Fast Thermalization of Hadron Resonance Gas via Hagedorn states

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13.01.2016

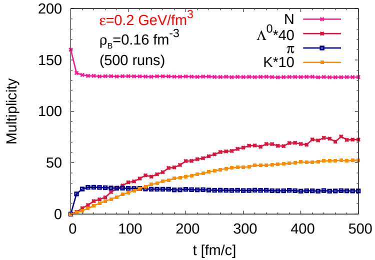
Transport Group Meeting

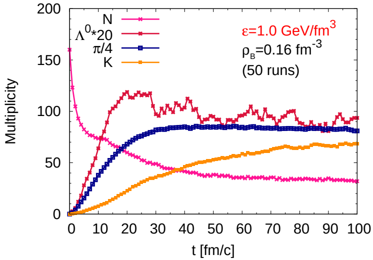
UrQMD box simulation setup

- cubic box with cyclic boundary conditions
- inital particles: 80 n + 80 p
- uniform distribution in configuration and momentum space
- string production disabled
- fixed $\rho_B = 0.16$ fm^{-3} and $\rho_S = 0$ fm^{-3}
- energy density $\epsilon = 0.2$ GeV/fm^3 (500 runs)
- energy density $\epsilon = 1.0$ GeV/fm^3 (50 runs)

Chem. Equil. in UrQMD (box) too long

cf. M. Belkacem et al., PRC 58 (1998) 1727
see also E. Bratkovskaya et al., NPA 675 (2000) 661





$t_\pi \approx 20$ fm/c	$t_\pi \approx 20$ fm/c
$t_N \approx 15$ fm/c	$t_N \approx 15$ fm/c
$t_\Lambda > 300$ fm/c	$t_\Lambda > 40$ fm/c
$t_K > 400$ fm/c	$t_K > 90$ fm/c

Application of Hagedorn States (HS) I:

J. Noronha-Hostler, C. Greiner, I. A. Shovkovy., PRL 100 (2008) 252301

- SPS energies: strong increase of antiprotons/antihyperons through 'clustering' of mesons

$$n_1\pi + n_2K \leftrightarrow \bar{Y} + p$$

- chemical equilibration time of $t_{\mathrm{eq}} \approx 1 - 3\,\mathrm{fm}/c$
- RHIC energies: $t_{\mathrm{eq}} \sim 10\,\mathrm{fm}/c$ for antibaryons
- quick chemical equilibration mechanism through HS

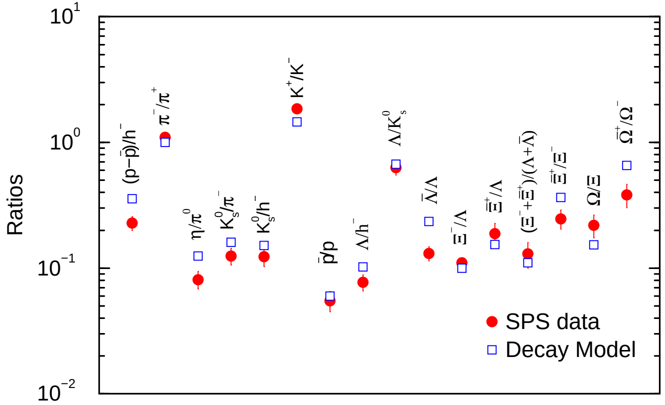
$$\left(n_1\pi + n_2K + n_3\bar{K} \leftrightarrow\right)\ HS \leftrightarrow \bar{B} + B + X$$

- dynamical evolution through set of coupled rate equations
- HS and pions in equilibrium $\rightarrow t_{\mathrm{eq}} \approx 5\,\mathrm{fm}/c$ for $B\bar{B}$-pairs

Application of Hagedorn States (HS) II:

S. Pal, P. Danielewicz, Phys.Lett. B627 (2005) 55

- statistical model for decay and formation of HS
- Hagedorn Temperature of $T_H \simeq 170$ MeV
- subsequent decay of one single heavy resonance (HS)



Intention: Hagedorn States in UrQMD

- UrQMD = Ultrarelativistic Quantum Molecular Dynamics (S. A. Bass et al., Prog.Part.Nucl.Phys. 41 (1998) 225)
- microscopic transport model for p+p, p+N and A+A for Bevalac and SIS up to AGS, SPS and RHIC energies
- detailed balance
  - is enforced: meson-baryon, meson-meson, resonance-nucleon, resonance-resonance
  - is violated by string and some hadron decays ($\omega \to 3\pi$)

- for $\sqrt{s} \geq 2.5 - 10\,\mathrm{GeV}$: HS production replaces strings

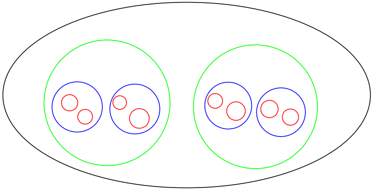
Observables:

- particle multiplicities
- chemical equilibration times
- estimates for $\frac{\eta}{s}$ (shear viscosity over entropy density)
- ...

Origin of Hagedorn states

1965: Rolf Hagedorn postulates "Statistical Bootstrap Model"
(R. Hagedorn, Nuovo Cim.Suppl. 3 (1965) 147-186)

- highly excited lumps of matter are not essentially different from observed hadronic resonances at lower excitation
- fireballs and their constituents are the same
- nesting fireballs into each other leads to
  self-consistency condition (bootstrap-equation)



- solution: “Hagedorn Spectrum”, exponentially rising

Spectrum τ and Decay Width Γ of HS

$$\tau_{\vec{C}}(m) = \frac{R^3}{3\pi m} \sum_{\vec{C}_1,\vec{C}_2} \int_{m_1^0}^{m} \mathrm{d}m_1 \int_{m_2^0}^{m-m_1} \mathrm{d}m_2\, \tau_{\vec{C}_1}(m_1)\, m_1$$

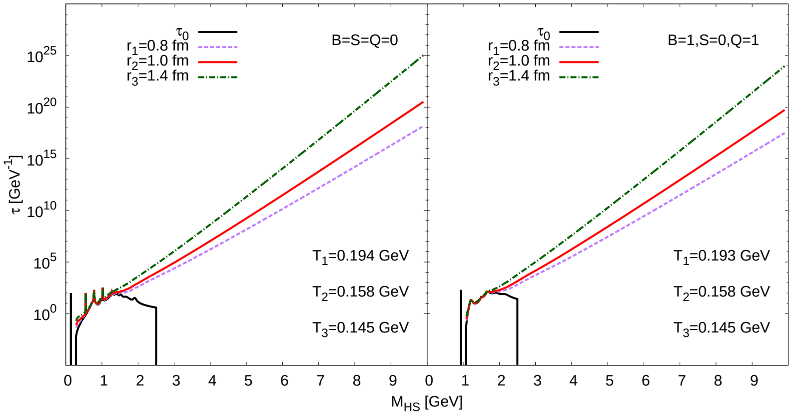
$$\times\, \tau_{\vec{C}_2}(m_2)\, m_2\;\, p_{cm}(m, m_1, m_2)\, \delta^{(3)}_{\vec{C},\vec{C}_1+\vec{C}_2}$$

$$\Gamma_{\vec{C}}(m) = \frac{\sigma}{2\pi^2 \tau_{\vec{C}}(m)} \sum_{\vec{C}_1,\vec{C}_2} \int_{m_1^0}^{m} \mathrm{d}m_1 \int_{m_2^0}^{m-m_1} \mathrm{d}m_2 \tau_{\vec{C}_1}(m_1)\, \tau_{\vec{C}_2}(m_2)$$

$$\times\, p_{cm}(m, m_1, m_2)^2\, \delta^{(3)}_{\vec{C},\vec{C}_1+\vec{C}_2}$$

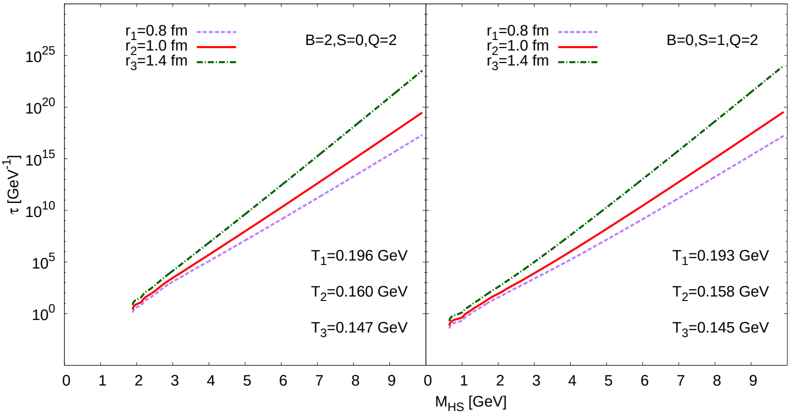
- τ: spectra at masses m and charges $\vec{C} = (B, S, Q)$
- R: HS (spherical) radius and σ: HS creation cross section
- p_{cm} momenta of decay products in rest frame of decaying HS

Mes. (l) and bar. (r) Hagedorn Spectra



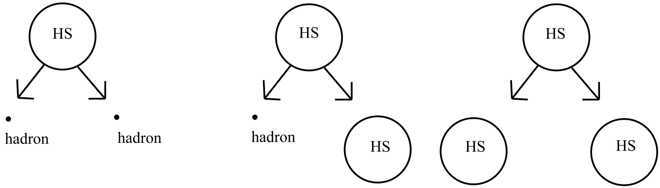
fit function: $f(m) = cm^a \exp\left(\frac{m}{T}\right)$

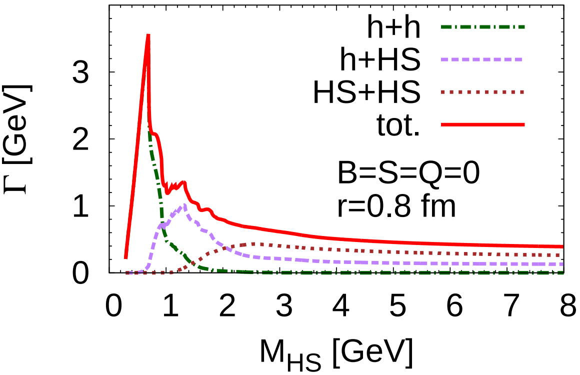
Exotic Hagedorn Spectra



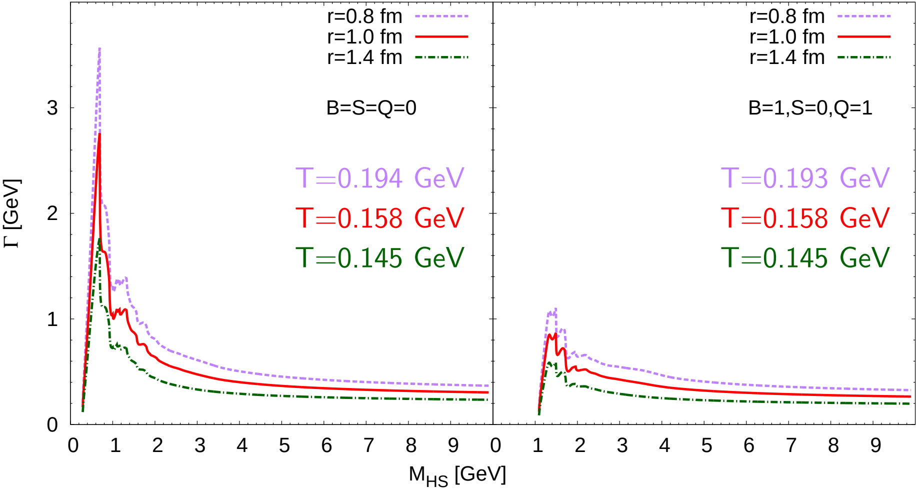
fit function: $f(m) = cm^a \exp\left(\frac{m}{T}\right)$

Hagedorn state decay modes

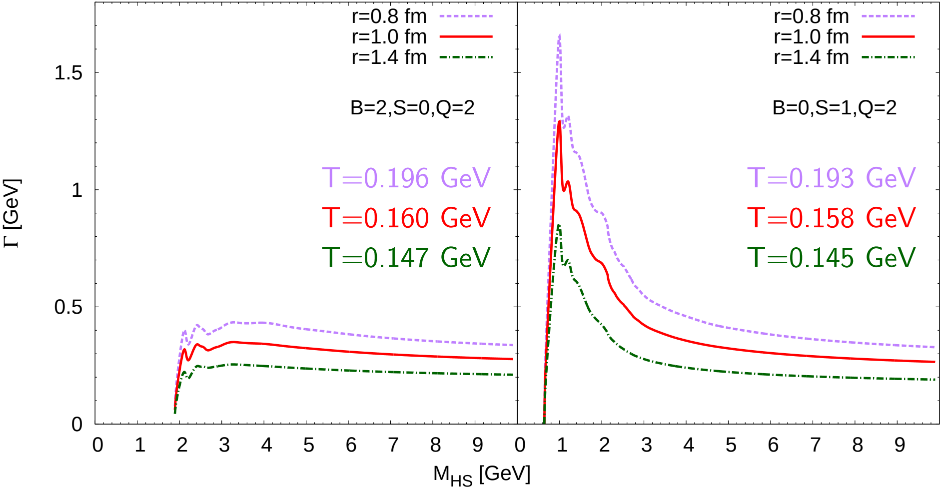




Decay Width for mes. (l) and bar. (r) HS



Decay Width for exotic HSs



Concept of Hagedorn State Gas

- HS appear most abundantly near Hagedorn temperature T_H
- HS - a microscopic tool for hadronization

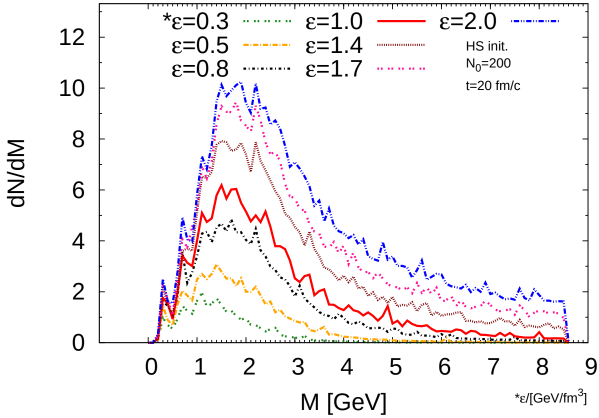
Scenario:

- QGP drop expands, cools and decays/dissolves into QGP droplets/HS
- assembly (gas) of HS is created and begins to evolve
- HS propagate, rescatter and decay into two hadrons, two (lighter) HS or one (lighter) and one hadron
- hadrons and HS collide elastically and inelastically and create (repopulate) new HS
- for all $h + h, HS + HS, h + HS \leftrightarrow HS$ inelastic collisions detailed balance holds
- dynamical, microscopical interplay between hadrons and/or HS drives hadrons and HS into thermal equilibrium

Simulation setup

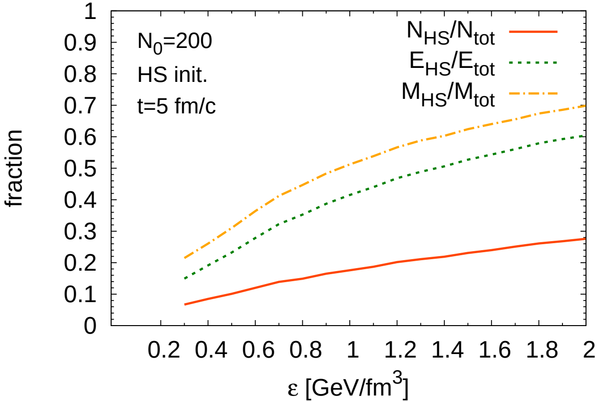
- cubic UrQMD box, volume $V = 1000\,\mathrm{fm}^3$ and reflecting walls
- energy density $(E_{tot.}/V)$ range $\epsilon = 0.2 - 2.0\,\mathrm{GeV}/\mathrm{fm}^3$
- number of initial HS $N_0 = 200$ with $\vec{C}_i = (0, 0, 0)$
- masses of initial HS range $m = 0.3\,\mathrm{GeV} - 8.6\,\mathrm{GeV}$, sampled uniformly
- uniform sampling of positions and momenta of the initial HS, ensures non-equilibrated system
- total momentum $\vec{p}$ $(= 0)$, total energy E and total charges $\vec{C}$ conserved exactly
- overall charge $\vec{C} = (0, 0, 0)$, whereas during simulation particles (hadrons and HS) with $\vec{C}_j \neq (0, 0, 0)$ appear too

Hagedorn state mass distribution



convolution of Boltzmann distribution $f \sim \exp(E/T)$ with Hagedorn spectrum $\tau \sim \exp(m/T_H)$

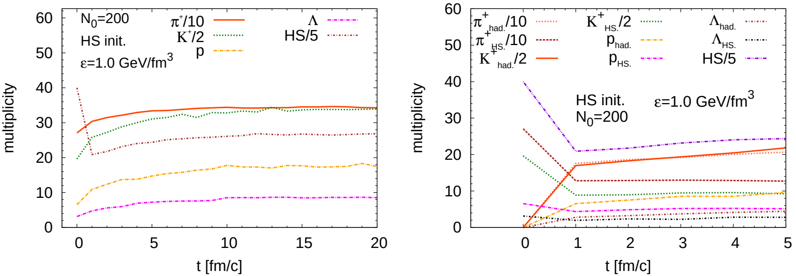
Impact of HS on the system



for $t \geq 5\,\mathrm{fm}/c$ and $\epsilon = 2.0\,\mathrm{GeV}/\mathrm{fm}^3$

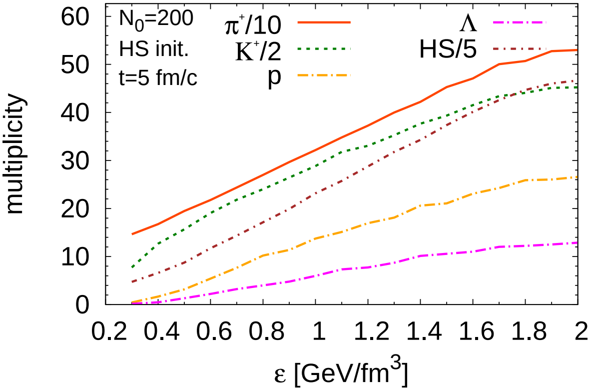
- every fourth particle is a HS
- $\sim$ 60% of total energy and $\sim$ 70% of total mass stored in HS

Multiplicity time evolution



- chem. equilibration of total multiplicities (left) within first $t < 3\,\mathrm{fm}/c$ for all species
- initial HS decays (right) provide therm. equilibration almost immediately

Multiplicity energy density dependence



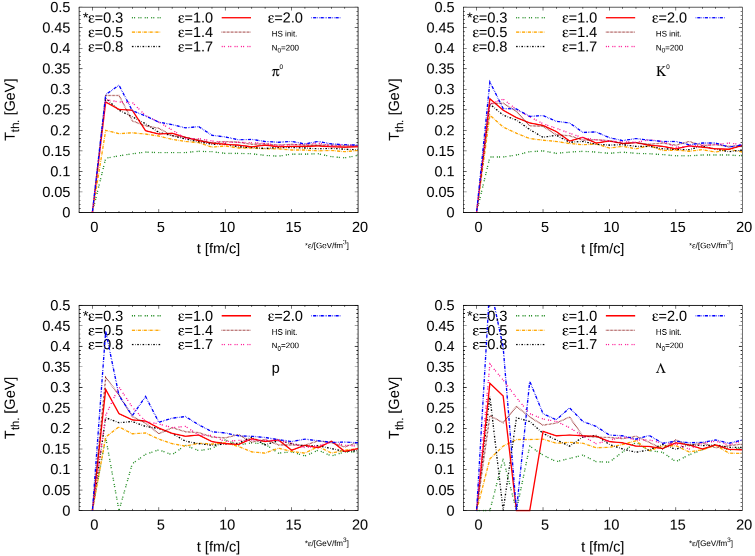
- yields determined by particle's masses, since $\vec{C} = (0, 0, 0)$ holds
- HS multiplicity has steepest slope in accordance to SBM

Comparison to experiment

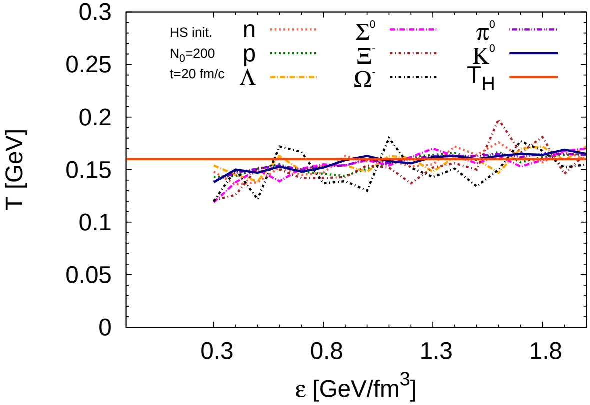
	p-p	Pb-Pb	0.3	0.8	1.0	2.0
K^-/π^-	0.123(14)	0.149(16)	0.192	0.197	0.193	0.185
$\bar{p}/\pi^-$	0.053(6)	0.045(5)	0.015	0.049	0.052	0.060
Λ/π^-	0.032(4)	0.036(5)	0.007	0.022	0.024	0.029
$\Lambda/\bar{p}$	0.608(88)	0.78(12)	0.475	0.456	0.469	0.499
$\Xi^-/\pi^- * 10^3$	3.000(1)	5.000(6)	1.565	6.492	5.769	7.106
$\Omega^-/\pi^- * 10^3$	-	0.87(17)	0.137	0.815	0.823	0.994

- p-p data at $\sqrt{s_{NN}} = 0.9\,\mathrm{TeV}$ (K. Aamodt et al. (ALICE Collaboration), Eur. Phys. J. C 71, 1594 (2011).
- Pb-Pb data at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ (B. B. Abelev et al. (ALICE Collaboration), Phys. Rev. Lett. 111, 222301 (2013))
- error denote experimental error in the last digits
- simulated ratios for $t = 20\,\mathrm{fm}/c$ for energy densities $\epsilon = 0.3, 0.8, 1.0, 2.0\,\mathrm{GeV}/\mathrm{fm}^3$

Temperature evolution of hadrons



Temperature energy density dependence



- temperature dependence independent of particle species
- (Boltzmann) temperature tend to limiting value
- accordance to SBM: $\lim_{\epsilon \to \infty} T = T_H$.

Summary and Outlook

- chem. equilibration times in (standard) UrQMD (box) too long
- presentation of Hagedorn spectra and HS total decay widths
- presentation of microscopic box simulation results (HS mass distribution, HS fraction on total energy, mass etc.)
- hadronic yield and temperature time evolutions
- thermalization of all hadrons with $t \leq 3\,\mathrm{fm}/c$
- comparison of multiplicity ratios with the experiment

- investigation of net-baryon fluctuations
- impact of HS on η/s in UrQMD
- extension of HS dynamics on heavy ion collision simulations