Statistical hadronization as a snapshot of a dynamical fireball evolution

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Statistical hadronization models are extremely successful in describing measured ratios of hadrons produced in heavy-ion collisions for a wide range of beam energies from SIS to RHIC. Using the idea of statistical hadronization at the phase boundary within the framework of a recently proposed dynamical model for the thermodynamics of fireballs, we establish a relation between the equation of state in the partonic phase probed at the phase transition temperature T_C and the measured hadron ratios. In this way, the ratios can be predicted parameter free. We demonstrate that this framework gives a consistent description of conditions both at SPS and RHIC. As the data on dilepton emission from heavy-ion collisions give evidence for strong in-medium modifications of hadronic properties, we schematically investigate the sensitivity of our results to such modifications and qualitatively sketch a consistent scenario involving such in-medium effects.

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I. INTRODUCTION

The goal of current investigations in heavy-ion collisions is to establish the existence of the quark-gluon plasma (QGP) phase and to study its properties. Several signals have been proposed as indicators for its creation. However, no unambiguous proof has been established so far. A large part of the problem lies in the difficulty to separate effects of the evolution of the hot and dense medium from characteristic changes in the physics of reactions taking place inside this medium. Therefore, it is mandatory to aim at a consistent description of as many observables as possible within a single model of the medium evolution.

In a recent paper [1], we have proposed a model for the evolution of a fireball assuming local thermal equilibrium and isentropic expansion. In this approach, the evolution is constrained by two major pieces of information. First, by measured hadronic momentum spectra and Hanbury-Brown Twiss interferometry data which reflect the freeze-out state; second, by information on the equation of state (EoS) obtained in lattice simulations and represented in terms of a quasiparticle picture. We have demonstrated that this evolution scenario is in agreement with data on dilepton emission measured by the CERES collaboration [2]. We have also used the same model to describe the emission of hard thermal photons [3] and found good agreement with the data measured by WA98 [4].

No explicit statement about the hadrochemical composition of the fireball is made in this model. Instead, we use phenomenological arguments to include the effects of enhanced pion phase space density into the EoS of hot hadronic matter. On the other hand, statistical models are extremely successful in describing the measured ratios of different hadron species for a range of collision energies from SIS to RHIC (see, e.g., Refs. [5–8]). It is the aim of this paper to show that our fireball evolution model is consistent with the idea of statistical hadronization.

The paper is organized as follows: First, we outline the version of statistical hadronization used in our model. After comments on technical details, we present results and compare to data both for SPS and RHIC conditions. We then investigate the sensitivity of these results to the model parameters; specifically we study the role of possible in-medium modifications of particle properties. We conclude by sketching a possible scenario in which in-medium modifications are possible while statistical hadronization is still in agreement with the data.

II. THE STATISTICAL HADRONIZATION MODEL

The fireball evolution model outlined in Ref. [1] contains a phase transition from partonic to hadronic matter. If one is interested in the composition of the hadronic system, one has to introduce a model of hadronization. In the present paper, we assume that the particle content of the fireball at the critical temperature T_C can be found by considering a system of (noninteracting) hadrons in chemical equilibrium, described by the grand canonical ensemble, which subsequently undergoes decay processes. This is based on ideas presented in Refs. [5–7], where it was shown that a huge number of hadron ratios can be explained by a fit of only two model parameters: temperature T and baryochemical potential μ_B.

Clearly, the notion of noninteracting hadrons close to the phase boundary is not suitable for the description of the phase transition thermodynamics on a fundamental level, but should rather be regarded as an effective prescription. The underlying assumption is that the level spacings and degeneracies of the QCD excitation spectrum along with the energy scale provided by the temperature already contain enough information to determine the relative contributions of different hadron species and that details of the interactions can either be absorbed into hadronic quasiparticle properties such as temperature dependent masses and widths or average out.

The calculation of hadronic abundancies in this framework is a two-step process: First, we have to specify the properties of the medium (the QGP) at the transition in terms of the densities of quarks, antiquarks, and gluons (this is most conveniently done by specifying the temperature T_C and baryochemical and strange chemical potentials μ_B, μ_S).

These parameters can be fitted to the observed hadron ratios (as done in Refs. [5–7]), calculated within a dynamical model (as done in the present paper for SPS) or inferred from experiment (as done in the present paper for RHIC).

Once the densities in the QGP have been specified, the hypothesis of statistical hadronization is used to map those into the hadron ratios observable in experiment. In detail, we use the following procedure to calculate ratios for SPS.

Employing the grand canonical ensemble, we expect the density for each particle species n_i to be given by

$$n_i = \frac{d_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp\{[E_i(p) - \mu_i]/T_C\} \pm 1}. \tag{1}$$

Here, d_i denotes the degeneracy factor of particle species i (spin, isospin, particle/antiparticle), the + (−) sign is used for fermions (bosons), and $E_i(p)=\sqrt{m_i^2+p^2}.m_i$ stands for the particle's vacuum mass. We use a value of 170 MeV for the critical temperature T_C as determined in lattice calculations for two light and one heavy flavors [9] and also used in the fireball evolution model. The chemical potential μ_i takes care of conserved baryon number B_i and strangeness S_i for each species:

$$\mu_i = \mu_B B_i - \mu_S S_i. \tag{2}$$

We neglect a (small) contribution $-\mu_{I_3} I_i^3$ coming from the isospin asymmetry in the colliding nuclei.

The baryochemical potential μ_B is then fixed by the requirement that the net number of baryons inside the thermalized region is equal to the number of collision participants N_{part} if the total volume V is known:

$$V\sum_i n_i B_i = N_{part}. \tag{3}$$

Similarly, strangeness conservation demands

$$V\sum_i n_i S_i = 0. \tag{4}$$

Thus, the only parameter of the model is the fireball volume V. At the phase transition, however, this volume can be determined from the EoS of the QGP evaluated at $T=T_C$ using the entropy density $s(T)$ as

$$V(T_C) = S_{tot}/s(T_C), \tag{5}$$

if the total entropy content S_{tot} of the fireball is known. This quantity, however, can be obtained from measuring charged particle multiplicities N^+ and N^- in suitable rapidity bins and calculating

$$D_Q = \frac{N^+ - N^-}{N^+ + N^-}. \tag{6}$$

The quantity D_Q stands for the inverse of the specific entropy per net baryon, S/B, and the product $D_Q(S/B)$ roughly measures the entropy per pion [10]. For SPS collisions at 160A GeV, we find an entropy per net baryon $S/B=26$ for central collisions.

At RHIC, hadron ratios are measured at midrapidity. It is known that the distribution of baryon number across rapidity is very inhomogeneous at collider energies, hence a prediction of the quark and gluon densities within a globally averaged framework as outlined for the SPS case using Eqs. (3) and (5) is bound to fail. For the sake of simplicity, we will not attempt to calculate μ_B in a (more complicated) dynamical model but rather infer it from the experimentally accessible (specific) entropy, keeping in mind that our results for RHIC do not test a dynamical model but only the statistical hadronization hypothesis (in principle, however, the baryon distribution in rapidity is calculable, e.g., Ref. [11]).

For RHIC 6% central Au-Au collisions at 130A GeV, the specific entropy $S/B=220$ at midrapidity is substantially higher due to the larger particle multiplicity and the smaller net baryon content in the central region. The transition volume is then estimated by using the EoS to determine the volume at which the measured entropy in the midrapidity slice corresponds to the temperature T_C if a backward extrapolation of the expansion in time is made. Note, however, that the transition volume is only relevant for excluded volume corrections and can be neglected for a first-order approximation since we are interested in hadron ratios and not in total abundancies. Thus, all ingredients entering Eq. (1) are determined (without additional free parameters) and we can evaluate the expression for a suitable choice of hadrons and resonances.

We include all mesons and mesonic resonances up to masses of 1.5 GeV, and all baryons and baryonic resonances up to masses of 2 GeV. This amounts to 30 (strange and nonstrange) mesonic states and 36 (nonstrange to multistrange) baryonic states. In order to compare to experimental results, we calculate their decay into particles which are long lived as compared to the fireball, such as $\pi, K, \eta, N, \Lambda, \Sigma$, and Ω.

In order to account for interactions between particles, which at small distances become repulsive, we assume a hard core radius R_C of 0.3 fm for all particles and resonances. The corresponding excluded volume $V_{ex}=\Sigma_i N_i V_{ex}^i$, with $V_i^{ex}=(4\pi/3)R_C^3$ for all species, is subtracted from the volume obtained in Eq. (5), which in turn affects the total number of produced particles. As the excluded volume itself depends on the total number of particles, we iterate the correction for a self-consistent result. The hard core radius of 0.3 fm for protons is determined by comparison with p-p collisions [12]. In the absence of such information for the other mesons and baryons, we assume its universality.

All data on particles are taken from Ref. [13]. For many higher-lying states, the properties as well as the decay channels are poorly known. In these cases, we proceed as follows: If a quantity (e.g., masses and widths) is given only within a certain range, the arithmetic mean of this range is used in the model. Decay channels which are reported to be "seen" are assumed to receive equal contributions from the branching ratio which is left after all known channels have been accounted for. Branching ratios less than 1% have been neglected. Decay chains (such as $a_2 \rightarrow \rho\pi \rightarrow \pi\pi\pi$) have been followed through. For resonances with large width, we integrate Eq. (1) over the mass range of the resonance using a Breit-Wigner distribution.

III. SOME REMARKS ON THERMODYNAMICS

As mentioned earlier, the notion of a noninteracting hadronic resonance gas cannot be expected to describe the full thermodynamics of the system close to the phase boundary. Therefore, one cannot expect all thermodynamical parameters to match smoothly coming from above and below the phase transition. An ensemble of free hadrons therefore should not be used to calculate thermodynamical properties of the hot hadronic medium, as there is strong evidence for rescattering processes in the hadronic phase from dilepton emission (see, e.g., our result in Ref. [1]) and these interactions certainly modify the thermodynamics.

This becomes apparent once we compare thermodynamic parameters directly. Coming from above T_C, we find from the quasiparticle model of the QGP

$$p/T_C^4 = 0.3, \quad \epsilon/T_C^4 = 7.0, \quad \text{and } s/T_C^3 = 7.3.$$

Calculating the corresponding hadronic resonance gas values at T_C (using the ensemble of particles and resonances described above), one obtains

$$p/T_C^4 = 1.0, \quad \epsilon/T_C^4 = 6.3, \quad \text{and } s/T_C^3 = 7.3.$$

The crucial observation is that the entropy density matches smoothly (one should keep in mind, however, that there are errors given by the extraction of T_C from lattice data, the extrapolation of lattice data to physical quark masses and the poor knowledge of high-lying resonances). This implies that we have not introduced a gross violation of the number of available degrees of freedom (which is important, as the goal of this study is to obtain particle numbers out of an *isentropic* expansion scenario with a crossover or second-order phase transition). If the entropy density did not match at T_C, we would have introduced a first-order phase transition which would certainly lead to a breakdown of the simple, "instantaneous" hadronization scenario used here.

On the other hand, in the pressure and energy density we find discontinuities at T_C. The difference of the energy density in both phases can be regarded as acceptable given the uncertainties, but in the case of the pressure the discrepancy is large. It is, however, certainly conceivable that attractive interactions in the system lower the pressure. Thermodynamical consistency then fixes the energy density via $\epsilon+p=sT$, achieving continuity in both quantities. A more fundamental approach in order to achieve continuity of all parameters across the phase transition, however, faces other difficulties.

(1) Any interacting model of hadrons will have to introduce additional coupling constants, which, at least for the high-mass resonance states, are poorly known.

(2) Incorporating all *known* interactions is of limited help: If one considers the free ensemble at T_C, one finds, e.g., that the sum of all excited Δ states is larger than the number of $\Delta(1232)$. This is also true for the nucleon and nuclear resonances. Hence, resonance states are no small contribution and cannot be neglected. If one is interested in the number of pions resulting after resonance decays, the role of heavy resonances is even further enhanced due to very pion-rich decay channels of these heavy states.

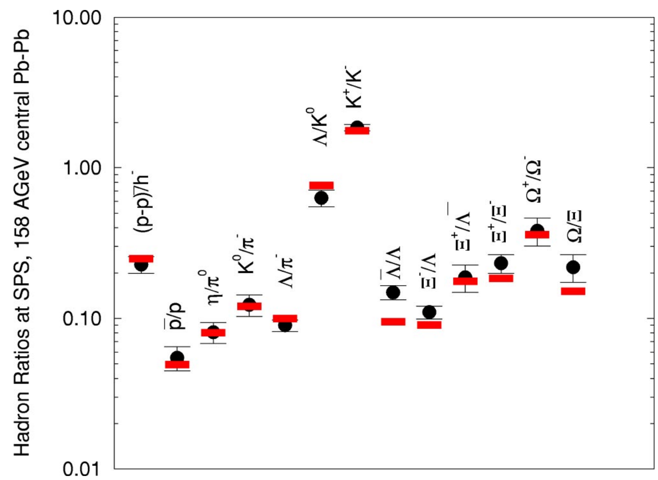

FIG. 1. Hadron ratios in the statistical hadronization model (dashed bands) as compared to experimental results (filled circles) for SPS, 158*A* GeV central Pb-Pb collisions.

(3) Accepting the limited knowledge of heavy-resonance properties, one might think of using some effective *ad hoc* prescription of restoring thermodynamical consistency. However, there is no unique way of doing so, therefore the model loses all predictive power.

In contrast, statistical hadronization is a simple prescription and completely determined by at most two parameters, which in the present context are given by the fireball evolution model. Therefore, it appears useful to accept the limitations of the present model for the benefit of a parameter-free calculation.

IV. RESULTS

The resulting hadron ratios are shown in Fig. 1 for the case of 158*A* GeV central Pb-Pb collisions at SPS, compared with the experimentally measured values [14–24]. One observes that the overall agreement with data is satisfactory with few exceptions, though not quite as good as in, e.g., Ref. [6] where a two-parameter fit to the data was performed. Note that not only the ratios of hadron yields agree to experiment in the present approach but also the absolute numbers, as the baryochemical potential μ_B is explicitly linked to the (known) number of participants.

The calculation yields a baryochemical potential $\mu_B=265$ MeV and a strange chemical potential $\mu_S=59$ MeV. Note that these quantities depend on the number of resonances included into the calculation; therefore, a direct comparison with the values obtained in other types of models is not necessarily meaningful.

For central collisions at RHIC at 130*A* GeV beam energy we present the results in Fig. 2 and compare to experimental data measured around midrapidity [25–30]. As the distribution of net baryon number in rapidity is very inhomogeneous at RHIC, the naive application of Eq. (3) fails, as we obtain a low entropy per baryon, $S/B=75$. At midrapidity, however, this ratio is closer to $S/B=220$. Using this value to calculate the ratios in a suitable interval around midrapidity, we find

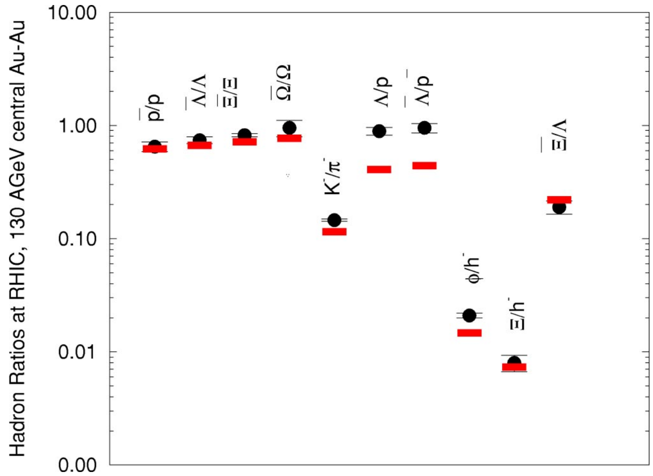

FIG. 2. Hadron ratios in the statistical hadronization model at midrapidity (dashed bands) as compared to experimental results (filled circles) for RHIC, 130*A* GeV central Au-Au collisions at midrapidity.

much better agreement with the data (see Fig. 2). Naturally, Eqs. (3) and (5) cannot be used in this case. Instead, one has to consider the volume of the rapidity slice in question and the number of baryons found inside this interval (which can either be predicted by a model or measured in experiment). Starting with this number and S/B, all ratios of produced hadrons within this rapidity slice are then predicted. Clearly, a more detailed fireball evolution model for the RHIC scenario is desirable to increase the predictive power.

V. IN-MEDIUM MODIFICATIONS

In the preceding section, we have demonstrated that the idea of statistical hadronization combined with our fireball evolution model is able to achieve good agreement in comparison with the data, provided that one uses the vacuum masses and widths of all resonances in Eq. (1). On the other hand, we have used the same fireball evolution to calculate dilepton emission and here we found that a significant broadening of the ρ meson was responsible for the observed enhancement in the invariant mass region below 700 MeV [1]. The underlying thermal field theory calculations of the modifications of the vector meson properties at finite temperature [31,32] and density [33] indicate not only a modified ρ but also broadening and mass shift of the ω and broadening of the ϕ due to the interaction with the medium.

All these calculations (as any other perturbative expansion) become unreliable in the vicinity of the phase transition, therefore these results cannot strictly be taken over to the current calculations where we require these quantities close to T_C. However, we may take them as a hint that two possible modifications of particle properties in a hot and dense medium may take place.

Mass shifts of particles in the medium are commonly related to the restoration of chiral symmetry. In, e.g., Ref. [34], by investigating scale invariance of an effective Lagrangian, the in-medium scaling laws

$$m_\rho^*/m_\rho \approx m_\omega^*/m_\omega \approx m_N^*/m_N \approx (\langle \bar{q}q\rangle^*/\langle \bar{q}q\rangle)^{1/3} \qquad (7)$$

were established (Brown-Rho scaling). In this equation, asterisks denote quantities at finite density, m_ρ and m_ω the masses of the ρ and ω meson, m_N is the nucleon mass, and $\langle \bar{q}q\rangle$ stands for the chiral condensate.

Decay widths of particles are in general increased in a medium due to the presence of new interaction channels. In Ref. [31], e.g., it was shown that the ω meson resonance experiences strong broadening in a hot environment due to the presence of the scattering process $\omega\pi \rightarrow \pi\pi$. Even in the absence of such effects, the decay width at a finite temperature is enhanced if the decay products are bosons due to the presence of bosons of the same type in the heat bath (Bose enhancement). As pions are the most abundant species in a thermal environment and most decays involve one or more pions, this effect should influence almost all resonances in a hot medium. The modification of decay widths is only relevant in Eq. (1) if the in-medium width is a sizable fraction of the particle mass. In this case, a large contribution to the particle yield comes from masses lower than the peak mass in the Breit-Wigner distribution, which are exponentially enhanced. This enhancement more than counterbalances the suppression of contributions shifted into the higher mass region. Therefore, an increase in the decay width of broad resonances acts similarly as a mass reduction.

There is a third possibility of in-medium particle properties which has no direct influence on the particle spectral function (and is therefore not visible in the dilepton data). The binding potential between the constituents of hadrons could be partially screened by thermal fluctuations, leading to an increase of the hadronic core radius.

Such *increased radii* would lead to an enhanced excluded volume correction. This effect hardly influences the results of Refs. [5–7], as the fireball volume is implicitly determined by matching the fitted baryochemical potential to the number of participants, but in the present approach we can expect to observe the influence of increased hard core radii, as the volume is kept fixed.

In a first step, we examine the effects of in-medium mass shifts in a qualitative way by tentatively multiplying the vacuum masses of all hadrons with the exception of the pion by a constant c. The result is shown in Fig. 3.

The result shows that even a moderate mass reduction of 10% in the medium is not in line with the observed hadron ratios. In particular, particle-antiparticle ratios are strongly affected. In the case of $\bar{p}/p$, one might argue that the relevant inelastic (annihilation) cross section is not small as compared to the elastic one and therefore this ratio cannot really be fixed at T_C, but must be adjusted dynamically in the subsequent evolution. Indeed, it was shown in Ref. [35] that this is possible if one takes the statistical hadronization prediction as an initial condition for rate equations. It is unclear if this is still possible for different initial conditions, but even if this is the case, this is not an option for the multistrange particle/antiparticle ratios.

The overall behavior of the result can be qualitatively understood as follows. The reduced nucleon mass implies a lower value of the baryochemical potential in order to pro-

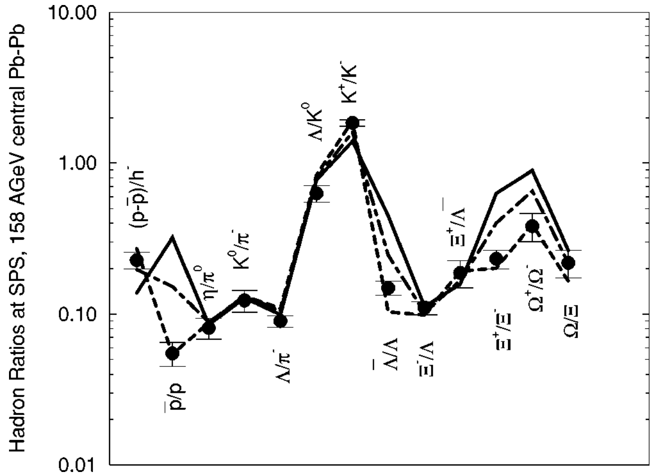

FIG. 3. Hadron ratios in the statistical hadronization model, for vacuum particle masses (dashed), assuming a reduction by 10% (dash dotted) and 20% (solid) as compared to data (filled circles) for SPS, 158*A* GeV central Pb-Pb collisions.

duce the observed number of participants, this in turn affects single and double strange particles and implies changes in μ_S via Eq. (4). Therefore, ratios of particles and antiparticles with two or three nonstrange valence quarks, such as $\bar{p}/p$ or $\bar{\Lambda}/\Lambda$ are most affected. Multistrange particle/antiparticle pairs follow the trend, though in a way less pronounced. In a second run, we investigate the effect of thermal broadening of resonances, increasing all widths by a constant multiplicative factor c_Γ. The resulting hadron ratios are shown in Fig. 4.

One observes the same qualitative behavior as for a mass reduction, as we have argued before. The effects of the increased width are, however, less dramatic. An increase by 20% in the width of all resonances is still in line with all data except $\bar{p}/p$ and even an increase of 50% is still acceptable for most of the ratios. This is reassuring, as there is almost certainly thermal broadening of resonances in a hot medium.

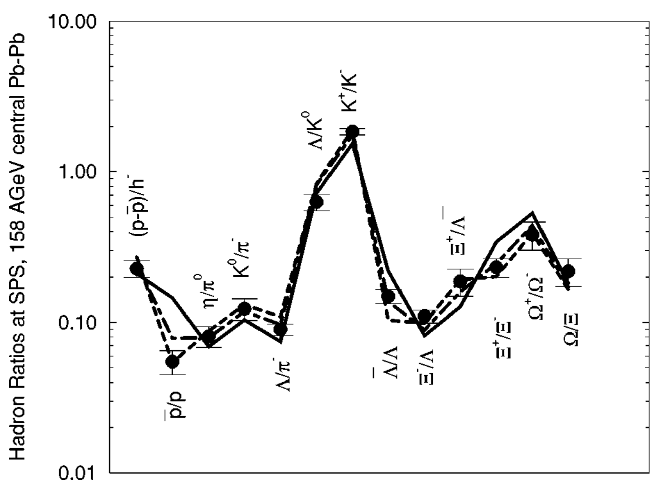

FIG. 4. Hadron ratios in the statistical hadronization model, for vacuum decay widths (dashed), assuming an increase by 20% (dash dotted), and 50% (solid) as compared to data (filled circles) for SPS, 158*A* GeV central Pb-Pb collisions.

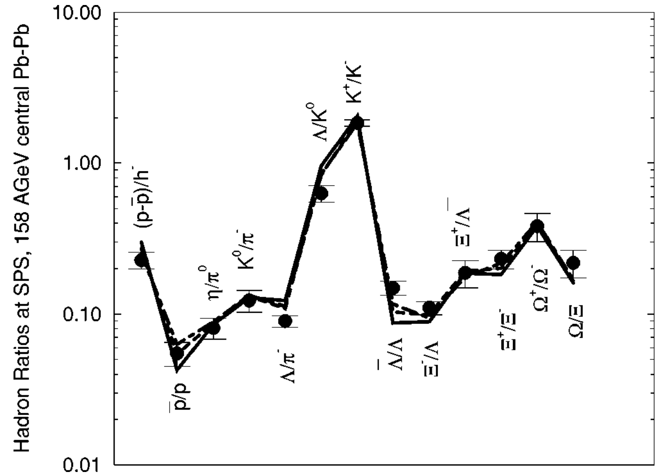

FIG. 5. Hadron ratios in the statistical hadronization model, for the standard choice of R_C=0.3 fm (dashed), assuming R_C=0.225 fm (dash dotted) and R_C=0.375 fm (solid) as compared to data (filled circles) for SPS, 158*A* GeV central Pb-Pb collisions.

As the behavior for both broadening of resonances and mass reduction (which are both in line with the dilepton data) is qualitatively the same for the hadron ratios, the effects of reduced masses cannot be compensated by introducing additional broadening. So if any of the effects fails in the description of the data, a combination of both will also fail.

In the third run, we explore the effect of different choices for the core radius R_C on the ratios. In order to investigate the sensitivity of our results to the initial choice of R_C, we do not only consider thermally increased radii but also a reduced initial choice. In Fig. 5, we show the model predictions for a reduction of R_C by 25% and for an increase of the same amount.

We observe that the overall sensitivity of the resulting hadron ratios to the hadronic core radius is rather weak. On the other hand, an enhanced excluded volume correction (dotted line in Fig. 5) acts in a rather peculiar way: In order to arrive at the same number of participants, the baryochemical potential has to *increase*. This effect is opposite to the behavior for in-medium mass reductions or increase of decay width. Therefore, one might expect that the net effect of both thermal broadening of resonances *and* increased core radius due to a thermally screened binding potential is moderate and partial compensation may occur.

In order to test this conjecture, we study a scenario in which the width of resonances has been increased by 50% and simultaneously the core radius has been set to 0.45 fm instead of 0.3 fm. The result is shown in Fig. 6.

One observes that indeed the expected compensation occurs and the model prediction approaches the data points. No effort has been made to obtain a best description of the data using c_Γ and R_{hc} as fit parameters.

VI. CONCLUSIONS

Assuming a thermalized system and statistical hadronization at the phase boundary with subsequent resonance decays, we have demonstrated that our recently proposed fire-

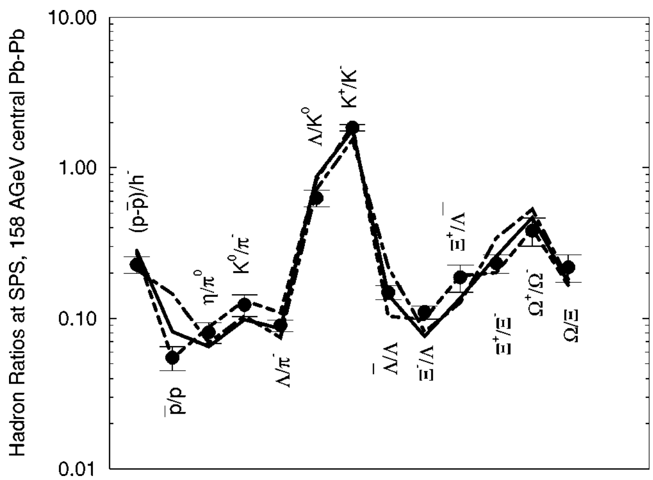

FIG. 6. Hadron ratios in the statistical hadronization model assuming all decay widths increased by 50%, for the standard choice of R_C=0.3 fm (dash dotted) and R_C=0.45 fm (solid) as compared to data (filled circles) for SPS, 158*A* GeV central Pb-Pb collisions.

ball evolution scenario [1] leads to a reasonable description of the data on hadron ratios, if the known vacuum properties of particles and resonances are used. This provides a valuable consistency check of three pieces of information.

(1) The entropy density at T_C=170 MeV can be calculated using the hadronic ensemble. The entropy density of the QGP has to agree with that number in order to produce a second-order transition or a crossover, as assumed in the fireball evolution scenario.

(2) The quasiparticle model predicts the entropy density at T_C, but without specifying an absolute value for T_C.

(3) The essential information of the absolute value of T_C is obtained in lattice calculations [9], and using this value, we find a consistent scenario. In that sense, hadron ratios provide information on the EoS of the quark-gluon plasma.

On the other hand, in-medium modifications of hadron properties are mandatory if one tries to explain the dilepton invariant mass spectrum measured by the CERES collaboration [2]. Specifically, the ρ channel requires strong broadening. Thermal effective field theory calculations indicate the presence of such effects for other particles as well [32,33].

In a schematic investigation, we have demonstrated that such strong broadening of resonances or mass reductions are not in line with the measured data, and no combination of these two effects can be. Such changes in particle properties are also inconsistent with the phase transition scenario used here, as they destroy the match of the entropy density and require in general a different choice of T_C. This is also apparent from the fact that the *absolute* numbers of particle production do not agree with measurements.

However, if one also considers the effect of a screened binding potential in a thermal environment, one can make the assumption that the core radius of hadrons grows. This effect can then compensate the effects of both increased decay widths and mass reductions to some degree, as demonstrated in Fig. 6. This result is reassuring, as it allows to reconcile the in-medium modifications observed in the dilepton data with the statistical model description of measured hadron ratios in a consistent model framework.

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