A NEW INTERPRETATION OF THE QCD PHASE TRANSITION AND OF STRANGENESS AS QGP SIGNATURE

SONJA KABANA
University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland
E-mail: sonja.kabana@cern.ch

We address the question of how to identify the QCD phase transition using measured light (u,d,s-structured) hadrons, without invoking comparison to the QCD $\epsilon_c$ predictions, and extract $\epsilon_c$ from the data. We analyse several particle and nuclear collisions and extract their chemical freeze-out temperature $T$ at zero baryochemical potential ($\mu_B$). We find at $\mu_B = 0$ a universal rise and saturation of both the $T$ and of the strangeness suppression factor $\lambda_s (= \frac{s^2 + d}{u^2})$ with increasing initial energy density ($\epsilon_i$). The onset of saturation of both $T$ and $\lambda_s$, is interpreted as due to the event of the QCD phase transition. The critical energy density is estimated to be $\epsilon_c \sim 1 +0.3 -0.5$ GeV/fm$^3$, corresponding approximately to a $\sqrt{s}$ of $\sim 8.8$ GeV for central Pb+Pb collisions. Concerning the role of strangeness, we identify trivial and non-trivial sources of strangeness enhancement: The peak of $\lambda_s$ in Pb+Pb collisions at $\sqrt{s}=8.8$ GeV and other phenomena of ‘strangeness enhancement’ defined with respect to p+p data, are trivially traced back to the different baryochemical potentials and $\epsilon_i$ of the compared systems. A non trivial redefined ‘$\lambda_s$ enhancement’ is however also present. The netbaryonfree $\lambda_s$ limit is estimated to be approximately reached in Au+Au collisions at the LHC.

1 Introduction

It has been repeatedly demonstrated in the literature[1,2,3] that in many cases the final state of nuclear and particle collisions is compatible with the hypothesis of an equilibrated source. In the following the discussion will concern only colliding systems for which this finding holds (measured by the $\chi^2$ of thermal model fits). Much work is presently concentrated on identifying the QCD phase transition at a certain $\sqrt{s}$, separating the colliding systems which go through the phase transition from those which dont. This defines the problem that we address. One way to approach this problem is to compare the estimated thermodynamic parameters temperature ($T$) and baryon chemical potential ($\mu_B$) at the chemical freeze-out extracted by thermal models from the data, to the expected critical ($T_c, \mu_B(\epsilon)$) values of QCD (e.g. [4]). However, the theoretical expectations for the critical temperature $T_c$ are uncertain. It is thus obviously interesting to try to extract informations on the critical parameters from the data, without any use of the QCD predictions. In this spirit, we approach this problem in the present study in a different way, namely by extrapolating the data to equivalent systems with zero $\mu_B$ and studying
their $T$. To see why this is interesting, we follow a line of arguments: If all measured colliding systems above a certain $\sqrt{s}$ are heated enough to go through the phase transition and back, they would appear to have the same $T$ (if they don’t freeze-out in a considerably different way) which we note as ‘limiting’ hadronic temperature $T_{lim}$. The colliding systems which do not reach the $T_c$ at any time because of their small $\sqrt{s}$, will exhibit a final $T$ smaller than $T_{lim}$. Therefore, in order to separate the colliding systems which went through the transition from the ones which did not, one can investigate the $T$ of all colliding systems at conditions of $\mu_B=0$, as a function of $\sqrt{s}$ or $dN/dy$ at midrapidity, and search for an increase of $T$ followed by a saturation starting at the $\sqrt{s}$ where the $T_c$ is reached. This would work if we use always the same projectile and target combination. Otherwise, one should correct for the fact that different projectile/target combinations at the same $\sqrt{s}$, reach different initial energy densities. For this reason, we will investigate the $T$ as a function of the initial energy density ($\epsilon_i$) reached at each collision after 1 fm/c based on the Bjorken estimate and also using other Ansätze especially at low $\sqrt{s}$. For a discussion on the uncertainty on $\epsilon_i$ see 6, 3, 7. The same conclusions can however be reached by the present analysis, while looking only at one projectile/target combination $A+A$, namely with $A\sim 200$ (that is at Pb+Pb and Au+Au central collisions), as a function of e.g. $\sqrt{s}$ instead of $\epsilon_i$.

2 Energy density dependence of temperature and $\lambda_{s}$

1. $T$: We compare the ratios of experimentally measured hadron yields in nuclear collisions with the prediction of a thermal model of non interacting free hadron resonances (for details see 4). We extract the thermodynamic parameters describing best the particle source: temperature, baryochemical potential ($\mu_B$) and strangeness chemical potential ($\mu_S$), imposing exact strangeness conservation. We then extrapolate all thermodynamic states with parameters ($T$, $\mu_B$, $\mu_S$) to equivalent states at zero chemical potentials ($T(\mu_B = 0)$, 0, 0) along isentropic paths. As demonstrated in figure the resulting temperature at $\mu_B = 0$ rises and saturates above $\epsilon_i \sim 1$ GeV/fm$^3$. We interpret the onset of saturation of $T$ as due to the reach of an initial temperature greater or equal to $T_c$. We therefore extract from the onset of saturation in fig. the ‘critical’ $\sqrt{s}$ of $\sim 8.8$ GeV/nucleon pair respectively the critical $\epsilon_i$ of $\sim 1 +0.3 -0.5$ GeV/fm$^3$ of the QCD phase transition, independently of the QCD predictions. An important assumption needed to support this interpretation is that the cooling until freeze-out of the particle source, is not significantly (as compared to the errors) dependent on the $\sqrt{s}$, in the range between $\sqrt{s}=2$
A discussion of $T$ rise and saturation can be found in \cite{9}, but not for the $\mu_B=0$ case. However, it is only when investigating systems with the same $\mu_B$, where this behaviour is expected to be exact. The importance of using a common $\mu_B$ becomes more apparent when investigating strangeness. This is the next topic.

Figure 1. The temperature extrapolated to zero fugacities along an isentropic path, as a function of the initial energy density for several nucleus+nucleus, hadron+hadron and lepton+lepton collisions. We demand for the fits confidence level $> 10\%$.

Figure 2. The $\lambda_s$ factor as a function of the initial energy density for several nucleus+nucleus, hadron+hadron and lepton+lepton collisions. Left for non zero $\mu_B$, right for zero $\mu_B$. Left, the lines $\alpha$ and $\beta$ show $\lambda_s$ at nonzero $\mu_B$, while the line $\gamma$ show $\lambda_s$ at zero $\mu_B$. We demand for the fits confidence level $> 10\%$.

2. $\lambda_s$: The so called 'strangeness suppression factor' $\lambda_s = \frac{\langle s \rangle}{\langle u+d \rangle}$ at nonzero $\mu_B$, rises with $\epsilon_i$ up to 1 GeV/fm$^3$ (line (a) in fig. 2 left) and then decreases (line (b) in fig. 2 left). After extrapolating to $\mu_B = 0$, $\lambda_s$ rises and saturates.

\footnote{Note that a similar behaviour (rise and saturation) was found in the $\epsilon_i$ dependence of the kaon number density $\rho_k$ which may be related to the behaviour seen in fig. 1.}
universally above $\epsilon_i \sim 1$ GeV/fm$^3$ (fig. 2, right). Therefore the peak of $\lambda_s$ at the 40 A GeV Pb+Pb (point at $\epsilon_i = 1$ GeV/fm$^3$ in fig. 2, left) is due to the high $\mu_B$ reached there. Furthermore, the so called ’strangeness enhancement’ defined usually as double ratio of strange/pion ratio in A+A over p+p collisions at the same $\sqrt{s}$, can be traced back to the different $\mu_B$ and $\epsilon_i$ of those reactions. In particular this explains why the so defined strangeness enhancement increases with decreasing $\sqrt{s}$ (fig. 7 in 2), since this corresponds to increasing $\mu_B$. If one eliminates the bias due to different $\mu_B$ by considering only $\lambda_s$ at $\mu_B = 0$, the non-trivial -with respect to the phase transition- ’strangeness enhancement’ is revealed (fig. 3, right) as a consequence of the behaviour of $T$ seen in fig. 3. We therefore redefine the ’strangeness enhancement’, as an enhancement of $\lambda_s$ in all thermalised systems above $\epsilon_c$, as compared to all thermalised systems with $\epsilon_i < \epsilon_c$, at the same $\mu_B$. We also analysed for this conference ratios from $e^+e^-$ collisions at $\sqrt{s}=3.6$ GeV 11 and found a $T$ of 124 +15 -20 MeV, and $\lambda_s=0.25 +0.06 -0.09$ with $\chi^2/DOF=4$ 10^{-3}/1. This $T$ is below $T_{lim}$, however the $\epsilon_i$ is difficult to extract due to lack of data. Extrapolating the A+A data in fig. 2, left, to higher $\epsilon_i$, we find that the approximately netbaryonfree limit of $\lambda_s$ in Au+Au collisions, is expected to be reached at LHC energies 11.

Conclusions

The problem we address is how to identify the onset of the QCD phase transition using measured light (u,d,s)-flavoured hadrons, and separate the colliding systems which go through the QCD phase transition from the ones which dont, without any use of the QCD predictions, as well as the role of strangeness. We achieve this by estimating for the first time 4, 3, 7, the equivalent temperature at zero baryochemical potential of the thermodynamic states describing several measured particle and nuclear collisions. We find at zero chemical potential ($\mu_B=0$) a universal rise and saturation of both the $T$ and of the strangeness suppression factor $\lambda_s = \frac{2s}{u+d}$ with increasing initial energy density ($\epsilon_i$) (fig. 3 and fig. 2, right). The onset of saturation of both $T$ and $\lambda_s$ at $\mu_B = 0$, allows to discriminate systems which go through the QCD phase transition from those which dont. The critical energy density is thus estimated at the onset of saturation to be $\epsilon_c \sim 1 +0.3 -0.5$ GeV/fm$^3$, corresponding approximately to a $\sqrt{s}$ of $\sim 8.8$ GeV for central Pb+Pb collisions. Further, we identify trivial and non-trivial (with respect to the phase transition) sources of ’strangeness enhancement’: e.g. the maximum of $\lambda_s$ at the 40 A GeV Pb+Pb collisions 11.

\footnote{Discussions of the QCD phase transition appearing possibly between AGS and SPS energy can be found e.g. in 3, however not at a common $\mu_B$.}
and other phenomena of 'strangeness enhancement', are 'trivially' traced back to the different baryochemical potentials and \( \epsilon_i \) of the compared systems (compare fig. 3 right with \( \mu_B=0 \) and left with nonzero \( \mu_B \)). This explains why e.g. the strange/pion double ratios in A+A over p+p collisions both at the same \( \sqrt{s} \), increase with decreasing \( \sqrt{s} \), because \( \mu_B \) increases and \( \epsilon_i \) differs for A+A and p+p collisions at the same \( \sqrt{s} \). It could explain also an enhancement of \( \lambda_s \) in p+A over p+p collisions. We redefine the non-trivial 'strangeness enhancement', as the increase of \( \lambda_s \) in all (thermalised) systems which reached \( \epsilon_c \) as compared to all (thermalised) systems which did not, at the same \( \mu_B \). It is a consequence of the \( \epsilon_i \) dependence of \( T \). The netbaryonfree \( \lambda_s \) limit is estimated to be approximately reached in Au+Au collisions at the LHC. In conclusion, in contrast to external non-equilibrium signatures like charmonia suppression or jet quenching which are important but may be overcritical, hadrons with \( u, d, s, \bar{u}, \bar{d}, \bar{s} \) quarks play a special role as equilibrium signatures and part of the plasma itself, in allowing to extract the critical parameters of the QCD phase transition.

**Acknowledgments**

We thank the Schweizerischer Nationalfonds for their support, as well as K. Pretzl and P. Minkowski for fruitful discussions. We also thank the organisers of ISMD2001 for creating an open and scientifically fruitful atmosphere.

**References**

1. P. Braun-Munzinger, J. Stachel, Nucl. Phys. A606 (1996) 320.
2. K. Redlich, hep-ph/0105104, proceedings of QM2001.
3. S. Kabana, P. Minkowski, New J of Phys 3 (2001) 4.
4. S. Kabana, J. of Phys. G 27, 3, (2001), 497, S. Kabana, hep-ph/0010246.
5. J D Bjorken, Phys. Rev. D 27 (1983) 140.
6. S. Kabana, New J. of Phys. 3 (2001) 16.
7. S. Kabana, Eur. Phys. J. C21, 3, (2001), 545, S. Kabana, hep-ph/0105154.
8. G. Ambrosini et al., (NA52 Coll.): J. of Phys. G27, 3, (2001), 495, hep-ph/0010045, New J. of Phys. 1 (1999) 22, New J. of Phys. 1 (1999) 23, Nucl. Phys. A661 (1999) 370c.
9. H. Stoecker et al., LBL-12971, (1981).
10. M. Gazdzicki, D. Röhrich, Z. Phys. C71, (1996), 55.
11. R. Brandelik et al., (DASP coll.), Nucl. Phys. B 148 (1979) 189.