# The Origin of Transverse Flow at the SPS

M. Bleicher, C. Spieles, C. Ernst, L. Gerland, S. Soff, H. Stöcker, W. Greiner

*Institut für Theoretische Physik, J. W. Goethe-Universität,*
*D-60054 Frankfurt am Main, Germany*

S. A. Bass*

*Department of Physics, Duke University*
*Durham, N.C. 27708-0305, USA*

## Abstract

We study the transverse expansion in central Pb+Pb collisions at the CERN SPS. Strong collective motion of hadrons can be created. This flow is mainly due to meson baryon rescattering. It allows to study the angular distribution of intermediate mass meson baryon interactions.

---

*Feodor Lynen Fellow of the Alexander v. Humboldt Foundation

An important question raised in the recent year is: Is there collective transverse expansion and flow at midrapidity in relativistic heavy ion collisions? This phenomenon has long been predicted [1,2] as a result of strong stopping and compression wave or shock wave formation with subsequent hydrodynamical sideward momentum transfer. Flow of baryons and mesons has been experimentally observed at the LBL/BEVALAC and at GSI/SIS in the 1 AGeV regime [3,4], as well as at the BNL/AGS [5,6].

The question now has been raised whether the strong blue shift of the inclusive hadron spectra for high multiplicity events observed last year at the SPS Pb(160 AGeV)+Pb system [7–9] can be theoretically explained by a microscopic calculation. Here we report that the observed strong increase of $p_t$ with $m_{\rm hadron}$ can be due to the large fraction of secondary meson baryon collisions.

A heavy ion collision can be divided into three phases: Incoming nucleons interact with each other, they produce secondary particles and gain transverse momentum. In the course of the rescattering stage, the system may reach thermal (or even chemical) equilibrium, while collective transverse expansion develops. Finally the system dilutes, strong interactions cease - the system freezes out.

The studies presented in this letter are performed within the UrQMD model [10], a microscopic hadronic transport approach based on the covariant propagation of mesonic and baryonic degrees of freedom. It allows for rescattering and the formation and decay of resonances and strings.

Let us briefly discuss how meson baryon reactions are modeled within UrQMD. In the low energy region, i.e. $\sqrt{s} \lesssim 2$ GeV, the inelastic cross section is dominated by s-channel resonance formation. It is calculated from detailed balance according to the sum of the possible final state baryon resonances (e.g. $\pi^- + p \rightarrow \Delta^0$ or $N^*$):

$$\sigma^{\rm MB}_{\rm total}(\sqrt{s}) = \sum_{R=\Delta,N^*} \langle j_B, m_B, j_M, m_M | J_R, M_R \rangle \, \frac{2I_R+1}{(2I_B+1)(2I_M+1)} \qquad (1)$$

$$\times \frac{\pi}{p^2_{\rm CMS}} \, \frac{\Gamma_{R\rightarrow MB}\Gamma_{\rm tot}}{(M_R-\sqrt{s})^2+\frac{\Gamma^2_{\rm tot}}{4}} \quad , \qquad (2)$$

which depends on the total decay width $\Gamma_{\rm tot}$, the partial decay width $\Gamma_{R\rightarrow MB}$, the spins of the particles $I$ and on the c.m. energy $\sqrt{s}$. According to its lifetime this resonance decays *isotropically* in its local restframe into (one or more) mesons and a baryon.

In the ultra high energy limit t-channel processes dominate the total cross section, which can be calculated from Regge theory [11]:

$$\sigma_{\text{total}} = X s^{\epsilon} + Y s^{-\eta} \quad . \tag{3}$$

Here the first term describes the pomeron exchange, while the second one is due to $\rho$, $\omega$, $f$ and $a$ meson exchange, while $s$ denotes the squared center of mass energy. The parameters are fixed by experimental data when available ($\pi + N$, $K + N$, ...). For completely unknown cross sections we employ additional rescaling factors from the additive quark model [12] under the assumption of a 40% reduced s-quark cross section (compared to u, d):

$$\sigma_{\text{AQM}} = 40 \left(\frac{2}{3}\right)^{m_1+m_2} \left(1 - 0.4\frac{s_1}{3-m_1}\right)\left(1 - 0.4\frac{s_2}{3-m_2}\right) [\text{mb}] \quad ,$$
$$\sigma_{\text{MB}_{\text{unkown}}}(\sqrt{s}) = \sigma_{\pi N}(\sqrt{s}) \frac{\sigma_{\text{MB}_{\text{AQM}}}}{\sigma_{\pi \text{N}_{\text{AQM}}}}$$

with $m_i = 1(0)$ for particle $i$ being a meson (baryon) and $s_i$ being the number of (anti-)strange quarks in particle $i$. One or both particles are now excited to longitudinal color flux tubes. Due to the extremely high relative momenta of the incident hadrons, the fragmentation of the strings leads to a strongly forward-backward peaked distribution of secondaries.

Heavy ion collisions at the AGS and, even more so, at the SPS exhibit an intricate scenario: Here, the typical MB collision energies are in the range of 2-10 GeV, thus cannot be assigned to one of the above discussed regimes. The necessity to bridge consistently from one picture of meson baryon interactions to the other becomes apparent if we look at the following reactions where a low momentum pion hits a nucleon

$$\pi + N(938) \rightarrow \Delta \rightarrow \pi + N(938) \quad \text{with an } \textit{isotropic} \text{ angular distribution,} \tag{4}$$

$$\pi + N(2000) \rightarrow \text{String} \rightarrow \pi + N(2000) \quad \text{with a } \textit{longitudinal} \text{ angular distribution.} \tag{5}$$

To investigate the influence of the modelling of meson baryon scattering on the collective transverse flow, the UrQMD model was used in two different modes:

1. A complete downward extrapolation of the high energy longitudinal color flux picture to $\sqrt{s} = 2$ GeV (refered to as forward-backward peaked (f-b) variant) .
2. An upward extrapolation of the resonance behaviour, i.e. an isotropic angular distribution of all outgoing particles in meson baryon reactions (indicated as (iso)).

These changes affect only MB collisions above the resonance region ($\sqrt{s} > 2$ GeV); all other channels, i.e. meson meson and baryon baryon reactions, remain unchanged.

Let us start by comparing both scenarios to recent preliminary experimental data. In Fig. 1 the mean transverse momentum of negatively charged particles ($h^- = \pi^- + K^- + \overline{p}$) as a function of rapidity in Pb+Pb, $b < 3.2$ fm at 160 AGeV is depicted. Open circles are NA49 data [8], open squares are calculated with the resonance extrapolation (iso) and full squares denote the high energy prescription (f-b). Overall good agreement for both ansatzes with the data on the 10% level is found from projectile to target rapidity.

Let us turn now to the transverse momentum spectra of baryons. Fig. 2 shows the "apparent temperature" of protons, "$T$", in Pb(160AGeV)+Pb for different rapidities in comparison with preliminary NA49 data (open circles) [8]. The inverse slope "$T$" is obtained from a fit to the transverse mass $m_T$ spectrum using

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \mathrm{e}^{-m_T/T} \quad . \tag{6}$$

In both scenarios, the "temperature" of the protons increases towards midrapidity. The maximum "temperatures" are 270 MeV (f-b, full squares) and 395 MeV (iso, open squares). Thus the isotropic meson baryon scattering prescription predicts a temperature at $y_{\rm CM}$ exceeding the preliminary data by 30%.

To gain further insight into the creation of transverse flow, Fig. 3 discusses the mean transverse momenta of particles for different mass bins at $|y| < 0.5$ in central Pb+Pb collisions at the SPS. Circles show the p(160 AGeV)+p events, open squares indicate the (f-b) Pb+Pb events and the full black squares show the MB-(iso)tropic model. In addition, we fit the resulting mass spectra with a simplified 2 parameter fireball plus flow model. The full black line is the mean transverse momentum $< p_T(m, T_0, \beta_T) >$ for different masses $m$ calculated from a thermal distribution with temperature $T_0 = 160$ MeV (to fit the $\pi$) without any additional flow ($\beta_T = 0$). The dashed line shows the $< p_T(m, T_0, \beta_T) >$ from an expanding thermal source ($T_0 = 170$ MeV) with an additional transverse flow velocity of $\beta_T = 0.34c$. This yields in the saddle point approximation a rough value for the "*apparent* temperature" $T$ [13]:

$$T \approx T_0 + m\beta_T^2 \quad . \tag{7}$$

The mean $p_T$ of all hadrons, from proton-proton reactions as well as from the high energy nucleus-nucleus (f-b) scenario show no significant difference to a non-expanding thermal source. However, additional *baryon* flow is visible due to further baryon baryon collisions. This results in a bump in the mean $p_T$ around $m \approx 1.1$ GeV. In contrast, the isotropic (MB) model produces a hadronic source which expands more strongly in the transverse direction. A significant transverse collective flow velocity of $0.34c$ is observed in this calculation. Due to its very small cross section in nuclear matter the $\Phi$-meson aquires less transverse flow compared to other hadrons. Note that the error bars are only statistical. These are given only for the (f-b) Pb+Pb reaction, in the (MB iso) and p+p case they are about the same.

The observed apparent "temperatures" (inverse slopes) at midrapidity ($|y| < 0.5$) depend strongly on the particle mass $m$ as depicted in Fig. 4. The calculated proton-proton collisions (crosses) show about the same freeze-out "temperature" $T \approx m_\pi$ for all particles from $m_\pi$ to $m = 2$ GeV. In Pb(160 AGeV)+Pb, the "$T$"-values increase -in contrast to the data- only weakly above the p+p values, if the forward backward scenario (MB) is applied. On the other hand, isotropic angular distributions for intermediate energy meson-baryon collisions (in line with the resonance picture) yield a linearly increasing apparent "temperature" with the particle mass for Pb(160 AGeV)+Pb, in agreement with the preliminary NA49 data.

We conclude that strong transverse flow can occur in massive reactions at the SPS. However, the hadron mass dependence of the apparent temperature is sensitive to the detailed modelling of the meson-baryon rescattering process above the resonance region

($\sqrt{s_{\rm MB}} > 2$ GeV) and below the high energy domain. Two distinct pictures of meson baryon scattering with $\sqrt{s_{\rm MB}} > 2$ GeV have been confronted: the high energy limit of longitudinal fragmenting color strings was extrapolated downward in energy, versus the concept of resonance formation of meson baryon scattering with isotropic decay. Both models describe the rapidity dependence of the transverse momentum of produced particles equally well, while the isotropic scattering prescription predict the apparent proton temperatures at midrapidity about 30% larger than preliminary data. However, strong increase of the transverse slope does *only* build up in the high energy 'resonance model'.

## ACKNOWLEDGEMENTS

This work is supported by the BMBF, GSI, DFG and Graduiertenkolleg 'Schwerionenphysik'. M. Bleicher and S. Soff acknowledge support by the Josef Buchmann Foundation.

# REFERENCES

[1] W. Scheid, H. Müller, W. Greiner, Phys. Rev. Lett. 32 (1974) 741

[2] L.P. Csernai, W. Greiner, H. Stöcker, I. Tanihata, S. Nagamiya, J. Knoll, Phys. Rev. C25 (1982) 2482;
H. Stöcker, W. Greiner, Phys. Rep. 137 (1986) 277

[3] K. H. Kampert, J. Phys. G17 (1989) 691

[4] H. H. Gutbrod, A. M. Poskanzer, H. G. Ritter, Rep. Prog. Phys. 52 (1989) 1267

[5] J. Barrette et al., (E877 Collaboration), Phys. Rev. C56 (1997) 3254

[6] R. Mattiello, H. Sorge, H. Stöcker, W. Greiner, Phys. Rev. C55 (1997) 1443

[7] I.G. Bearden et al., (NA44 Collaboration), Phys. Rev. Lett. 78 (1997) 2080

[8] P. G. Jones et al., (NA49 Collaboration), Nucl. Phys. A610 (1996) 188c;
G. Roland et al., (NA49 Collaboration), Nucl. Phys. A (1998) in print

[9] T. Peitzmann (WA98 Collaboration), Talk given at the Quark Matter ’97, Nucl. Phys. A (1998) in print

[10] S. A. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, L. Bravina, C. Ernst, L. Gerland, M. Hofmann, S. Hofmann, J. Konopka, G. Mao, L. Neise, S. Soff, C. Spieles, H. Weber, L. A. Winckelmann, H. Stöcker, W. Greiner, Ch. Hartnack, J. Aichelin, N. Amelin, to be published in Prog. Part. Nucl. Phys. 41 (1998)

[11] A. Donnachie, P.V. Landshoff, Phys. Lett. B296 (1992) 227

[12] K. Goulianos, Phys. Rep. 101 (1983) 169

[13] K.S. Lee, U. Heinz, E. Schnedermann, Z. Phys. C48 (1990) 525

# FIGURES

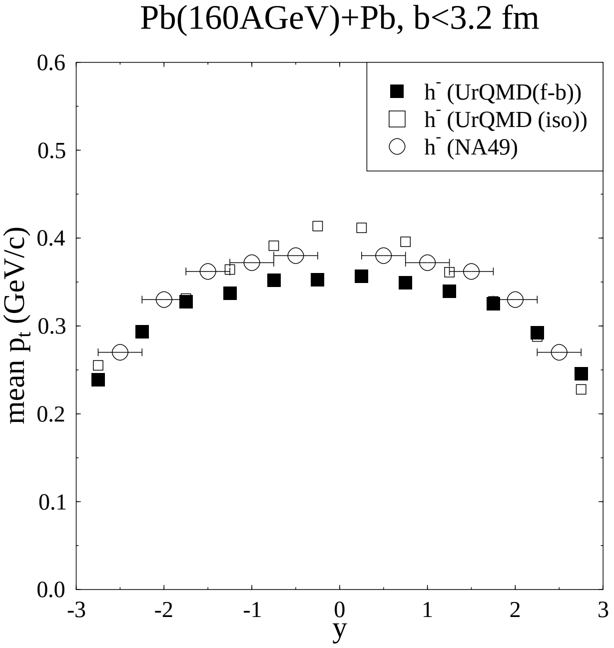

FIG. 1. Average transverse momentum of $h^- = \pi^- + K^- + \overline{p}$ in central Pb(160GeV)+Pb reactions at the SPS.

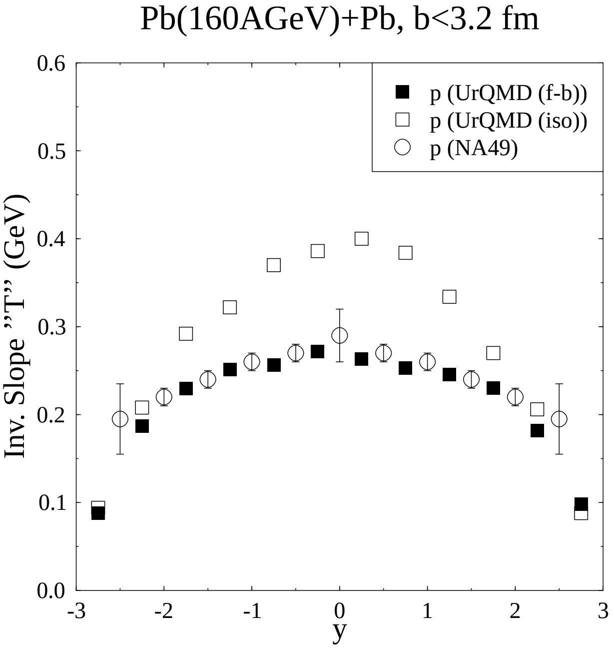

FIG. 2. Apparent temperature of protons as a function of rapidity in central Pb(160GeV)+Pb reactions at the SPS.

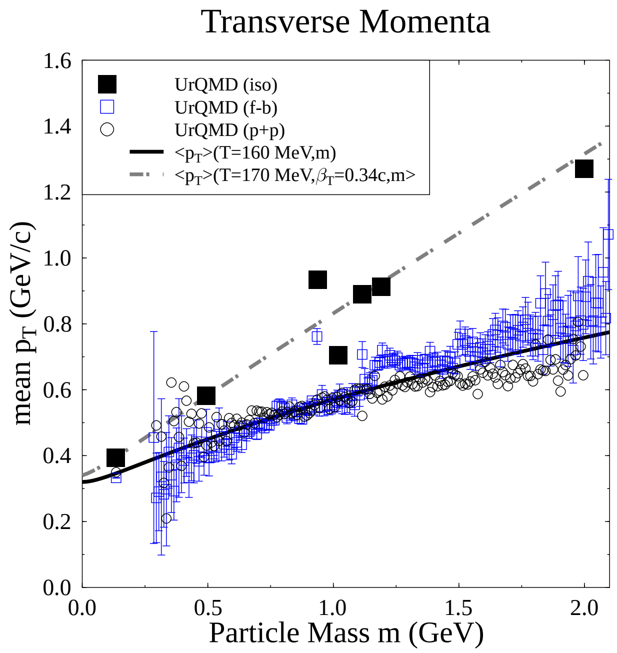

FIG. 3. Mean $p_t$ at midrapidity ($|y| < 0.5$) as a function of particle mass in central Pb(160GeV)+Pb reactions (compared to p(160GeV)+p).

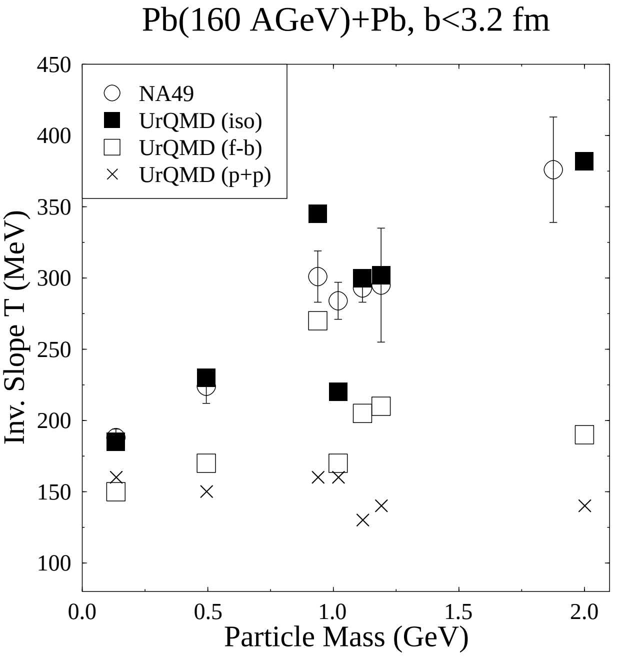

FIG. 4. Midrapidity ($|y| < 0.5$) inverse slope parameter T as a function of particle mass in central Pb(160GeV)+Pb reactions (compared to p(160GeV)+p).