Nuclear clusters in an off-equilibrium thermal model

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Mini-workshop “Origin of nuclear clusters in hadronic collisions”
May 19, 2020

• Nucleosynthesis in heavy-ion collisions via the Saha equation

• Off-equilibrium light nuclei production with rate equations
  V.V., D. Oliinychenko, V. Koch, to appear
Loosely-bound objects in heavy-ion collisions

[STAR collaboration, Nature 473, 353 (2011)]

[ALICE Collaboration, PLB 754, 360 (2016)]

binding energies: $^2\text{H}$, $^3\text{He}$, $^4\text{He}$, $^3\Lambda$H: 2.22, 7.72, 28.3, 0.130 MeV $\ll T \sim 150$ MeV

“snowballs in hell”

The production mechanism is not established. Common approaches include thermal nuclei emission together with hadrons [Andronic et al., PLB ’11;…] or final-state coalescence of nucleons close in phase-space [Butler, Pearson, PRL ’61; Scheibl, Heinz, PRC ’99;…]
Two experimental observations at the LHC

1. Measured yields are described by thermal model at $T_{ch} \approx 155$ MeV

2. Spectra described by blast-wave model at $T_{kin} \approx 100 – 120$ MeV

What happens between $T_{ch}$ and $T_{kin}$?
Hadronic phase in central HICs

- At $T_{ch} \approx 150 - 160$ MeV inelastic collisions cease, yields of hadrons frozen
- Kinetic equilibrium maintained down to $T_{kin} \approx 100 - 120$ MeV through (pseudo)elastic scatterings
• Hadrons (nucleons) form and “freeze-out” chemically before nuclei
• Bosons (photons or pions) catalyse nucleosynthesis
  
  e.g. $p + n \leftrightarrow d + \gamma$ vs $p + n + \pi \leftrightarrow d + \pi$
Saha equation (1920)

- Ionization of a gas (one level)

\[
\frac{n_e^2}{n_0} = \frac{2}{\lambda_e^3} \frac{g_1}{g_0} \exp(-\frac{\epsilon}{T})
\]

\[n_1 = n_e \quad \lambda_e : \text{deBroglie}\]

Megh Nad Saha, Phil. Mag. Series 6 40:238 (1920) 472

- Equivalently, chemical potentials:

\[\mu_0 = \mu_1 + \mu_e\]
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Nuclear equivalent: detailed balance in an expanding system (early universe/HIC)

Deuteron number evolution through \( pnX \leftrightarrow dX \), in kinetic equilibrium

\[
\frac{dN_d}{d\tau} = \langle \sigma_{dX} v_{\text{rel}} \rangle N_d^0 n_x^0 e^{\mu_p/T} e^{\mu_n/T} e^{\mu_X/T} - \langle \sigma_{dX} v_{\text{rel}} \rangle N_d^0 n_x^0 e^{\mu_d/T} e^{\mu_X/T}
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small \quad gain \quad big \quad loss

big
Saha equation (1920)

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\]

Small \[ \text{big} \]

gain \[ \text{loss} \]

\[ \text{gain} \approx \text{loss} \quad \rightarrow \quad \mu_d \approx \mu_p + \mu_n \]

Saha equation \[ = \text{detailed balance} \]

\[ = \text{law of mass action} \]
LHC nucleosynthesis: BBN-like setup

- Chemical equilibrium lost at $T_{ch} = 155$ MeV, abundances of nucleons are frozen and acquire effective fugacity factors: $n_i = n_i^{eq} e^{\mu_N/T}$
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- Isentropic expansion driven by effectively massless mesonic d.o.f.

\[
\frac{V}{V_{ch}} = \left(\frac{T_{ch}}{T}\right)^3, \quad \mu_N \approx \frac{3}{2} T \ln \left(\frac{T}{T_{ch}}\right) + m_N \left(1 - \frac{T}{T_{ch}}\right)
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- Detailed balance for nuclear reactions, $X + A \leftrightarrow X + \sum_i A_i$, $X$ is e.g. a pion

\[ \frac{n_A}{\Pi_i n_{A_i}} = \frac{n_{A_i}^{eq}}{\Pi_i n_{A_i}^{eq}}, \quad \Leftrightarrow \quad \mu_A = \sum_i \mu_{A_i}, \quad \text{e.g. } \mu_d = \mu_p + \mu_n, \mu_{^3\text{He}} = 2\mu_p + \mu_n, \ldots \]

_Saha equation_
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$$\frac{n_A}{\prod_i n_{A_i}} = \frac{n_{A}^{eq}}{\prod_i n_{A_i}^{eq}}, \quad \Leftrightarrow \quad \mu_A = \sum_i \mu_{A_i}, \quad \text{e.g. } \mu_d = \mu_p + \mu_n, \mu_{^3\text{He}} = 2\mu_p + \mu_n, \ldots$$

$$X_A = d_A \left[ (d_M)^{A-1} \zeta(3)^{A-1} \pi^{1-A} \frac{1-A}{2} 2^{-3+A} \right] A^{5/2} \left( \frac{T}{m_N} \right)^{\frac{3}{2}(A-1)} \eta_B^{A-1} \exp \left( \frac{B_A}{T} \right)$$

$d_M \sim 11 - 13, \quad \eta_B \simeq 0.03$ fixed at $T_{ch}$
LHC nucleosynthesis: BBN-like setup

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  \]

- Detailed balance for nuclear reactions, $X + A \leftrightarrow X + \sum_i A_i$, $X$ is e.g. a pion
  \[
  \frac{n_A}{\Pi_i n_{A_i}} = \frac{n_A^{eq}}{\Pi_i n_{A_i}^{eq}}, \quad \Leftrightarrow \quad \mu_A = \sum_i \mu_{A_i}, \quad \text{e.g. } \mu_d = \mu_p + \mu_n, \ \mu_{^3\text{He}} = 2\mu_p + \mu_n, \ ... \quad \text{Saha equation}
  \]

\[
X_A = d_A \left[ (d_M)^{A-1} \zeta(3)^{A-1} \frac{1-A}{2} 2^{-\frac{3+A}{2}} \right] A^{5/2} \left( \frac{T}{m_N} \right)^{\frac{3}{2}(A-1)} \eta_B^{A-1} \exp \left( \frac{B_A}{T} \right)
\]

\[d_M \sim 11 - 13, \quad \eta_B \simeq 0.03 \quad \text{fixed at } T_{ch}\]

BBN: \[
X_A = d_A \left[ \zeta(3)^{A-1} \frac{1-A}{2} 2^{\frac{3A-5}{2}} \right] A^{5/2} \left( \frac{T}{m_N} \right)^{\frac{3}{2}(A-1)} \eta_b^{A-1} X_p^Z X_n^{A-Z} \exp \left( \frac{B_A}{T} \right)
\]

(BBN-like) Saha equation vs thermal model

**Saha equation:**

\[
\frac{N_A(T)}{N_A(T_{ch})} \sim \left( \frac{T}{T_{ch}} \right)^{\frac{3}{2}(A-1)} \exp \left[ B_A \left( \frac{1}{T} - \frac{1}{T_{ch}} \right) \right]
\]

**Thermal model:**

\[
\left[ \frac{N_A(T)}{N_A(T_{ch})} \right]_{eq.} \sim \left( \frac{T}{T_{ch}} \right)^{-\frac{3}{2}} \exp \left[ -m_A \left( \frac{1}{T} - \frac{1}{T_{ch}} \right) \right]
\]

**Strong exponential dependence on the temperature is eliminated in the Saha equation approach**

Further, quantitative applications require numerical treatment of full spectrum of *massive* mesonic and baryonic resonances
Partial chemical equilibrium (PCE)

Expansion of hadron resonance gas in partial chemical equilibrium at \( T < T_{ch} \)


Chemical composition of stable hadrons is fixed, kinetic equilibrium maintained through pseudo-elastic resonance reactions \( \pi \pi \leftrightarrow \rho, \pi K \leftrightarrow K^*, \pi N \leftrightarrow \Delta, \) etc.

E.g.: \( \pi + 2\rho + 3\omega + \cdots = \text{const}, \quad K + K^* + \cdots = \text{const}, \quad N + \Delta + N^* + \cdots = \text{const}, \)

Effective chemical potentials:

\[
\tilde{\mu}_j = \sum_{i \in \text{stable}} \langle n_i \rangle_j \mu_i, \quad \langle n_i \rangle_j - \text{mean number of hadron } i \text{ from decays of hadron } j, \quad j \in \text{HRG}
\]

Conservation laws:

\[
\sum_{j \in \text{hrg}} \langle n_i \rangle_j n_j(T, \tilde{\mu}_j) V = N_i(T_{ch}), \quad i \in \text{stable}
\]

\[
\sum_{j \in \text{hrg}} s_j(T, \tilde{\mu}_j) V = S(T_{ch})
\]

Numerical solution

\[\{\mu_i(T)\}, \ V(T)\]

Numerical implementation within (extended) **Thermal-FIST** package


open source: [https://github.com/vlvovch/Thermal-FIST](https://github.com/vlvovch/Thermal-FIST)
"Initial conditions": $T_{ch} = 155$ MeV, $V_{ch} = 4700$ fm$^3$ (chemical freeze-out)

values from V.V., Gorenstein, Stoecker, 1807.02079
Deviations from thermal model predictions are moderate despite significant cooling and dilution. Is this the reason for why thermal model works so well?

Echoes earlier transport model conclusions for d [D. Oliinychenko, et al., PRC 99, 044907 (2019)]

For $T = T_{\text{kin}}$ similar results reported in [X. Xu, R. Rapp, EPJA 55, 68 (2019)]
Hypernuclei stay close to the thermal model prediction. An exception is a hypothetical $\Xi\Xi$ state ← planned measurement in Runs 3 & 4 at the LHC

[LHC Yellow Report, 1812.06772]
Light nuclei production with rate equations

with D. Oliinychenko and V. Koch, to appear
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\[
\frac{dN_d}{d\tau} = \left( \sigma_d \chi \nu_{rel} \right) N_d^0 n_x^0 e^{\mu_p/T} e^{\mu_n/T} e^{\mu_x/T} - \left( \sigma_d \chi \nu_{rel} \right) N_d^0 n_x^0 e^{\mu_d/T} e^{\mu_x/T} \\
\text{small} \quad \text{gain} \quad \text{big} \quad \text{loss} \\
\text{big}
\]

gain ≈ loss \quad → \quad \mu_d \approx \mu_p + \mu_n

\text{Saha equation} = \text{detailed balance} = \text{law of mass action}
Light nuclei production with rate equations

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\[
\frac{dN_d}{d\tau} = \langle \sigma_{dX} v_{\text{rel}} \rangle N_d^0 n_x^0 \frac{e^{\mu_p/T}}{T} \frac{e^{\mu_n/T}}{T} - \langle \sigma_{dX} v_{\text{rel}} \rangle N_d^0 n_x^0 \frac{e^{\mu_d/T}}{T} \frac{e^{\mu_X/T}}{T}
\]

\[\text{gain} \quad \text{loss}\]

\[\text{big}\]

Relax the assumption of equilibrium for \( AX \leftrightarrow \sum_i A_iX \) reactions
Light nuclei production with rate equations

• Pion catalysis of light nuclei reactions. Destruction through $A\pi \rightarrow \sum_i A_i\pi$ and creation through $\sum_i A_i\pi \rightarrow A\pi$. Detailed balance principle respected but relative chemical equilibrium not enforced

• Bulk hadron matter evolves in partial chemical equilibrium, unaffected by light nuclei

$$\frac{dN_A}{d\tau} = \langle \sigma_{A\pi}^{\text{in}} \nu_{\text{rel}} \rangle n_{\pi}^{\text{pce}} \left( N_A^{\text{saha}} - N_A \right)$$

Static fireball: $n_{\pi}^{\text{pce}}, N_A^{\text{saha}}, \langle \sigma_{A\pi}^{\text{in}} \nu_{\text{rel}} \rangle = \text{const}$

$$N_A(\tau) = N_A^{\text{saha}} + (N_A(\tau_0) - N_A^{\text{saha}}) e^{-\frac{\tau - \tau_0}{\tau_{eq}}}, \quad \tau_{eq} = \frac{1}{\langle \sigma_{A\pi}^{\text{in}} \nu_{\text{rel}} \rangle n_{\pi}^{\text{pce}}}$$

Saha limit: $\tau_{eq} \rightarrow 0 \left( \sigma_{A\pi}^{\text{in}} \rightarrow \infty \right)$
Model input

- **Cross sections**

  **Optical model** for $\sigma_{A\pi}^{in}$ [J. Eisenberg, D.S. Koltun, ’80]

  Being implemented in SMASH [Dima’s talk]

  In practice  $\langle \sigma_{A\pi}^{in} v_{rel} \rangle \gtrsim 30 \cdot A$ [mb]

- **Expansion** (both transverse and longitudinal)

  $$\frac{V}{V_{ch}} = \frac{\tau}{\tau_{ch}} \frac{\tau^2_{\perp} + \tau^2_{\parallel}}{\tau^2_{\perp} + \tau^2_{ch}}, \quad \tau_{ch} = 9 \text{ fm}, \quad \tau_{\perp} = 6.5 \text{ fm}
  $$

  [Y. Pan, S. Pratt, PRC 89, 044911 (2014)]
Rate equations at LHC

![Graph showing rate equations for Pb-Pb collisions at 2.76 TeV, 0-10% centrality. The graph indicates normalized ratios for d/p, ³He/p, and ⁴He/p as functions of temperature (T) and time (τ). The graph compares thermal model predictions with Saha equation predictions and ALICE experimental data.](image)
Rate equations at LHC

Grey band: x2 variation in $c_A^{in}$
Degree of equilibration

\[ \tau_{\text{eq}}^{-1} = \langle \sigma_{A\pi}^\text{in} \nu_{\text{rel}} \rangle n_{\pi}^\text{pce} \]

- Local equilibration times remain small (but also \( \tau_A^{\text{eq}} \ll B_A^{-1} \))
- \((\text{gain} + \text{loss}) \gg |\text{gain} - \text{loss}| \) \rightarrow \text{Saha equation at work}
Can snowballs survive hell?

Count only the nuclei produced at “QGP hadronization” (at $T_{ch}$)

$$\frac{dN_A^{qgp}}{dT} = -\langle \sigma_{A\pi}^p v_{rel} \rangle n_{\pi}^{pce} N_A^{qgp},$$

survival probability $= \frac{N_A^{qgp}(\tau)}{N_A^{qgp}(T_{ch})}$

![Graph showing survival probability as a function of $\tau$ and temperature.](Image)
Can snowballs survive hell?

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$$\frac{dN_A^{qgp}}{dT} = -\langle \sigma_{A\pi} V_{rel} \rangle n^{pce}_\pi N_A^{qgp}, \quad \text{survival probability} = \frac{N_A^{qgp}(\tau)}{N_A^{qgp}(T_{ch})}$$

- Survival down to 100 MeV is unlikely
- Peripheral collisions might offer better chances

Dashed lines: $T_{kin}$ values from A. Motornenko et al., 1908.11730
Rate equations at LHC

Grey band: x2 variation in $\sigma_A\pi$
Rate equations at LHC

Pb-Pb, 2.76 TeV, 0-10%

\( \frac{d}{p} \)

3He/p

4He/p

Grey band: x2 variation in \( c_{\text{in}} \)

\( N_A^0 = N_A^{\text{thermal}} \)

\( N_A^0 = 0 \)

\( N_A^0 = 3 \times N_A^{\text{thermal}} \)

thermal model
Saha equation
ALICE

T [MeV]

\( \tau \) [fm/c]
Rate equations at LHC

Grey band: x2 variation in $\sigma_A^\text{in}$

Start "cooking" after kinetic freeze-out

Rate equations
- $N_A^0 = N_A^\text{thermal}$
- $N_A^0 = 0$
- $N_A^0 = 3 \times N_A^\text{thermal}$
- $N_A^0 = 0$ at 100 MeV

Pb-Pb, 2.76 TeV, 0-10%
Summary and outlook

• Nucleosynthesis in HICs at LHC via the Saha equation is in analogy to initial stages of big bang nucleosynthesis in the early universe. Results agree with the thermal model, but any $T < T_{ch}$ permitted!

• Description of pion-catalyzed nuclear cluster production using rate equations agrees with the Saha equation, for all nuclei up to $^4$He.

• “Snowballs” produced at hadronization do not survive “hell” down to $T_{\text{kin}} = 100$ MeV.

• Outlook: Rate equations for resonances and $B\bar{B}$ annihilations.

• Open questions: $\tau_A^{eq} \ll B_A^{-1}$, i.e. deuteron in the hadronic phase cannot yet know that it is deuteron. Quantum mechanical treatment of bound systems in medium needed.
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Thanks for your attention!
Backup slides
Saha equation:

\[
\frac{N_A(T)}{N_A(T_{ch})} \simeq \left( \frac{T}{T_{ch}} \right)^{\frac{3}{2}(A-1)} \exp \left[ B_A \left( \frac{1}{T} - \frac{1}{T_{ch}} \right) \right]
\]

Thermal model:

\[
\left[ \frac{N_A(T)}{N_A(T_{ch})} \right]_{eq.} \simeq \left( \frac{T}{T_{ch}} \right)^{-\frac{3}{2}} \exp \left[ -m_A \left( \frac{1}{T} - \frac{1}{T_{ch}} \right) \right]
\]

Strong exponential dependence on the temperature is eliminated in the Saha equation approach

Further, quantitative applications require numerical treatment of full spectrum of \textit{massive} mesonic and baryonic resonances
Full calculation: deuteron yield

Resonance feed-down is important in precision studies
Saha equation and excluded volume effects

**Eigenvolumes:** effective mechanism for nuclei suppression at large densities

Excluded-volume effects go away as the system dilutes. At $T \approx 100$ MeV agrees with the point-particle model. Does not describe data for $T = T_{ch}$
Rate equation for nuclei and resonances

Treat both nuclear reactions and resonances decays using rate equations, i.e. PCE not enforced

Rate equations for all particles

\[
\frac{dN_A}{dT} = \langle \sigma_{A\pi} \nu_{rel} \rangle N_\pi \ n_A^{eq} (e^{A\mu_N/T} - e^{\mu_A/T})
\]

\[
\frac{dN_R}{dT} = \langle \Gamma_{R\rightarrow\sum_i a_i} \rangle N_R^{eq} (e^{\sum_{i\in R} \mu_i/T} - e^{\mu_R/T})
\]

Entropy production: 0.6% at \( T_{kin} = 100 \) MeV

Results are very close to Saha equation
Big Bang nucleosynthesis

- Nuclei start to form after proton-neutron ratio freeze-out ($T < 1$ MeV)
- Early stage of Big Bang nucleosynthesis described by Nuclear Statistical Equilibrium, $\mu_A = A\mu_N$ (Saha equation)

$$X_A = d_A \left[ \zeta(3)^{A-1} \frac{1}{\pi} \frac{1}{2^A} 2^{3A-5} \right] A^{\frac{5}{2}} \left( \frac{T}{m_N} \right)^{\frac{3}{2}(A-1)} \eta^{A-1} X_p^2 X_n^{A-Z} \exp \left( \frac{B_A}{T} \right)$$

$\eta \sim 10^{-10}$ – baryon-to-photon ratio

Big Bang vs LHC nucleosynthesis

**Similarities:**

- Inelastic nucleonic reactions freeze-out before nuclei formation
- Isentropic expansion of boson-dominated matter (photons in BBN vs mesons in HIC), baryon-to-boson ratio: $\eta_{BBN} \sim 10^{-10}$, $\eta_{LHC} \sim 0.05$
- Strong nuclear formation and regeneration reactions → Saha equation

**Differences:**

- Time scales: $1-100$ s in BBN vs $\sim 10^{-22}$ s in HIC
- Temperatures: $T_{BBN} < 1$ MeV vs $T_{HIC} \sim 100$ MeV
- Binding energies, proton-neutron mass difference, and neutron lifetime important in BBN, less so in HICs
- $\mu_B \approx 0$ at the LHC, $\mu_B \neq 0$ in BBN
- Resonance feeddown important at LHC, irrelevant in BBN
Microscopic study of deuteron production in PbPb collisions at $\sqrt{s} = 2.76$ TeV via hydrodynamics and a hadronic afterburner

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Law of mass action at work

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FIG. 1. Deuteron-pion interaction cross sections from SAID database [40] and partial wave analysis [41] are compared to our parametrizations (Tables II and III in the Appendix). Inelastic $d\pi$ ↔
$O_{t,p,d}$

$O_{t,p,d} = N_t N_p/(N_d)^2$ suggested as a possible probe of critical behavior

[Ref. K.J. Sun et al., PLB '17, PLB '18]

Possible to obtain a non-monotonic behavior of $O_{t,p,d}$ in ideal gas picture

Relevance of excited $^4$He states also pointed out in baryon preclustering study [Torres-Rincon, Shuryak, 1910.08119]
Saha equation: Entropy production effect
Resonance suppression in hadronic phase

Yields of resonances are not conserved in partial chemical equilibrium. For example, $K^*$ yield dilutes during the cooling through reactions $\pi K \leftrightarrow K^*$.

Fitting the yields of short-lived resonances is a new way to extract the kinetic freeze-out temperature.
Kinetic freeze-out temperature from resonances

Fit of $K^0$ and $\rho^0$ abundances extracts the kinetic freeze-out temperature

Solves the $T_{\text{kin}}$-vs-$\langle \beta_T \rangle$ anticorrelation problem of blast-wave fits