Towards solving the puzzle of high temperature light (anti)-nuclei production in ultra-relativistic heavy ion collisions

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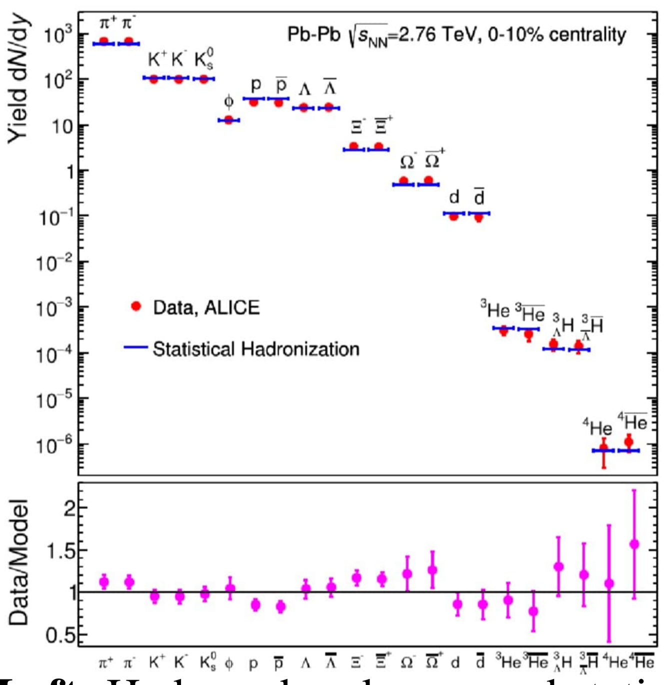
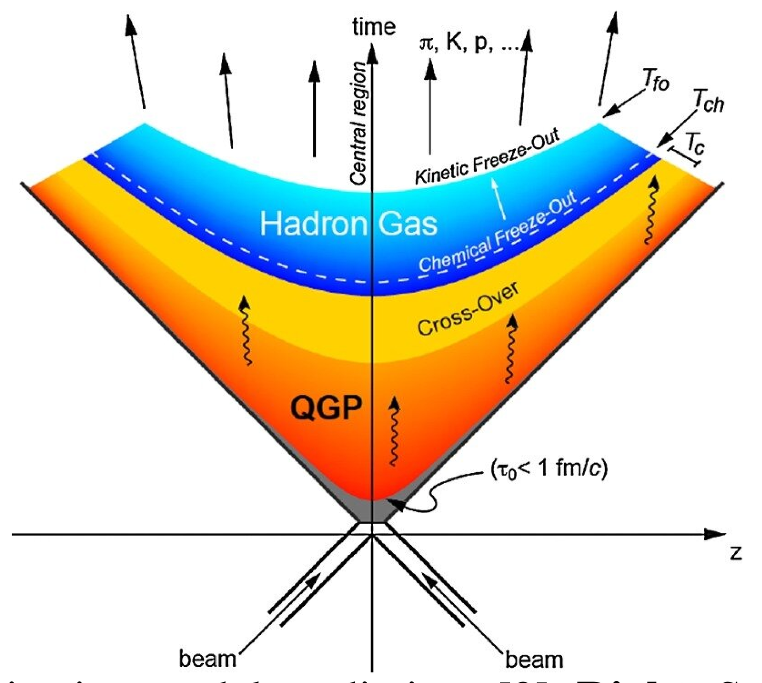
Introduction

- at LHC, the ALICE collaboration measured the yields of light nuclei [1]





Left: Hadron abundances and statistical hadronization model predictions [2]; **Right:** Space-time diagram of a HIC [3].

- why do these "snowballs in hell" exist?
- nucleosynthesis in heavy-ion collisions can be described by the Saha equation [4]
- we use the principle of detailed balance to construct rate equations for the light nuclei
- the important reactions are of the following type: $\frac{dN_A}{dt} = \frac{\left\langle \sigma_{A+X\to a\cdot N+X} v_{rel} \right\rangle}{V} N_X(-N_A + R\cdot N_N^a)$
- where $R = \frac{N_A^{equ} N_X^{equ}}{N_N^{equ}}$, A is a light nucleus and X is a caltalysing Pion or Kaon
- have to determine the averaged cross sections, the volume and the multiplicities in chemical equilibrium in dependence of T
- particles: nucleons, the light nuclei and their corresponding anti-particles, π, ρ, ω, K, K^*, Δ, Λ, Σ, Ξ and Ω

Thermal averaged cross sections

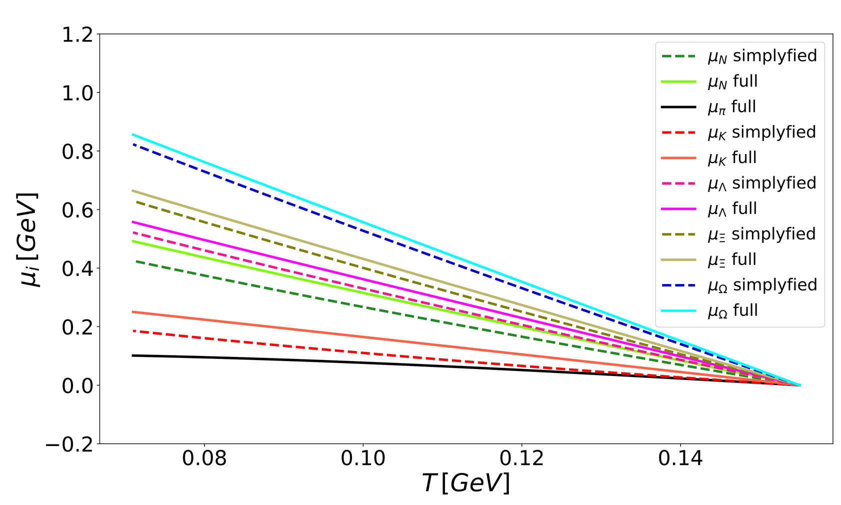
- average over Boltzmann distribution: $\left\langle \sigma_{A+X\to a\cdot N+X} v_{rel} \right\rangle = \frac{\int \frac{d\vec{p}_A^3}{(2\pi)^3} \int \frac{d\vec{p}_X^3}{(2\pi)^3} e^{-(E_A+E_X)/T} \sigma(p_{lab}) v_{rel}(\vec{p}_A,\vec{p}_X)}{\int \frac{d\vec{p}_A^3}{(2\pi)^3} \int \frac{d\vec{p}_X^3}{(2\pi)^3} e^{-(E_A+E_X)/T}}$
- the known cross sections are taken from the PDG [5]
- we are interested in the case were the nuclei are splited in their nucleonic constituents $\rightarrow$ inelastic cross sections

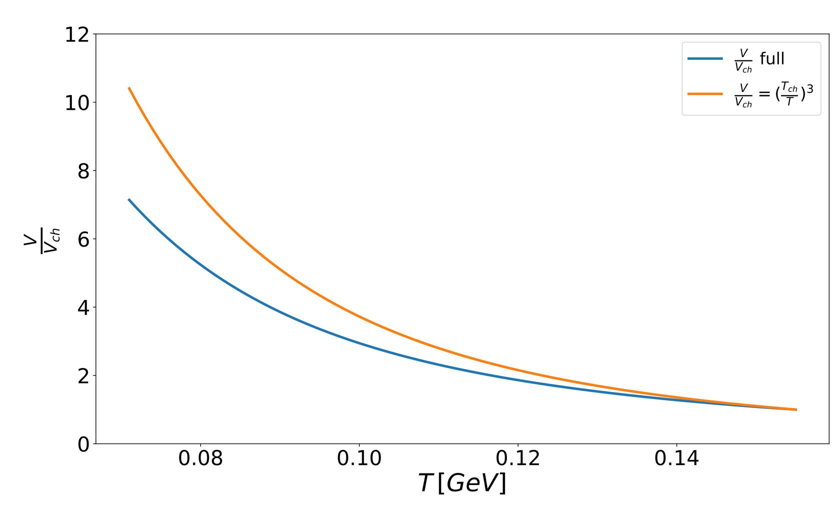
Thermal Model and Saha equation

- in the analytical approach: system is dominated by effectively massles pions and expand isentropicly : $V \propto T^{-3}$
- for all particles without the pions the non-relativistic approximation is used:
  $N_i(T) \approx g_i \left(\frac{m_i T}{2\pi}\right)^{\frac{3}{2}} e^{-m_i/T} e^{\mu_i/T} V$
- using $N_i(T_c) = N_i(T)$ and $\mu_i(T_c) = 0$ [4]: $\mu_i(T) = \frac{3}{2} T\, ln\left(\frac{T}{T_c}\right) + m_i(1 - \frac{T}{T_c})$
- calculate the normalised ratio $\frac{N_A(T)}{N_A(T_c)} = \left(\frac{T}{T_c}\right)^{\frac{3}{2}(a-1)} e^{B_A(\frac{1}{T} - \frac{1}{T_c})}$; $B_A = a\cdot m_N - m_A$
- this result is different to the standard thermal model result $\left.\frac{N_A(T)}{N_A(T_c)}\right|_{stand.} = \left(\frac{T}{T_c}\right)^{\frac{3}{2}} e^{-m_A(\frac{1}{T} - \frac{1}{T_c})}$
- major difference is in the exponential: $\mathscr{O}(2MeV) \approx B_A \ll m_A \approx \mathscr{O}(1000MeV)$
- to gain the full solution (HRG in PCE) we need to consider also the contributions of the other particles [4]

$$
\begin{aligned}
S_{\rm eff}(T_c) &= V \textstyle\sum_{j\in all particles} s_j(T, \tilde{\mu}_j, \mu_B, \mu_S) \\
N_{i\rm eff}(T_c) &= V \textstyle\sum_{j\in all particles} \left\langle n_i \right\rangle_j n_j(T, \tilde{\mu}_j, \mu_B, \mu_S) \\
B_{\rm eff}(T_c) &= V \textstyle\sum_{j\in all particles} B_j n_j(T, \tilde{\mu}_j, \mu_B, \mu_S) \\
0 &= V \textstyle\sum_{j\in all particles} S_j n_j(T, \tilde{\mu}_j, \mu_B, \mu_S)
\end{aligned}
$$

- $\left\langle n_i \right\rangle_j$ is the averaged number of stable hadrons i which came from the decay(-chain) of hadron j
- the chemical potentials are given as $\tilde{\mu}_j = \sum_{i\in stable} \left\langle n_i \right\rangle_j \mu_i$; $j \in all particles$
- by solving the set of non-linear equations we will get $V(T)$, $\mu_i(T)$, $\mu_B(T)$ and $\mu_S(T)$

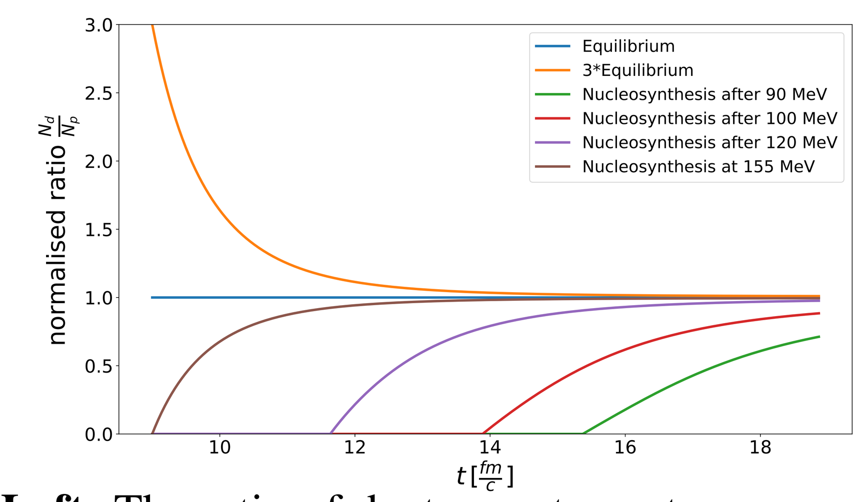


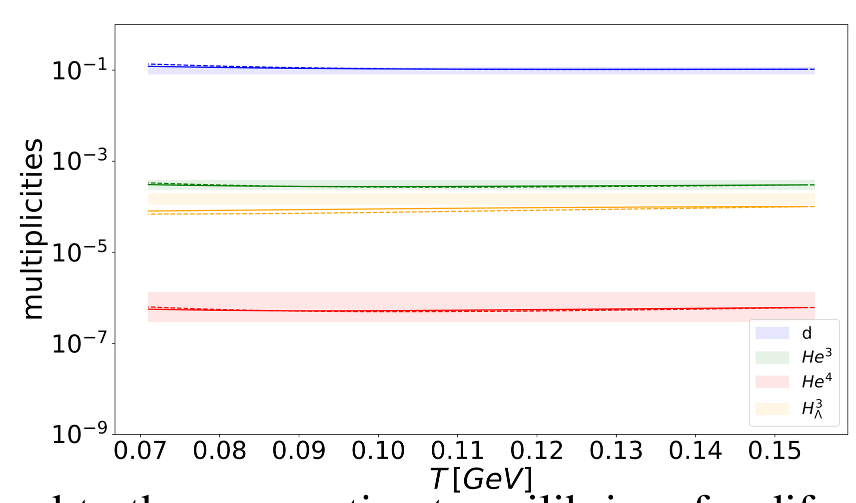


Left: The μ_i's of the as stable considered hadrons in dependence of T; **Right:** The volume ratio in dependence of T.

Solving the rate equations

- for all light nuclei up to He^4 rate equations has been implemented, but also the decays of ρ, ω, K^* and Δ has been considered
- we have just related the volume and temperature, but the system contains ODE's in time
- here we consider a parametrisation $V(t)$ [6]: $\frac{V(t)}{V_{ch}} = \frac{t}{t_{ch}} \frac{t_\perp^2 + t^2}{t_\perp^2 + t_{ch}^2}$; $t_\perp = 6.5\frac{fm}{c}$; $t_{ch} = 9\frac{fm}{c}$

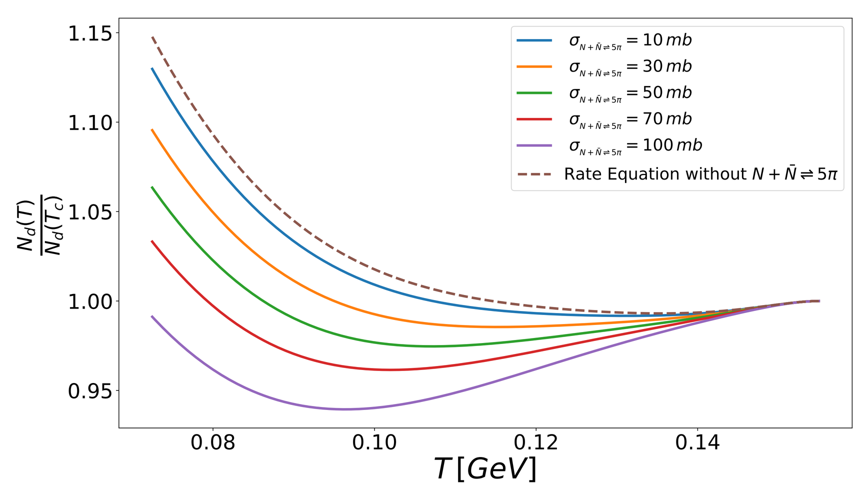




Left: The ratio of deuterons to protons normalized to the same ratio at equilibrium for different initial conditions with $g_\Delta^{\rm eff} = 2g_\Delta$.; **Right:** solid lines represent the results of the rate equations, while dashed curves show the result of the HRG in PCE. The colored bands represent the experimental data (ALICE).

Effect of the $N + \overline{N} \rightleftharpoons 5\pi$ reaction

- a big advantage of the rate equation approach is the possibility of the annihilation of stable hadrons e.g. nucleons
- the averaged cross section is about $50mb$ for $p + \overline{p}$ scattering
- this type of reaction exlicitly violates the conservation of stable hadrons, but the net baryon number is still conserved



- Normalised particle number of deuterons to the value at $T_c = 155MeV$ and $g_\Delta^{\rm eff} = 2g_\Delta$

Conclusions and outlook

- both approaches are in great agreement with each other and also in the error range of the experimental data
- under-occupation in the nucleons leads to a suppression of the light nuclei
- calculations also support earlier assumptions, that the nuclei do not need to be formed at the chemical freeze-out
- the same procedure could be done for RHIC or SPS energies
- this approach neglects the formation time of the nuclei
- a quantum mechanical description of creation and decay of bound states (the nuclei) in an open thermal system (fireball) is needed
- for look up: Physics Letters B 827 (2022) 136891

References

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