Strangeness Production in Relativistic Heavy Ion Experiments

Stathes D. Paganis
Department of Physics, University of Texas at Austin
Austin, Texas 78712

Abstract

The role of Strangeness as a signal of the Quark Gluon Plasma in relativistic heavy ion experiments is discussed. The current experimental status is briefly presented. Several scenarios which explain the CERN data are discussed.

1 Introduction

QCD, the quantum field theory of the strong interactions, is expected to contain two very interesting non-perturbative effects in its low energy regime: Confinement and Chiral Symmetry Breaking (CSB). Since the QCD degrees of freedom are quarks and gluons which in the present universe temperature are confined in the observed hadrons, it is widely accepted that strongly interacting matter at low energy density is sufficiently described by massive hadrons. These are the effective degrees of freedom of many low energy effective field theories of the strong interactions. From the hadron spectrum and the very low masses of the pseudoscalar mesons (pions and kaons) it is expected that QCD in its massless quark limit exhibits spontaneous symmetry breaking of its Chiral Symmetry at low temperatures. The pseudoscalar mesons are the Goldstone bosons of this spontaneous symmetry breaking and the hadronic masses (like the proton mass) mainly come from the quark condensate $\langle \bar{q}q \rangle$ which gets a non zero value below the critical temperature.

It is expected that nuclear matter under high enough energy density undergoes a transition to a new form of matter where the degrees of freedom are free, almost massless quarks and gluons. This new form of matter has been proposed long ago and is called the Quark Gluon Plasma (QGP). This expectation is motivated...
by a series of lattice QCD results [2] and has not been theoretically proven since QCD has not been solved. Consequently experiment is needed to settle the question. Relativistic heavy ion collisions are used as an experimental tool to study strongly interacting matter under high energy and baryon densities. In such experiments one hopes that if a QGP is formed, then certain experimental observables will be measured which might be significantly different than the observables measured when a Hadronic Gas (HG) is formed. These observables are usually called signals or signatures of the QGP.

In this talk I will focus on a distinctive signal of QGP, the predicted enhancement of strange particle production. In the first section the use of strangeness production as a QGP signal is justified. In the second section experimental results are presented and various theoretical explanations are briefly discussed. The transition from a HG to QGP actually involves two transitions, one related to confinement-deconfinement and the other to chiral symmetry restoration. Typically in the literature the critical temperature for both transitions is predicted to be the same [3],[4]. In the last section of this paper we will sketch what could happen in a different scenario where the two transitions occur at significantly different critical temperatures.

2 Why Strangeness?

Strange particle production in relativistic heavy ion collisions is interesting because it may provide a signal of QGP formation and because of the possible existence of new exotic forms of matter. In this section the strangeness enhancement as a signal of QGP formation is discussed. The hypothesized existence of a stable strange matter is briefly mentioned.

During a relativistic heavy ion collision a space-time region containing many particles with small mean free path is formed, the so-called fireball [4]. The fireball can be described in terms of thermodynamic variables such as temperature. As it was mentioned in the introduction at a high enough temperature a transition from a HG to QGP is expected. A higher strangeness production (in terms of $s\pi$ pairs) is expected if a QGP forms with respect to a HG, usually referred to as strangeness enhancement. I discuss three main factors responsible for the strangeness enhancement: the kinematical factor, medium effects and the short fireball lifetime.

The principal reason for enhanced strangeness production in a QGP relative to that in a HG is due to the respective kinematic thresholds. In a hadron gas the threshold for the following typical reaction,

$$p + p \rightarrow \Lambda + K + p$$

is about 700$MeV$, while in a QGP strangeness production occurs via the following
with a corresponding threshold of $2m_s \simeq 300\,MeV$ since the bare mass of the strange quark is about $150\,MeV$. The gluon channel is the dominant one: while gluons are confined within hadrons in a HG, in QGP they are free within the fireball leading to a large cross section for this process \[5\].

Medium effects are also responsible for strangeness enhancement. In QGP the ratio of $\bar{s}$ quarks with respect to $\bar{u} + \bar{d}$ is expected to be much higher than in a HG. The reason is that in a HG there is always some finite initial baryon density (because of the protons and neutrons that are stopped during the collision) which suppresses further production of $NN$ pairs (Pauli blocking is in effect and more energy is required to create a nucleon). In this case a low $\Lambda$ phase space density is expected because the $\Lambda$ production proceeds via the abundance of antinucleons which are already suppressed \[6\]. On the other hand in a QGP the $s\bar{s}$ production is only suppressed due to the strange quark mass (there is no net initial strangeness in the fireball). So, an antistrangeness enhancement is expected in QGP. Experimentally we expect the $\Lambda/N$ ratio to increase.

The lifetime of the fireball is very short ($c\tau \simeq 3 - 5\,fm$) with respect to the weak interaction time scale, so that strangeness can be considered as a conserved quantum number. Because of this short lifetime, strangeness equilibration is very questionable. By strangeness equilibrium we mean that the fireball system (either in a HG or in a QGP phase) has reached a state in which the strange quark density has reached a saturation density $\rho_s$ after a time $\tau_s$ \[7\]. The degree of strangeness equilibration $\gamma_s$ during the lifetime of the fireball determines the amount of final strangeness production in a heavy ion collision. Theoretical calculations \[8\] have shown that strangeness chemical equilibration is 10-30 times slower in a HG at the same temperature and baryon density than in QGP where $c\tau_s \simeq 3\,fm$. This means that during the fireball lifetime of a QGP all the available (from phase space) strangeness is produced while for a HG much less is produced. This results in expected strangeness enhancement in the case of QGP formation and makes strangeness production a good signal of the HG $\rightarrow$ QGP transition.

Finally understanding strangeness production and evolution in heavy ion experiments is also important for more exotic reasons; the hypothesized stability of strange matter by Witten \[9\] and the possible existence of strangelets \[10\], or multiquark hadrons such as the $H$ dibaryon \[11\]. These phenomena have cosmological implications such as the existence of strange stars, understanding of the nature of the dark matter and others.
3 Current Experimental Status

Experimentally strangeness production is measured in the form of various strange to non-strange particle ratios; the most common being the $K/\pi$ ratio. The strangeness suppression factor $\lambda_s$ is defined as \[ \lambda_s = \frac{\langle s\bar{s}\rangle}{\frac{2}{3}(\langle u\bar{u}\rangle + \langle d\bar{d}\rangle)}. \] (4)

This ratio can be approximated by actual particle ratios; in experiment NA35 at the CERN-SPS the following approximation was chosen \[ \lambda_s \approx \frac{\langle \Lambda \rangle + 4\langle K^0 \rangle}{3\langle \pi^- \rangle}. \] (5)

This ratio was measured to be around 0.35 in Sulphur+Sulphur collisions and 0.15–0.2 in Nucleon-Nucleon collisions. The conclusion is that there is a significant strangeness enhancement as one goes from N+N to S+S collisions. An increase in the multistrange particle yields was also observed in both CERN and AGS-BNL \[ \text{[13].} \]

Another very interesting ratio is the $\Lambda(\bar{u}\bar{d}s)/p(\bar{u}\bar{u}d)$ ratio. As we said in the previous section if a QGP is formed this ratio is expected to increase dramatically. In figures 1, 2 and 3 the $\Lambda$ production and the $\Lambda/p$ are shown for various collisions, ranging from $p+p$ to $S+Au$ \[ \text{[14].} \] A remarkable increase in the ratio is observed especially for the $S+S$ collisions. As fig. 3 shows, this increase is mainly due to the $\Lambda$ increase or equivalently due to an increase of the $\pi$ production.

Thermal statistical models were used to analyze the CERN data \[ \text{[13].} \] Their results suggest that there is no QGP at CERN and the large strangeness equilibration obtained, $\gamma_s \approx 60 - 70\%$ is only due to some strangeness production mechanisms present in the hadronic level. These data can be explained by microscopic models that do not require a QGP.

A different but not as popular point of view suggests that there is a transition from a HG at AGS to a QGP at CERN \[ \text{[13].} \] According to this view the experimental results indicate an increase of the effective degrees of freedom between BNL and CERN. The observables used in this study were entropy and strangeness.

4 Future

The current understanding of the data from heavy ion experiments is that the QGP phase has not yet been formed and higher energies are needed; the current CERN SPS energies are $\sqrt{s} \simeq 20AGeV$. In 1999 the new heavy ion collider RHIC at BNL New York will begin running and the STAR and PHENIX experiments will
start data collection \[14\]. The energy involved is \( \sqrt{s} \approx 200 \text{AGeV} \), i.e. one order of magnitude higher than CERN and is expected to put the system above the critical temperature.

Some of the advantages of higher RHIC energy with respect to measurement of strange particle production are:

- Higher expected fireball temperature.
- Longer fireball lifetime is expected to allow higher strangeness chemical equilibration.

The main advantages of the STAR detector are:

- Large acceptance. STAR covers a large portion of the phase space providing very high statistics even in an event by event basis. As a result various important observables can be measured in an event by event basis.
- Good low \( p_{\perp} \) coverage. The silicon vertex tracker SVT is capable of tracking pions with momenta as low as 50 MeV/c.
- Good reconstruction of short lived singly strange baryons and mesons, and with the SVT, multiply strange baryons and antibaryons.

STAR will collect a number of observables for the same set of events and will try to make a statement about the formation of QGP based on dramatic changes in these observables when some thermodynamic parameters (like temperature) change.

Finally, a future CERN heavy ion experiment, ALICE in LHC has been approved to run in year 2005. The energy is very high \( \sqrt{s} \approx 6 \text{ATeV} \) thus providing even better chances for producing QGP.

5 Epilogue

In the quest for the experimental proof of the predicted QCD transition from HG to QGP, strangeness production is one of the most important observables. A significant strangeness enhancement has already been observed for high energy heavy ion collisions at CERN-SPS. This observation together with the very recent and exciting observation of \( J/\psi \) suppression at CERN (\[17\], \[18\]) and the unexpectedly high pion (i.e. entropy) production at CERN compared to the lower AGS, motivated speculation about possible plasma creation at SPS energies. This situation is reviewed in \[13\] where it was stated that thermal statistical hadron gas models fit the CERN results for large strangeness equilibration \( \gamma_s \approx 60 - 70\% \). The large strangeness production and high pion multiplicities are attributed to hadronic mechanisms. On the other hand the observed \( J/\psi \) suppression should also be due to some hadronic mechanism if the HG scenario is the correct one for CERN-SPS energies \[19\].
The models described above assume that the two QCD transitions occur at the same temperature. This assumption has no direct justification. In fact, some time ago Manohar and Georgi [20] suggested that the successes of the non-relativistic quark model and the smallness of the effective strong coupling $\alpha_s$ are due to the two scales of QCD: $\Lambda_{QCD} \simeq 200MeV$ and $\Lambda_{\chi SB} \simeq 1GeV$, for the confinement-deconfinement and chiral symmetry breaking scales in zero temperature field theory. The success of QCD sum rules also suggest this picture. Based on this chiral quark picture there is a region between the two scales where the effective degrees of freedom are constituent quarks, gluons and Goldstone bosons. Phenomenologically this means that in this region although chiral symmetry is broken and the non-perturbative effects are significant, confinement has not set in yet. I believe that this opens a new possibility for the heavy ion experiments: the chiral symmetry might be harder to restore than to produce a deconfined phase. If this is the case in the CERN energies, then one should expect some moderate strangeness enhancement, a jump in the energy and entropy densities because of the change in the degrees of freedom and deconfinement effects like the observed $J/\psi$ suppression. The author is currently investigating what the observable predictions of such a phase (deconfined but not chirally restored) are.

We close our discussion stressing that there are many physics pictures that could explain the current experimental data. More experimental points in different energies (lower and higher) are needed. This additional data will be provided by future experiments at RHIC and CERN.

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Figure 1: Rapidity distribution of $\bar{\Lambda}$ produced in various central S+A collisions [14].
Figure 2: \( \bar{\Lambda}/\bar{p} \) ratio near midrapidity in nucleon-nucleon, minimum bias proton-nucleus and central nucleus-nucleus collisions as a function of the rapidity at midrapidity of negatively charged hadrons [14].
Figure 3: $\bar{\Lambda}$ and $\bar{p}$ production near midrapidity in central S+S collisions compared to nucleon-nucleon data scaled by the corresponding pion multiplicity ratio in full phase space [14].