

Ralf Rapp and Edward V. Shuryak

*Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800, U.S.A.*

(September 2, 2000)

We argue that the observed antiproton production in heavy-ion collisions at CERN-SpS energies can be understood if (contrary to most sequential scattering approaches) the backward direction in the process  $p\bar{p} \leftrightarrow \bar{n}\pi$  (with  $\bar{n}=5-6$ ) is consistently accounted for within a thermal framework. Employing the standard picture of subsequent chemical and thermal freezeout, which induces an over-saturation of pion number with associated chemical potentials of  $\mu_\pi \simeq 60-80$  MeV, enhances the backward reaction substantially. The resulting rates and corresponding cross sections turn out to be large enough to maintain the abundance of antiprotons at chemical freezeout until the decoupling temperature, in accord with the measured  $\bar{p}/p$  ratio in Pb(158A GeV)+Pb collisions.

## I. INTRODUCTION

Over the last decade substantial progress has been made in the understanding of the dynamics of strong interactions probed through (ultra-) relativistic heavy-ion collisions. Although the main challenge of an unambiguous identification of the QCD phase transition to the Quark-Gluon Plasma (QGP) persists, we have greatly advanced our knowledge on properties of highly excited hadronic matter close to the expected phase boundary. A variety of collective phenomena has been observed indicating that the produced systems have indeed reached macroscopically large sizes, justifying the use of equilibrium techniques such as thermo- and hydrodynamics.

One of the important results that will be used below is that the final-state hadron abundances, including antibaryons, can be rather accurately characterized by the so-called *chemical* freezeout stage [1] with a common temperature  $T_{ch}$  and baryon chemical potential  $\mu_{B,ch}$  (the specific values depending on collision energy).

At SpS energies, this chemical freezeout is clearly distinct from the *thermal* one (with corresponding temperature  $T_{th} < T_{ch}$ ), from where on the particles stream freely to the detectors. This follows from the kinetics of hadronic reactions [2,3], *i.e.*, a significant difference between elastic and inelastic collision rates at low relative energies, and has been confirmed by a variety of experimental evidences (see, *e.g.*, ref. [4]). *E.g.*, in central Pb+Pb collisions a nucleon at mid-rapidity is elastically rescattered on average about 10-15 times, but less than once inelastically [5]. Also, as shown in [3], most of the collective flow effects at SpS are generated *in between* these two freezeouts, and their observation leaves no doubt about the existence of such an intermediate stage.

Another consequence is that abundances of secondary mesons (pions, kaons, etc.) are not subject to significant changes when the system evolves from  $T_{ch}$  to  $T_{th}$ . Again, this is conceivable as the rates for number changing reactions are too small to maintain chemical equilibrium on the time scales of  $t \simeq 10$  fm/c. Since, on the other hand, elastic scattering (*e.g.*,  $\pi\pi \rightarrow \rho \rightarrow \pi\pi$ ) is still effective, thermal equilibrium is approximately maintained. In a statistical mechanics language such a scenario entails additional conservation laws, which can be implemented via effective (pion-, kaon-, etc.) chemical potentials to guarantee fixed particle numbers. For pions (kaons), *e.g.*, typical values of  $\mu_\pi = 60-80$  MeV ( $\mu_K = 100-130$  MeV) are reached at  $T_{th} = 110-120$  MeV, see [2,3,6]. The ensuing 'over-saturation' of the pion phase space is to play the key role in what follows.

## II. ANTIPROTON KINETICS AT SPS

The situation for antibaryons is different from mesonic secondaries as the pertinent *inelastic* (or annihilation) cross section is *not* small. At the relevant (thermal) energies in the comoving frame of collective expansion,  $\sqrt{s} = 2(m_N + E_{N,th}) \simeq 2.3$  GeV, one has  $\sigma_{p\bar{p} \rightarrow n\pi} \simeq 50$  mb. Taking an average baryon density of  $0.75\rho_0$  around  $T = 150$  MeV in the course of the hadronic evolution and a typical (anti-) proton velocity of  $v_{th} = p/E_{tot} = 0.56c$  (from  $E_{p,th} = (3/2)kT \simeq 225$  MeV), we obtain for the chemical equilibration time scale

$$\tau_{ch} = \frac{1}{\sigma_{ann} \rho_B v_{th}} \simeq 3 \text{ fm/c} . \quad (1)$$

This is well below the fireball lifetime in the pure hadronic phase of  $\tau_{had} \simeq 7\text{fm}/c$  [3,6]; in other words, only a fraction of  $\exp[-\tau_{had}/\tau_{ch}] \simeq 10\%$  does *not* rescatter towards thermal freezeout. Thus, in spite of the good agreement of the final  $\bar{p}$  yields with the standard chemical freezeout predictions, one should reconsider antibaryon production.

Naively one might expect most of the antiprotons to be annihilated, and various transport calculations (*e.g.*, ARC [7] and UrQMD [8]) have indeed been unable to account for the measured number, falling short by significant factors. Consequently, speculations have been raised that the puzzle could be resolved by strong in-medium effects leading to either a reduction of the annihilation rate [7] or an enhanced production [8].

A generic problem with transport/cascade simulations is that, although multi-body resonance decays are included, the inverse reactions are not. As is well-known, this latter violates detailed balance and, in principle, prevents the simulations from reaching the proper thermodynamic limit [9]. The discussions are typically focused on three-body reactions; in the present context it is even 5 or 6-pion collisions which are most relevant for producing baryon-antibaryon pairs. A widespread belief is that those reactions have insignificant rates under the conditions probed in the hadronic stages of heavy-ion collisions. However, as we will argue below, this is not the case; inverse reactions have to be addressed and are, in fact, capable of explaining the observed antiproton yield.

The expression for the thermal reaction rate for the process  $p\bar{p} \leftrightarrow n\pi$  can be written as

$$\mathcal{R}_{th} = |\mathcal{M}_n|^2 \left[ z_p z_{\bar{p}} \exp[-(E_p + E_{\bar{p}})/T] - z_{\pi}^n \exp[-\sum_{i=1}^n \omega_{\pi,i}/T] \right]. \quad (2)$$

where  $\mathcal{M}_n$  denotes the invariant scattering matrix element (which, of course, is identical for the back- and forward direction due to time-reversal invariance of strong interactions);  $z_x = e^{\mu_x/T}$  are the fugacities of particle species  $x$  (in Boltzmann approximation), and  $n$  is the number of pions produced in a  $\bar{p}p$  annihilation at a given energy (to be discussed in more detail in the next section). For a nonvanishing net nucleon number and in chemical equilibrium, one has  $\mu_N > 0$ ,  $\mu_{\bar{N}} = -\mu_N$  and  $\mu_{\pi} = 0$ . Under SpS conditions, typical values at chemical freezeout are [1] ( $T_{ch}, \mu_{N,ch}$ )  $\simeq (170, 260)$  MeV, which results in an antiproton-to-proton ratio of

$$\begin{aligned} \frac{\bar{p}}{p} &\propto \frac{\exp[-(E_{\bar{p}} + \mu_N)/T]}{\exp[-(E_p - \mu_N)/T]} \\ &= \exp[-2\mu_N/T] = 4.7\%, \end{aligned} \quad (3)$$

consistent with the experimental value of  $(5.5 \pm 1)\%$  [10]. Note also that at chemical freezeout  $z_p z_{\bar{p}} = 1$ ,  $z_{\pi} = 1$ , and the forward and backward rates in eq. (2) are simply equal (the Boltzmann factors in both terms contain the same total energy). This implies, *e.g.*, that cascade simulations ignoring the back-reaction at comparable pion densities ( $\rho_{\pi} \simeq 0.2 - 0.25 \text{ fm}^{-3}$ ) cannot give a proper account of the antiproton production.

The evolution towards thermal freezeout can be constructed using a thermal fireball model which, assuming isentropic expansion, leads to  $(T_{th}, \mu_{N,th}) \simeq (120, 415)$  MeV. At first sight, this implies a  $\bar{p}/p$  ratio of  $\exp[-2\mu_N/T] \simeq 0.1\%$ , a factor of  $\sim 50$  below the measured number. However, this estimate is lacking an important ingredient. A correct statistical treatment including pion-number conservation forces us to introduce individual chemical potentials/fugacities for anti-/protons and pions. Insisting on equilibrium for the reaction in question, the following relation holds:

$$z_{\bar{p}} = (z_p)^{-1} \langle z_{\pi}^n \rangle. \quad (4)$$

Since antibaryons constitute only a small fraction of the produced secondaries, they have an insignificant impact on the evolution of nucleon- and pion-chemical potentials. Therefore, eq. (4) provides an estimate of the antiproton fugacity at thermal freezeout. The crucial point here is that pion over-saturation will generate a strong enhancement of the back-reaction  $n\pi \rightarrow p\bar{p}$ .

### III. MULTI-PION ANNIHILATION AT FINITE $\mu_{\pi}$

For a more quantitative assessment it is important to have a rather accurate determination of the pion multiplicity distributions in  $p\bar{p}$  annihilation. A nice discussion of its systematics has been given, *e.g.*, in ref. [11], which we will follow here to incorporate the empirical knowledge. For  $\bar{p}p$  annihilation at rest ( $\sqrt{s} = 2m_N$ ), the data can be represented by a least-square fit to a Gaussian probability distribution (normalized to one),

$$P(n) = \frac{1}{\sqrt{2\pi}\sigma} \exp[-(n - \langle n \rangle)^2 / 2\sigma^2], \quad (5)$$

with a mean  $\langle n \rangle = 5.02$  and width  $\sigma = 0.90$  (see also ref. [12]). At larger *c.m.*-energies both the average number and width increase. For the former, linear [13] and logarithmic [14] dependencies have been proposed,

$$\begin{aligned}\langle n \rangle &= c_1 + c_2 s^{0.5} \\ \langle n \rangle &= \tilde{c}_1 + \tilde{c}_2 \ln(s)\end{aligned}\tag{6}$$

( $s$  in  $[\text{GeV}^2]$ ), which both reproduce the measured multiplicities up to at least  $\sqrt{s} = 5$  GeV using the parameters  $c_1 = 2.6 \pm 0.5$ ,  $c_2 = (1.3 \pm 0.2) \text{ GeV}^{-1}$  and  $\tilde{c}_1 = 2.65$ ,  $\tilde{c}_2 = 1.78$ , respectively. For the latter, the energy dependence of the width has also been given as [14]

$$\sigma^2 = 0.174 \langle n \rangle s^{0.2} .\tag{7}$$

For our application in a thermal environment at  $T = 150$  MeV (implying  $\sqrt{s} = 2.33$  GeV) we fix  $\langle n \rangle = 5.65$  (in accordance with eq. (6)) together with a 10% increase in  $\sigma$  (as suggested by eq. (7)) to extract discrete weights  $w_n = P(n; \langle n \rangle, \sigma)$ . The averaged pion-fugacity enhancement factor then follows as

$$\langle z_\pi^n \rangle = \sum_{n=2}^{n_{max}} w_n \exp[n\mu_\pi/T] ,\tag{8}$$

where  $n_{max} = 9$  for any practical purpose. Inserting now thermal freezeout values  $T_{th} = 120$  MeV and  $\mu_{\pi,th} \simeq 65$  MeV (as arising, *e.g.*, in a thermal fireball model [6]), yields  $\langle z_\pi^n \rangle = 25$ . This implies a large enhancement of the antiproton-to-proton ratio, from 0.1% to 2.5%. In fact, owing to the high power of the pion fugacity, slightly larger chemical potentials of  $\mu_\pi = 75$ -80 MeV result in an enhancement factor of 42-54, rendering the pertinent  $\bar{p}/p$ -ratio in line with the observed (chemical freezeout) value.

Such slightly increased values for the pion chemical potential close to thermal freezeout can in fact be easily argued for. Within the thermal fireball model of ref. [6] elastic  $\pi N \rightarrow B$  scattering ( $B$ : baryonic resonances up to  $m_B \simeq 1.7$  GeV) was assumed to be frequent enough to maintain (relative) chemical equilibrium for the occupation of the excited baryonic states. However, with typical corresponding cross sections of  $\sigma_{\pi N \rightarrow B} \simeq 15$ -30 mb [15], this might not be fully justified anymore for the last few fm/c prior to thermal freezeout. Consequently, a larger fraction of the pion number resides in explicit pionic degrees of freedom rather than in excited resonances, which translates into an effectively larger  $\mu_\pi$ .

#### IV. CONCLUSIONS

We have analyzed the  $\bar{p}/p$ -ratio at SpS energies within an equilibrium approach. So far this observable has been difficult to understand within, *e.g.*, transport models which only included the annihilation channel, creating doubts whether the latter is actually active, or whether one needs to invoke unconventional mechanisms for enhanced production. We have shown, however, that the 'puzzle' can be resolved in a rather standard statistical-mechanics framework upon inclusion of the inverse process of multipion scattering into  $\bar{p}p$  pairs, which can be supported until thermal freezeout. Our main ingredient was that effective pion-number conservation produces pion over-saturation at the later stages of a heavy-ion collision, as described by the build-up of appreciable pion chemical potentials. Raised to a large power ( $n \sim 6$ ) the corresponding pion fugacities sustain a high antibaryon fraction, thus counter-balancing the loss from  $B\bar{B}$  annihilation. This mechanism also complies with the measured centrality dependence being essentially constant, as to be expected from a hadro-chemistry varying little with impact parameter.

Our findings give further support to the concept of subsequent chemical and thermal freezeout stages, which has already proven successful in the explanation of a variety of observables, such as hadron abundances, collective flow, HBT radii and electromagnetic radiation.

#### ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Grant No. DE-FG02-88ER40388.

---

[1] P. Braun-Munzinger, J. Stachel, J.P. Wessels and N. Xu, Phys. Lett. **B365** (1996) 1;  
P. Braun-Munzinger, I. Heppe and J. Stachel, Phys. Lett. **B465** (1999) 15.

- [2] E. Shuryak, Phys. Lett. **B207** (1988) 345; Phys. Rev. **D42** (1990) 1764;  
P. Gerber, H. Leutwyler and J. L. Goity, Phys. Lett. **B246** (1990) 513;  
H. Bebie, P. Gerber, J.L. Goity and H. Leutwyler, Nucl. Phys. **B378** (1992) 95.
- [3] C.M. Hung and E. Shuryak, Phys. Rev. **C57** (1998) 1891.
- [4] R. Stock, Nucl. Phys. **A661** (1999) 282c.
- [5] H. Sorge, Phys. Rev. **C52** (1995) 3291.
- [6] R. Rapp and J. Wambach, Eur. Phys. J. **A6** (1999) 415.
- [7] Y. Pang, D.E. Kahana, S.H. Kahana and H. Crawford, Phys. Rev. Lett. **78** (1997) 3418.
- [8] M. Bleicher, M. Belkacem, S.A. Bass, S. Soff and H. Stöcker, Phys. Lett. **B485** (2000) 133.
- [9] M. Belkacem *et al.*, Phys. Rev. **C58** (1998) 1727.
- [10] M. Kaneta for the NA44 collaboration, Nucl. Phys. **A638** (1998) 419c.
- [11] C.B. Dover, T. Gutsche, M. Maruyama and A. Faessler, Prog. Part. Nucl. Phys. **29** (1992) 87.
- [12] W. Blümel and U. Heinz, Z. Phys. **C67** (1995) 281.
- [13] P. Gregory *et al.*, Nucl. Phys. **B102** (1976) 189.
- [14] R. Stenbacka *et al.*, Nuovo Cim. **51A** (1979) 63.
- [15] D.E. Groom *et al.*, Eur. Phys. J. **C15** (2000) 1.