective motion by systematic studies of results from different collision systems, using light (Si at BNL and S at CERN) and heavy (Au at BNL and Pb at CERN) ion beams [4–6]. A high degree of nuclear stopping and a strong Coulomb effect (also due to the high stopping) have already been reported in Pb+Pb central collisions [7,8]. In this Letter, we present transverse momentum distributions of pions, kaons, and protons, measured in the NA44 spectrometer, from Pb+Pb and S+S collisions. Results of calculations from a hydrodynamical model [5] will be used to aid in this analysis.

The NA44 magnetic focusing spectrometer consists of two room-temperature dipoles and three superconducting quadruples. Particles originating from the target are focused at a plane about 10 meters downstream and detected by a tracking system consisting of a pad chamber – strip chamber – scintillator hodoscope complex. Particle identification is done with two threshold Cherenkov counters and two highly segmented TOF hodoscopes. The phase-space coverage (transverse momentum p_T vs. rapidity y) is determined by the combination of the spectrometer angle (relative to the beam direction) and the nominal momentum setting of the magnets. The momentum resolution is typically $\sigma_p/p \leq 0.2\%$ and the TOF counters have an average time resolution of 100 ps. More details of the spectrometer can be found elsewhere [9].

The spectrometer momentum range is $\pm20\%$ around the nominal values of 4 and 8 GeV/c. For kaons and protons, the 8 GeV/c setting was used and the rapidity coverage is (2.5-3.4) and (2.4-2.8) for kaons and protons, respectively. Two angular settings (44 and 130 mrad) were utilised in order to cover the transverse momentum range $0 \leq p_T \leq 1.6$ GeV/c. For the pion data, the 4 and 8 GeV/c low angle data were combined (for details of this procedure see Ref. [7]) and the overall rapidity window is (3.0-4.1). For a symmetric colliding system, all particles are near mid–rapidity $y_{cm} = 2.9$ and $y_{cm} = 3.0$ for the beam energies of 158 and 200 A·GeV. The 10% and 6.4% most central collisions were selected from the S+S and Pb+Pb data, respectively.

For the 158A·GeV Pb+Pb central collisions, the mid–rapidity transverse mass distributions, $(1/m_T)dN/dm_T$ as a function of $m_T - \mathrm{m}$ ($m_T = \sqrt{p_T^2 + \mathrm{m}^2}$), for both signs of pions, kaons, and protons are shown in Fig. 1 as open circles. The dashed lines in figure 1 are fits to the function:

$$\frac{1}{m_T}\frac{dN}{dm_T} = A \cdot exp(-\frac{m_T}{T}), \tag{1}$$

with A an arbitrary constant and T characterizing the slope of the distribution. For kaons and protons, the fitting is done in the range $0 \leq m_T - \mathrm{m} \leq 1$ GeV. In order to exclude the m_T range populated heavily by resonance decays, the fitting range for pions is $m_T - \mathrm{m} \geq 0.25$ GeV.

The systematic errors for kaon and proton spectra are estimated to be less than 5%, for pions less than 15%. The larger uncertainties in the pion spectra mainly arise from two sources. One of these is the acceptance correction which was done neglecting the rapidity dependence of the slope parameter. However, the measured [10] pion mean p_T from Pb+Pb collisions does not vary significantly within $3.0 \leq y \leq 4.5$, validating this assumption. We estimate an error of 10% in the final pion slope parameter from this source. The other contribution is the fitting range. Because of resonance decays, a pion spectrum over a wide transverse momentum range is normally not exponential with respect to the transverse mass

m_T. It can be seen in Fig. 1 that the exponential fits represent the data very well for all cases except for pions in the low $p_T \leq 0.2$ GeV region. The discrepancies between data and the fits in this region are most likely due to the resonance decays [11–15].

The slope parameter T, from the Pb+Pb collisions at $\sqrt{s} = 17.2$ A·GeV increases with particle mass and the trend is independent of the sign of the particle under consideration. Slope parameters of these particles were also determined from $\sqrt{s} = 19.4$ A·GeV/c S+S central collisions measured in the NA44 spectrometer. The behaviour is similar to that described above for Pb+Pb. The values of slope parameter from p+p, S+S, and Pb+Pb collisions are listed in Table I. The p+p ($\sqrt{s}$ =23GeV) results are taken from Refs. [16,17].

In order to visualise the systematic trends in the data, we summarise the slope parameters for pions, kaons, and protons from the three collision systems in Fig. 2. On the left are the slopes for positive particles and on the right for negative particles. Both particles and anti–particles exhibit similar behaviour. A distinct difference between the elementary p+p and heavy-ion collisions is reflected in the slope parameters. While for p+p the slope parameters (triangles) remain constant as a function of the particle mass, these parameters increase with increasing mass for heavy-ion collisions. Furthermore, for a given mass, the heavier the colliding system, the higher the slope parameter. It is particularly interesting to observe that all curves converge to a point about $T \approx 140 \pm 15$ MeV as the particle mass approaches zero [18], this range is indicated by the shaded bars in the figure 2. It is worth noting that a plot similar to Fig. 2 can be made for data at AGS energies ($E_{beam} \approx 10 - 15$A·GeV) [19]. Remarkably, the characteristic slope is also about 145 MeV. On the other hand, at lower beam energies of $E_{beam} \approx 0.2 - 5$A·GeV, one finds that this T decreases dramatically as the beam energy decreases [20]- [23].

In a hydrodynamical picture, matter flows, *i.e.* particles of different mass all move with the same velocity. Classically, the collective kinetic energy will then depend on the particle mass: particles with higher mass will carry more energy. The experimental slope parameter measures the particle energy which contains both thermal (random) and collective (due to secondary collisions among the produced particles, or rescattering) contributions. The intrinsic freeze–out temperature, namely the temperature when the particles cease to interact with each other, is determined by the thermal motion. As rescattering is not important in p+p collisions, the slope parameter should be due only to the thermal motion and thus may reflect the true freeze–out temperature. This interpretation is strengthened by the observation that the slope parameter remains nearly constant (around 140-150 MeV) for all particles from the p+p data. When the size of the colliding nuclei increases, so does the number of rescatterings and, as a consequence, collective motion develops. The rise of T with particle mass seen in Fig. 2 is indeed characteristic of such hydrodynamical behaviour. The cascade code RQMD [24] predicts a similar trend in the slope parameters as a function of particle mass. However, it systematically underestimates the values for kaons and protons for all collision systems.

Table I. Slope parameters T (in MeV unit) of pions, kaons, and protons for p+p, S+S, and Pb+Pb colliding systems at CERN energies. Error bars are statistical only. The systematic errors for kaons and protons are less than 5% while for pions is less than 15%.

	π^+	K^+	p	π^-	K^-	$\bar{p}$
p	139±13	139±15	148±20	141±8	150±10	151±16
S	148±4	180±8	208±8	148±4	180±7	190±7
Pb	156±6	234±6	289±7	154±8	235±7	278±9

The correlation between the slope parameter and particle mass m may be described qualitatively by the relationship:

$$T = T_{fo} + \mathrm{m}\langle v_T \rangle^2. \tag{2}$$

The parameters T_{fo} and $\langle v_T \rangle$ can be identified with the freeze-out temperature and the averaged collective flow velocity, respectively. Fitting the p+p data with this expression, one finds a temperature of around 140 MeV and a flow velocity consistent with zero for both particles and anti–particles. On the other hand, for S+S and for Pb+Pb, the fits give nearly the same temperature but a large velocity. Results of the fits are presented in

Table II, where the quoted errors are statistical only. Due to the assumption of a linear mass dependence used in the fit, the uncertainty in the resulting velocity is estimated to be 15%. The difference between the proton and anti-proton freeze-out temperatures from the Pb+Pb collisions is less than 1.5σ. In p+p collisions, the density of produced particles is low, insufficient to produce an appreciable collective flow. Therefore, the slope parameters show no dependence on the particle mass [25,26]. Conversely, for heavy colliding systems the density of produced particles is rather high, giving rise to significant rescattering, and thus collective transverse motion. In Ref. [27], the authors discuss a similar relationship between slope parameter and particle mass within the framework of a hydrodynamical model. There the $\langle v_T \rangle$ is interpreted as the mean expansion velocity at the freeze-out surface.

Table II. Fitted [Eq.(2)] temperature parameter T_{fo}(in MeV unit) and averaged velocity parameter $\langle v_T \rangle$ for p+p, S+S, and Pb+Pb colliding systems at the CERN energies. Error bars are statistical only. The '+' and '-' signs are for positive and negative particles, respectively.

	T^+_{fo}	$\langle v_T \rangle^+$ (c)	T^-_{fo}	$\langle v_T \rangle^-$ (c)
p+p	136±15	0.09±0.17	140±10	0.12±0.15
S+S	138±5	0.28±0.10	142±5	0.24±0.10
Pb+Pb	140±7	0.41±0.11	167±13	0.36±0.14

Using the hydrodynamical model of Refs. [4,5], the transverse momentum distributions are calculated with the form:

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T sinh(\rho)}{T_0}\right) K_1\left(\frac{m_T cosh(\rho)}{T_0}\right), \tag{3}$$

where $\rho = \tanh^{-1}\beta_r$, $\beta_r(r) = \beta_s(\mathrm{r/R})^\alpha$ with $\alpha = 1$, and I_0, K_1 are modified Bessel functions. Two free parameters, the temperature T_0 and the surface transverse velocity β_s, determine the shape of the m_T spectra. The calculated result is used to fit all measured pions, kaons, and protons, from a given reaction.

Fig. 3 shows the results of the fitting as solid lines which agree well with experimental data. For kaons and protons, within statistical errors, no dependence on the fitting range was found. However, as mentioned earlier, pion distributions are affected by resonance decays at low p_T. In order to account for this effect, resonance decays are included in the calculations. In principle there are two ways to estimate the resonance decays. Assuming a thermal population for the heavy resonances, the pion distribution can be calculated [5,6]. This implicitly assumes a chemical equilibrium and the unmeasured longitudinal distributions of these resonances have to be assumed as well. An alternative way to evaluate the resonance effect is to use a cascade code like RQMD [28]. We calculate the ratio of the pions with and without resonance decays as a function of transverse mass. This ratio is then applied to the thermal model result. Thermal equilibrium is implicitly assumed in this approach, but this is much less strict than the chemical equilibrium assumption although all assumptions that went into the cascade model calculations are in principle included in the ratio estimation. In the RQMD model [28], we find that at least 50% of final midrapidity pions are from resonance decays for both Pb+Pb and S+S collisions.

With the intrinsic temperature fixed at $T_0 = 140$ MeV, the maximum velocities are found to be 0.6 and 0.41c for Pb+Pb and S+S collisions, respectively. (These values correspond to average transverse flow velocities of 0.4 and 0.27c.) The fit results show an anti-correlation between the temperature T_0 and the maximum velocity β_s. Within a temperature range 100 $\leq T_0 \leq$ 150 MeV, the fits are equally good. The choice of $T_0 = 140$ MeV is based on Fig.2 and Refs. [5,24,29,30]. The success of fitting the different mass particle spectra with one expanding source lends credence to the naive interpretation of the slope trend as evidence of collective expansion.

Note that Eq.(2) does not include any details of the freeze-out process. However, the hydrodynamical model Eq.(3) includes a specific shape of the freeze-out surface Ref. [5]. The extracted values of the mean velocity are similar for the two models. From the data we can not tell whether this is accidental or the single-particle distributions are not sensitive to the freeze-out surface.

In summary, we report NA44 results on transverse mass spectra of pions, kaons, and protons from the symmetric system of 200A·GeV S+S and 158A·GeV Pb+Pb collisions.

While no collective effect is found in p+p reactions, collective transverse flow is clearly evident in the heavy-ion collisions. The strongest transverse flow is found in the Pb+Pb system. The reason for this trend is that a high nuclear stopping is reached in heavy-ion collisions and particles experience many collisions before they leave the system.

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FIGURES

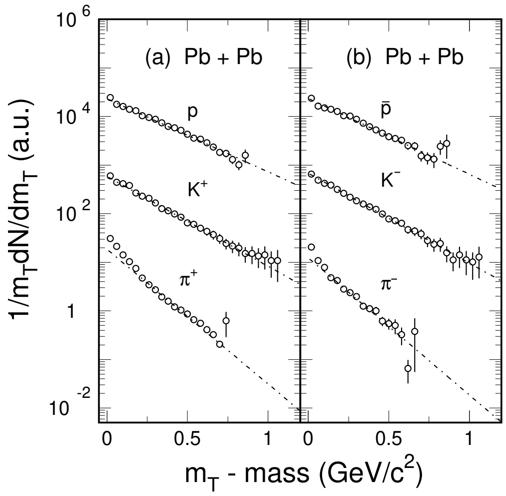

FIG. 1. Transverse mass distributions for pions, kaons, and protons from 158A·GeV Pb+Pb central collisions. Dashed lines represent the exponential fits.

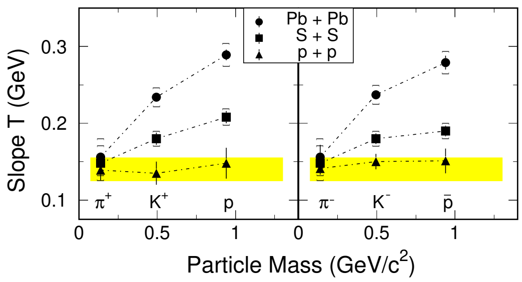

FIG. 2. Slope parameter T as a function of particle mass. The p+p results are taken from Refs. [16,17]. The systematic errors are shown by the vertical brackets. The shaded band shows the range where the slopes converge at zero mass.

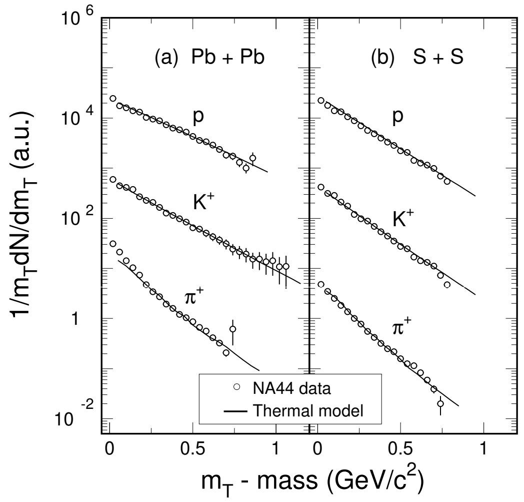

FIG. 3. Transverse mass distributions for pions, kaons, and protons (open circles) compared with results of a thermal model calculation (lines). Resonance decays are included in the pion spectra and resonance effects on kaon and proton spectra are neglected.