Thermodynamic Signatures of Additional Strange and Charm Baryons

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Heavy-ion collisions: a sketch

- initial state
- pre-equilibrium
- QGP, hydro. expansion
- hadronization
- freeze-out

Temperature

Time

√s

T_c, μ_c

T^f, μ^f

detectors: hadrons

freeze-out stage

"observed" in HIC
Hadrons yields at the freeze-out

well described by: Hadron Resonance Gas (HRG)
thermal gas of uncorrelated hadrons with vacuum masses

\[ \hat{P}_h \sim f(\hat{m}_h) \cosh\left[ B_h \hat{\mu}_B + Q_h \hat{\mu}_Q + S_h \hat{\mu}_S + C_h \hat{\mu}_C \right] \]

thermal abundance of hadrons
compare with expt. hadron yields

\[ \hat{P}_{\text{tot}} = \sum_{\text{all hadrons}} \hat{P}_h \]
hat → dimensionless in T units

freeze-out parameters
thermal conditions "observed" in HIC

LQCD: validity of hadronic description

baryon – charge/strangeness/charm correlations:

\[ \chi_{BX}^{nm} = \left. \frac{\partial^{n+m} \hat{P}}{\partial \hat{\mu}_B \partial \hat{\mu}_X} \right|_{\hat{\mu} = 0} \]

HRG: \( \hat{P}_h \sim f(\hat{m}_h) \cosh[B_h \hat{\mu}_B + Q_h \hat{\mu}_Q + S_h \hat{\mu}_S + C_h \hat{\mu}_C] \)

\[ \chi_{BX}^{nm} = B^n \times F(\hat{m}) \]

\[ \frac{\chi_{BX}^{nm}}{\chi_{BX}^{km}} = B^{n-k} \]

= 1, when dof are hadronic with B=1

< 1, when dof are quarks with B=1/3

independent of hadron mass spectrum, relies only on changing quantum number

uncorrelated hadron gas description is valid right till the QCD crossover region

chiral crossover:

\[ T_c = 154 \pm 9 \text{ MeV} \]
LQCD: validity of hadronic description

baryon – charge/strangeness/charm correlations:

HRG: \( \hat{P}_h \sim f(\hat{m}_h) \cosh[B_h \hat{\mu}_B + C] \)

\[ \chi_{BX}^{nm} / \chi_{BX}^{km} = B^{n-k} \]

\[ \chi_{BX}^{n} / \chi_{BX}^{km} = B^{n-k} \]

= 1, when dof are hadronic with \( B = 1 \)

< 1, when dof are quarks with \( B = 1/3 \)

independent of hadron mass

\( T_c = 154 \pm 9 \) MeV
Probing hadron spectrum using thermodynamics

hadronic pressure: \( P^C = \sum_{h \in \text{all hadrons}} P_h \)  

expt. observed hadrons + unobserved ones

Quark Model
charm baryons

\( \Lambda_C \) [GeV]

\( \Sigma_C \) [GeV]

PDG states

Probing hadron spectrum using thermodynamics

hadronic pressure: $P^C = \sum_{h \in \text{all hadrons}} P_h$  expt. observed hadrons + unobserved ones

Quark Model  charm baryons  LQCD


Padmanath et.al.: arXiv:1311.4806 [hep-lat]
Probing hadron spectrum using thermodynamics

hadronic pressure: $P_s = \sum_{h \in \text{all hadrons}} P_h$

Quark Model

strange baryons

Probing hadron spectrum using thermodynamics

hadronic pressure: \( P^s = \sum_{h \in \text{all hadrons}} P_h \) -> expt. observed hadrons + unobserved ones

Quark Model

LQCD


Probing hadron spectrum using thermodynamics

significant contributions of these unseen states to the ratios of partial pressures of baryon to meson near the QCD crossover

probing hadron spectrum using thermodynamics

LQCD: operators to identify separate thermodynamic contributions of strange/charm baryons/mesons

similar results with LQCD spectra
Operators for partial pressures of baryons & mesons

suitable combinations of up to 4th order baryon – charm/strangeness correlations

\[ \chi_{\text{BX}}^{nm} = \left. \frac{\partial^{n+m} \hat{P}}{\partial^{n} \hat{\mu}_B \partial^{m} \hat{\mu}_X} \right|_{\bar{\mu}=0} \]


a simplified example:

hadron gas → \[ \hat{P}^C \sim P^C_M \cosh[\hat{\mu}_C] + P^C_B \cosh[\hat{\mu}_B + \hat{\mu}_C] \]

partial pressure of |C|=1 mesons partial pressure of |C|=1 baryons

neglect contributions of heavier |C|=2,3 baryons, x1000 suppressed

\[ \chi_k^C \sim P^C_M + P^C_B \]

\[ \chi_{mn}^{BC} \sim P^C_B \]
Signatures of additional charm baryons

relative contributions:

charm baryons to charmed mesons

\[ \frac{\chi_{13}^{BC}}{\left( \chi_4^C - \chi_{13}^{BC} \right)} = \frac{P_B^C}{P_M^C} \]

charged charm baryons to charged charmed mesons

strange charm baryons to strange charmed mesons

signatures of additional, yet unobserved charm baryons from QCD thermodynamics
Thermodynamic contributions of additional strange baryons

relative contributions of strange baryons to strange mesons

partial pressure of strange mesons:

\[ M_1^S = \chi_2^S - \chi_{22}^S \]
\[ M_2^S = \frac{1}{12} \left( \chi_4^S + 11 \chi_2^S \right) + \frac{1}{2} \left( \chi_{22}^S + \chi_{13}^S \right) \]

partial pressure of strange baryons:

\[ B_1^S = -\frac{1}{6} \left( 11 \chi_{11}^S + 6 \chi_{22}^S + \chi_{13}^S \right) \]
\[ B_2^S = \frac{1}{12} \left( \chi_4^S - \chi_2^S \right) + \frac{1}{3} \left( 4 \chi_{11}^S - \chi_{13}^S \right) \]

+ undiscovered strange baryons

contributions of all expt. observed strange hadrons

Thermodynamic contributions of additional strange baryons

relative contributions of $S=1$ baryons to strange mesons

relative contributions of $S=3$ baryons to strange mesons
Hierarchical freeze-out of light & strange hadrons?


~10-5 MeV systematic difference in freeze-out T from separate fits to light and strange hadrons

two separate freeze-out stages for light and strange hadrons?

Europhys. Lett. 104, 22002 (2013) ...
Strange baryon yields in heavy-ion collisions

\[ \frac{n_{\bar{\Lambda}}}{n_{\Lambda}}, \frac{n_{\bar{\Xi}}}{n_{\Xi}}, \frac{n_{\bar{\Omega}}}{n_{\Omega}} = \exp \left[ -\frac{2\mu_B^f}{T^f} \left( 1 - \frac{\mu_S^f}{\mu_B^f} |S| \right) \right] \]

This expression does not assume the spectrum of the hadron gas, only assumes hadron yields are thermal.
medium formed in HIC is strangeness neutral: \[ \langle n_S \rangle = 0 \]

\[ \frac{\mu_S}{\mu_B}(T, \mu_B/T) \approx \frac{\chi^{BS}_1(T)}{\chi^S_2(T)} + \ldots \]

relative contribution of strange baryons to mesons

LQCD results are reproduced by including additional Quark Model states

a given value of \( \frac{\mu_S}{\mu_B} \) is realized at a lower temperature

Strangeness, LQCD and freeze-out in HIC

freeze-out $T$ by comparing $\mu_S/\mu_B$ from LQCD and expt.

not reproduced by strangeness neutral hadrons gas with only PDG states

Additional strange hadrons & freeze-out in HIC

inclusion of additional strange hadrons reduces freeze-out $T$ & agrees with LQCD+expt. determination

indirect evidence for so-far undiscovered strange baryons at RHIC?

Additional strange hadrons & RHIC BES

signature for unobserved strange baryons persists for RHIC BES-II

\[
\begin{align*}
\ln\left(\frac{N_{K^-}}{N_{K^+}}\right) = \mu_S^f \mu_B^f \\
\ln\left(\frac{N_{\bar{p}}}{N_p}\right) = \mu_S^f \mu_B^f
\end{align*}
\]

can also be extracted from expt. measured

need accurate expt. measurements & feed-down corrections
Summary

hot-dense LQCD:
additional, yet unobserved strange & charm baryons become thermodynamically relevant near the QCD crossover

these additional strange baryons are important for determining the `observed' freeze-out temperatures of heavy-ion collision experiments

freeze-out temperatures for strange hadrons obtained comparing LQCD and HIC expt. favors presence of these additional hadrons