Strangeness trapping

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If the deconfinement phase transformation of strongly interacting matter is of first-order and the expanding chromodynamic matter created in a high-energy nuclear collision enters the corresponding region of phase coexistence, a spinodal phase separation might occur. The matter would then condense into a number of separate blobs, each having a particular net strangeness that would remain approximately conserved during the further evolution. We investigate the effect that such *strangeness trapping* may have on strangeness-related hadronic observables. The kaon multiplicity fluctuations are significantly enhanced and thus provide a possible tool for probing the nature of the phase transition experimentally.

1. INTRODUCTION

One of the major goals of high-energy heavy-ion research is to explore the equation of state of strongly interacting matter, particularly its phase structure. Depending on the beam energy, various regions of temperature and baryon density can be explored. While systems with a very small net baryon density are formed at RHIC, it is expected that the creation of the highest possible baryon densities will occur at more moderate beam energies, such as those becoming available at the planned FAIR facility at GSI [1].

Our understanding of the QCD phase diagram is best developed at $\mu_B = 0$, where lattice QCD calculations are most easily carried out, and they indicate that the transformation from a low-entropy hadron resonance gas to a high-entropy quark-gluon plasma occurs smoothly at the temperature is raised, with no real phase transition being present [2]. On the other hand, at zero temperature most models predict the occurrence of a first-order phase transition when the density is raised [3], though no firm results are yet available for the corresponding value of the chemical potential, μ_0. However, if the $T = 0$ transformation is in fact of first order, one would expect the phase boundary to extend into the region of finite temperature and terminate at a critical endpoint, (μ_c, T_c) [3]. Recent lattice QCD results [4] suggest the presence of such a first-order phase transition line and an associated critical end-point, though its precise location is not well determined.

It is therefore important to consider how this key issue could be elucidated on the basis of experimental data. Generally, one might expect that if the expanding matter created in a high-energy nuclear collision crosses a first-order phase-transition line then the associated non-monotonic behavior of the thermodynamic potential might have observational consequences.

2. IDEALIZED MODEL OF SPINODAL DECOMPOSITION

A universal feature of first-order phase transitions is the occurrence of spinodal decomposition, which results from the convex anomaly in the associated thermodynamic potential [5]. This phenomenon occurs when bulk matter, by a sudden expansion or cooling (a quench), is brought into the convex region of phase coexistence. Since such a configuration is thermodynamically unfavorable and mechanically unstable, the uniform system seeks to reorganize itself into spatially separate single-phase domains. Moreover, since this spinodal phase separation develops by means of the most unstable collective modes, the resulting domain pattern exhibits a characteristic scale. This general phenomenon, which is known in many areas of physics and has found a variety of technological applications, appears to be an important mechanism behind the multifragmentation phenomenon in medium-energy nuclear collisions [5,6], where the first-order phase transition is between the nuclear liquid and a gas of nucleons and light fragments.

For a such spinodal decomposition to occur, not only must the equation of state have a first-order phase transition, but the dynamics must bring the bulk of the system sufficiently quickly into the spinodal region of phase coexistence to achieve a quench and yet the overall expansion should be sufficiently slow to allow the growth of the dominant instabilities to cause a break-up. While none of these features are yet well established, we may nevertheless explore the possible observational consequences of such a phenomenon.

We start by considering the expanding system when it is still in the plasma phase. At this stage the system is spatially uniform and the strange quarks and antiquarks can be considered as being randomly distributed throughout the system, irrespective of what the net baryon density happens to be. We imagine that the bulk of the expanding and cooling plasma enters the region of phase coexistence and that the associated spinodal instability will cause it to break up into separate subsystems, blobs, which are assumed to all have the same size, as they would tend to have in a spinodal breakup. Each of these blobs now proceed to expand and hadronize while maintaining its net strangeness. The resulting assembly of hadrons is determined at freeze-out by a sampling of the statistical phase space, subject to the appropriate canonical strangeness constraint.

3. ILLUSTRATIVE RESULTS

For the present calculations, we assume that blobs of volume $V_q = 50\,\mathrm{fm}$ are formed at the temperature $T_q = T_0 = 170$ MeV. In an ideal plasma, the different quark flavors are distributed independently and the probability for ending up with a given blob strangeness S_0 is independent of the prevailing baryon and charge contents and can be expressed as a modified Bessel function, $P(S_0) = I_{S_0}(2\zeta_s)\exp(-2\zeta_s)$, where $\zeta_s = \ln \mathcal{Z}_s$ is the mean multiplicity of s (or $\bar{s}$) quarks. Then $\prec S_0 \succ = 0$ and $\sigma_{S_0}^2 = \prec S_0^2 \succ = 2\zeta_s$.

Each isolated blob is assumed to expand further while hadronizing, until the freeze-out volume $V_h = \chi V_q$ has been reached. Its temperature is then $T_h(\mu_B) \approx T_0[1-(\mu_B/m_N)^{5/2}]$. The strangeness is kept strictly equal to S_0, while μ_Q is adjusted to ensure average conservation of Q/B. [For the hadron gas we include 124 hadronic species from the $\pi^0(135)$ and up though the $\Omega^-(1672)$.] More details are given in Ref. [7].

Figure 1 (*left*) shows the resulting average K^+ multiplicities for three different scenarios. The first scenario is the usual global grand-canonical treatment [8], while the second is

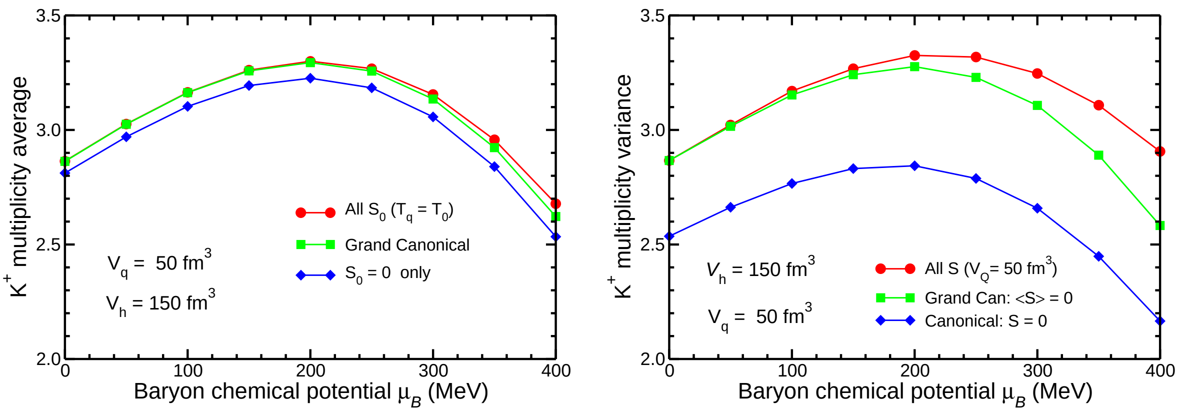

Figure 1. The average (*left*) and the variance (*right*) of the K^+ multiplicity as functions of the baryon chemical potential μ_B in the three scenarios described in the text.

our spinodal scenario in which the blob strangeness is determined at the plasma stage and then kept fixed during the hadronization. Both of these scenarios consider all possible values of S_0 but while the distribution of this quantity is determined at the hadronic freeze-out in the former, it is determined already in the plasma in the latter. In the third "restricted canonical" scenario the blob strangeness is always required to vanish, $S_0 = 0$.

The corresponding K^+ multiplicity variances are shown in Fig. 1 (*right*). While the overall behavior is qualitatively similar to the behavior of the averages, there are several important differences. First, in the restricted scenario (where only $S_0 = 0$ is included) the suppression of the variance is significantly larger than was the case for the average, amounting here to 8-10%. Furthermore, at the larger values of μ_B, where the net baryon density becomes significant, the grand-canonical variance suffers more from the decreasing freeze-out temperature than the spinodal variance. This important divergence is a result of the fact that the larger average baryon number implies a correspondingly larger baryon-number variance as well and therefore also a larger variance in the strangeness.

However, it is experimentally more convenient to consider multiplicity *ratios*. Therefore, we consider $\langle\pi^+\rangle\sigma^2(K^+/\pi^+)$ (which is approximately volume independent) in Fig. 2 (*left*). Although the ratio variances are less sensitive to the specific scenario than the variances themselves, the differences at large μ_B are still clearly brought out.

The above results have been obtained for a given expansion factor, $\chi \equiv V_h/V_q = 3$. Since this is only a rough approximation, it is important to consider also other degrees of expansion, as illustrated in Fig. 2 (*right*). Two opposing effects should be recognized: There are more degrees of freedom in the plasma phase, which enhances the fluctuations, but the hadronic freeze-out volume V_h is larger than the volume V_q where the strangeness trapping occurs. The crossover happens to occur at $\chi \approx 3.3$, a value rather near our adopted estimate, $\chi = 3$. Should it turn out that there is less change in volume from the formation of the plasma blob to the hadronic freeze-out, then the relative effect of the strangeness trapping will be considerably larger. For example, if the degree of expansion were only ten per cent smaller, the enhancement effect would be about twice as large.

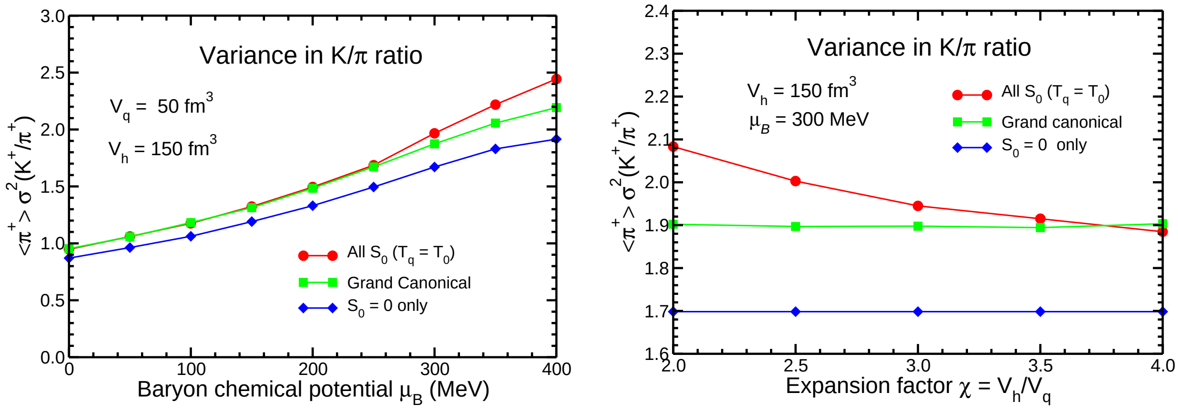

Figure 2. The variance in the K^+/π^+ ratio for the three scenarios considered in Fig. 1, multiplied by the average π^+ multiplicity to render the result scale invariant, either as a function of μ_B for $\chi = 3$ (*left*) or as function of $\chi = V_h/V_q$ for $\mu_B = 300$ MeV (*right*).

4. CONCLUDING REMARKS

The present idealized studies suggest that a spinodal decomposition might enhance the strangeness fluctuations to the degree observed by NA49 [9]. However, before such a conclusion could be made with confidence, further studies are be required. Both strong and weak decays must be taken into account and the fluctuation enhancements should be correlated with other expected effects, such as N-body kinematic correlations [10]. The baryon-rich equation of state should be better determined and refined dynamical calculations should be made to elucidate whether the spinodal region is in fact likely to be encountered and, if so, to what degree a phase decomposition may actually develop.

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