Production of resonances in a thermal model: invariant-mass spectra and balance functions

W. Florkowski\textsuperscript{1,2}, W. Broniowski\textsuperscript{1}, and P. Bożek\textsuperscript{1}

\textsuperscript{1} The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Kraków, Poland
\textsuperscript{2} Institute of Physics, Świętokrzyska Academy, PL-25406 Kielce, Poland

Abstract. We present a calculation of the $\pi^+\pi^-$ invariant-mass correlations and the pion balance functions in the single-freeze-out model. A satisfactory agreement with the data for Au+Au collisions is found.

PACS numbers: 25.75.-q, 24.85.+p

Thermal models of particle production in ultra-relativistic heavy-ion collisions turned out to be very successful in describing hadron yields \cite{1–4}, spectra \cite{5, 6}, the elliptic-flow coefficients $v_2$ \cite{7, 8}, and the HBT radii \cite{7, 9}. In view of this fact it is challenging to study correlation observables in the thermal approach and compare the results to the data. Particular examples of such observables are the $\pi^+\pi^-$ invariant-mass spectra \cite{10} and the balance functions \cite{15, 16}. The latter describe correlation between opposite-charge particles in the rapidity space and are closely related to charge fluctuations \cite{17–19}.

In order to analyze the $\pi^+\pi^-$ invariant mass spectra measured in Ref. \cite{10} with the like-sign-subtraction technique, we make the assumption that all the correlated pion pairs are obtained from the decays of neutral resonances: $\rho$, $K_0^0$, $\omega$, $\eta$, $\eta'$, $f_0/\sigma$, and $f_2$. The phase-shift formula for the volume density of a $\pi-\pi$ resonance with spin degeneracy $g$ is given by the formula \cite{13}

$$\frac{dn}{dM} = g \int \frac{d^3p}{(2\pi)^3} \frac{d\delta_{\pi\pi}(M)}{\pi dM} \left[ \exp \left( \frac{\sqrt{M^2 + p^2}}{T} \right) - 1 \right]^{-1},$$

which was used in Ref. \cite{11}, as well as by Pratt and Bauer \cite{14} in a more recent analysis. We have performed a calculation in the framework of the single-freeze-out model of Ref. \cite{5}, including the flow, experimental kinematic cuts, and decays of higher resonances. The full results are shown in Ref. \cite{11}. In the left panel of Fig. 1 we compare the model predictions to the STAR data. The mass of the $\rho$ meson was scaled down by 10\% in accordance to the experimental evidence for the dropping mass \cite{10, 20}. Our results were filtered with the detector efficiency correction (we are grateful here to P. Fachini). We can conclude that the model does a very good job in reproducing the gross features of the experimental invariant-mass spectra. In the right panel of Fig. 1 we show the model predictions for the tranverse momentum spectra for several resonances,
confronted to data. The overall agreement is impressive. Note that all the parameters of the model (two thermal and two geometric) had been fixed with the help of the spectra of pions, kaons, and protons, such that there was no more freedom left in the analysis of resonances.

The balance functions, measured by the STAR Collaboration [21, 22], are defined by the formula

\[
B(\delta, Y) = \frac{1}{2} \left\{ \frac{\langle N_{+-}(\delta) \rangle - \langle N_{++}(\delta) \rangle}{\langle N_+ \rangle} + \frac{\langle N_{--}(\delta) \rangle - \langle N_{-+}(\delta) \rangle}{\langle N_- \rangle} \right\},
\]

where \( N_{+-}(\delta) \) denotes the number of the opposite-charge pairs such that both members of the pair fall into the rapidity window \( Y \) with relative rapidity \( |y_2 - y_1| = \delta \), \( N_+ \) is the number of positive particles in the interval \( Y \), etc. The measurement [21] showed that the widths of the balance functions are smaller than expected from models discussed in Ref. [15]. This problem was discussed by Bialas in Ref. [23] in the framework of the quark coalescence model [24]. Here we present the results of the calculation of the \( \pi^+\pi^- \) balance function [25] based on the model or Ref. [5]. In a more recent paper Pratt et al. [26] showed that the measured balance function may also be satisfactorily reproduced in the blast-wave model.

In our approach the \( \pi^+\pi^- \) balance function has two contributions related to two different mechanisms of the creation of an opposite-charge pair. The first one (resonance contribution) comes from decays of neutral hadronic resonances, whereas the second one (non-resonance contribution) is related to other possible correlations. We assume that the second mechanism forces the two opposite-charge pions to be produced at the same space-time point and with thermal velocities. The first contribution includes neutral resonances which have a \( \pi^+\pi^- \) pair in the final state (we explicitly include \( K_S, \eta, \eta', \rho^0, \omega, \sigma, \) and \( f_0 \)); here the correlations are completely determined by the kinematics. The details of the model and other technical remarks are given in Ref. [25].

According to the above discussion, the \( \pi^+\pi^- \) balance function can be constructed.
as a sum of the two terms,

\[ B(\delta) = B_R(\delta) + B_{NR}(\delta). \]  

The functions \( B_R(\delta) \) and \( B_{NR}(\delta) \) resulting from our model calculation are presented in Ref. [25]. The value of the temperature used in the calculation was \( T = 165 \text{ MeV} \), and the expansion parameters of the model had been fitted to the spectra of hadrons [5]. This procedure yields the average transverse flow of 0.5\( c \). One can observe that the widths of the two contributions are similar. The calculated total width, \( \langle \delta \rangle = 0.66 \), turns out to be somewhat larger than the experimental value for the most central collisions. The STAR result for the most central events (\( c = 0 - 10\% \)) is \( \langle \delta \rangle = 0.594 \pm 0.019 \), for the mid-central (\( c = 10 - 40\% \)) \( \langle \delta \rangle = 0.622 \pm 0.020 \), for the mid-peripheric (\( c = 40 - 70\% \)) \( \langle \delta \rangle = 0.633 \pm 0.024 \), and for the peripheric (\( c = 70 - 96\% \)) \( \langle \delta \rangle = 0.664 \pm 0.029 \). Such dependence of the width of the balance function on centrality cannot be reproduced in our model via changing the transverse flow within the limits consistent with the single-particle spectra.

In Fig. 2 our results are compared to the experiment. The normalization of the model curves was adjusted in each case, since we were not able to take into account, in a more sophisticated way, the effect of the limited detector efficiency and acceptance. On the other hand, the kinematic cuts in pseudorapidity and transverse momentum were included [25]. The shapes of the model balance functions agree well with the data except for the most central case where the theoretical width is slightly larger. The dips of the experimental balance functions at very small values of \( \delta \) are caused by the HBT correlations, not included in our approach. We also note that the effects of the detector
efficiency may influence the width of the balance function [26].

In conclusion, we state that the single-freeze-out model gives a satisfactory description of the pion invariant-mass correlations and of the balance functions. The results for the transverse-momentum spectra of resonances are in remarkable overall agreement with the experiment.

We are grateful to Patricia Fachini for numerous helpful discussions and for preparing the figures. This research has been supported in part by the Polish State Committee for Scientific Research grant 2 P03B 059 25.

[1] P. Braun-Munzinger, D. Magestro, K. Redlich, and J. Stachel, Phys.Lett. B518 (2001) 41.
[2] W. Florkowski, W. Broniowski, M. Michalec, Acta Phys. Pol. B33 (2002) 761.
[3] J. Rafelski and J. Letessier, Nucl. Phys. A715 (2003) 98.
[4] F. Becattini, M. Gazdzicki, A. Keranen, J. Manninen and R. Stock, Phys. Rev. C 69 (2004) 024905.
[5] W. Broniowski and W. Florkowski, Phys. Rev. Lett. 87 (2001) 272302; Phys. Rev. C 65 (2002) 024905; W. Broniowski, A. Baran, and W. Florkowski, Acta Phys. Pol. B33 (2002) 4235; A. Baran, W. Broniowski, and W. Florkowski, Acta Phys. Pol. B35 (2004) 779.
[6] G. Torrieri and J. Rafelski, Phys. Rev. C 68 (2003) 034912; J. Phys. G 30 (2004) S557.
[7] W. Broniowski, A. Baran, and W. Florkowski, AIP Conf. Proc. 660 (2003) 185.
[8] M. Csanád, T. Csörgő, and B. Lörstad, nucl-th/0310040
[9] T. Csörgő, Heavy Ion Phys. 15 (2002) 1.
[10] J. Adams et al., STAR Collaboration, nucl-ex/0307023 P. Fachini, STAR Collaboration, Acta Phys. Polon. B35 (2004) 183; P. Fachini, these proceedings.
[11] W. Broniowski, W. Florkowski, and B. Hiller, Phys. Rev. C 68 (2003) 034911.
[12] T. Csörgő and B. Lörstad, Phys. Rev. C 54 (1996) 1390; T. Csörgő, L. P. Csernai, Y. Hama, and T. Kodama, nucl-th/0306004
[13] R. Dashen, S. Ma, and H. J. Bernstein, Phys. Rev. 187 (1969) 345; R. F. Dashen and R. Rajaraman, Phys. Rev. D 10 (1974) 694; ibid. p. 708; W. Weinhold, B. L. Friman, and W. Nörenberg, Acta Phys. Pol. B 27 (1996) 3249; Phys. Lett. B 433 (1998) 236; W. Weinhold, Thermodynamik mit Resonanzzuständen, Dissertation, TU Darmstadt, 1998; K. G. Denisenko and S. Mrówczyński, Phys. Rev. C 35 (1987) 1932.
[14] S. Pratt and W. Bauer, Phys. Rev. C 68 (2003) 064905.
[15] S. A. Bass, P. Danielewicz, and S. Pratt, Phys. Rev. Lett. 85 (2000) 2689.
[16] S. Jeon and S. Pratt, Phys. Rev. C65 (2002) 044902.
[17] S. Jeon and V. Koch, Phys. Rev. Lett. 85 (2000) 2076.
[18] M. Asakawa, U. W. Heinz, and B. Müller, Phys. Rev. Lett. 85 (2000) 2072.
[19] M. Gaździcki and S. Mrówczyński, Z. Phys. C 54 (1992) 127.
[20] E. V. Shuryak and G. E. Brown, Nucl. Phys. A 717 (2003) 322; P. F. Kolb and M. Prakash, Phys. Rev. C 67 (2003) 044902; R. Rapp, Nucl. Phys. A725 (2003) 254.
[21] J. Adams et al., STAR Collaboration, Phys. Rev. Lett. 90 (2003) 172301.
[22] M. B. Tonjes, PhD thesis, Michigan State University (2002).
[23] A. Białas, Phys. Lett. B579 (2004), 31.
[24] T. S. Biro, P. Levai, and J. Zimanyi, Phys. Lett. B347 (1995) 6.
[25] P. Bożek, W. Broniowski, and W. Florkowski, nucl-th/0310062
[26] S. Cheng, C. Gale, S. Jeon, S. Petreconi, S. Pratt, M. Skoby, V. Topor Pop, Q. H. Zhang, nucl-th/0401008