THERMAL HADRON PRODUCTION IN CENTRAL 4.2$\boldsymbol{A}$ GeV/$\boldsymbol{c}$ C+C AND C+Ta COLLISIONS

Lj. Simić, I. Mendaš and M. Kornicer

Institute of Physics, P.O. Box 68, 11080 Belgrade, Yugoslavia

(Received March 10, 2000)

The transverse mass and rapidity spectra of participant protons and negative pions in central C+C and C+Ta collisions at 4.2A GeV/c, have been interpreted, in the full phase space, on the basis of thermal model with assumption that several fireballs in relative motion are formed, and that each fireball represents a mixture of ideal relativistic gases of protons, pions and Δ resonances in thermal equilibrium. For adequate description of the particle spectra, the stopping and symmetry/asymmetry of the colliding system require three fireballs (two fragmentation and one central) in the case of C+C and two fireballs (fragmentation and central) in the case of C+Ta. By using the classical regime, we find that regardless of the colliding system, the freeze-out temperature of the fragmentation (central) fireballs is in the range 65–75 MeV (170–180 MeV), while the average relative velocity of the fragmentation fireball(s), with respect to the central one, is (0.55–0.60)c. Also, we find that (20–30)% of protons and (50–60)% of negative pions originate from Δ resonance decays.

PACS numbers: 25.75.–q, 25.75.Dw, 24.10.Pa

1. Introduction

Relativistic nucleus–nucleus collisions are a valuable tool to investigate hot and dense nuclear matter in the laboratory. Emerging protons, pions and other particles are, in principle, expected to contain information on the conditions at freeze-out giving in turn information on the degree of equilibration. To a certain extent, a model that assumes thermal (and also chemical) equilibrium can explain transverse mass and rapidity spectra, and also the various particle yield ratios [1–6]. Here, the transverse mass and rapidity spectra of participant protons and negative pions, from the 10 % most central C+C and C+Ta collisions at 4.2A GeV/c, are interpreted in the full phase space within the thermal model with the assumption that several fireballs in relative motion are formed.

Possible existence of several fireballs is generally indicated by the shape of the proton rapidity distributions in both symmetric, C+C, and asymmetric, C+Ta, collisions. It is found that these rapidity distributions are best fitted with the sum of several Gaussians, their number depending on the stopping power and the symmetry/asymmetry of the collision system [7]. The use of several Gaussians reflects strong deviations from the predictions of the single-fireball model. The simplest conceivable explanation of such experimental results appears to be the presence of several fireballs in relative motion. This last, in fact, emulates the longitudinal flow with added flexibility that the temperature is not necessarily the same in different fireballs. One additionally assumes that each fireball represents a mixture of ideal relativistic gases of protons, pions, and Δ resonances, in thermal equilibrium and all sharing the same fireball volume.

The physical picture that we envisage in this approach, takes into account mainly the participant protons (nucleons). The spectators, which did not collide with other nucleons at all, suffer only a small energy and momentum transfer and therefore are of little interest. In the case of symmetric collisions (such as C+C) there will be, for a given impact parameter, an overlap between the target and the projectile. After collision, the overlapping regions fuse together and partially come to rest in the center-of-mass frame. The halted region subsequently forms the central fireball. The two broken off parts continue in their paths after collision with reduced momentum and with a smaller amount of initial collision energy. These eventually create the two fragmentation fireballs. In central collisions of an asymmetric system (such as C+Ta), the smaller projectile nucleus penetrates right trough the target, forming in the process the early stage of the central fireball. The target and/or projectile participant nucleons left behind lead subsequently to the only one, slower, fragmentation fireball. Thus one expects, for an asymmetric system and central collisions, only two fireballs.

In the case of central C+Ta and C+C collisions at $4.2A$ GeV/c, we find that within such few-fireball model, and using additionally the classical regime, one is able to obtain good overall agreement between the model and experimental data simultaneously for protons and negative pions by adjusting four independent fitting parameters. These parameters are the freeze-out temperatures, T_1 and T_2, and the average fireball rapidities, y_1 and y_2.

2. Spectra from a stationary thermal sources

Transverse mass, m_{T}, and rapidity, y, spectra of particles radiated by stationary thermal source — fireball with temperature T are described in the classical regime with equations

$$\frac{dN^{\rm th}}{m_{\rm T}dm_{\rm T}} = \frac{2gCm_{\rm T}}{(2\pi)^2}K_1\Big(\frac{m_{\rm T}}{T}\Big) \equiv F^{\rm th}(g,C,m_{\rm T},T)\,, \tag{1}$$

and

$$\begin{aligned}\frac{dN^{\rm th}}{dy} &= \frac{gCT^3}{(2\pi)^2}\Big(\frac{m^2}{T^2}+\frac{2m}{T\cosh y}+\frac{2}{\cosh^2 y}\Big)\exp\Big(-\frac{m}{T}\cosh y\Big)\\ &\equiv G^{\rm th}(g,C,m,T,y)\,, \end{aligned}\tag{2}$$

where g is the degeneracy factor for the particle species, $C = V{\rm e}^{\mu/T}$, V is the fireball volume at freeze-out, and μ is the chemical potential. The total number of particles, N, of given species present in the fireball, and the total energy E, of all particles of given species, in the fireball rest frame are:

$$N^{\rm th} = \frac{gCTm^2}{2\pi^2}K_2\Big(\frac{m}{T}\Big) \equiv C\mathsf{N}(g,T,m)\,, \tag{3}$$

$$E^{\rm th} = \frac{gCT^2m^2}{2\pi^2}\Big[\frac{m}{T}K_3\Big(\frac{m}{T}\Big) - K_2\Big(\frac{m}{T}\Big)\Big] \equiv C\mathsf{E}(g,T,m)\,, \tag{4}$$

where $K_i(x)$ with i=1, 2 and 3 denote the modified Bessel functions. The Eqs. (1)–(4) are basic for the thermal model, and determine kinematical characteristics of hadrons at the freeze-out point, whether they are stable (on the strong interaction scale) or excited resonances. However, before reaching detector the resonances decay completely into lower mass hadrons. The kinematical characteristics of these decay products are different from kinematical characteristics of thermal particles. This posed the problem to calculate from a given resonance distributions (Eqs. (1), (2)), the distributions, $dN^{\rm dec}/dm_{Ti}^2$, $dN^{\rm dec}/dy_i$ of particular decay particle. A general treatment of this problem for two- and three-body decay was presented in [8]. Here we give only the final equations for transverse mass and rapidity distributions, in the fireball rest frame, for the particle originating from the two-body decay

$$\begin{aligned}\frac{dN^{\rm dec}}{m_{\rm T}dm_{\rm T}} &= \frac{bg_{\rm R}C^{\rm R}m_{\rm R}}{4\pi^3p^*}\int\limits_{\tilde y_{\rm R}^{(-)}}^{\tilde y_{\rm R}^{(+)}} d\tilde y_{\rm R}\frac{1}{\sqrt{m_T^2\cosh^2\tilde y_{\rm R}-p_{\rm R}^2}}\\ &\quad\times\int\limits_{m_{T_{\rm R}}^{(-)}}^{m_{T_{\rm R}}^{(+)}} dm_{T_{\rm R}}\frac{m_{T_{\rm R}}^2K_1\Big(\frac{m_{T_{\rm R}}}{T}\Big)}{\sqrt{(m_{T_{\rm R}}^{(+)}-m_{T_{\rm R}})(m_{T_{\rm R}}-m_{T_{\rm R}}^{(-)})}}\\ &\equiv bF^{\rm dec}(g_{\rm R},C^{\rm R},m_{\rm R},m_{\rm T},T)\,, \end{aligned}\tag{5}$$

$$\frac{dN^{\rm dec}}{dy} = \frac{bg_{\rm R}C^{\rm R}m_{\rm R}}{8\pi^3 p^*}\int\limits_{m}^{\infty} m_{\rm T}dm_{\rm T}\int\limits_{\tilde{y}_{\rm R}^{(-)}}^{\tilde{y}_{\rm R}^{(+)}}\frac{\cosh(y_{\rm R})dy_{\rm R}}{\sqrt{m_T^2\cosh^2(y-y_{\rm R})-p_{\rm T}^2}}$$

$$\times\int\limits_{m_{T_{\rm R}}^{(-)}}^{m_{T_{\rm R}}^{(+)}}\frac{dm_{{\rm T}_{\rm R}}m_{T_{\rm R}}^2}{\sqrt{(m_{T_{\rm R}}^{(+)}-m_{{\rm T}_{\rm R}})(m_{{\rm T}_{\rm R}}-m_{T_{\rm R}}^{(-)})}}e^{-\frac{m_{{\rm T}_{\rm R}}}{T}\cosh(y_{\rm R})}$$

$$\equiv bG^{\rm dec}(g_{\rm R},C^{\rm R},m_{\rm R},y,T)\,. \tag{6}$$

In Eqs. (5) and (6), the quantities

$$y_{\rm R}^{(\pm)} = y \pm ln[(\sqrt{E^{*2}+p_{\rm T}^2}+p^*)/m_{\rm T}]\,,$$

and

$$m_{T_{\rm R}}^{(\pm)} = \frac{m_{\rm R}\left[E^*m_{\rm T}\cosh(y-y_{\rm R}) \pm p_T\sqrt{E^{*2}+p_T^2-m_T^2\cosh^2(y-y_{\rm R})}\right]}{m_T^2\cosh^2(y-y_{\rm R})-p_{\rm T}^2},$$

are the limits of the kinematically allowed rapidity and $m_{\rm T}$ ranges for the resonance, p^* and E^* are the momentum and the energy of the particle in the resonance rest frame, and $\tilde{y}_{\rm R}^{(\pm)} = y_{\rm R} - y$ (henceforth the subscript or superscript R refers to variables related to the resonance). The number of particles from resonance decay is $N^{\rm dec} = bN_{\rm R}$, where $N_{\rm R}$ is the total number of produced resonances at temperature T given by Eq. (3), and b is the branching ratio of the considered decay, multiplied with the Clebsch–Gordan coefficient. The total average energy of particles from resonance decays, $E^{\rm dec}$, in the fireball rest frame is $E^{\rm dec} = bE_{\rm R}E^*/m_{\rm R}$, where $E_{\rm R}$ is the total average energy of resonances given by Eq. (4). For simplicity we omit the summation in Eqs. (5) and (6), and also in the expressions for $N^{\rm dec}$ and $E^{\rm dec}$, over all resonance states contributing to multiplicity of considered particle species. Throughout this paper, we consider the simplest case when only one kind of resonances is produced. Finally, the resulting transverse mass and rapidity distributions are obtained by adding Eqs. (1) and (5), and Eqs. (2) and (6), respectively. The total number of particles of given species, $N = N^{\rm th} + N^{\rm dec}$, and total energy of particles in the fireball rest frame, $E = E^{\rm th} + E^{\rm dec}$ are determined similarly.

In the case of several fireballs (say three, for definitiveness), their rectilinear motion, viewed from a given ("laboratory") frame, is specified by the rapidity parameters y_i, with $i = 1, 2$ and 3. These rapidities are related to the corresponding fireball speeds β_i in the lab frame via $y_i = \tanh^{-1}\beta_i$. In each fireball one treats different particle species, protons, negative pions, and Δ's, as a mixture of ideal relativistic gases sharing the same volume. Under the assumption of thermal equilibrium, (in each fireball but not between them) the resulting transverse mass and rapidity distributions for a given particle species are (*cf.* Eqs. (1) and (5))

$$\frac{dN}{m_{\mathrm{T}}dm_{\mathrm{T}}} = \sum_{i=1}^{3}\Big[F^{\mathrm{th}}(g, C_i, m_{\mathrm{T}}, T_i) + bF^{\mathrm{dec}}(g_{\mathrm{R}}, C_i^{\mathrm{R}}, m_{\mathrm{T}}, T_i)\Big], \tag{7}$$

and analogously (*cf.* Eqs. (2) and (6))

$$\frac{dN}{dy} = \sum_{i=1}^{3}\Big[G^{\mathrm{th}}(g, C_i, m, T_i, y-y_i) + bG^{\mathrm{dec}}(g_{\mathrm{R}}, C_i^{\mathrm{R}}, m_{\mathrm{R}}, T_i, y-y_i)\Big]. \tag{8}$$

The quantities such as degeneracy factor, mass and chemical potential are specific to each particle species, while it is assumed that the volumes V_i and temperatures T_i of the fireballs are common to all particle species. These quantities, if not Lorentz invariant, are all measured with respect to the rest frame of the corresponding fireball. Average total number of particles of given species in all three fireballs is invariant quantity and is given by (*cf.* Eq. (3))

$$N^{\mathrm{tot}} = \sum_{i=1}^{3}\Big[C_i\mathsf{N}(g, T_i, m) + bC_i^{\mathrm{R}}\mathsf{N}(g_{\mathrm{R}}, T_i, m_{\mathrm{R}})\Big]. \tag{9}$$

The corresponding total energy in the lab frame is (*cf.* Eq. (4))

$$E_{\mathrm{lab}}^{\mathrm{tot}} = \sum_{i=1}^{3}\gamma_i\left[C_i\mathsf{E}(g, T_i, m) + bC_i^{\mathrm{R}}\mathsf{E}(g_{\mathrm{R}}, T_i, m_{\mathrm{R}})\frac{E^*}{m_{\mathrm{R}}}\right], \tag{10}$$

where $\gamma_i \equiv (1-\beta_i^2)^{-1/2}$. For a symmetric collision system (such as C+C), the kinematic symmetry requires equality of the relative speeds of the two fragmentation fireballs (with respect to the central fireball). Since rapidities add under collinear boosts, one finds $y_3 = 2y_2 - y_1$. Also by symmetry $T_1 = T_3$, $\mu_1 = \mu_3$, $V_1 = V_3$ so that $C_1 = C_3$ and $C_1^{\mathrm{R}} = C_3^{\mathrm{R}}$. In central collisions of an asymmetric system (such as C+Ta), one expects only two fireballs [7] and in Eqs. (7)–(10) one simply drops the contribution from the third fireball. Therefore, for both symmetric and asymmetric collision systems the unknown parameters are: the average fireball rapidities y_1 and y_2, the freeze-out temperatures T_1 and T_2, and the positive constants C_1 (C_1^{R}), and C_2 (C_2^{R}).

In order to reduce the number of free parameters we start with a simple hadrochemical composition of the fireball by assuming that among the resonance states only the $\Delta(1232)$ is excited. This is a rough approximation, but good enough for estimating the influence of resonances on the temperatures, and on m_{T} and y distributions in the few-fireball model. Since there is one chemical potential for each conservation law, and since the baryon number conservation implies baryon chemical potential, we further assume equality of chemical potentials of protons and Δ resonances, $\mu_p{=}\mu_\Delta$. This also implies that $C^p = C^\Delta$ and in that case y_1, y_2, T_1 and T_2 is a minimal set of independent fitting parameters in the model, for both C+C and C+Ta collisions. The positive constants for protons (C_1^p, C_2^p) and negative pions ($C_1^{\pi^-}$, $C_2^{\pi^-}$) are not independent since equations (9) and (10) for their total multiplicity and energy form a system of four linear equations. For a given y_1, y_2, T_1 and T_2, the solution determines uniquely all normalization constants.

Finally, the transverse mass and rapidity distributions, Eqs. (7) and (8), are written down for each particle species. These distributions all depend on the same four fitting parameters, y_1, y_2, T_1 and T_2, since the latter are (by assumption) the fireball attributes and are not specific to the particle species. By minimising the corresponding overall χ^2, we find the values of the four fitting parameters which lead to the best agreement between all, model and experimental, transverse mass and rapidity distributions, simultaneously for all particle species.

3. Results and discussion

In this paper we interpret the transverse mass and rapidity spectra of participant protons and negative pions in 4.2A GeV/c central C+C and C+Ta collisions. The two data sets, consisting of 7327 C+C, and 1989 C+Ta inelastic events, are obtained with the 2-m propane bubble chamber exposed at the JINR Dubna synchrophasotron. The events with the largest multiplicity of secondary particles corresponding to $\approx 10\%$ cross section cut, are classified as central. The chamber allows measurement of multiplicity and momenta of negative pions and protons. All recorded negative particles, except the identified electrons, are taken to be π^- mesons. The contamination by unidentified fast electrons and negative strange particles is estimated to 5% and 1% of the pion multiplicity respectively. All positive particles with momenta less than 0.5 GeV/c are classified either as protons or π^+ mesons according to their ionisation density and rang. Positive particles above 0.5 GeV/c are taken to be protons, and subsequently the admixture of π^+ of about 18% (7%) in C+C (C+Ta), due to this, is subtracted statistically using the π^+ and π^- momentum distributions. From the resulting number of protons, the projectile spectator protons (with momenta > 3 GeV/c and emission angle $\theta < 4^0$) and target spectator protons (with momenta < 0.3 GeV/c) are further subtracted. The resulting number of participant protons still contains some 4% (16%) of deuterons (with momenta > 0.48 GeV/c) which are subtracted statistically. The admixture of tritons, with momenta > 0.65 GeV/c is not considered. Further details concerning the measurement, identification and corrections due to particle loss, are given in [7, 9, 10].

The results of the three-fireball (one central and two fragmentation) calculation for C+C central collisions are shown by the solid lines in Fig. 1. Similarly, the results of the two-fireball model calculation for C+Ta central

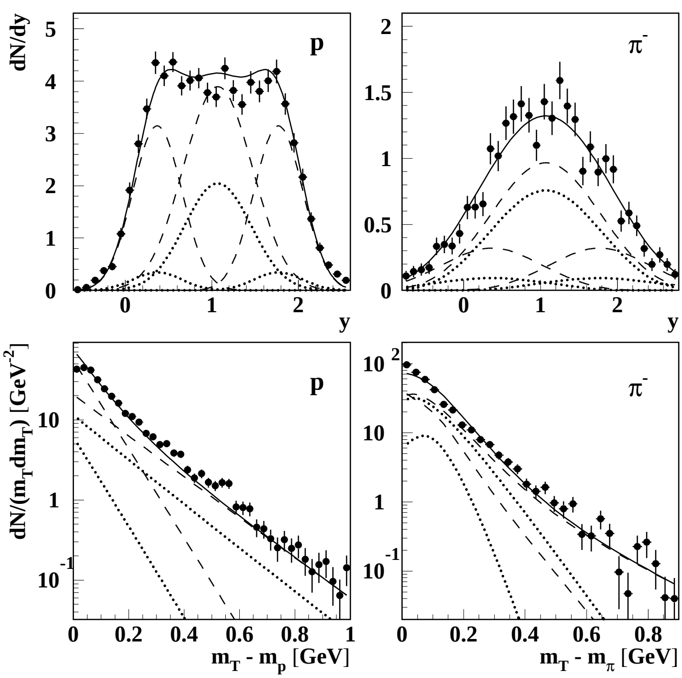

Fig. 1. The rapidity (top) and transverse mass spectra (bottom) of protons and negative pions in central C+C collisions. The solid lines represent the three-fireball model calculations for the values of fitted parameters given in Table II. The dashed lines represent fireball contributions, while dotted lines represent the spectra of particles from Δ decays in each of the fireballs.

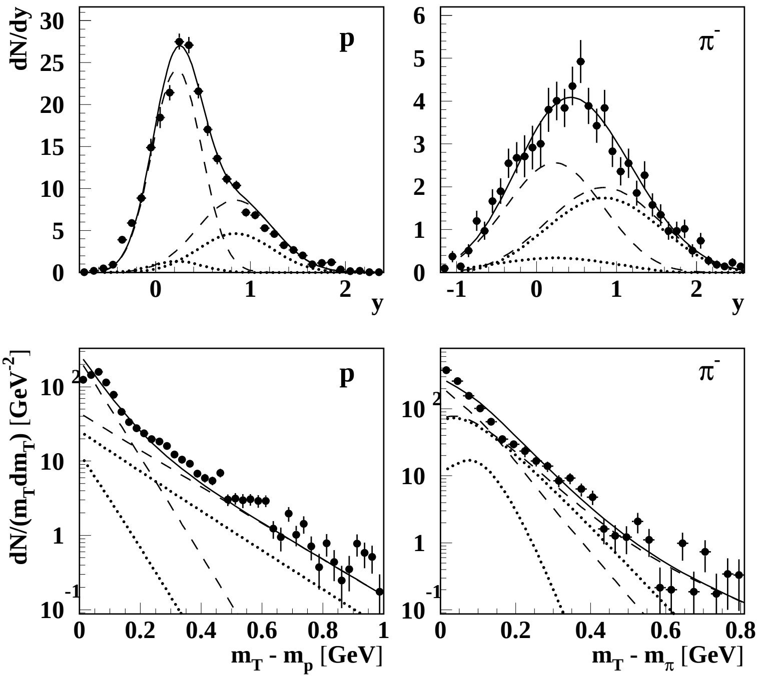

Fig. 2. The same as Fig. 1, but for central C+Ta collisions

collisions are shown in Fig. 2. The best-fit parameters are obtained from simultaneous fit to all four, transverse mass and rapidity, spectra of both protons and negative pions by minimizing the overall χ^2. and with the help of the experimentally determined $N^{\rm tot}$ and $E_{\rm lab}^{\rm tot}$ given in the Table I.

TABLE I

Total multiplicity and energy of participant protons and negative pions in central C+C and C+Ta collisions.

	C + C		C + Ta	
	p	π^-	p	π^-
$N^{\rm tot}$	8.26 ± 0.06	2.73 ± 0.06	24.2 ± 0.3	7.3 ± 0.2
$E_{\rm lab}^{\rm tot}$ (GeV)	17.6 ± 0.2	1.68 ± 0.04	31.7 ± 0.3	2.83 ± 0.09

The best-fit parameters, with their uncertainties at 90 % confidence limits, and the corresponding constants, which provide the correct normalization of the model spectra are given in Table II. The normalization constants are extremely sensitive to small changes in the values of the corresponding fitting parameters so that C_i quoted in Table II represent only the order of magnitude estimates. The values of the fireball rapidities, given in Table II, imply the average relative velocity $\beta = \pm 0.60$, for C+C, and $\beta = 0.55$, for C+Ta, of fragmentation fireball(s) with respect to the central one. The contributions of the fireballs to the resulting transverse mass and rapidity spectra are also shown in Figs. 1 and 2 by the dashed lines. According to the fit, in the case of C+C (C+Ta) collisions, the central fireball provides $\approx 50\%$ ($\approx 35\%$) of the total number of protons and $\approx 60\%$ ($\approx 45\%$) of the total number of π^- mesons, while fragmentation fireballs provide the rest. The dotted lines in Figs. 1 and 2 represent the rapidity and transverse mass spectra of protons and negative pions, originating from Δ resonance decays, in each of the fireballs. The contributions of the protons and pions from Δ resonance decays to their total multiplicity in each of the fireballs are given in Table III. These yields are calculated under the assumption of isosymmetry of the system and are determined with the help of the normalization constants and decay probabilities $b_{\Delta\to p}$=1/2, $b_{\Delta\to\pi^-}$=1/3. The asymmetry between neutrons and protons in C+Ta collisions causes unequal production of different isospin Δ states, but does not change essentially the values of the fitting parameters. It affects only yields of particles from Δ decays in a way that they become closer to the values obtained for C+C collisions. From the

TABLE II

Temperatures T, fireball rapidities y, all at 90 % confidence level, and normalization constants obtained from simultaneous fit of proton and negative pion transverse mass and rapidity spectra in central C+C and C+Ta collisions. For C+C collisions the kinematical symmetry requires equality of temperatures and normalization constants for the fragmentation fireballs, while $y_3 = 2y_2 - y_1 = 1.77 \pm 0.05$.

	C + C		C + Ta	
	Fragmentation	Central	Fragmentation	Central
T (MeV)	73 ± 7	176 ± 10	64 ± 5	179 ± 13
y (lab)	0.37 ± 0.03	1.07 ± 0.01	0.23 ± 0.02	0.84 ± 0.04
C^p (fm^3)	$2. \times 10^6$	$2. \times 10^2$	$1. \times 10^8$	$5. \times 10^2$
C^{π^-} (fm^3)	$1. \times 10^2$	6.	$2. \times 10^3$	4.
χ^2/NDF	2.4		3.9	

TABLE III

Relative multiplicity of particles from resonance decays in each of the fireballs, and summed over all fireballs.

		Fragmentation fireball	Central fireball	Summed over all fireballs
C+C	p	0.09	0.51	0.28
	π^-	0.28	0.77	0.58
C+Ta	p	0.06	0.53	0.23
	π^-	0.15	0.91	0.49

values quoted in Table III we see that particles from Δ decays contribute mostly to the central fireball. The contributions of protons and pions from Δ decays to the total multiplicity, summed over all fireballs, are also given in Table III. Calculations show that in C+C (C+Ta) collisions 28% (23%) of protons and 58% (49%) of negative pions originate from Δ resonance decays. Next we examine the influence of Δ resonance decays on the hadronic spectra within one fireball, and also within several fireballs. The spectra of particles from Δ decays, and spectra of directly emitted thermal particles, with the relative normalization corresponding to the central fireball in C+C collisions (see Table III) are plotted in Fig. 3.

For comparison, the resulting spectra normalized to unity, are shown additionally. For both thermal particles and particles from Δ decays, the rapidity distributions are Gaussians of similar width, and this explains the small influence of the resonance decays on the shape of resulting rapidity distributions in the single fireball. Also, the m_{T} distributions of thermal protons and protons from Δ decays have similar slopes. This is because the proton is the massive daughter in the Δ decay modes, with the mass close to its parent, and its momentum is strongly correlated with the momentum of its parent. Hence, the Δ resonance production does not affect the shape of the final proton m_{T} spectra. Contrary to the protons, the slope of the m_{T} distribution of pions from Δ decays is steeper than the slope of the m_{T} distribution of direct thermal pions. The kinematics of Δ decay focuses π^- mesons at low p_{T}, leading to the two-component structure in the resulting m_{T} distribution from the single fireball. Summed over all fireballs, the transverse mass and rapidity distributions of particles from resonance decays and direct thermal particles are plotted in Figs. 4 and 5. In the rapidity space, the protons originating from Δ decay are dominant in central rapidity region, while direct thermal protons are dominant in fragmentation region(s). As in the case of single fireball, the influence of Δ resonances on

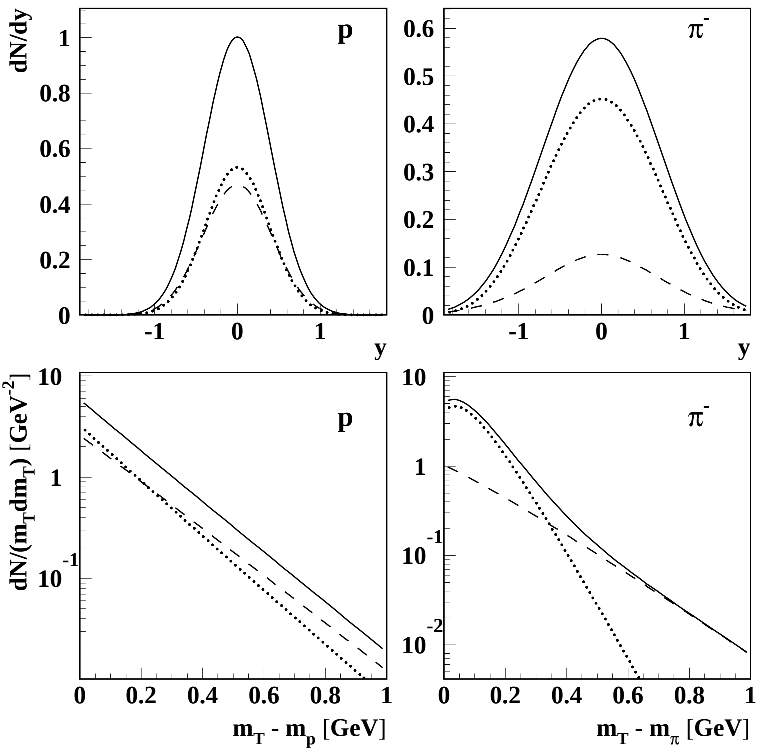

Fig. 3. The rapidity and transverse mass spectra of protons and negative pions emitted from stationary thermal source at temperature $T = 176$ MeV, normalized to unity (full lines). The dashed lines represent spectra of direct thermal particles while dotted lines represent spectra of particles from Δ decays, with the relative contributions quoted in Table III.

the proton m_{T} spectra is not significant. The negative pions from Δ decay are populated mostly in the central rapidity region, while in the m_{T} space, they fall in the range of low values of transverse mass ($m_{\mathrm{T}} < 0.5$ GeV). Consequently, the contributions of the fireballs and resonance decays are combined in a way that the resulting transverse mass distribution of protons and negative pions is reproduced approximately with two decreasing exponential functions [9,10]. Also, the final rapidity distribution of negative pions is single Gaussian [10], while the proton rapidity distribution is the sum of three (two) Gaussians [7].

In the case of central C+C and C+Ta collisions at $4.2A$ GeV$/c$, the thermal few-fireball model with included resonance decays is able to capture the main features of the experimental transverse mass and rapidity spectra, simultaneously for protons and negative pions. This indirectly indicates that

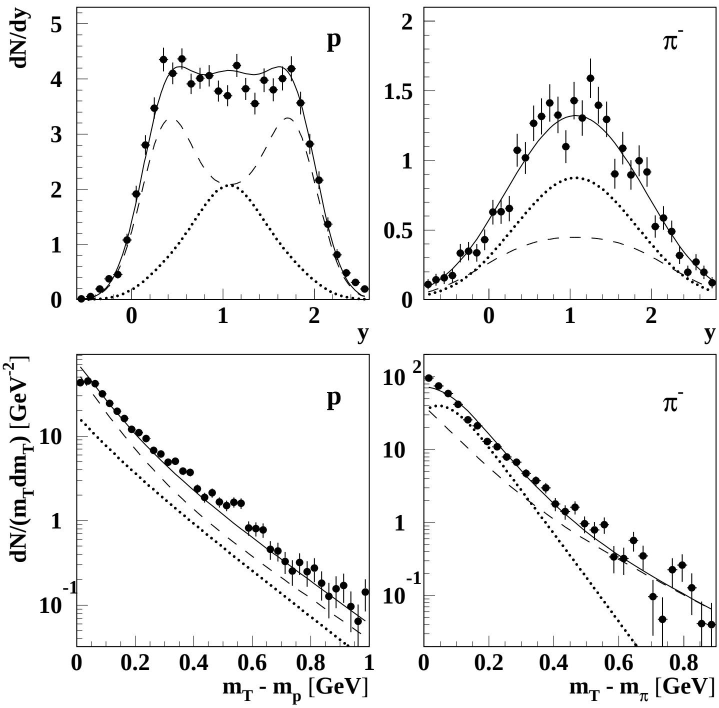

Fig. 4. The rapidity and transverse mass spectra of direct thermal particles (dashed lines), and particles from Δ decays (dotted lines) summed over all three fireballs in central C+C collisions.

the early stages of the fireballs separate before the thermal equilibrium has been established, and that subsequently at least partial thermal equilibrium is attained, on the short time scales available, separately in each fireball. The agreement between the model and data is good, despite the fact that in the finite fireball volume and during its short lifetime, the thermal equilibrium can only be approximately achieved. Also, the calculations within thermal few-fireball model suggest that resonance decays are necessary ingredient for any thermal model. Numerous thermal analyses [1, 2, 4, 5] of hadron production in heavy ion collisions, include contributions of all resonances with masses up to about 2 GeV. In this analysis among the resonance states we assume only the $\Delta(1232)$ which dominate at this energy. Since the inclusion of the $\Delta(1232)$ entails only a small change of the fit parameters (compared to the values obtained in the case of the stable hadronic gas), and provides at the same time a better description of all hadronic spectra, we can expect that the inclusion of the other resonance states would not significantly change the obtained results.

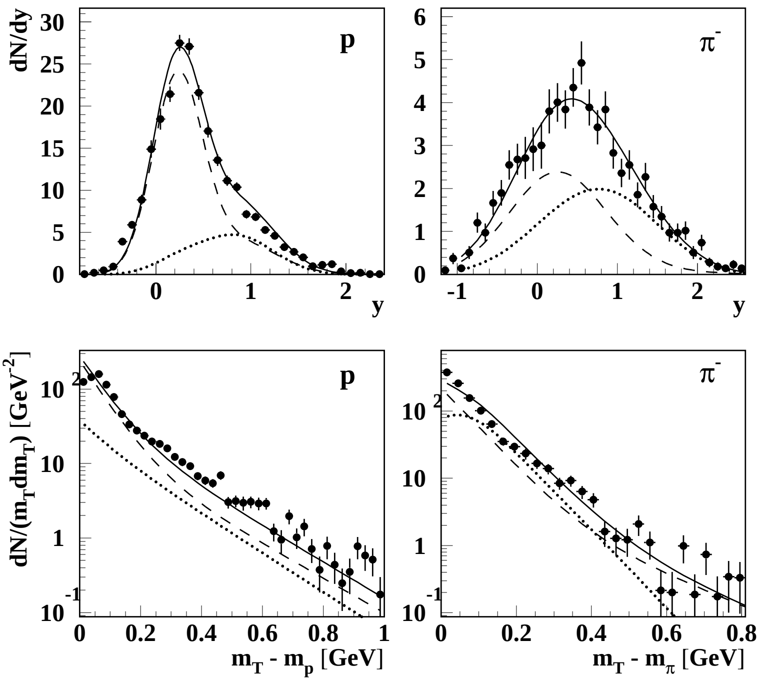

Fig. 5. The same as Fig. 4, but for central C+Ta collisions

The complete analysis of this data in terms of a realistic model would require to take into account the radial transversal flow. However, the introduction of this flow into the few fireball calculation would not lead to a unique combinations of the fitting parameters since the fit of the p_{T} spectra only, within the thermal blast model [11], reveals that there are different combinations of the temperature and radial flow velocity leading to a good agreement with the measured p and π^- spectra in central C+C and C+Ta collisions. The fireball temperatures obtained in our approach are their upper bounds, since the introduction of the radial flow necessarily reduces the temperatures, as compared to a static thermal scenario.

In summary, we have used a simple thermal few-fireball model that includes resonance decays in order to interpret the transverse mass and rapidity distributions of participant protons and negative pions in the 10 % most central C+C and C+Ta collisions at 4.2A GeV/c. The model is essentially based on two assumptions. First is the presence of several fireballs (two in the case of C+Ta, and three in the case of C+C) in relative motion. Second is that each fireball represents a mixture of ideal relativistic gases of protons, pions, and Δ resonances in the classical regime, in thermal equilibrium and sharing the same volume. We find that this is the minimal set of assumptions needed to describe well the basic features of the experimental transverse mass and rapidity spectra for protons and negative pions, for both symmetric and asymmetric colliding systems. We estimate that for protons and negative pions, regardless of the colliding system the freeze-out temperature of the fragmentation fireball(s) is in the range 65–75 MeV, and that the freeze-out temperature of the central fireball is in the range 170–180 MeV. The average relative velocity of the fragmentation fireball(s), with respect to the central one, is (0.55–0.60)c. According to this thermal model, (20–30)% of protons and (50–60)% of negative pions originate from Δ decays. The resonances are necessary ingredient of thermal model that provides a good description of all hadronic spectra. The satisfactory agreement between the model and the somewhat limited experimental data does not support conclusively that the thermal equilibrium is achieved in each fireball separately, with different freeze-out temperatures, since there exists a possibility that the fireballs partially overlap in the momentum and in the configuration space as well.

REFERENCES

[1] E. Schnedermann, J. Sollfrank, U. Heinz, *Phys. Rev.* **C48**, 2462 (1993).

[2] P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, *Phys. Lett.* **B344**, 43 (1995); *Phys. Lett.* **B365**, 1 (1996).

[3] F. Becattini, *J. Phys. G* **23**, 1933 (1997); F. Becattini, M. Gaździcki, J. Sollfrank, *Eur. Phys. J.* **C5**, 143 (1998).

[4] J. Sollfrank, U. Heinz, H. Sorge, N. Xu, *Phys. Rev.* **C59**, 1637 (1999).

[5] J. Cleymans, A. Keränen, M. Marais, E. Suhonen, *Phys. Rev.* **C56**, 2747 (1997); J. Cleymans, D. Elliott, A. Keränen, E. Suhonen, *Phys. Rev.* **C57** 3319 (1998).

[6] J.R. Nix, *Phys. Rev.* **C58**, 2303 (1998).

[7] Lj. Simić, M. Kornicer, *Phys. Rev.* **C58** 2585 (1998).

[8] J. Sollfrank, P. Koch, U. Heinz, *Phys. Lett.* **B252**, 256 (1990).

[9] S. Backović, D. Salihagić, Lj. Simić, D. Krpić, S. Drndarević, R.R. Mekhdiyev, A.P. Cheplakov, H.N. Agakishiev, E.N. Kladnitskaya, S.Yu. Sivokolov, *Phys. Rev.* **C46**, 1051 (1992).

[10] Lj. Simić, S. Backović, D. Salihagić, A.P. Cheplakov, E.N. Kladnitskaya, R.R. Mekhdiyev, *Phys. Rev.* **C52**, 356 (1995).

[11] P.J. Siemens, J.O. Rasmussen, *Phys. Rev. Lett.* **42**, 880 (1979).