# The thermodynamics of heavy light hadrons at freezeout

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Introduction

- Correlations between conserved quantum numbers like baryon number(B) and electric charge(Q) provide important information on the degrees of freedom and interactions in the hot QCD medium.
- The charm quarks are created early before the QGP forms.
- Thermal production of charm quarks in the QGP expected to be small since the temperature of the medium < 500 MeV at RHIC and LHC energies.
- This makes them good probes of the hot QCD medium :
  Sequential melting of the charm mesons $J/\psi, \eta_c$ [Matsui, Satz, 86] ?
  Hadronization at freezeout leading to statistical regeneration [Braun-Munzinger, Redlich, Stachel, 06]?
- Strange quarks thermally generated in the medium $\Rightarrow$ enhancement a signal for QGP. [Rafelski, et. al. 86]

courtesy: alicematters.web.cern.ch

courtesy: Talk by E. Scomparin, ECT*, 2013
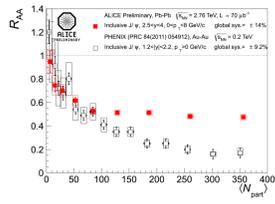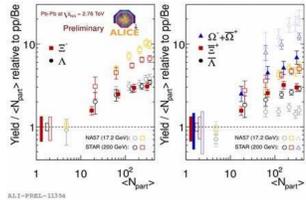
The issues addressed in this work

- Deconfinement of the light quarks in QCD occurs simultaneously with chiral symmetry restoration.
  Do heavy degrees of freedom behave in the same way as the light in the deconfined phase?

- Does the confined medium give information about abundances of open charmed and strange hadrons?

The set-up

- Construct correlations and fluctuations between X=B,Q,S,C in terms of generalized susceptibilities on the lattice,

$$\chi_{ijkl}^{BQSC} = -\frac{T}{V}\frac{\partial^{i+j+k+l}}{\partial\hat{\mu}_B^i\partial\hat{\mu}_Q^j\partial\hat{\mu}_S^k\partial\hat{\mu}_C^l} P_{QCD}(\hat{\mu}_X)|_{\hat{\mu}_X=0} \ , \ \hat{\mu}_X = \mu_X/T \ .$$

- Construct ratios of different correlations to get an idea about the relevant degrees of freedom.

Details of simulations

- Lattice size: $24^3 \times 6$ and $32^3 \times 8$.
- Highly Improved Staggered quark(HISQ) configurations used.
- $N_f = 2 + 1$: strange quark mass is at physical value, $m_s/m_l = 20 \rightarrow$ pion mass $= 160$ MeV.
- The charm quarks are quenched.
- The charm quark masses at different temperature are fixed by setting the mass of the spin averaged charmonium mass $\frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ to its physical value.
- For each determination of the susceptibilities 1500 stochastic sources were used for the light and 6000 for the charm quarks $\rightarrow$ errors for charm correlations mainly statistical.
- 16000-1600 configurations analyzed from lowest temperature to highest to reduce statistical errors.
- The chiral crossover temperature in the continuum limit for physical quarks: $T_c = 154 \pm 9$ MeV.

The melting of the open charmed hadrons

- The partial pressure of an ensemble of non-interacting charmed hadrons at $\mu_Q = 0$ is given as,

$$P(\hat{\mu}_C, \hat{\mu}_B) = P_M \cosh(\hat{\mu}_C) + P_{B,C=1}\cosh(\hat{\mu}_B + \hat{\mu}_C) + P_{B,C=2}\cosh(\hat{\mu}_B + 2\hat{\mu}_C) + P_{B,C=3}\cosh(\hat{\mu}_B + 3\hat{\mu}_C) \ .$$

- The partial pressures can be constructed out of second order χ_2^C, χ_{11}^{BC} and fourth order χ_4^C, χ_{31}^{BC}, χ_{22}^{BC}, χ_{13}^{BC} correlations and fluctuations. [Bielefeld-BNL collaboration, 13]
- The fluctuations dominated by the meson terms:

$$\chi_2^C(\hat{\mu}_X = 0) = P_M + 1^2 P_{B,C=1} + 2^2 P_{B,C=2} + 3^2 P_{B,C=3} \ .$$

- B-C correlations contain contribution from baryons of different charm content:

$$\chi_{nm}^{BC}(\hat{\mu}_X = 0) = 1^m P_{B,C=1} + 2^m P_{B,C=2} + 3^m P_{B,C=3} \ , \ n, m > 1, n + m = even.$$

- Masses of C=2 baryons is substantially larger than C=1 baryons, $\Delta = m_{C=2} - m_{C=1} \simeq 1.2$ GeV. The relative contribution to pressure $e^{-\Delta/T} \simeq 10^{-3}$.
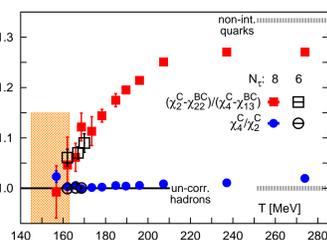- Consequence: $\chi_{mn}^{BC} \simeq P_{B=1}$.

- The $P_M = \chi_2^C - \chi_{22}^{BC}$ or equivalently $\chi_4^C - \chi_{13}^{BC}$.
  Ratio is unity in a hadron gas.
  Departure of the ratio of these two quantities from unity $\Rightarrow$ melting of mesons.
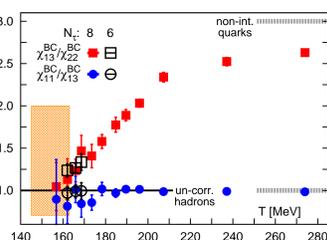- $T > 300$ MeV: gas of massive charm $P(\mu_c, \mu_B) = P_{C=1}\cosh(\frac{1}{3}\hat{\mu}_B + \mu_C)$.

- Upper bound of the contribution of $C > 1$ hadrons= $\chi_4^C - \chi_2^C \rightarrow$ Data confirms negligible contribution at crossover transition.
- Ratios of $P_{B,C=1}$ differs from unity at crossover region.
- At high T, $\chi_{1n}^{BC} = \chi_{1m}^{BC}$, $n \neq m$ for massive charm gas: Not a good observable to study deconfinement.


Conclusion: Melting of charmed baryons and mesons occur at chiral crossover.
Similar conclusion observed for the open strange hadrons [Bielefeld-BNL collaboration, 13].

The hadron resonance gas model for charm and strangeness

- High energy processes driven by strong interactions $\Rightarrow$ large number of hadrons with exponential density of states.[Hagedorn, 65]
- Conservation of quantum numbers are controlled by chemical potentials.
- For light quarks, thermodynamic quantities below chiral crossover depicted well by a gas of non-interacting hadrons+resonances $\rightarrow$ Hadron Resonance gas model.
  [Braun-Munzinger, Cleymans, Oeschler, Redlich, 02]
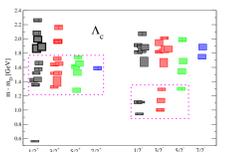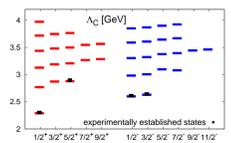
- Strong dynamics relevant for strange and charm sector as well
- In the Particle data table: Open charm mesons D_s, D and its excitations well known
- Charm baryons spectrum: Not very clear
- Many more states are predicted from Quark Model (QM-HRG) [Ebert et. al, 10] and the lattice [Padmanath et. al, 13]: Many excited states of Λ_c and Σ_c even below the highest measured double strange baryon Ξ_c

- States $\lesssim 3$ GeV important for thermodynamics at chiral crossover
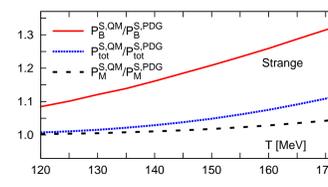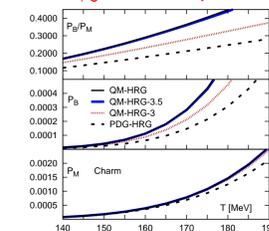

- Same is true for the strange hadrons as well !

Hints of more open heavy flavoured hadrons from QCD

- We construct baryon to open charm meson partial pressures with different quantum numbers:
  1. For all hadrons: $\frac{\chi_{13}^{BC}}{\chi_4^C - \chi_{13}^{BC}}$
  2. For S=1,2 hadrons: $\frac{\chi_{112}^{BSC}}{\chi_{13}^{SC} - \chi_{112}^{BSC}}$
  3. For Q=1,2 hadrons : $\frac{\chi_{112}^{BQC}}{\chi_{13}^{QC} - \chi_{112}^{BQC}}$

- Strange hadron sector: Baryon to meson partial pressure in agreement with QM-HRG model.
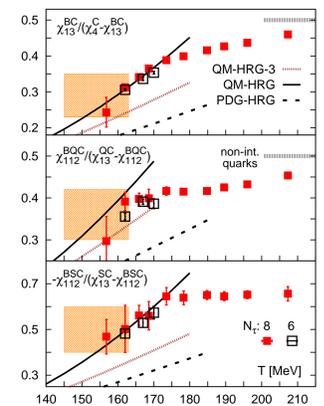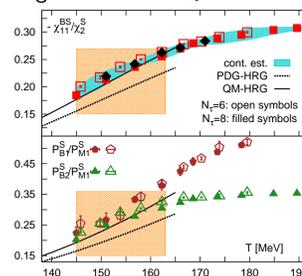

Ratios of partial pressure not sensitive to the hadron masses: good quantities for comparison
PDG-HRG: all experimentally measured hadrons
QM-HRG: PDG +additional quark model states

Conclusions

- Our data from QCD supports QM-HRG model.
- Charmed baryons with different strangeness and charge content melt approximately in the same region.
- Similar observation for the strange hadrons.

Correlations of charm and strangeness

- The ratios of susceptibilities with different quantum numbers constructed: Unity in the HRG.
- Departure from unity $\rightarrow$ change in the quantum numbers of degrees of freedom
- The open heavy states melt at the chiral crossover transition.
- Beyond T_c, they exist as strongly interacting quasi-particles
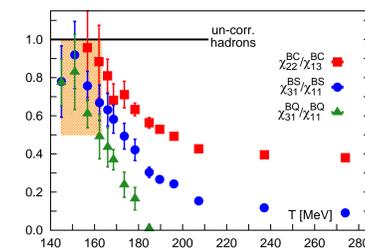
Summary

- Melting of open charm mesons and baryons happens at $T_c \rightarrow$ independent of the details of spectrum
- Robust for different electric charge and strange charmed hadrons
- We found evidence for existence of many more strange and charm baryons from their contribution to QCD thermodynamics at $T \lesssim 160$ MeV.

Consequences

- Additional charm baryons decay into lighter D mesons and could contribute to the statistical hadronization at the freezeout $\rightarrow$ reconsider feed-down corrections?
- Additional strange hadrons and excitations yield a 5-8 MeV decrease of the freezeout temperature for the strange sector $\rightarrow$ explain differences in T_f for light and strange sectors?[Talk by C.Schmidt, Wednesday]

- Reference: A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa, Swagato Mukherjee, H. Ohno, P. Petreczky, C. Schmidt, S. Sharma, W. Soeldner and M. Wagner, arxiv: 1404.4043 & 1404.6511.