THERMAL MODEL AT RHIC: PARTICLE RATIOS AND $p_\perp$ SPECTRA

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Abstract

Predictions of the single-freeze-out model for the particle spectra at RHIC are presented. The model assumes that the chemical and thermal freeze-outs occur simultaneously, and incorporates in simple terms the longitudinal and transverse flow. All resonance decays are included. The model predictions and the data are in striking agreement in the whole available range of momenta.

Much has been said during this Workshop on the predictions for the particle ratios within the thermal approach (see the contribution by J. Stachel), hence in this talk we concentrate entirely on the $p_\perp$ spectra [1, 2]. We only wish to mention that our study [3] of the particle ratios at RHIC confirms, within statistical errors, the results of [4], with the following values of the thermal parameters:

$$T = 165 \pm 7 \text{ MeV}, \quad \mu_B = 41 \pm 5 \text{ MeV}. \quad (1)$$

Strangeness conservation gives $\mu_S = 9 \text{ MeV}$, and isospin asymmetry of the gold nuclei yields $\mu_I = -1 \text{ MeV}$. For more details, review of the thermal models, and references, see [5].

Our model for the spectra incorporates the following assumptions:

1. Chemical and thermal freeze-outs occur simultaneously on a freeze-out hypersurface. In other words, elastic rescattering after the freeze-out is neglected. This simplification, which opposes the traditional picture with two distinct freeze-outs at noticeably different temperatures, works very well, as can be seen from our figures. Note that rapid expansion of the system inhibits the collision rate. Also, the Van der Waals corrections discussed at the end of this talk make the system more dilute at freeze-out, reducing its opacity. Arguments hinting rapid expansion have also been presented in the contributions by H. Appelshäuser and T. Hirano.
2. At freeze-out the particles are distributed according to the statistical distribution functions. The two thermodynamic parameters are obtained from the analysis of the ratios of the particle multiplicities. Since these depend rather weakly on centrality, we treat the thermal parameters as universal.

3. The resonances are treated in a complete way, with all particles from the PDG tables incorporated. Their sequential decays are included exactly, in a semi-analytic fashion. The role of the resonances is very important, resulting in substantial “cooling” of the spectra.

4. The freeze-out hypersurface is a simple generalization of the Bjorken model. It is parameterized with two geometric parameters specified below: the invariant time, \( \tau \), and the transverse radius, \( \rho_{\text{max}} \). For simplicity, Hubble-like expansion is assumed, with the four-velocity proportional to the coordinate, \( u^\mu = x^\mu/\tau \). Clearly, other parameterizations of the fireball expansion, e.g. those following from the hydrodynamic evolution in various models, can be implemented and tested.

5. The only parameters of the model are the two universal thermal parameters and the two geometric parameters, \( \tau \) and \( \rho_{\text{max}} \) (different for each centrality).

The parameterization of the freeze-out hypersurface, taken in the spirit of the Buda-Lund model, is as follows:

\[
\begin{align*}
t &= c \sqrt{\tau^2 + \rho^2}, \\
z &= s \sqrt{\tau^2 + \rho^2}, \\
x &= \rho \cos \phi, \\
y &= \rho \sin \phi,
\end{align*}
\]

with \( \rho \leq \rho_{\text{max}} \). The parameter \( \tau \) fixes the overall normalization of the spectra, while the ratio \( \rho_{\text{max}}/\tau \) determines their shape. The standard Cooper-Frye formalism is applied to obtain the spectra. The details of our procedure, including the technicalities of the resonance decays, are given in the Appendix of Ref. 2.

Fig. 1 shows our results for the PHENIX minimum-bias data at \( \sqrt{s} = 130 \) GeV A. The fitted values of the geometric parameters are \( \tau = 5.55 \text{ fm} \) and \( \rho_{\text{max}} = 4.50 \text{ fm} \). We note excellent agreement in the whole available data range, with the magnitude of the spectra spanned over five decades. Virtually all points are crossed by the model curves within error bars. Similar agreement, not shown, has been found for \( \pi^0 \). Note that all the non-trivial experimental features are reproduced in Fig. 1. In particular, we find the convex shape of the pion spectra, the crossing of \( p \) and \( \pi^+ \) around \( p_{\perp} = 2 \text{ GeV} \), and of \( K^+ \) and
π\(^+\) around 1 GeV (we note in passing that a similar effect of crossing occurs for the SPS data plotted in the \(p_{\perp}\) variable, cf. Fig. 3). The model results at \(p_{\perp} > 2\) GeV should be taken with a grain of salt, since hard processes are expected to be important in that region (see the talk by P. Levai).

Fig. 2 shows our results for the most central collisions at RHIC, where we find from the fit \(\tau = 7.66\) fm and \(\rho_{\text{max}} = 6.69\) fm \[1\]. These numbers are, as expected from geometry, larger than for the minimum-bias case, which averages over centralities. The data in Fig. 2 come from \[7, 8, 9, 10\]. All data except for Λ are absolutely normalized. The normalization for Λ, not available experimentally in \[10\], has been adjusted arbitrarily. We have found later that this norm is consistent with the newly-released normalized data of \[11\]. The curves for other hyperons are predictions. Again, the agreement in Fig. 2 is remarkable, except for the \(\pi^-\) data from STAR, however these data have been corrected for weak decays through the use of the HIJING model \[8\], which led to about 20% decrease. Our model curves in all plots include the full feeding from the weak decays. The fact that our approach reproduces the \(\pi^-\) yields brings a support for the single-freeze-out idea. This is because the large annihilation cross section of \(\pi\) would decrease its abundance if it
interacted with the protons. Thus the single-freeze-out solves the anti-baryon puzzle discussed in the talk by R. Rapp. The fact that the \( \phi \) data are well reproduced also deserves a credit. This meson interacts rather weakly with the medium, thus it can serve as an accurate thermometer of the system at freeze-out. Fits of similar quality as in Fig. 2 can be found for non-central collisions.

The value of \( \rho_{\text{max}} \) of Fig. 2 leads to the following values of the average and maximum transverse flow velocity: \( \langle \beta_\perp \rangle = 0.49, \beta_\perp^{\text{max}} = 0.66 \).

Fig. 3 shows the model fits to the most central NA49 data. For all particles very reasonable agreement is achieved, except for the \( \Omega^- \) (not shown), where the model slope is much too low.

Now we remark on the problem of the HBT radii. As pointed out in the talk by D. Hardtke, our transverse size \( \rho_{\text{max}} \) is small, such that the expected value of \( R_s \) would be too low, of the order of 3.5 fm. However, there are two important effect which increase \( R_s \). The first is the decay of resonances. The resonances travel about of 1 fm before they decay, which increases the radius. Since three quarters of pions come from resonance decays, this increases \( R_s \). The other, more pronounced, effect is the excluded volume/Van der Waals correction. The excluded volume correction brings in a factor of \( (1 + vn)^{-1} \), where \( v \approx 5 \text{ fm}^3 \) is the eigenvolume of the particle (assumed, for simplicity, the same for all particles) and \( n \approx 0.5 \text{ fm}^{-3} \) is the density of particles. Another factor comes from the modification of the chemical potential, and (for the Boltzmann distributions) has the form \( \exp(-pv/T) \), where \( p \) is the pressure.
The product of these factors, which we denote by $s$, is significantly smaller than 1. It changes the normalization of the integrals for the particle multiplicities and spectra. It can be compensated by simultaneously rescaling $\tau$ and $\rho_{\text{max}}$ by $s^{-1/3}$. The procedure leaves the particle ratios and the spectra intact (!), however, it scales up the HBT radii by $s^{-1/3}$. A detailed self-consistent inclusion of the Van der Waals corrections is necessary to obtain detailed estimates. We expect that the needed 50-60% increase will follow naturally. Hence, our approach has no fundamental problem with the size of the HBT radii, provided the resonance decays and the Van der Waals effect is incorporated. Also, with
the inclusion of the Van der Waals effects the size parameters are raised comfort-
ably above the geometric size of the gold nuclei, making room and time for
the collective flow to develop. Certainly, it is important to see in detail what
are the predictions of our model for all HBT radii, in particular for the ratios,
where most approaches have serious problems. This research is under way.

In conclusion, the agreement with the $p_{\perp}$ spectra for all species of particles,
achieved with just two thermal and two geometric parameters, is surprisingly
good cf. Figs. 1-2. Thus, our analysis provides a very strong support for the
thermal approach to the particle production at RHIC.

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