Calibrating the Medium Effects of Light Clusters in Heavy-Ion Collisions

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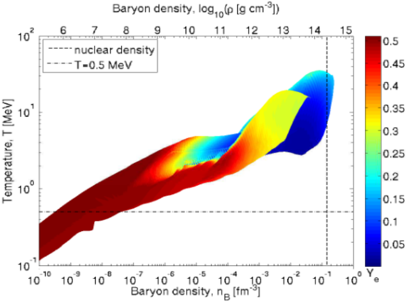
Motivation

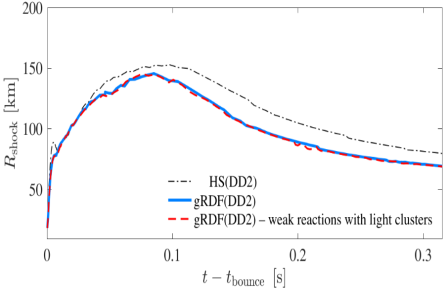
• Light nuclei might be present in both Core-Collapse Supernova and Binary Neutron Star Mergers

• Their presence influences the dynamics of these astrophysical events

• Accounting for in-medium modifications to the light clusters is essential to determine their correct abundances



Fischer et al. EPJA, **50**, 46 (2014)



Fischer et al. PRC, **102**, 055807 (2020)

Relativistic Nuclear Field Theory

• In Relativistic Mean-Field Theory, the interactions are mediated via the exchange of virtual mesons:

$$\sigma, \omega, \rho \tag{1}$$

• The Lagrangian density for matter made of protons, neutrons and light clusters is:

$$\mathcal{L} = \sum_{b=n,p} \mathcal{L}_b + \sum_{m=\sigma,\omega,\rho} \mathcal{L}_m + \sum_{\substack{i={}^2\mathrm{H},{}^3\mathrm{H},\\ {}^3\mathrm{He},{}^4\mathrm{He}}} \mathcal{L}_i \tag{2}$$

[Typel et al, PRC **81**, 015803 (2010), Pais et al., PRC **97**, 045805 (2018)]

Relativistic Nuclear Field Theory

- The Lagrangian density for the **nucleons** is:

$$\mathcal{L}_b = \bar{\Psi}_b(x) \left[i\gamma_\mu D_b^\mu - m_b^* \right] \Psi_b(x) \ , \quad (3)$$

$$iD_b^\mu = i\partial^\mu - g_{\omega b}\omega^\mu - g_{\rho b}\vec{I}_b \cdot \vec{\rho^\mu} \quad (4)$$

$$m_b^* = m_b - g_{\sigma b}\sigma \quad (5)$$

- Couplings $g_{\sigma b}, g_{\omega b}, g_{\rho b}$ are **free** parameters of the model and must be calibrated to experimental **nuclear properties** :

→ FSU [Todd-Rutel and Piekarewicz, PRL, **95**, 122501 (2005)]

→ DD2 [Typel et al. PRC, **81**, 015803 (2010)]

Relativistic Nuclear Field Theory

• **Light nuclei** ($i =$ ^{2}H, ^{3}H, ^{3}He, ^{4}He) can be included as point-like independent **quasi-particles**, in the same way as nucleons, taking into account their corresponding spins

• As new degrees of freedom, the cluster-meson couplings are free parameters of the model:

$$g_{\sigma i} = x_s A_i g_{\sigma N} \tag{6}$$

$$g_{\omega i} = x_\omega A_i g_{\omega N} \tag{7}$$

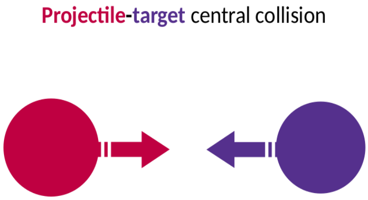
$$g_{\rho i} = g_{\rho N} \tag{8}$$

• x_s and x_ω are a way of accounting for in-medium modification of the clusters self-energies

INDRA Intermediate Energy Heavy-Ion Collisions

$^{136,124}Xe + ^{124,112}Sn$ (32MeV/nucleon)

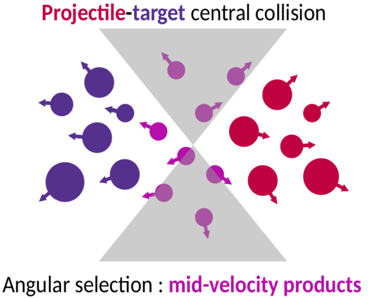
Bougault et al. PRC **97** (2018), Bougault et al. JPG **47** (2020)



Data Selection

→ **Centrality** (most violent events, low impact parameter)

→ **Angular selection** to reduce secondary decays from other sources



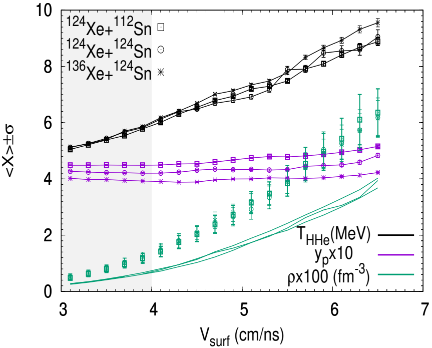
Credits: Alex Rebillard-Soulié

Constructing Statistical ensembles

→ Data sorted in **bins** of the average **Coulomb-corrected particle velocities** $v_{\mathbf{surf}}$ (correlated to the dynamics of the expansion, and therefore to the effective temperature of the source [Qin et al. PRL **108** (2012)])

Ideal Gas treatment of chemical equilibrium

- T and ρ were estimated considering an ideal gas of nucleons and light nuclei in the grand-canonical ensemble [Mekjian PRL **38**, 640 (1977), Das Gupta Physics Reports, **72**(3) (1981)]
- Consistent with the picture of an expanding cooling gas



Bougault et al. JPG, **47**, 025103 (2020), Pais et al. PRL, **125**, 012701 (2020)

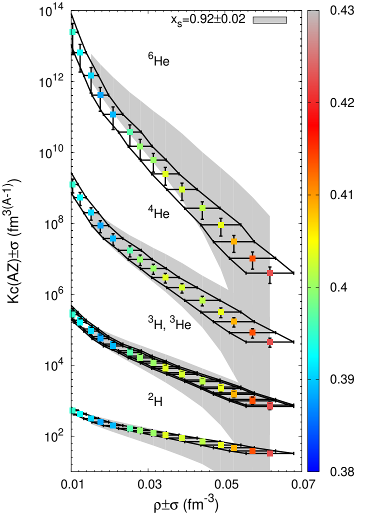
Ideal Gas treatment of chemical equilibrium

- With these estimated values for particle densities, chemical equilibrium constants (K_c) were calculated:

$$K_{c,i} = \frac{\rho_i}{\rho_n^{N_i} \rho_p^{Z_i}}$$

- An excellent agreement was obtained with $K_{c,i}$ calculated with FSU

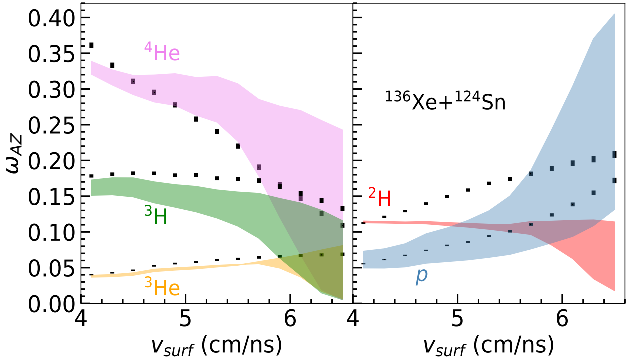
- x_s was constrained to 0.92 ± 0.02 for FSU



Pais et al. PRL, **125**, 012701 (2020)

Ideal Gas treatment of chemical equilibrium

• However, experimental mass fractions are poorly described by RMF considering (T, ρ) extracted with the ideal gas scenario



Custodio et al. PRL, **134**, 082304 (2025)

Calibrating T,ρ,x_s with mass fractions from HIC

- If in-medium effects are important, considering an ideal gas should be a bad approximation

- We propose a reanalysis of (T, ρ, x_s) avoiding the ideal gas assumption, with statistical ensembles being described by RMF theory

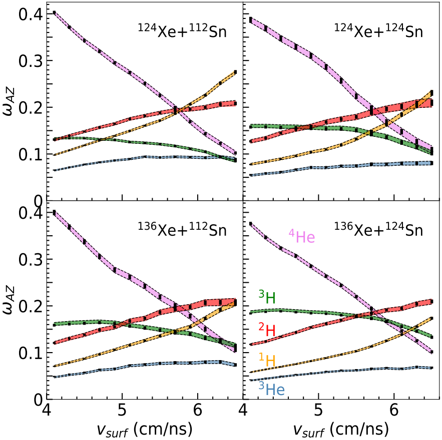
- For each system and v_{surf} bin, we carry out an independent Bayesian inference on the measured mass fractions

$$p_i\left(\theta|\{\omega_{AZ}\}\right) = \frac{p_\theta}{\mathcal{Z}}\mathcal{L}_{\text{g}}\left(\{\omega_{AZ}\}_i|\theta\right), \quad \theta = \{T, \rho, x_s\} \tag{9}$$

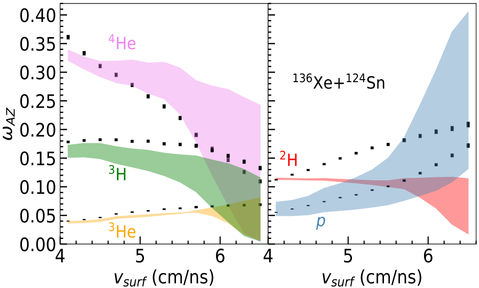
$$\omega_{AZ} = \frac{A\,Y_{AZ}}{\sum_{AZ} A\,Y_{AZ}}\;, \; j = n, {}^1\text{H}, {}^2\text{H}, {}^3\text{H}, {}^3\text{He}, {}^4\text{He} \tag{10}$$

Mass Fractions

Present Study (FSU & DD2)



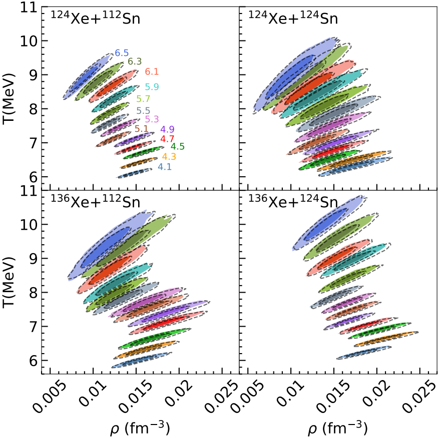
Modified Ideal Gas (FSU)

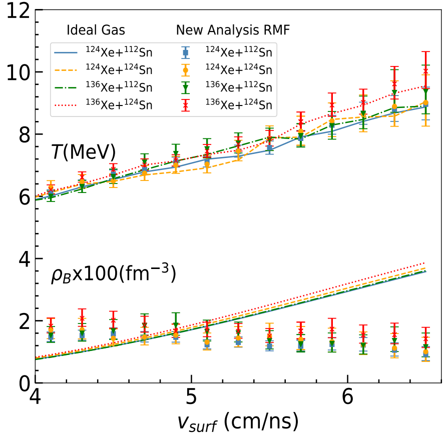


Custodio et al. PRL, **134**, 082304 (2025)

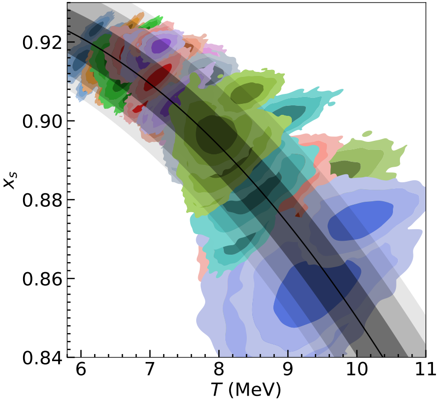
Calibrated Temperatures and Densities

- Temperature evolution similar to the ideal gas estimation
- Results compatible with a single density ∼0.015 fm^{-3}: chemical freeze-out density at the surface of the emitting source





Calibrated $x_s(T)$

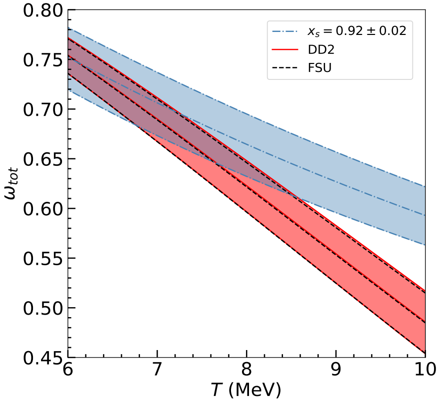


- x_s is temperature dependent
- Interaction weakens with T
- $x_s(T)$ compatible for all four entrance channels
- Limited ρ range cannot provide information on possible x_s dependence on ρ

Parameter	Unit	Median	1σ	2σ
a	MeV^{-2}	-0.00203	± 0.00003	± 0.00006
b	MeV^{-1}	0.01477	± 0.00047	± 0.00093
c		0.90560	± 0.0018	± 0.00355

Table: Parameter estimates a, b, c with 1, 2σ uncertainties for the quadratic fit $x_s = aT^2 + bT + c$

Consequences of $x_s(T)$ for light cluster abundances

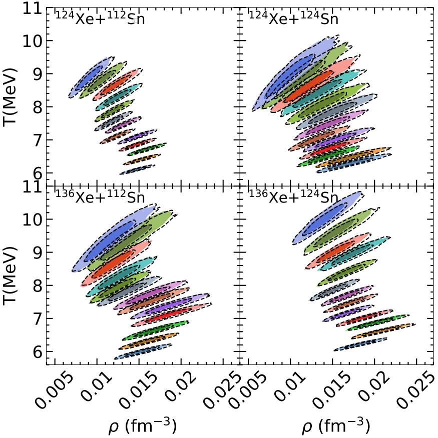


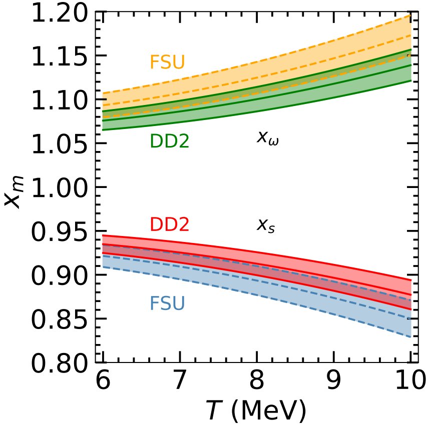
- Above $T \sim 8$ MeV abundances are systematically lower than the predictions of modified ideal gas
- Smaller x_s corresponds to weaker cluster-σ coupling, resulting in less bound clusters and, consequently, smaller abundances

Degeneracy between x_s and x_ω

$$g_{\sigma i} = x_s A_i g_{\sigma N} \quad , \quad g_{\omega i} = x_\omega A_i g_{\omega N}$$

$$(T,\, \rho,\, x_\omega)$$





Custodio et al. PRC **113**, 064619, (2026)

Degeneracy between x_s and x_ω

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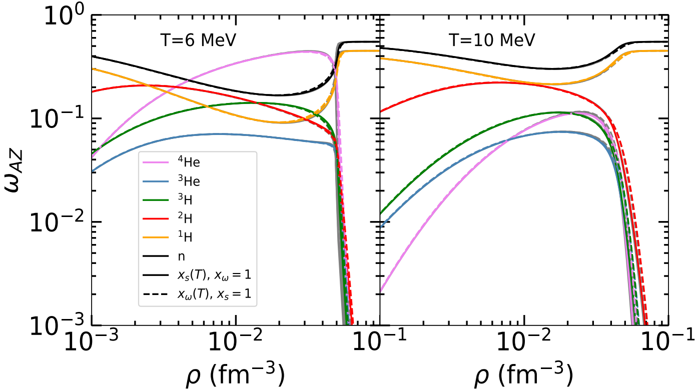

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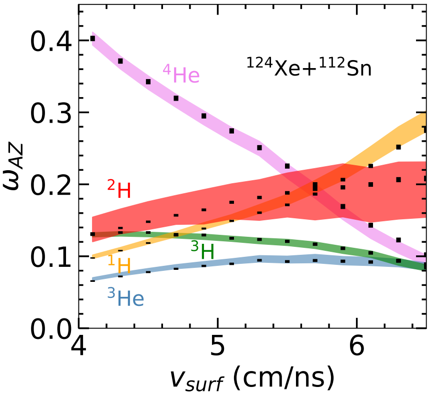
Possible ^{2}H out-of-equilibrium effects

$$\omega_i^{\text{red}} = \frac{A_i\,Y_i}{\sum_j A_j\,Y_j}\ , j = n,^1\text{H}, \cancel{^2\text{H}}\,,^3\text{H},^3\text{He},^4\text{He} \tag{11}$$



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- Low ^{2}H binding energy could lead to final-state interactions
- If true, detected ^{2}H multiplicity would be systematically lower than the equilibrium prediction
- The theoretical prediction of the RMF model is consistent with experimental data when ^{2}H information is not fed to the Bayesian analysis
- No evidence for ^{2}H out-of-equilibrium effects were found

Summary

- Previously, $(T,\, \rho)$ were estimated considering an ideal gas of clusters
- However, unlike K_c, experimental mass fractions were poorly described
- In this work, a Bayesian inference was performed with a RMF model using mass fractions to determine temperature, density and cluster couplings
- A much better description of experimental abundances was obtained for two different RMF parametrizations: FSU and DD2.
- T shows same increasing behaviour as before but the density turned out to be constant: chemical freeze-out
- A degeneracy was observed between the scalar and vector cluster couplings (x_s, x_ω)
- No deuteron out-of-equilibrium effects were observed

Thank you!