Understanding the $p/\pi$ ratio at LHC due to QCD mass spectrum

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Abstract

Thermal fits have consistently reproduced the experimental particles yields of heavy ion collisions, however, the proton to pion ratio from ALICE Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV is over-predicted by thermal models - known at the $p/\pi$ puzzle. Here we test the relevance of the extended mass spectrum, i.e., include Hagedorn states (resonances that follow an exponential mass spectrum and have very short life times) on the $p/\pi$ puzzle. We find that the extended mass spectrum is able to reproduce particle ratios at both RHIC and the LHC as well as being able to match the lower $p/\pi$ ratio at the LHC through dynamical chemical equilibration.

Keywords: hadron resonance gas, relativistic heavy-ion collisions, extended mass spectrum, Hagedorn states, dynamical hadronic interactions, thermal fits

1. Introduction

Final state particle ratios and yields have been matched using thermal fit models\cite{1,2} in order to determine the chemical freeze-out temperature and baryonic chemical potential to aid in describing the nuclear phase diagram\cite{3}. Heavy ion experiments such as RHIC and SPS have found very precise matching to thermal models. Using previous results, predictions were then made for the LHC\cite{4}. However, recent results at ALICE Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV for the LHC have proven to be difficult to fit by thermal models and the thermal models consistently overpredict the proton to pion ratio, $p/\pi$ - known as the $p/\pi$ puzzle\cite{5}.

Various attempts have been made in understanding this puzzle\cite{6} and an overview of these attempts can be found in\cite{7}. However, these attempts have not considered the effects of the extended mass spectrum (exponentially increasing mass spectrum of yet to be measured resonances with very short lifetimes) and/or multi-mesonic reactions. Evidence for the extended mass spectrum is found through the exponential behavior of the known hadrons\cite{8}. Previous work on the extended mass spectrum has found that they play a large role in the context of heavy ion collisions. Most significantly, the extended mass spectrum decreases the shear viscosity to entropy density ratio in the hadron gas phase close to the AdS/CFT limit near to the critical temperature\cite{9,10,11}. The extended mass spectrum is also able to extend the region of the thermodynamical quantities that we are able to match with lattice QCD\cite{12} from around $T = 130 - 140$ MeV (for the standard hadron resonance gas) up to $T \approx 155$ MeV when the added resonances are present\cite{10,13}. Elliptical flow is also suppressed in hybrid model calculations due to the extended mass spectrum when switching temperatures of $T_{SW} \approx 155$ MeV or higher are used\cite{14}. Other effects of the extended mass spectrum have been found: an improvement of thermal fits\cite{9}, the phase change order\cite{15}, and cumulants and correlations of charge fluctuations\cite{16}.

Here we include the effects of the extended mass spectrum in order to explain the $p/\pi$ ratio at the LHC. Dynamical chemical reactions are used that are catalyzed by quickly decaying non-strange, mesonic Hagedorn states\cite{17}. We
find that adding in the effects of the extended mass spectrum using out-of-chemical equilibrium dynamics can, indeed, explain the lower \( p/\pi \) ratio at the LHC.

2. Setup

The standard modeling of heavy-ion collisions has the following pattern: initial conditions until a time of \( \tau_0 \approx 0.5 - 1 \) fm, relativistic hydrodynamics is then initiated and allowed to expand and cool until the fluid cells reach a switching temperature of \( T_{SW} \approx 155 \) MeV, once the fluid is converted into particles it is described by either a hadronic afterburner or hadronic transport model until chemical and kinetic freezeout is reached. For simplicity’s sake, we begin a Bjorken expansion with an accelerating radial flow that begins at \( \tau_0 \) using

\[
V(\tau) = \pi v_0 (\tau - \tau_0) + \frac{1}{2} a_0 (\tau - \tau_0)^2
\]

(1)

to describe the relativistic hydrodynamical expansion. Here we use the initial radius size of \( r_0 = 7.1 \) fm, and initial flow \( v_0 = 0 \) for both RHIC and LHC, whereas initial time is \( \tau_0 = 0.6 \) and 1.0 fm and the acceleration is \( a_0 = 0.03 \) and 0.02 \( fm^{-1} \) for LHC and RHIC, respectively. We ensure that causality is preserved and the final velocity is reasonable (\( v_{final} \approx 0.5 - 0.7 \) ). We assume \( T_{SW} = 155 \) MeV for both LHC and RHIC, which corresponds to the temperature region where we expect the extended mass spectrum to be valid [10, 13, 14].

After the switching temperature, we populate the hadrons using multihadronic decay reactions driven through Hagedorn states. To do so we must first establish the form of the mass spectrum, which is used to calculate the thermodynamics and chemical equilibrium values of the hadrons. In this proceedings we consider only the simplest form of the Hagedorn spectrum

\[
\rho = A e^{m/T_H}
\]

(2)

where \( A = 2.84(1/GeV) \) and \( T_H = 0.252 \) GeV. However, in [18] we explore different descriptions of the extended mass spectrum, which also describe different types of decays. The Hagedorn state decays that catalyze the other hadrons to quickly reach chemical equilibrium are

\[
n\pi \leftrightarrow HS \leftrightarrow n'\pi + X\bar{X}.
\]

(3)

where a Hagedorn state can either decay into multiple \( n \) pions or \( n' \) pions plus an \( X\bar{X} \) where \( X\bar{X} = p\bar{p}, K\bar{K}, \) or \( \Lambda\bar{\Lambda} \). The exact rate equations used to describe these decays can be found in [18] with further details and tests of the robustness of our current assumptions.
3. Results

In Fig. 1 our results are shown compared to Au+Au RHIC $\sqrt{S_{NN}} = 200$ GeV data and in Fig. 2 our results are shown in comparison to Pb+Pb LHC $\sqrt{S_{NN}} = 2.76$ TeV data. The solid black dots represent the situation where there are no initial protons, kaons, and lambdas in our system (while the pions and Hagedorn states begin in chemical equilibrium) whereas the outlined circles represent the scenario when all hadrons begin in chemical equilibrium. Follow these initial conditions the hadrons are then allowed to dynamically equilibrate over the expansion period. The LHC calculations end at $T_{\text{end}} = 133$ MeV and the RHIC calculations end at $T_{\text{end}} = 135$ MeV. We caution against using $T_{\text{end}}$ MeV as a chemical equilibration temperature because it is highly dependent on the choice of parameters when describing the extended mass spectrum [18].

In a previous papers [19, 20, 21] we explored the effect of the extended mass spectrum at RHIC and found that they were able to match experimental data points. However, we have since updated our mass spectrum to fit to more recent lattice data [12] and have also updated our modeling method to reflect the current modeling procedures of heavy ion collisions. Thus, it is important to note that even after these changes the extended mass spectrum is able to match experimental particle ratios at RHIC (when the protons begin underpopulated). This is an essential point because the same procedure that is used to match particle yields at RHIC using thermal fits was not able to adequately explain the lower $p/\pi$ ratio at LHC [5, 4].

One can see in Fig. 2 that once again we are able to match the experimental data points at the LHC, which includes the lower $p/\pi$ ratio that has been unexplained by thermal fits [5, 4]. However, this is only possible in the scenario where there is an initial underpopulation of protons and lambdas. When the protons start in chemical equilibrium, then the proton to pion ratio is significantly overpopulated, which implies that both the extended mass spectrum combined with dynamical chemical equilibration is needed to explain the $p/\pi$ puzzle at the LHC.

4. Conclusions

Our results indicate that the inclusion of the extended mass spectrum into dynamical hadron gas interactions can then explain the suppressed $p/\pi$ ratio at the LHC. Our current model is somewhat limited in that we can only consider non-strange, mesonic Hagedorn states. We hope in the future to combine the transport model that includes the extended mass spectrum [22] with a relativistic event-by-event hydrodynamical code [23] to provide a more systematic check of the effect of the extended mass spectrum on the particles yields and collective flow. We also plan on exploring the effect of the extended mass spectrum on multi-strange particles and additionally how strange and/or baryonic Hagedorn states would populate those states.
However, these results provide a strong indication that we could be seeing an effect from the extended mass spectrum at the LHC. Already the extended mass spectrum plays a role in the transport coefficients, specifically the shear viscosity to entropy density ratio \([9, 10]\), and that additional strange baryons can affect cumulants and correlations of charge fluctuations \([16]\). Thus, it is natural to question what other effects the extended mass spectrum will play on the signals of the Quark Gluon Plasma once they are integrated into hadronic after burners and transport methods.

J. Noronha-Hostler acknowledges Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for financial support. This work was supported by the Bundesministerium fur Bildung und Forschung (BMBF), the HGS-HIRe and the Helmholtz International Center for FAIR within the framework of the LOEWE program launched by the State of Hesse.

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