Hadron resonances and phase threshold in heavy ion collisions

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We show that a measurement of the reaction energy ($\sqrt{s}$) dependence of relative hadron resonance yields in heavy ion collisions can be used to study the phase structure of the dense strongly interacting matter created in these collisions and investigate the origin of the trends observed in the excitation functions of certain soft hadronic observables. We show that the presence of chemical nonequilibrium in light quark abundance imparts a characteristic signature on the energy dependence of resonance yields that differs considerably from what is expected in the equilibrium picture.

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I. INTRODUCTION

The exploration of the properties of strongly interacting, dense quark-gluon matter—specifically, the equation of state, transport coefficients, degree of equilibration, and phase structure—and the dependence of these properties on the energy and system size is one of the main objectives of heavy ion research. A natural approach to these challenges is the study of soft particle multiplicities produced in these reactions. This provides information about the system properties occurring when these particles are created (chemical freeze-out conditions), as well as about bulk matter properties (e.g., entropy) which can probe deep into the birth history of the fireball.

Statistical mechanics techniques have in this context a long and illustrious history [1–4]. The systematic and quantitative comparison of data with the statistical hadronization (SH) model is, however, a comparatively recent field [5–11]. A consensus has developed that the SH model can indeed fit most, if not all, particle yields measured at experiments conducted at a wide range of energies. Measurements conducted at the GSI Schwerionen Synchrotron (SIS), BNL Alternating Gradient Synchrotron (AGS), CERN Super Proton Synchrotron (SPS), and BNL Relativistic Heavy Ion Collider (RHIC) have successfully been analyzed using SH *Ansätze*.

When this consensus is considered more carefully, we see that in technical detail, the applied SH models differ regarding the chemical equilibration condition that is presumed. As a result, it has not yet been possible to agree that statistical physics, if any, is responsible for the striking trends observed in the energy dependence of some observed hadronic yields.

In this paper, we will indicate that further progress can be made with the help of hadron resonances. Hadron resonances, such as, e.g., Δ^{++} excitation of the proton p, differ typically from the "stable" particle by internal structure rather than chemical quark content. Hence, within the SH approach, their production is mostly controlled by the "temperature" T at which they are created.

II. EQUILIBRIUM AND NON-EQUILIBRIUM FREEZE-OUT CONDITION

In the SH model, there are two types of chemical equilibrium [12]; all models assume relative chemical equilibrium, but some also assume absolute chemical equilibrium which implies the presence of just the right abundances of valance of up, down, and even strange quark pairs. There are qualitative differences in the results obtained in the description of hadron production when using or not using the hypothesis of absolute chemical equilibrium.

If the system of produced hadrons is considered to be in absolute chemical equilibrium, then at the highest heavy ion reaction energy, one obtains chemical freeze-out temperature $T \sim 160$–170 MeV. Values as low as $T \sim 50$ MeV are reported at lowest reaction energies available.

The energy dependence of the freeze-out temperature then follows the trend indicated in Fig. 1(a): as the collision energy increases, the freeze-out temperature increases and the baryonic density (here baryonic chemical potential μ_B) decreases [8]. An increase of freeze-out temperature with $\sqrt{s}$ is expected on general grounds, since with increasing reaction energy a greater fraction of the energy is carried by mesons created in the collision, rather than by preexisting baryons [13].

Further refinements in the approach described above are often implemented and could be of relevance:

(i) Allowance for strangeness chemical nonequilibrium is necessary to obtain a good description of strange particle yields [14–16] at low $\sqrt{s}$. This is accomplished by introducing strangeness phase space occupancy γ_s.

(ii) At smaller reaction energies and for smaller reaction system sizes, the fireball is likely to be well away from the thermodynamic limit. In this case, canonical treatment of strangeness is applied [17,18].

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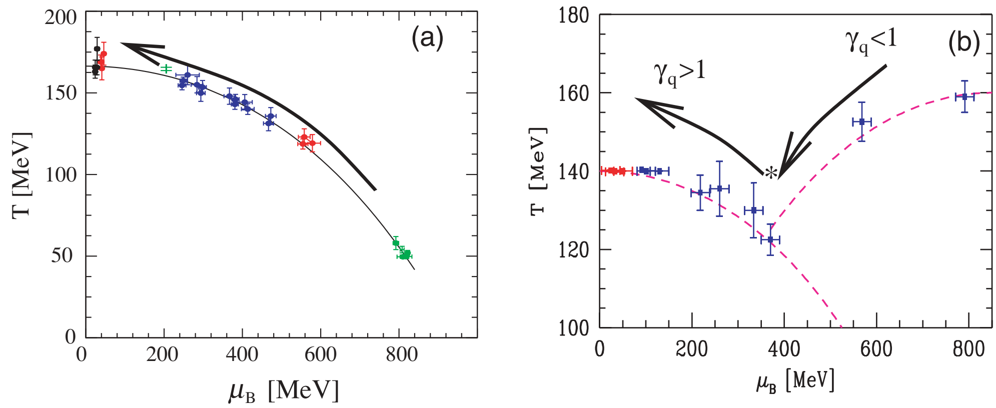

FIG. 1. (Color online) Dependence of freeze-out temperature T and baryochemical potential μ_B on reaction energy in the equilibrium (a) [8] and nonequilibrium (b) [9] freeze-out models. Arrow direction corresponds to increasing $\sqrt{s}$. The equilibrium dependence of T and μ_B in (a) is not significantly altered by the introduction of the fitted phase space occupancy γ_s and/or the implementation of the canonical ensemble for strangeness. The star in (b) corresponds to the point where the transition to the supercooled regime occurs and the phase space changes from chemically undersaturated ($\gamma_q < 1$) to chemically oversaturated ($\gamma_q > 1$). This point also corresponds to the energy of the kink and tip of the horn.

These effects do not materially alter the behavior of the temperature and chemical potential shown in Fig. 1(a).

What is most striking in these results is that there is no sign of any structure when the reaction energy varies. However, there are noncontinuous features in the energy dependence of hadronic observables, such as the "kink" in the multiplicity per number of participants and the "horn" [9,19–21] in certain particle yield ratios. An effort was made to interpret this in terms of a shift from baryon to meson dominance [21] of the hadron yields. However, no matter how hard one tries, in the chemical equilibrium model, even the simple observable such as K^+/π^+ remains a smooth function of reaction energy, in contrast to the experimental results. Introduction of γ_s and deviations from the thermodynamic limit, while it helps bring some of the model predictions closer to the data, has so far not managed to reproduce the sharpness of such features as the kink and horn.

Nonmonotonic behavior of particle yield ratios could indicate a novel reaction mechanism, e.g., onset of the deconfinement phase [20]. In such a situation, the smoothness of the chemical freeze-out temperature dependence on energy would be surprising, since it would imply that at all energies, from about 1A GeV at SIS to the highest RHIC values, there is no change in either the fireball evolution dynamics or any other imprint from the deconfined phase on the freeze-out condition, which, however, is visible in the strangeness and entropy yield that K^+ and π^+, respectively, represent.

Furthermore, we note that the fireball of hadronic matter formed is a relatively small system, expanding rapidly, with its content undergoing a phase transformation, or even phase transition. In this complex and rapidly evolving circumstance, one could imagine that the absolute chemical equilibrium, not always, or even ever, holds. In particular, if the expanding system undergoes a fast conversion from a quark-gluon plasma (QGP) to hadrons, the chemical nonequilibrium [5] and supercooling [22,23] go hand in hand because of entropy and flavor conservation requirements.

One can look at this situation again without the hypothesis of absolute chemical equilibrium among hadrons produced. The systematic behavior of T with energy in this case is quite different [9], as shown in Fig. 1(b). The two higher T values at the right are for 20A (lowest SPS) and (most to the right) for 11.6A GeV (highest AGS) reactions. In these two cases, the source of particles is a hot chemically undersaturated ($T \sim$ 170 MeV) fireball. Such a system could be a conventional hadron gas fireball that had not the time to chemically equilibrate. Other options were considered in Refs. [9,24], such as a phase of constituent massive quarks.

Following the thick arrow in Fig. 1(b), we note that somewhat smaller temperatures are found with further increasing heavy ion reaction energies. Here, it is possible [22,25] to match the entropy of the emerging hadrons with that of a system of nearly massless partons when one considers supercooling to $T \sim 140$ MeV, while both light and strange quark phase spaces in the hadron stage acquire significant oversaturation with the phase space occupancy $\gamma_{q=u,d} > 1$ and at higher energy also $\gamma_s > 1$. A drastic change in the nonequilibrium condition occurs near 30A GeV, corresponding to the dip point on the right in Fig. 1(b) (marked by an asterisk). At heavy ion reaction energy below [i.e., to the right in Fig. 1(b)] of this point, hadrons have not reached chemical equilibrium, while at this point as well as at the heavy ion reaction energy above [i.e., at and to the left in Fig. 1(b)], hadrons emerge from a much denser and chemically more saturated system, as would be expected were QGP formed at and above 30A GeV. This is also the heavy ion reaction energy corresponding to the kink, which tracks the QGP's entropy density (higher with respect to a hadron gas), and to the peak of the horn [19], which tracks the strangeness over entropy ratio (also higher with respect to a hadron gas).

Concluding this discussion, comparing Figs. 1(a) and 1(b), we see a quite different behavior. In Fig. 1(a), for the chemical equilibrium model, with an increase of the collision energy following the black arrow, we see a monotonic increase of the chemical freeze-out temperature, with no hint of new physics in a wide range of heavy ion collision energies spanning the range of SIS, AGS, SPS, and RHIC. In Fig. 1(b), we see that when relative and absolute chemical equilibria are considered [12], with yields of individual hadrons satisfying the relative but not the absolute chemical equilibrium, the experimental particle yield data are best described with a temperature profile as a function of reaction energy which is not monotonic. There is a minimum value of T at the point at which the rapid change of the chemical composition of produced hadrons is occurring. This is clearly suggestive of a change in the reaction mechanism.

The main reason for the wider acceptance of the equilibrium approach $\gamma_i = 1$ is its greater simplicity: there are fewer parameters. Moreover, considering the quality of the data, the nonequilibrium parameter γ_q is not necessary to pull the statistical significance above its generally accepted minimal value of 5%. On the other hand, the parameters γ_q and γ_s were introduced on *physical* grounds [12,22,25], thus these are not arbitrary fit parameters. Moreover, these parameters, when used in a statistical hadronization fit, converge to theoretically motivated values. They also help explain the trends observed in the energy dependence of hadronic observables. Finally, $\gamma_q > 1$ in *AA* reactions describes the enhancement of the baryon-to-meson ratio yield at RHIC as compared with elementary interactions, which dynamically arises in the recombination hadronization at fixed hadronization temperature.

III. RESONANCE RATIOS AS CHEMICAL FREEZE-OUT TEMPERATURE PROBES

In this paper, we propose the energy dependence of the resonance yields as a possible experimental observable, capable of discriminating between the two scenarios—chemical equilibrium and nonequilibrium—and thus establishing the need to use γ_q in statistical hadronization analysis of experimental data.

Many strong interaction resonances, a set we denote by the collective symbol R^* [such as $K^{*0}(892)$, $\Delta(1232)$, $\Sigma^*(1385)$, $\Lambda^*(1520)$, and Ξ^* (1530) [26]] carry the same valance quark content as their ground-state counterparts R (corresponding to K, N, Σ, Λ, Ξ). R^* typically decay by emission of a pion, $R^* \rightarrow R + \pi$. Considering the particle yield ratio R^*/R in the Boltzmann approximation (appropriate for the particles considered), we see that all chemical conditions and parameters (equilibrium and nonequilibrium) cancel out, and the ratio of yields between the resonance and its ground state is a function of mass and the freeze-out temperature, with second-order effects coming from the cascading decays of other, more massive resonances [5,27], that is,

$$\frac{N_{R^*}}{N_R} \simeq \frac{g_{R^*} W\left(\frac{m_{R^*}}{T}\right) + \sum_{j\rightarrow R^*} b_{jR^*}\, g_j W\left(\frac{m_j}{T}\right)}{g_R W\left(\frac{m_R}{T}\right) + \sum_{k\rightarrow R} b_{kR} g_k W\left(\frac{m_k}{T}\right)}, \quad (1)$$

where $W(x) = x^2 K_2(x)$ is the (relativistic) reduced single-particle phase space with $K_2(x)$ being a Bessel function, g is the quantum degeneracy, and b_{jR} is the branching ratio of resonance j decaying into R.

When we study the results arising from Eq. (1), we consider only strong decay contributions, so weak decay feed down, such as $\Lambda \rightarrow p$, $\Sigma \rightarrow p$, $\Xi \rightarrow \Lambda$, and $\Omega \rightarrow \Xi$, has to be eliminated from the data sample. Given that existing SPS [28] and RHIC [29] experiments, as well as the planned Compressed Baryonic Matter (CBM) experiment [30], have both a tracking resolution permitting precise primary vertex cuts (weak decay tracks originate from points well away from the primary vertex) and a momentum resolution capable of identifying resonances [31–33], this requirement is realistic.

Because of the radically different energy dependence of freeze-out temperature in the scenarios of Refs. [8] and [9], seen in Fig. 1, the predictions for the resonance ratios Eq. (1) vary greatly between these two scenarios. In the equilibrium scenario, the temperature goes *up* with heavy ion reaction energy, and thus the resonance abundance should go smoothly up for all resonances. On the other hand, the nonequilibrium scenario, with a low temperature arising only in some limited reaction energy domain, will lead to resonance abundance which should have a clear dip at that point but otherwise remain relatively large.

We have evaluated several resonance relative ratios shown in Fig. 2 within the two scenarios, using the statistical hadronization code SHARE [27,34]. For the nonequilibrium scenario, we used the parameters given in Ref. [9], Table I. For the equilibrium scenario, we used the parametrization given in Ref. [8], Figs. 3 and 4. In the latter case, the strangeness and isospin chemical potentials μ_s and μ_{I3} were obtained by requiring that net strangeness be zero, and net charge per baryon in all particles produced be the same as in the colliding system. We performed spot checks of the validity of the statistical parameters used and found that under the assumptions made, these are the best parameter sets.

As seen in Fig. 2, the expected trend with $\sqrt{s}$ is apparent in all considered resonance ratios, though in cases where the mass difference is large, the effect is much more pronounced than in some others. Indeed, for many of the ratios we present, the experimental error may limit the usefulness of our results; however, the opposite energy dependence may prove to be helpful in discriminating the behavior. In principle, we have presented 12 different ratios, though in some cases, the difference between the particle and antiparticle ratio is small. It is smallest in cases when the baryochemical potential has neither a direct nor a large indirect influence, and the difference in light quark flavor content is the smallest.

It is interesting to note here that the often ignored quark flavor effect (isospin effect) is responsible for most of the difference between particle and antiparticle ratios. This is at first a counterintuitive result, but it can be understood in a quantitatively simple manner. We recall the relation $u/d \propto \lambda_{I3} \propto \bar{d}/\bar{u}$, where u and d refer to the yield of up and down, respectively, valance quarks. In cases such as, e.g., $\Sigma^* \rightarrow \Lambda$, the u, d valance quark content is different for the R^* and R particles, leading to λ_{I3} dependence of the R^*/R ratio. High mass cascading resonances, where the *strangeness* content can be different [e.g., $\Xi(1690) \rightarrow K\Sigma$], are a further source of difference between particle and antiparticle resonance ratios, especially in the high baryochemical potential regime.

Many of the experimental data points needed in the analysis presented in Refs. [9] and [8] are still preliminary. This means that some of the results we rely on could in the end be

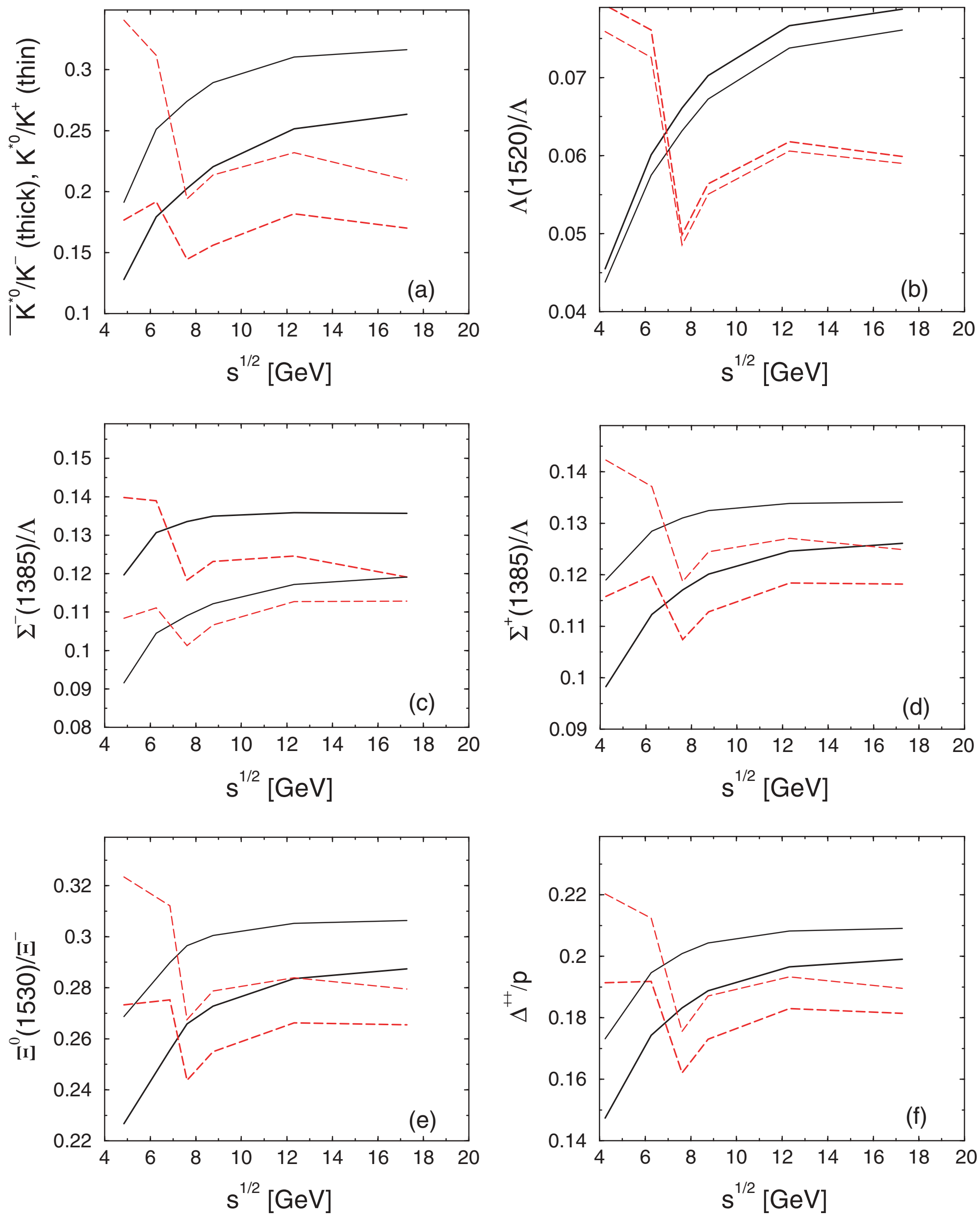

FIG. 2. (Color online) Ratio of resonance to the stable particle. Thick lines for particles with strange quark content, thin lines for particles with antistrange quark content, as a function of energy. Solid black lines refer to the equilibrium fits ($\gamma_{q,s} = 1$), with the parameters for AGS and SPS energies taken from Ref. [8]. Dashed red lines refer to nonequilibrium fits ($\gamma_{q,s}$ fitted), with the best fit parameters for AGS and SPS energies taken from Ref. [9].

somewhat different. However, because of the cancellation (to a good approximation) of the baryochemical and strangeness chemical potentials, the qualitative prediction for the *energy dependence* of the resonance yields within the two models is robust. Namely, within the chemical equilibrium model, the temperature of chemical freeze-out must steadily increase and so does the R^*/R ratio. For the chemical nonequilibrium model, the R^*/R dip primarily relies on the response of T to the degree of chemical equilibration: prior to chemical equilibrium for the valance quark abundance, at a relatively low reaction energy, the freeze-out temperature T is relatively high. At a critical energy, T drops as the hadron yields move to or even exceed light quark chemical equilibrium, yet the reaction energy is still not too large, and thus the baryon density is high and meson yield low. As reaction energy increases farther, T increases, and the R^*/R yield from that point on increases. The drop in R^*/R at critical T would be completely counterintuitive in an equilibrium picture. It would hence provide overwhelming evidence that nonequilibrium effects such as supercooling, where such a drop would be expected, are at play. We further argue that such a drop cannot be reproduced by resonance rescattering/regeneration.

Pseudoelastic processes such as $R\pi \to R^* \to R\pi$ and post-decay $R^* \to R\pi$ scattering of decay products in matter could potentially considerably alter the observable final ratio of *detectable* R^* to R. The combined effect of rescattering and regeneration has not been well understood. We have argued that the formation of additional *detectable* resonances is negligible [35], while scattering of decay products can decrease the visible resonance yields except for the sudden hadronization case. Other groups have studied this in a quantitative manner.

Assuming a long-lived hadron phase, the energy dependence of most of the resonance ratios considered here has been calculated in a hadronic quantum molecular dynamics model. The result (Figs. 7 and 8 in Ref. [36]) is qualitatively similar to the chemical equilibrium results for resonance ratios, that is, we see a smooth rise with energy. Thus, in the case of chemical equilibrium, with a considerable separation between chemical and thermal freeze-out inherent in Ref. [36], rescattering and regeneration will affect the *quantitative* R^*/R ratio, but will not alter the *dependence on heavy ion reaction energy* shown in Fig. 2. On the other hand, chemical nonequilibrium implies absence of a long-lived hadron phase. Because of this, the calculation [36] would not be applicable and the resonance abundance should be in closer quantitative, as well as qualitative, agreement with the predictions of Fig. 2. Rescattering and regeneration, therefore, should not alter the predicted pattern of either the equilibrium model, where all R^*/R should rise with energy, or the nonequilibrium model, where at the critical energy, all R^*/R should experience a dip.

If both of these predictions prove inaccurate and the R^*/R abundance turns out to be resonance specific with no uniform rises and dips as function of energy, this would signify that freeze-out is determined by reaction kinetics rather than thermodynamic conditions. In this case, R^* abundance is determined more by $\Gamma_{R^*}\tau$, where τ is the lifetime of the fireball, than by m_{R^*}/T.

IV. CONCLUSIONS

In conclusion, we suggest that a measurement of the energy dependence of such ratios as K^*/K, Δ/p, Σ^*/Λ, $\Lambda(1520)/\Lambda$, Ξ^*/Ξ, and others might be instrumental in clarifying the freeze-out conditions in heavy ion collisions, especially at low reaction energy. A resonance abundance monotonically rising with energy from the AGS energy range would suggest that the best statistical description of heavy ion data is based on chemical equilibrium, and that as collision energy increases, freeze-out temperature rises monotonically. If, on the other hand, resonance abundance shows a consistent dip, possibly at the energy coinciding with the other nonmonotonic features recently observed in particle yields and ratios [19], it would be strong evidence that what we are seeing is, at and above this dip, a freeze-out from a supercooled high entropy density phase.

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