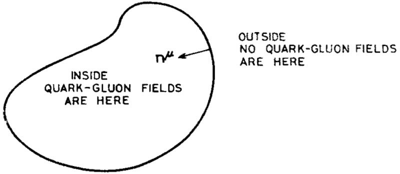
Introduction to Hadron Resonance Gas and its applications

Jwalit N Panchal
School of Physical Sciences, UM-DAE CEBS, Mumbai
Guided By- Prof. Victor Roy
School of Physical Sciences, NISER, Bhubaneshwar

What is HRG?

- It is a form of matter that forms after the thermalization of Quark-Gluon Plasma (QGP). This QGP existed some time after the big-bang, exists today in the core of neutron stars and is formed when heavy-nuclei are collided in colliders like L.H.C. and R.H.I.C. Baryons and mesons are present in the HRG. 2 ways of QGP: **i)** high temperature $\approx 144 MeV$, **ii)** high baryonic density $\approx 0.72 fm^{-3}$
  HRG-QGP transition temperature $\approx 1.7 \times 10^{12} K$
  Sun's core's temperature $\approx 15 \times 10^{6} K$
- The MIT Bag Model:



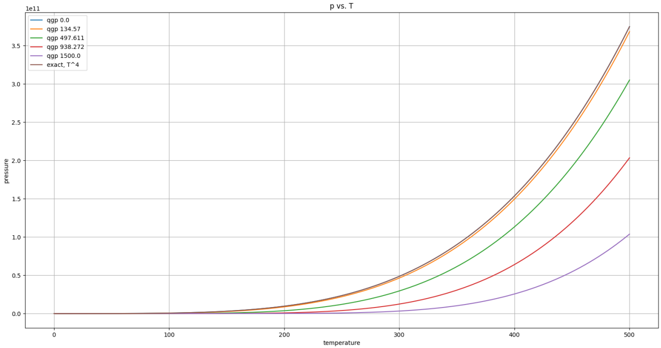
Ideal HRG

Id-HRG assumes hadrons to have zero radius, i.e., no repulsive effect is considered.

Pressure

$$p_i^{id} = \frac{g_i}{6\pi^2}\int_0^\infty \frac{k^4}{\sqrt{k^2+m_0^2}} \frac{dk}{\left(\exp(\frac{\sqrt{k^2+m_0^2}-\mu_i}{T}) + \eta_i\right)} \tag{1}$$

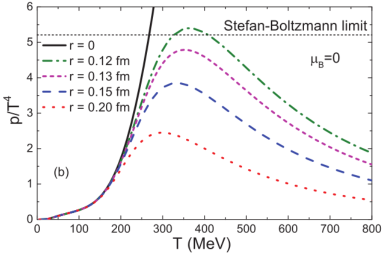
- **Pressure under Boltzmann Approximation**: set $\eta_i = 0$
  1. **mass** $= 0.0\ MeV$
     $$p_i^{id} = \frac{g_i T^4}{6\pi^2}\Gamma(4) \tag{2}$$
  2. non-zero finite mass:
     $$p_i^{id} = \frac{g_i m_0^4 c^5}{6\pi^2\hbar^3} e^{\frac{\mu_i}{K_B T}} \left(\frac{K_B T}{m_0 c^2}\right)^4 K_2\left(\frac{m_0 c^2}{K_B T}\right) \frac{4!}{4\cdot 2!}\left(\frac{m_0 c^2}{K_B T}\right)^2 \tag{3}$$



An example plot showing pressure at same temperatures for different values of mass.

Shortcoming of Ideal HRG

The Id-HRG model treats hadron gas as constituted by point-like masses, i.e., the hard-core radii of the hadrons involved are $r_i = 0 \; \forall \; i$. However, this causes one problem. At high temperatures, the id-HRG pressure predicted by this model exceeds the **Stefan-Boltzmann limit**. This is apparent from the following image (courtesy Ref. PHYSICAL REVIEW C 91, 024905 (2015)):



Number Density Boltzmann Approximation

$$n_i = \frac{g_i \cdot m_0^2 T \cdot e^{\frac{\mu_i}{T}}}{2\pi^2} \cdot K_2\left(\frac{m_0}{T}\right) \tag{4}$$

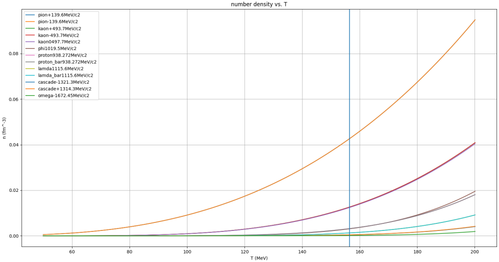
$$\implies V_{exp} = \frac{N_1 \cdot 197.33^3}{n_1} \tag{5}$$

Using Kaon+ number to fix the particle numbers of other particles and volume of fireball. The volume estimated at 156.5MeV is **8162.91 fm^3**.

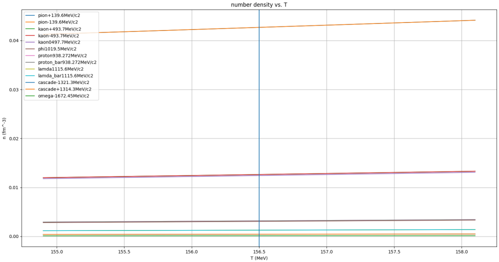
Particle	Number Predicted
pion+	368.2
pion-	368.2
kaon+	109.0
kaon-	109.0
kaon0	107.2

phi	26.4
proton	26.7
proton-bar	26.7
lamda	10.7
lamda-bar	10.7
cascade-	3.6
cascade+	3.7
omega-	1.0

Table: Particle yield calculated


number density vs. T
pion+139.6MeV/c2
pion-139.6MeV/c2
kaon+493.7MeV/c2
kaon-493.7MeV/c2
kaon0497.7MeV/c2
phi1019.5MeV/c2
proton938.272MeV/c2
proton_bar938.272MeV/c2
lamda1115.6MeV/c2
lamda_bar1115.6MeV/c2
cascade-1321.3MeV/c2
cascade+1314.3MeV/c2
omega-1672.45MeV/c2
n (fm^-3)
T (MeV)

(a)


number density vs. T
pion+139.6MeV/c2
pion-139.6MeV/c2
kaon+493.7MeV/c2
kaon-493.7MeV/c2
kaon0497.7MeV/c2
phi1019.5MeV/c2
proton938.272MeV/c2
proton_bar938.272MeV/c2
lamda1115.6MeV/c2
lamda_bar1115.6MeV/c2
cascade-1321.3MeV/c2
cascade+1314.3MeV/c2
omega-1672.45MeV/c2
n (fm^-3)
T (MeV)

Scatter Plot of Particle Yield

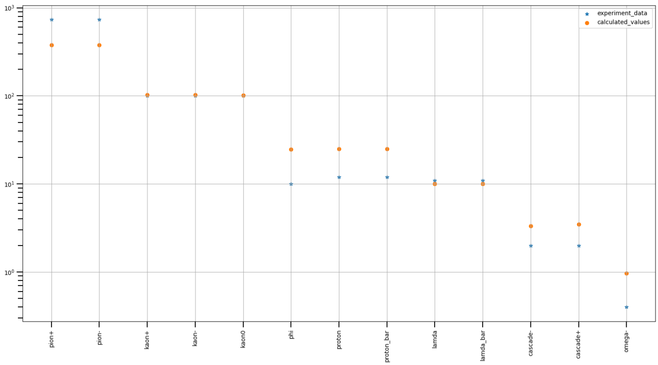
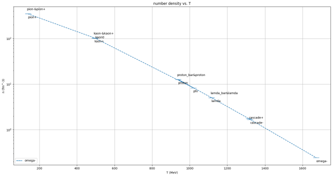


Figure: Scatter-plot comparing data points and predicted thermal yield points. The orange dots are thermal yield points and blue are experimental points. The data for the experimental dots are taken from https://doi.org/10.1038/s41586-018-0491-6

Particle-yield vs. particle-mass



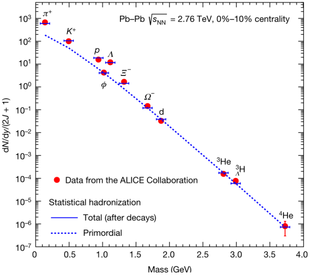
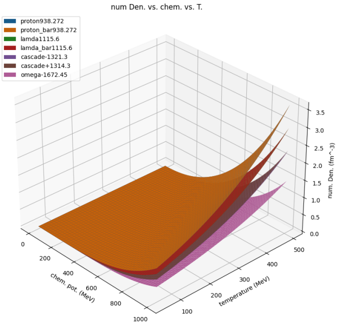


Figure: Image courtesy- https://doi.org/10.1038/s41586-018-0491-6

3D Plot Number Density vs. Temperature vs. Chemical Potential

$$n_i = \frac{g_i \cdot m_0^2 T \cdot e^{\frac{\mu_i}{T}}}{2\pi^2} \cdot K_2\left(\frac{m_0}{T}\right) \tag{6}$$



Decay Contributions

Let N_{tot}, N_T and N_d denote the total, thermal and decay yields respectively. Then:

$$N_{tot} = N_T + N_d \tag{7}$$

Let N_r denote the number of resonances of the r^{th} kind, and let n_r be the branching ratio of of resonance r decaying into particle h, then:

$$N_d = \sum_r N_r \cdot n_r \tag{8}$$

$$\implies N_{tot} = N_T + \sum_r N_r \cdot n_r \tag{9}$$

Consider the decay of Kaon, Λ and Ξ particles to pions. Their respective branching ratios are given in the following table:

Particle	Branching Ratio (%)
kaon	28.013
Λ	63.90
Ξ	99.89

Table: List of Particles that were taken as parent particles for pion and their corresponding branching ratios.

Particle	Before	After
Pion+	368.155	418.085
Pion-	368.155	418.085

Table: Comparision of particle yield number before and after adding the decay contributions

Summary

- Thermal Hadronization model of HRG was studied. From this, using bag-pressure (MIT Bag model), critical temperature is obtained around 144 MeV.
- Boltzmann Approximation is a good approximation for HRG at temperature 156.5 MeV.
- A simple model as this can be used to fit particle-yield data spanning 3 orders of magnitude. It is possible to fix the volume of fire-ball using particle number of one particle.
- Baryo-chemical potential can be varied along with temperature to obtain a particle-yield surface. These surfaces are suggestive on ratios of particles at different points in QCD phase diagram.
- Mainly, the particle-yield registered in ALICE detectors is not thermal yield alone, but also has decay yield.

Acknowledgment

I would like to thank my guide Prof. Victor Roy for this opportunity to work and learn under his guidance, for fruitful discussions and warm meetings. Also PhD scholars Ankit and Krishanu for their help.
I also thank Prof. Prushti for arranging this online presentation. Also NISER management for the in-campus stay facilities.