PREDICTIONS FROM MICROSCOPIC MODELS ON PARTICLE CORRELATIONS AT RHIC *

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(Received December 18, 2003)

We review the recent developments on microscopic transport calculations for two-particle correlations at low relative momenta in ultrarelativistic heavy ion collisions at RHIC.

PACS numbers: 25.75.–q, 12.38.Mh, 24.10.Lx

1. Introduction

This contribution reviews the recent developments on microscopic transport calculations for two-particle correlations at low relative momenta in ultrarelativistic heavy ion collisions at RHIC. We will start with the discussion of a simple hadronic rescattering model, will then continue with the predictions of a hadron+string model (RQMD), and subsequently present the features of a combined hydrodynamical and microscopic hadron+string model (Hydro+UrQMD). We will then address the impact of partonic (elastic) scatterings (MPC) and also discuss the correlation results for a combined parton+hadron model (AMPT).

For two-particle correlations of bosons at low relative momenta, Bose–Einstein correlations, *i.e.*, the symmetrization of the two-particle wave functions, are usually the desired effect. One is interested in the space-time extent of the particle-emitting source. However, the situation is complicated by the strong time dependence of the dynamical multi-particle system. Thus, two-particle interferometry is not only sensitive to some geometric size parameters but also to the dynamics (for example, collective flow) and many other features of the source as the passing through a phase transition [1–3]. Indeed, it was predicted that, in case of a first-order phase transition, the correlation radii should be anomalously large due to the large latent heat

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.

that needs to be converted into the hadronic phase while the number of degrees of freedom is reduced simultaneously which in turn should lead to large hadronization times. A characteristic measure, being sensitive to the emission duration of the source, was thought to be the ratio of two correlation lengths $R_{\rm out}/R_{\rm side}$. The ratio was originally predicted to grow to large values like 5 or 10, reflecting the rather large emission times, for ultrarelativistic heavy ion collisions (for example Au+Au at RHIC, $\sqrt{s}_{nn} = 200\,{\rm GeV}$), that is, for conditions where a deconfined phase should be produced. However, experimental results from RHIC [4,5] show ratios close to unity, even for various transverse momenta. One might conclude from this that hadronization times are short, possibly too short to support a first-order phase transition scenario. Indeed, there are indications (even though not settled yet) from lattice QCD that at RHIC (high T, low μ) a cross-over transition might take place instead. For a thorough theoretical understanding of the underlying dynamics and the corresponding correlations one needs transport theory. Hydrodynamics has the advantage of its simple conceptual idea and the possibility to study explicitly the impact of different equations of state. However, two-particle interferometry at low relative momenta is also very sensitive to the dynamics close to the decoupling from the system (at the *freeze-out*). Microscopic transport theory allows one to calculate explicitly the freeze-out without relying on particular prescriptions. This provides one of many motivations to study the correlations in the framework of microscopic transport theory. Here, we systematically review the recent predictions from various microscopic transport models and discuss what can be learned from obvious discrepancies or seeming agreement.

2. Correlation functions and the $R_{\rm out}/R_{\rm side}$ ratio from microscopic freeze-out information

The microscopic description provides discrete phase-space points for the last (strong) interactions. For Gaussian sources, the geometrical size parameters (correlation lengths) in the out-side-long coordinate system can be written as (see, for example, [3])

$$R_{\rm s}^2 = \langle \tilde{y}^2 \rangle, \quad R_{\rm o}^2 = \langle (\tilde{x} - \beta_{\rm t}\tilde{t})^2 \rangle, \quad R_{\rm l}^2 = \langle (\tilde{z} - \beta_{\rm l}\tilde{t})^2 \rangle, \tag{1}$$

where $\tilde{t}, \tilde{x}, \tilde{y}$, and $\tilde{z}$ are the space-time coordinates relative to the mean source centers $\tilde{x}_\mu = x_\mu - \langle \tilde{x}_\mu \rangle$. These expressions enlighten the mutual interplay of spatial and temporal components for the correlation radii and also enable their disentanglement. However, for a direct comparison to experimental data the explicit calculation of correlation functions

$$C_2 - 1 \simeq \frac{\int d^4x S(x, \boldsymbol{K}) \int d^4y S(y, \boldsymbol{K}) \exp[2ik\,(x-y)]}{\left| \int d^4x S(x, \boldsymbol{K}) \right|^2} \tag{2}$$

is necessary [6–9]. $S(x, K)$ represents the classical source function depending on position and momentum. The C_2's are subsequently fitted to a Gaussian form of the correlator,

$$C_2 = 1 + \lambda \exp(-q_\mathrm{o}^2 R_\mathrm{o}^2 - q_\mathrm{s}^2 R_\mathrm{s}^2 - q_\mathrm{l}^2 R_\mathrm{l}^2)\,. \tag{3}$$

This procedure is the standard method how to extract the correlation radii.

As a first example we report the findings obtained with a simple **hadronic rescattering** model [10]. Starting from an initial thermalized state at $\tau_\mathrm{had} = 1\,\mathrm{fm}/c$ with a temperature $T = 300\,\mathrm{MeV}$ and a width of a Gaussian rapidity distribution $\sigma_y = 2.4$, hadrons are rescattering until they reach freeze-out. The parameters were chosen such that the final global observables are reproduced. Surprisingly, the results of this purely hadronic approach for the correlation radii show only small differences to the data. The ratio $R_\mathrm{o}/R_\mathrm{s}$ is only slightly larger than unity and the radii are roughly reproduced. This model relies on rather strong assumptions as the very fast hadronization or the existence of hadrons at large energy densities of several $\mathrm{GeV/fm^3}$; hence, the interpretation of the obtained results is rather difficult although they contribute to the general picture of HBT correlations from microscopic models at RHIC.

The **RQMD** model, relying on (di)quark, hadron and string degrees of freedom, has also been applied to extract the correlation radii [6]. The fitted radii are again roughly reproduced (the calculated radii are typically $\sim 1\,\mathrm{fm}$ larger than the exp. data), the ratios are 1.2–1.4 for the calculations and closer to unity for the data (0.9–1.1) by possibly exhibiting an opposite p_t-dependence. This model does not *explicitly* include a phase transition to quark–gluon matter. However, during the high density phase the effective degrees of freedoms are string excitations and constituent (di)quarks. The finite (default) formation times (until string fragmentation) may lead to a lack of pressure (that are reflected in elliptic flow values smaller than data). Still the obtained radii do show reasonable magnitudes indicating that the freeze-out dynamics may dominate the HBT radii. Using such a sophisticated microscopic model only for the later, more dilute stages of the system evolution and describing the high density phase by hydrodynamics has several advantages. One can explicitly study the dependencies on the equation of state by simultaneously following a realistic freeze-out. The **UrQMD** model has been coupled at the hadronization hypersurface to an initial **hydrodynamic scaling flow** for the early phase [7, 8, 11]. First-order phase transition scenarios with different values for the critical temperature T_c ($\sim$ latent heat) have been studied. The fitted R_s radii agree with data while R_o (and R_l) are overpredicted ($\sim$20–30%). Several studies have been performed to check possible improvements. In-medium modifications (of the ρ meson), for example, improve the comparison (in particular for R_l) [8] that correspond to effectively increased opacities. Another sensitivity, that to the transition temperature T_switch (hydro-micro) is shown in the figure. The comparison to data improves if this transition is performed later in the hadronic phase ($T_\mathrm{switch} = 130\,\mathrm{MeV}$) instead of the default transition temperature at hadronization ($T_\mathrm{switch} = T_\mathrm{c} = 160\,\mathrm{MeV}$). Then, the non-ideal microscopic phase is shorter, reducing the radii.

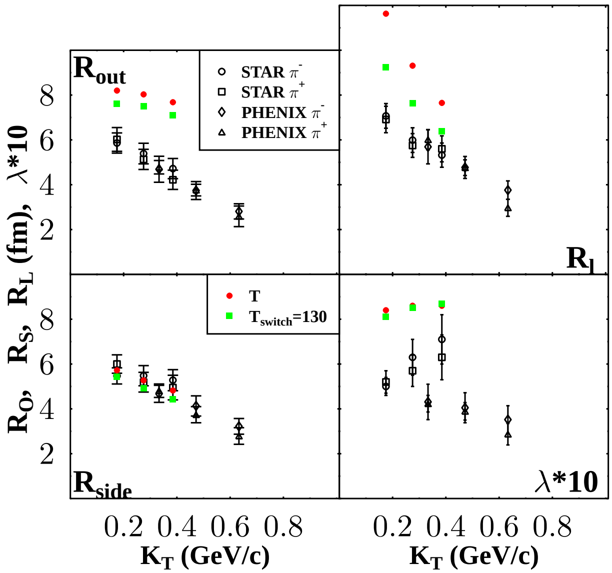

Fig. 1. HBT-radius parameters R_out, R_side, R_long, and intercept parameter λ as a function of the transverse momentum K_T as calculated from the phase space distribution of the 'QGP+hadronic rescattering' model (Hydro+UrQMD) for central nucleus nucleus collisions at RHIC compared to data from STAR and PHENIX. The transition temperature is varied from $T_\mathrm{sw} = T_\mathrm{c} = 160\,\mathrm{MeV}$ (full circles) to $T_\mathrm{sw} = 130\,\mathrm{MeV}$ (full squares).

Eventually, we discuss models that are (partially) based on partonic degrees of freedom. The **MPC** models a classical gluon gas including elastic collisions [12]. The main ingredient studied is the transport opacity $\chi \sim \sigma_\mathrm{tr} \cdot dN_g(\tau_0)/d\eta$ being proportional to the transport cross section and gluon density. It has to be emphasized that no hadronic phase or resonances have been taken into account. Thus, the pure parton dynamics effects are studied without asking whether these dependencies survive a possible subsequent hadronic phase and/or resonance effects. Larger opacities naturally lead to later decoupling times. The calculated radii increase with opacity (R_o, R_l) but are still smaller than data (opposite to ideal hydro). R_s seems to be unaffected by the early parton dynamics, *i.e.*, it does not depend on χ.

While these trends are important for demonstrating the sensitivities of HBT to the early dynamics it has to be kept in mind that for a quantitative comparison to data hadrons/resonances have to be taken into account (beyond the simplified mapping gluon $\rightarrow \pi$).

Finally, **AMPT**, a combined model of initial (hard+soft) collisions, elastic parton scatterings, and a hadron cascade has been used to study the impact of different elastic parton cross sections and the so-called string fusion mechanism (the parton content of the soft strings is required to participate in the parton cascade) [9]. With this mechanism and $\sigma_{\rm part} \approx 10\,{\rm mb}$ the calculations come closest to the data, in particular to $R_{\rm o}/R_{\rm s} \approx 1$. It is interesting to note that within this model the $x_{\rm out}, t$-correlations are positive. Hence, they give a negative contribution to $R_{\rm o}$ (see Eq. (1), mixed term of $R_{\rm out}$). This seems to be different, in particular, from the cross correlations in hydrodynamical models which are negative.

3. Conclusions

There has been enormous progress in the approaches to understand the wealth of correlation data. Several new transport models have been applied to the correlation analysis. The overall magnitude of the correlation radii is understood. The *HBT-puzzle*, that is, the detailed $p_{\rm t}$-dependence of the $R_{\rm o}/R_{\rm s}$ ratio, however, cannot be considered to be fully solved and needs further studies [6–13]. The importance of the early stage opacity and parton cross sections has been demonstrated. Similarly, the late stage decoupling, opacities, in-medium effects play an important role. The space-time correlations $(x_{\rm out}, t)$ represent an important contribution that need to be checked independently, for example, by means of nonidentical particle pair correlations.

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