The reconstructed final state of $Au + Au$ collisions from PHENIX and STAR data at $\sqrt{s} = 130$ AGeV - indication for quark deconfinement at RHIC

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Abstract. The final state of $Au + Au$ collisions at $\sqrt{s} = 130$ AGeV at RHIC has been reconstructed within the framework of the Buda-Lund hydrodynamical model, by performing a simultaneous fit to final data on two-particle Bose-Einstein correlations of the STAR and PHENIX Collaborations, and final identified single particle spectra as measured by the PHENIX Collaboration. The results indicate a strongly three dimensional expansion, with a four-velocity field that is almost a spherically symmetric Hubble flow. We find large transverse geometrical source sizes, $R_G = 9.8 \pm 1.2$ fm, relatively short mean freeze-out time, $\tau_0 = 6.1 \pm 0.3$ fm/c and a short duration of particle emission, $\Delta \tau = 0.02 \pm 1.5$ fm/c. Most strikingly, we find an indication for a hot central part of the hydrodynamically evolving core, characterized by a central temperature of $T_0 = 202 \pm 13$ MeV, that is close to (or even above) the deconfinement temperature of the quark-hadron phase transition. The best fit indicates a cold surface temperature of $T_s = 110 \pm 16$ MeV. When the possibility of the hot center is excluded, the confidence level of the fit decreases from 28.9% to 1.0%. Predictions are made for the rapidity dependence of the slope parameters and for the transverse mass dependence of the rapidity width of the single particle spectra, and the transverse velocity dependence of the non-identical particle correlations.

Keywords: Heavy ion collisions, correlations, flow, quark-gluon plasma search

PACS: 24.10.Nz, 25.75.-q, 25.75.Ld, 47.15.Hg
1. Introduction

The reconstruction of hadronic final state from the measured single particle spectra and two-particle correlation functions is of great current research interest in high energy heavy ion collisions. The goal of these studies is to characterize the final state with the help of a few simple parameters like the mean freeze-out temperature or the mean transverse flow, or the geometrical size of the system at the mean freeze-out time. From the properties of the hadronic final states, one aims to identify one (or more) new phases of hot and dense hadronic matter in the collisions of the biggest nuclei at the highest available bombarding energies.

Space-time picture reconstruction of particle emitting sources in high energy physics is based on improved methods of intensity interferometry, a technique invented originally by the radio astronomers R. Hanbury Brown and R. Q. Twiss [1] to measure the angular diameter of main sequence stars. Intensity correlations in high energy physics are measured in momentum space, in contrast to stellar intensity interferometry, where the correlations are determined in the coordinate space. Intensity correlations of identical particles appear due to quantum statistics as well as Coulomb and strong final state interactions. Dominated by quantum statistical effects, correlations of identical bosons are frequently referred to as Bose-Einstein correlations (and the name of fermionic correlations is Fermi-Dirac correlations). The radius parameters of the two-particle Bose-Einstein correlation functions are frequently referred to as HBT radii to honor Hanbury Brown and Twiss. In particle physics, correlations of pions with small opening angles were observed first by G. Goldhaber, S. Goldhaber, A. Pais and W. Lee, [2] hence they are also referred to as GGLP correlations.

Our tool for the space-time picture reconstruction is the Buda-Lund hydro (BL-H) model, introduced in refs. [3, 4] and reviewed recently in ref. [5]. See also refs. [6, 7, 8] for recent reviews on particle interferometry in high energy physics.

First of all, let us remind the readers about the difficulty of the interpretation of the experimental data on correlations and spectra in high energy heavy ion collisions. High expectations seem to exist each time, when a new accelerator starts its data taking. Our hopes suggest that we enter a whole new land to explore, and we tend to forget about the landscape that we have just left behind.

Let us remember, that the “RHIC HBT puzzle” [9] is in fact not a RHIC specific phenomena: a similar discrepancy between predictions and final data prevailed already at CERN SPS, see refs. [10, 11]. Essentially, the RHIC HBT puzzle is that the ratio of the outward and the sideward HBT radii was measured to be $R_o/R_s \approx 1.0$, see refs. [12, 13, 14], and this result was in contrast to certain theoretical expectations. The “CERN SPS HBT puzzle” could be similarly formulated: Why the difference between the outward and the sideward HBT radii is zero at CERN SPS? This question can be based on Fig. 4 of ref. [10], see ref. [15] for the most recent data with such a behavior in Pb+Pb collisions at CERN SPS, valid not only for pions but also for kaons. At CERN SPS, the situation seems to be strikingly similar to the happenings at RHIC. Perhaps the story at CERN SPS is so old by...
now, that its moral has been almost forgotten.

Apparently, failed predictions of the RHIC HBT data can be assigned to models that were not tuned to successfully describe the single particle spectra and the two-particle Bose-Einstein correlation functions at CERN SPS. On the other hand, models that worked well at CERN SPS describe RHIC spectra and HBT data rather well, see e.g. refs. [13, 14, 17, 18, 19, 20, 21].

There were two classes of predictions for the measurable HBT radius parameters in Au + Au collisions at RHIC. The predominant expectation was, that a soft, long lived, evaporative quark-gluon plasma phase will be produced, and the large duration of the particle emission can be observed from the big increase of the out component of the Bose-Einstein correlation functions, $R_{\text{out}} \gg R_{\text{side}}$, a phenomena first observed by S. Pratt in refs. [22, 23]. Similarly motivated calculations, with more realistic geometry and initial conditions were performed by Bertsch [24] and collaborators as well as by Gyulassy and Rischke [25].

However, there was another, less well known class of predictions for RHIC: instead of predicting $R_{\text{out}}/R_{\text{side}} \gg 1$, refs. [26, 3, 4] predicted $R_{\text{out}}/R_{\text{side}} \approx 1$. It is also mentioned there how the sudden freeze-out of hadrons is related to an explosive particle production from a supercooled quark-gluon plasma [24], or a quark matter [27], where the gluonic degrees of freedom are not active. Such a picture may emerge from a quasi-particle picture of a QGP, where the quarks and the gluons dress up in the vicinity of the phase transition, the constituent quark mass being of the order of 300 MeV, with a gluon mass $m_g \gg T_c$ [28]. The sudden, explosive particle production, the hard equation of state and the quark combinatorics of particle yields [29] support such a scenario at RHIC.

As the characteristic nucleation times of hadronic bubbles inside a quark gluon plasma are of the order of 100 fm/c, which is an order of magnitude larger than the characteristic life-time of the expanding system, bubble formation is not fast enough to keep the system close to the Maxwell construction and near-equilibrium phase transition. Instead, a negative pressure state developes very soon which then decays due to its mechanical instability, the cavitation. Such process may happen through a time-like deflagration and a process was predicted to end in a pion flash, with a short, 1-3 fm/c duration of particle emission. See ref. [23] for greater details and signatures of this process.

In this manuscript, we present an indication for the existence of a transient quark matter state at RHIC1.

The structure of the body of the paper is as follows. In section 2, we highlight the most important fitting formulas of the BL-hydro model. In section 3, the fits to the single particle spectra and the two-particle Bose-Einstein correlation functions are shown. In section 4 we summarize the results, and discuss their interpretation of the results and the correlations between the various fitting parameters. In section 5 we predict the rapidity dependence of the observables. We also make a prediction for the transverse mass, and rapidity dependence of non-identical particle correlation functions. Finally, we conclude.
2. Single particle spectra and two particle correlations from the Buda-Lund hydro model

Our direct aim is to reconstruct the hadronic final state from the measurable single-particle spectra and two-particle correlation functions. From this reconstructed final state and the knowledge of the equation of state of hot and dense hadronic matter (e.g., from lattice QCD calculations) one can, in principle, reconstruct the initial state of the reaction by running the (relativistic) hydrodynamical equations backwards in time, and determine if this initial state had been in the QGP phase or not. Here we report on such a direct reconstruction of the hadronic final state within the framework of the Buda-Lund hydro (BL-H) model, but we do not consider the more indirect reconstruction of the initial state.

The BL-H model is a hydrodynamical parameterization of the hadronic final state, that has to be clearly distinguished from a fully developed, time dependent solution of relativistic hydrodynamics. However, the BL inspired a whole new series of non-relativistic and relativistic, simple analytic solutions of fireball hydrodynamics. The non-relativistic hydro solutions correspond to the non-relativistic limit of the BL hydro model, with time-dependent model parameters, \[30, 31, 32, 33, 34, 35\]. It is very interesting to note, that the governing equations for the scale parameters are similar to that of the Zimányi-Bondorf-Garpman hydrodynamical solution \[36\] and its ellipsoidally symmetric generalization \[37\].

However, in the relativistic domain, only the coasting (accelerationless) hydro solutions were found analytically until now \[38, 39, 40\], in an attempt to figure out the governing equations for the BL-H model parameters. Although Bjorken’s well known solution of relativistic hydrodynamics \[41\] belongs also to this class of accelerationless solutions, and the new coasting relativistic solutions include finite 1+1 dimensional solutions \[38\], 1+3 dimensional solutions with cylindrical \[39\] and ellipsoidal symmetry \[40\], the search is still going on for even more realistic, relativistic hydro solutions that can interpolate from the non-relativistic domain to the relativistic one even if the acceleration of the matter is significant.

Furthermore, the Buda-Lund flow profile, with a time-dependent radius parameter \(R_G\), was recently shown to be an exact solution of relativistic hydrodynamics of a perfect fluid at a vanishing speed of sound \[42\]. It turned out \[33, 34\], that the flow field is a generalized Hubble flow and the average transverse flow at the geometrical radius is formally similar to Hubble’s constant that characterizes the rate of expansion in our Universe, \(\langle u_t \rangle = \gamma_t R_G = \gamma_t H\) \[43\]. This emphasizes the similarity between the Big Bang of our Universe and the Little Bangs of heavy ion collisions.

The invariant single particle spectrum is obtained \[3, 5\] from BL-H as

\[
N_1(k) = \frac{d^3n}{2\pi m_1 dm_1 dy} = \frac{g}{(2\pi)^3 E V C} \exp \left( \frac{u^\mu(x) k^\mu}{T(x)} - \frac{\mu(x)}{T(x)} \right) + s, \quad (1)
\]

where all the terms have an intuitive, but mathematically well defined meaning,
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see ref. [5] for more detailed definitions. The invariant form of the two-particle Bose-Einstein correlation function (HBT) of the BL-H is found in the binary source formalism [44, 5] as:

\[ C_2(k_1, k_2) = 1 + \lambda_* \Omega(Q_{||}) \exp \left( -Q_{||}^2 \mathcal{R}_{||}^2 - Q_{||}^2 \mathcal{R}_{||} - Q_{||}^2 \mathcal{R}_{\perp} \right). \] (2)

The dependence of the fit parameters on the value of the mean momentum of the pair is suppressed, see ref. [5] for the complete set of definitions of the variables and the radius parameters in terms of the BL-H model parameters. The pre-factor \( \Omega(Q_{||}) \) of the BECF induces oscillations within the Gaussian envelope as a function of \( Q_{||} \). This oscillating pre-factor satisfies \( 0 \leq \Omega(Q_{||}) \leq 1 \) and \( \Omega(0) = 1 \). In practice, the period of oscillations is larger, than the corresponding Gaussian radius, so the oscillations are difficult to resolve. The above BL-H form of the two-particle correlation is explicitly boost-invariant, as all the relative momentum dependent variables \( Q_{||}, Q_{\perp} \) and all the corresponding radius parameters, \( \mathcal{R}_{||}, \mathcal{R}_{\perp} \), are defined in an explicitly boost invariant manner. The BL correlation function can be equivalently expressed in the frequently used, but not invariant Bertsch-Pratt (BP) form in the LCMS frame [46], within the \( \Omega = 1 \) approximation:

\[ C_2(k_1, k_2) = 1 + \lambda_* \exp \left[ -R_{||}^2 Q_{||}^2 - R_{||}^2 Q_{||} - R_{||}^2 Q_{\perp}^2 - 2 R_{||} Q_{\perp} Q_{\perp} \right]. \] (3)

The above formulas for the BECF and IMD, as were used in the fits, have been introduced in refs. [3, 4, 47, 17], and summarized recently in ref. [5]. The analytic formulas that relate the BL-H model parameters to the above forms for the spectra and correlation functions, are given by eqs. (84-105), (115-118) and (129-140) of ref. [5]. Note, however, that eq. (132) of ref. [5] contains an unfortunate misprint, \( \langle u_t \rangle + \langle \Delta T/T \rangle \) in the denominator should be replaced by \( \langle u_t \rangle^2 + \langle \Delta T/T \rangle^2 \), so the correct form of eq. (132) of ref. [5] given explicitly by eq. (3) of the present manuscript.

3. Buda-Lund fits to RHIC-1 spectra and correlations

Here, we reconstruct the space-time picture of particle emission in Au + Au collisions at RHIC within the BL-H framework, by fitting simultaneously the PHENIX and STAR final data on two-particle correlations and single-particle spectra presented in refs. [14, 13, 12]. The BL model, in certain domain of the parameter space [3], features a scaling limiting behavior of all the HBT radius parameters, \( R_{\text{out}} \sim R_{\text{side}} \sim R_{\text{long}} \approx 70 \sqrt{T_{0}/m_t} \). A unique feature of the BL model is that it has been successfully tested against a detailed description of the single-particle spectra and the two-pion Bose-Einstein correlation functions in both \( h + p \) and \( Pb + Pb \) collisions at CERN SPS bombarding energies [17, 18].

The measured and the calculated single particle spectra are connected with the help of a core-halo correction factor \( \propto 1/\sqrt{\lambda_*} \), where the experimental values of the intercept parameter \( \lambda_*(y, m_t) \) are to be taken from the measurements. In the lack
of these $\lambda_s(y, m_t)$ values we have utilized their average $\lambda_s$ for a core-halo correction when fitting the PHENIX $K^-$ and $p^-$ spectra. In particular, the following average values were used for the various particle types: $\lambda_s(K) = 0.80$ (estimated from the NA44 data on kaon-kaon correlations at CERN SPS \cite{11}, $\lambda_s(p) = 0.995$ (the fraction of long lived resonances that decay to anti-protons is neglected). For pions, we have utilized the $\lambda_s(m_t)$ values given in refs. \cite{12, 13}.

3.1. Improving on earlier results

Note also that we have performed the data analysis within a Gaussian approximation to the oscillating prefactor, improving on our earlier results \cite{8}, where we have utilized the $\Omega = 1$ approximation. As the oscillating prefactor $\Omega$ depends only on $Q_{\parallel}$, a Gaussian approximation to $\Omega$ results in a Gaussian form of the Bose-Einstein correlation function in the Buda-Lund variables, but with a modification of the invariant longitudinal size of the source,

$$R_{\parallel, \Omega}^2 = R_{\parallel}^2 \left[1 + \frac{\Delta \eta^2}{\cosh^2(\eta)}\right],$$

(4)

where $R_{\parallel}^2$ is given by eq. (138) of ref. \cite{5}. This modified invariant longitudinal radius parameter, $R_{\parallel, \Omega}^2$ replaces $R_{\parallel}^2$ in eqs. (116-118), when making the transformation from the Buda-Lund radius parameters to the experimentally determined Bertsch-Pratt radius parameters following the lines of ref. \cite{5}.

Furthermore, we improved on our earlier results \cite{8} by taking into account an $m_t$ dependent core-halo correction for the PHENIX spectra and correlations, and by fitting the absolute normalization of the single particle spectra in both experiments, properly utilizing the degeneracy, fugacity and quantum statistical factors. This allows us to extract the chemical potential in the center of the fireball, in contrast to our earlier fits \cite{8} where the absolute normalization of the particle spectra and the central value of the chemical potential distribution were not yet determined.

In ref. \cite{19}, we have attempted to determine the central value of the chemical potentials from the preliminary data. We improve also on this analysis by using the final, published data, by releasing the central value of the pion chemical potential, that was previously fixed to 0, and by using the correct value of the $g = 2s + 1$ the degeneracy factors, i.e. $g = (1, 1, 2)$ for $(\pi^-, K^-, p^-)$.

Fig. 1 illustrates the best combined fit to the single particle spectra of negative pions, kaons and anti-protons of PHENIX, as well as to the transverse mass dependent HBT radii of STAR and PHENIX. Thus the hypothesis, that pions, kaons and protons are emitted from the same hydrodynamical source is in a good agreement with the fitted data, and the PHENIX and the STAR datasets are compatible with one another. The parameters of the combined fit to PHENIX and STAR data are summarized in Table 1.

A very important improvement over our earlier results is that now we have utilized the final PHENIX and STAR data points, in contrast to the earlier results,
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I. $T_0$ [MeV] = 202 ± 13
II. $\langle u_t \rangle = 1.08$ ± 0.17
III. $R_G$ [fm] = 9.8 ± 1.2
$\tau_0$ [fm/c] = 6.1 ± 0.3
$\Delta \tau$ [fm/c] = 0.02 ± 1.5
$\Delta \eta$ = 0.84 ± 0.24
$\langle \Delta T \rangle_r$ = 1.3 ± 0.4
$\mu_0^{-}$ [MeV] = 75 ± 19
$\mu_{0K^-}$ [MeV] = 107 ± 14
$\mu_0^{p}$ [MeV] = 305 ± 41
$\chi^2$/NDF = 74/68 = 1.09
CL = 28.9%

Table 1. Source parameters from simultaneous fits of final $Au+Au$ RHIC data of PHENIX and STAR on particle spectra and HBT radius parameters with the Buda-Lund hydrodynamical model.

where the preliminary data points were utilized. Unique minima are found and a statistically acceptable $\chi^2$/NDF is obtained for the combined fit of both PHENIX and STAR datasets. Furthermore, the $\chi^2$/NDF values are good not only on the combined data set, but on each of the fitted spectra and HBT radii, perhaps with the exception of the out radius parameter $R_o$ at the largest transverse mass value, where the fit overestimates the measured point by about 2.5 standard deviations.

The improvements did lead to a refinement of the fitted parameters and their values, but, typically, the changes were within 3 standard deviations of the errors, with the exception of the central value of the freeze-out temperature, which increased significantly, from the preliminary RHIC average of $T_0 = 142 ± 4$ MeV to the final $T_0 = 202 ± 13$ MeV, which is a significant, close to 5 standard deviation modification. Due to the above improvements, the analysis of the final STAR and PHENIX data now indicates the existence of a hot central part of the core, which was not resolved in the preliminary analysis. Clearly, more data points would be very useful to confirm or invalidate this observation. In particular, HBT radius parameters of pions and kaons in the $m_t \approx 1$ GeV domain would provide very useful constraints on the parameters of the BL-hydro model.

4. Discussion

We emphasize that the way how the data were presented are not ideal for fitting the BL-hydro model parameters. In particular, the BL-hydro model parameters can be determined easier, if the rapidity dependent transverse mass spectra are given for as
Table 2. Calculated parameters, the surface values of the temperature, flow and chemical potential distributions, as evaluated from the simultaneous fits of Table 1 to final \( Au + Au \) RHIC data of PHENIX and STAR on particle spectra and HBT radius parameters with the Buda-Lund hydrodynamical model. The surface temperature is \( T_s = T_0 / (1 + \langle \Delta T/T \rangle_r) \), the average surface three-velocity is \( \langle \beta_t \rangle = \langle u_t \rangle / \sqrt{1 + \langle u \rangle^2} \) and the surface chemical potentials are given by \( \mu_s = \mu_0 - T_0/2 \) for all particles.

| BL hydro parameters | Best fit \( T_0 = 140 \text{ MeV} \) | \( T_0 = 110 \text{ MeV} \) |
|---------------------|----------------------------------|--------------------|
| \( T_s \) [MeV]     | 110 ± 16                         | 127 ± 5            |
| \( \langle \beta_t \rangle \) | 0.73 ± 0.06                      | 0.62 ± 0.04        |
| \( \mu_s^{-} \) [MeV] | -25 ± 21                         | 34 ± 15            |
| \( \mu_s^{K^{-}} \) [MeV] | 6 ± 29                           | 103 ± 16           |
| \( \mu_s^{\pi^{-}} \) [MeV] | 204 ± 49                         | 343 ± 17           |
| Conf. level         | 28.9 %                           | 1.0 %              |

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The major difference between the final state of heavy ion collisions at RHIC and at CERN SPS seems to be not only the increased freeze-out time and the increased transverse flow or Hubble constant and relevantly larger transverse geometrical radius at RHIC, but, most strikingly, the existence of a hot center located close to the beam axis, which evaporates particles with a temperature that is very close to, or above the deconfinement temperature, \( T_0 = 202 \pm 13 \text{ MeV} \). This effect was not seen at CERN SPS, when the NA44, NA49 and WA98 data on particle spectra and correlations were analyzed with the help of the BL-hydro model [18]. We have checked, that this minimum satisfies eqs. (16-18) of ref. [18], i.e. the conditions for the validity of the saddle-point approximation are satisfied.

We tried to determine the significance of this result by setting the central temperature to the value of \( T_0 = 140 \text{ MeV} \), artificially requiring that the temperature
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of the hottest zone at RHIC be similar to the value of $T_0$, that were found in $h+p$ and $Pb+Pb$ reactions at CERN SPS [17, 18]. A reasonable fit was obtained, however, the confidence level of the fit decreased from 29% to 1.2%, and the $\chi^2/\text{NDF}$ increased correspondingly, see the second column of Table 2. The blast-wave model describes the preliminary transverse mass dependence of the STAR data on negative pions, kaons, anti-protons and anti-lambdas with $T_0 = 120^{+50}_{-25}$ MeV, and $\langle \beta_t \rangle = 0.52^{+0.12}_{-0.08}$ [51]. Within errors, we recover this minimum from the combined fits to the PHENIX final spectra and the final STAR and PHENIX HBT radius parameters, if we require a vanishing transverse temperature gradient in the BL-hydro model, or, if we fix by hand the central value of the freeze-out temperature distribution to $T_0 = 110$ MeV, see the third column of Table 1. However, we find that this minimum is statistically not acceptable, as the confidence level of the fit is very small. We have done another check, when determining the stability of the fit results for the variation of the central value of the freeze-out temperature. We have investigated the stability of the surface temperature for the variation of $T_0$ (best fit value versus $T_0 = 140$ MeV fixed versus $T_0 = 110$ MeV fixed). Interestingly, we found that the transverse temperature gradient, $\langle \Delta T/T \rangle_r$ is strongly correlated to $T_0$, so a higher central temperature in the fit implies a larger temperature gradient, in such a way, that the surface temperature, $T_s = T_0/(1 + \langle \Delta T/T \rangle_r)$ remains within errors the same. We have also calculated the 3-velocity of the matter on the surface in the transverse direction, $\langle \beta_t \rangle = \langle u_t \rangle / \sqrt{1 + \langle u \rangle_t^2}$ for a comparison, and the chemical potentials on the $r_t = R_G$ surface, that are given by $\mu_s = \mu_0 - T_0/2$ for all particles. The freeze-out temperature and the average transverse velocity at $r_t = R_G$ are remarkably stable parameters of the fits, but, only the results in the first column of Table 2 are statistically acceptable. According to this column, the chemical potential of negative pions and kaons approximately vanishes at the $r_t = R_G$ surface, and the chemical potential for anti-protons is significantly bigger, than zero on the surface.

Furthermore, the surface temperature and the surface three-velocity was found to be similar to the average freeze-out temperatures that were obtained from the Regensburg model in ref. [50] and the blast-wave model analysis of the RHIC final state in ref. [17]. Our results are qualitatively as well as quantitatively similar to the findings of Florkowski and Broniowski [20], who analyzed the PHENIX and STAR single particle spectra at RHIC in a hydro model that includes a spherically symmetric Hubble flow and similar in spirit to the BL-hydro and the blast-wave models. They find that a value of $T_0 = 165 \pm 7$ MeV, $\mu_b = 41 \pm 5$ MeV and an average transverse flow velocity of $\langle \beta_t \rangle = 0.49$ describes the STAR and PHENIX preliminary data on the single particle spectra not only for negative pions, kaons and anti-protons, but also for $\phi$ mesons and $\Lambda$-s, $\bar{\Lambda}$-s, and $K^*$-s. [21].

We have found a non-vanishing chemical potential for negative pions, kaons and anti-protons in the center of the fireball from the absolutely normalized single-particle spectra. The pion and kaon data were well described in all cases with a chemical potential that (within errors) vanishes on the $r_t = R_G$ surface of the fireball. These values together with the inhomogeneous chemical potential distribution
of eq. (124) of ref. [5] indicate a clear deviation from chemical equilibrium in the hadronic final state, as reconstructed within the Buda-Lund hydro model.

The similarities and the differences between an effective Quark Matter (QM) stage and a Quark Gluon Plasma (QGP) phase have been summarized recently in ref. [27]. The observed short duration of particle emission and the large transverse flow at RHIC contradicts to the picture of a soft, long-lived, evaporative Quark Gluon Plasma phase, that would consist of massless quarks and gluons. However, the final state does not exclude a transient, explosive, suddenly hadronizing Quark Matter phase, that could be characterized by massive valence quarks, the lack of gluons as effective degrees of freedom, and a hard equation of state.

5. Buda-Lund Predictions - What Next?

In the above fits, we have utilized only mid-rapidity data points as given by the PHENIX and STAR collaborations. Additional measurements provide more stringent restrictions on the value of the fit parameters.

5.1. (Pseudo-)rapidity dependent measurements

Recently, BRAHMS has published the pseudorapidity distribution of charged particles [57], which helps to restrict the value of the width parameter $\Delta \eta$, and also to get a more precise handle on the difference between the central and the surface temperature of the fireball, as the broadening of the pseudo-rapidity distribution depends on this parameter. Preliminary results indicate an agreement with the value of $\Delta \eta = 2.5$ utilized in the fits presented here.

The Buda-Lund hydro model predicts a specific a coupling between the rapidity and the transverse mass dependent single particle spectra. In particular, due to the finite longitudinal size of the expanding fire-tube it predicts [3, 4, 5], that the effective slope parameter decreases in the target and the projectile fragmentation regions as

$$ T_{\text{eff}}(y) = \frac{T_*}{1 + a(y - y_0)^2}, \quad (5) $$

where (transverse mass dependent) slope parameter at mid-rapidity is given by

$$ T_* = T_0 + m_t \langle u_t \rangle^2 \frac{T_0}{T_0 + m_t \langle \Delta T_T \rangle} \frac{T_0}{T_0 + m_t \langle \Delta T_T \rangle}, \quad (6) $$

and parameter $a$ is also expressed as a function of the BL fit parameters in ref. [8]. Note that in the original BL papers [3, 4] the slope parameters were evaluated at $m_t = m$, in an approximation that neglected the transverse mass dependence of these values. If the fits are done at low $p_t$, such an approximation can be warranted. If the temperature gradient effects are expected to be small, the phenomenological formula appears in its simplest form,

$$ T_* = T_0 + m \langle u_t \rangle^2. \quad (7) $$
It would be important to experimentally test the transverse mass dependence of the slope parameters, i.e., the difference between eqs. (6) and (7). It would also be very important to experimentally investigate the rapidity dependence of the single particle spectra, and the decrease of the slope parameters in the target and projectile fragmentation regions, as suggested by eq. (5).

Note that the BL hydro also predicts that the rapidity width of the double-differential invariant momentum distribution depends on the transverse mass in a specific manner, which is very sensitive to the central temperature $T_0$. In particular, the prediction is

$$
\Delta y^2(m_t) = \Delta \eta^2 + \frac{T_0}{m_t}.
$$

Hence plotting the squared rapidity width of the single-particle momentum distribution as a function of $1/m_t$ would provide a straight line, and its slope parameter would yield us an independent handle for the value of the central temperature in the hottest and densest regions of the fireballs at RHIC. This information would be very valuable when concluding about the temperature gradient effects and establishing the significance of a hot, central region with $T_0$ approximately the critical temperature of the quark-hadron phase transition, as suggested by the present analysis.

5.2. Measurements at large $m_t$

More precise determination of the model parameters will be possible if new data points become available for the effective source sizes (HBT radii) for pions and kaons at higher value of the transverse mass of the pair. The important point is that the $1/\sqrt{m_t}$ scaling of the HBT radius parameters is predicted to emerge in the high transverse mass limiting case, with small scaling violating terms, that play a larger role at small values of the transverse mass. Such a behavior is indeed seen in the BL fits in Fig. 1, in particular, the scaling violating terms are rather apparent in the low transverse mass $R_l$ data points. If the temperature gradient effects are not so important, the center of particle emission for particles with larger transverse masses moves more and more out from the $r_z$ axis, hence more and more transverse flow effects result in a faster than $1/\sqrt{m_t}$ decrease in the out component. However, if the temperature gradient effects are important, all the 3 radius components will follow the $1/\sqrt{m_t}$ scaling law in the large transverse mass domain. A measurement of the effective proton source as a function of $m_t$ and perhaps proton-deuteron coalescence measurements would be also tremendously useful to clarify the status of this scaling law.

5.3. Non-identical particle correlations

The BL model could be extended to study non-identical particle correlations \[52\], that provide very important keys to tell what kind of particles are emitted first from the hot and dense decaying fireball. In particular, non-identical particle correlations are sensitive to both the temporal and spatial separations of the different kind of
emitted particles. Preliminary data from the STAR collaboration indicates, that protons are emitted closer to the surface, than kaons, and kaons are emitted closer to the surface, than pions. In the BL model, the production of heavier particles is more and more focussed to the collision axis, the transverse momentum and mass dependence of the center of particle production in the transverse plane is given by eq. (132) of ref. [3], which simplifies at mid-rapidity to

$$r_x = R - \frac{p_t(u_t)}{T_0 + m_t(u_t)^2 + \langle \Delta T_T \rangle r},$$

which implies that at any given value of the transverse momentum $p_t$ the center of particle production for heavier particles is closer to the collision axis, than that of the lighter ones. Note, that the BL-hydro also predicts, that the protons come from a smaller effective source than the pions, and due to this effect, some of the pions may appear from behind the protons.

In non-identical particle interferometry, the effects are maximal if the velocity of the different particles are approximately the same. It is striking to observe, that plotting eq. (9) as a function of the mean transverse velocity of the particle pair, heavier particles with a given velocity are emitted from a more forward region than the lighter particles! This feature of the BL model is qualitatively similar to the observations by the preliminary STAR data on non-identical particle correlation [53, 54].

This feature of the BL model is closely related to the transverse mass scaling of the HBT radius parameters, and it would be very important to check experimentally. The BL model predicts a similar, focussing effect in the longitudinal direction too, namely that the center of emission of heavier particles at any given value of rapidity is closer to the midrapidity, than that of the lighter particles,

$$\eta = y_0 - y,$$

$$r_x = \tau_0 \sinh(y + \eta),$$

$$r_z = \tau_0 \cosh(y + \eta),$$

where $y$ is the rapidity of the particle, $y_0$ stands for the value of mid-rapidity and $\eta$ is the space-time rapidity of the particle in the LCMS ($y = 0$) frame, while the center of particle production is given in the frame of observation. Due to Lorentz boost effects, this result implies that within the Buda-Lund picture, heavier particles are also emitted earlier, than the lighter ones, if the observation of the temporal and spatial sequence is done in the LCMS ($y = 0$) frame.

6. Conclusions

We find that the PHENIX and STAR data on single particle spectra of identified $\pi^-$, $K^-$ and $\eta$ as well as detailed $m_t$ dependent HBT radius parameters are consistent with the Buda-Lund hydro model as well as with one another.
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The major difference between the final state of heavy ion collisions at RHIC and at CERN SPS seems to be not only the increased freeze-out time and the increased transverse flow or Hubble constant and relevantly larger transverse geometrical radius at RHIC, but, most strikingly, the existence of a hot center located close to the beam axis, which evaporates particles with a temperature that is very close to the deconfinement temperature, \( T_0 = 202 \pm 13 \text{ MeV} \). This effect was not seen at CERN SPS, when analysed in terms of the Buda-Lund hydro model. We find that this parameter can be determined independently from the temperature and the velocity of the surface, for which parameters we found rather conventional values.

Note also that our findings are in qualitative agreement with numerical results found from Humanic’s cascade \(^{[15,16]} \) as well as from URQMD \(^{[55]} \). It seems that at RHIC-1, some of the pions, kaons and protons are emitted directly from a rather hot zone, that has (within the errors of the reconstruction) the deconfinement temperature of QCD, which even at finite chemical potential is predicted to be below the \( T_c = 172 \pm 3 \text{ MeV} \) value \(^{[56]} \). The hot center seems to be surrounded by a cooler hadronic matter, with a surface temperature of about \( T_s \approx 110 \text{ MeV} \). Clearly, precision data from RHIC-2 in a broad rapidity and transverse mass domain are needed to finalize the conclusions about the significance of this surprising result, in particular, the measurement of the pion and kaon HBT radius parameters at \( m_t \approx 1 \text{ GeV} \) would provide a very stringent restriction on the models.

Acknowledgment(s)

This research has been supported by the Hungarian OTKA T038406, T034269, by a NATO Science Fellowship, and by the US NSF - Hungarian MTA-OTKA grant 0089462.

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Fig. 1. Simultaneous fits to the final PHENIX particle spectra and the final PHENIX and STAR HBT radius parameters within the framework of the Buda-Lund hydro model. Solid line stands for the best Buda-Lund fits using parameter set Fit-I, as given in the first column of Table 1. The quality of the fit is statistically acceptable, CL = 29 \%.
Fig. 2. Simultaneous fits to the final PHENIX particle spectra and the final PHENIX and STAR HBT radius parameters within the framework of the Buda-Lund hydro model, with $T_0 = 110$ MeV fixed. Solid line stands for the Buda-Lund fits using parameter set Fit-III, as given in the third column of Table 1. Although the fit does not look too bad, statistically the fit is not acceptable, as the confidence level of the fit is as low as $10^{-5}$. When comparing with Fig. 1, it is clear that the $m_t$ dependences of the side and the out radius parameters are not strong enough and the number of pions with high transverse momenta is too small.
Fig. 3. The mean production point of pions and protons with a given velocity from the BL hydro model, corresponding to eq. (9), utilizing the best fit values given in column I of Table 1. Surprisingly, we find that within the BL-hydro model, heavier particles are emitted with larger transverse coordinate values, than lighter particles, when non-identical particles with the same velocity are compared. The BL hydro model predicts according to this figure, that both in the small and the large transverse velocity limits the difference between the transverse displacement of the pion and proton production points disappears.