THE ROLE OF RESONANCES IN HOT HADRONIC MATTER

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Hampton University and Jefferson Lab

Monday, February 6, 2017
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 Au+Au

HIPS 2017
New Opportunities with High-Intensity Photon Sources

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New Opportunities with High-Intensity Photon Sources
Outline

- Missing hadrons
- Hot hadronic matter
- The hot Hadron Resonance Gas
- HRG and LQCD
- HRG and heavy ion collisions
- Hyperon effects in the HRG
- Remarks and conclusions
Missing hadrons: Mesons in PDG

SU(3) octets → # Kaons = # non-strange mesons

Number of PDG dof: 469
**Missing baryons in PDG**

<table>
<thead>
<tr>
<th>SU(3)</th>
<th>PDG</th>
<th>All listed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$# \Sigma = # \Xi = # N + # \Delta$</td>
<td>26; 12; 49</td>
<td></td>
</tr>
<tr>
<td>$# \Omega = # \Delta$</td>
<td>4; 22</td>
<td></td>
</tr>
<tr>
<td>$# \Lambda = # N + # \text{singlets}$</td>
<td>18; 29</td>
<td></td>
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</tbody>
</table>

\[ SU(3): \quad \# Y = 3(\# \text{N} + \# \Delta) + \text{singlets} \]

**Important aspects of excited hyperon physics**

- Test the existence of complete SU(3) multiplets
- Study SU(3) breaking effects in excited baryons
- Test the indications that excited baryons form SU(6) x O(3) multiplets
- Important source of information to test the $1/N_c$ expansion of QCD in baryons
- Possible role of hyperons in high energy heavy ion collisions
Present status of hyperons from PDG

\[ \frac{1}{N_c} \text{ baryon mass formulas} \]

for 56-plets \( \ell = 0, 2 : 24 \) excited hyperons

for 70-plet \( \ell = 1 : 23 \) excited hyperons
Phases of QCD

LQCD, RHIC (but off chemical equilibrium)

LQCD thermodynamics gives results at vanishing or small chemical potentials: this is the QCD thermo of the early universe!

RHIC gives results in a range of $\mu_B$ down to zero, but at freeze out system is well off chemical equilibrium: QGP phase as in early universe, but not so the hadronic phase.
What can QCD thermodynamics tell about missing hadrons?

We need to investigate the hadronic phase

Framework is needed to try to answer the question: model of hadronic phase

Compare with LQCD: it gives only thermodynamics observables

Compare with RHICs: it gives lots of detail from where one can derive thermodynamics, but lots of uncertainties

What thermodynamic observables need to be looked at?
The model for Hot hadronic matter:
Hadron Resonance Gas -- HRG

dof: meson-, baryon- and antibaryon- stable states and resonances
only light quarks here (heavy hadrons give very small contributions)

EoS

\[ p_n(T, \mu) = \frac{(-1)^{1+B(n)}d(n)}{(2\pi)^3} T \int d^3p \log \left( 1 + \frac{(-1)^{1+B(n)} \exp \left( - \frac{\sqrt{p^2 + m_n^2} - \mu}{T} \right)}{1+B(n)} \right) \]

\[ B(n) = \text{Baryon number}, \quad d(n) = (2J_n + 1)(2I_n + 1) \]

or expansion in Bessel functions

\[ p_n(T, \mu) = T^2 d(n) \frac{m_n^2}{2\pi^2} \sum_k (-1)^{B_n(k+1)} \frac{1}{k^2} K_2(km_n/T) \exp(k\mu/T) \]

In chemical equilibrium: \( \mu_s, \mu_B \)

HRG determined by spectrum of QCD
Baryons: states up to \( \sim 2.7 \text{ GeV} \)

\[ SU(6) \times O(3) \] Multiplets

\[ [56, \ell = 0] \] ground state

\[ [56, \ell = 0, 2, 4] \]

\[ [70, \ell = 1, 2, 3] \] Number of dof: 1946

many missing states: in SU(3) multiplets and also spin-flavor multiplets (QM & LQCD)

use simple mass formulas fitted to known states to provide masses for the missing states
mass formulas: neglect spin-orbit splittings

\[ M_{56,GS}(S = 1/2, S) = m_0 - \frac{1}{2}c_{HF} - c_S S \]
\[ M_{56,GS}(S = 3/2, S) = m_0 + \frac{1}{2}c_{HF} - c_S S \]
\[ M_{56}(S = 1/2, S) = m_0 - \frac{1}{6}c_{HF} - c_S S \]
\[ M_{56}(S = 1/2, S) = m_0 + \frac{1}{6}c_{HF} - c_S S \]
\[ M_{70}(S = I, S) = m_0 + \frac{1}{3}c_{HF} \left( \frac{5}{3} S(S + 1) - \frac{7}{4} \right) - c_S S \]
\[ M_{70}(S = I - 1, S) = m_0 + \frac{1}{3}c_{HF} \left( S(S + 2) - \frac{3}{4} \right) - c_S S \]
\[ M_{70}(S = I + 1, S) = m_0 + \frac{1}{3}c_{HF} \left( S^2 - \frac{7}{4} \right) - c_S S \]
\[ \Lambda_{70}^1 = m_0 - \frac{1}{2}c_{HF} + c_S \]
HRG and LQCD

A. Bazavov et al

µ_S = µ_B = 0

early universe at T < T_c:
chemically equilibrated
meson dominated HRG
The hot hadronic system produced in high energy HICs is for most of its brief expansion off chemical equilibrium. In the HRG description, this requires the inclusion of chemical potentials to account for the overabundance of the different hadrons. The presentation here is basic, ignoring possible effects of hydrodynamics, and corresponds to describing the thermodynamics of the HRG in the local co-moving frame; it should be reasonably good for discussing particle yields. In the absence of net $B$, $S$, and $Q$, we associate to each isospin multiplet a chemical potential equal to that of the corresponding antiparticles. Processes which remain in equilibrium give relations between chemical potentials.

At the crossover there are about 0.5 hadrons/$\text{fm}^3$.
More sensitive probes: correlations

\[ \chi_{ij}^2 = \frac{1}{T^2} \frac{\partial^2 p}{\partial \mu_i \partial \mu_j} \quad i, j : Q, S, B \]

LQCD results: Bazavov et al.
Correlations in the Entropy

Entropy weighs heavier states more than pressure does.

In principle accessible in LQCD, but calculations need results at more temperatures: very crude results with available data, or study correlations involving trace anomaly.
Hot hadronic matter in heavy ion collisions

RHICs produce around central rapidity a fireball that starts as a ~thermalized QGP which expands crossing over to a hadronic fireball
key characteristic of fireball: it is off chemical equilibrium

\[ \tau_{\text{ch}} \sim \frac{1}{\sigma_{\text{ann}} \rho v_{\text{th}}} \]

Inelastic collision rates are low and hadron gas is off chemical equilibrium

\[ \tau_{\text{ch}} \text{ can be very large } > 10^\prime s \text{ fm} \]

Bebie et al; Shuryak; JLG; Koch et al; ...

\[ N\bar{N} \rightarrow n\pi \text{ is not that slow and should be taken into account at early stages of hadronization} \]

Rapp & Shuryak
Chemical potentials

for HRG off chemical equilibrium one assigns chemical potentials to all hadrons

detailed balance

\[ A + B \leftrightarrow C + D \implies \mu_C + \mu_D = \mu_A + \mu_B \]

stable hadrons develop effective chemical potentials

\[ \mu_\pi, \mu_K, \mu_N, \mu_\Sigma, \mu_\Xi, \mu_\Omega \]

baryon annihilation

\[ B\bar{B} \leftrightarrow nM \quad \mu_B = \frac{\bar{n}}{2} \mu_M \]

assume dominance of 2-body

resonance decay as approximation

\[ \mu_i^{M^*} = \sum_{j=\pi,K} \nu_{ij}^{M^*} \mu_j , \quad \mu_i^{B^*} = \sum_{j=N,\Sigma,\Lambda,\Xi,\Omega} \nu_{ij}^{B^*} (\mu_j + \delta_{Si} S_j \mu_\pi + \delta_{Si} (S_j \pm 1) \mu_K) \]
\[ \nu_{ij}^{M^*} = \delta_{S_i0} \delta_{j\pi} \bar{n}_i + \delta_{S_i \pm1} (\delta_{jK} + (\bar{n}_i - 1)\delta_{j\pi}) \]
\[ \nu_{ij}^{B^*} = \delta_{S_i0} \delta_{s_j0} + \delta_{|s_i|3} \delta_{|s_j|2} + \sum_{S=1,2} \delta_{|s_i|} (r_i \delta_{s_i s_j} + \frac{1}{2} \frac{r_i}{\delta_{s_i}(s_j \pm 1)}) \]

cases considered: \( r_i = r, \quad r = 0.5, 1 \)

effective particle numbers: stable hadrons at kinetic freeze-out

\[ \bar{n}_{i}^{M} = n_{i}^{M} + \sum_{j} \nu_{ji}^{M^*} n_{j}^{M^*} , \quad \bar{n}_{i}^{B} = n_{i}^{B} + \sum_{j} \nu_{ji}^{B^*} n_{j}^{B^*} \]

baryon resonance decays affect very little the meson abundance
Effects of chemical potentials

\[ \mu_M = \mu_B = 0 \]

\[ \mu_M = 100 \text{ MeV} \quad \mu_B = 250 \text{ MeV} \]

Excited hyperons

\[ s=0 \]
Simple model of hadron fireball expansion for assessing the possible role of baryon resonances

- adiabatic expansion

conservation of $\frac{\bar{n}_i}{s}$ during expansion

- scenario considered: only resonances are kept in chemical equilibrium; two body inelastic reactions of stable hadrons are frozen.

conserved ratios: $\frac{\bar{n}_\pi}{s}$, $\frac{\bar{n}_K}{s}$, $\frac{\bar{n}_N}{s}$, $\frac{\bar{n}_\Sigma}{s}$, $\frac{\bar{n}_\Xi}{s}$, $\frac{\bar{n}_\Omega}{s}$

use measured particle yield ratios to set initial conditions of the expansion: one unknown is left, e.g. $\mu_\pi$
Particle yield ratios

\[ \frac{n_K}{n_{\pi}} \] as thermometer to determine freeze-out of \( \pi\pi \leftrightarrow K\bar{K} \)

\( \mu_K = \mu_{\pi} \)
\[ \bar{n}_i^M = n_i^M + \sum_j \nu_{ji}^{M*} n_j^{M*}, \quad \bar{n}_i^B = n_i^B + \sum_j \nu_{ji}^{B*} n_j^{B*} \]

Initial conditions @ 0.150 GeV

\[ \mu_\pi = 0.025 \text{ GeV} \]

Fit to freeze-out particle ratios

No clear indication of resonance effects in bulk thermodynamic observables
More sensitive probe: correlations in RHICs

define off chemical equilibrium correlations

\[ \chi_{ij}^2 = \frac{1}{T^2} \frac{\partial^2 p}{\partial \mu_i \partial \mu_j} \]

measurable ratios

\[ R_{ij}^{kl} = \frac{\chi_{ij}^2}{\chi_2^2}. \]

sensitive to hyperon resonances when \( r < 1 \): here \( r = 0.5 \)

what is needed: event by event measurement of \( N \) and hyperon yields close to central rapidity

measurements of charge multiplicity moments

have been done: STAR @ RHIC
Remarks

• Effects of excited baryons, in particular $Y^*$s, are not easy to pin down in hot QCD: best thermodynamic observables are correlations, which can select conserved or approximately conserved particle numbers.

• LQCD: study of correlations (susceptibilities) is most sensitive tool. HRG model, modulo possible corrections, shows effects of $Y^*$s.

• RHICs: global thermo does not show sensitivity: main reason is lack of chemical equilibrium, which brings in uncertainties. Some details of resonance decay BRs is also needed. Correlations defined off chemical equilibrium are sensitive in principle to baryon resonances.