Light nuclei formation at chemical freezeout: A Statistical thermal model description

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We have reviewed the thermal description of light nuclei at the chemical freezeout. First, we have verified the equilibration of the light nuclei, and then we have introduced a new method to investigate the light nuclei formation. We have studied the proximity between the phase space density of light nuclei ratios and their hadronic constituents e.g. $d/d$ and $(\Lambda n/pn)$. We have found that if we exclude the decay feed-down from the hadronic yields from the thermal model, then the hadronic representations have good agreement with the light nuclei ratios. We performed a similar analysis with the ratio of $\Lambda$ hypernuclei and $^3$He, which relates to the ratio $\Lambda/p$. In this context, we have also addressed the strangeness population factor $S_3$. These results indicate that the nuclei and hypernuclei formation may occur near the standard chemical freezeout and before the decay of the hadronic resonances. This method will serve as a guideline to discuss the light nuclei formation and the inclusion of decay into their hadronic constituents.

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I. INTRODUCTION

The light nuclei and hypernuclei yields are available for a wide range of collision energies, from AGS [1, 2], SPS [3] to RHIC [4, 5] and LHC [6, 8]. The existence of these light nuclei at the chemical freezeout boundary is uncertain, as their binding energies (few MeV) are much lower than the typical freezeout temperature (150 MeV) [9]. Despite these difficulties, a thermal model representation of these bound states is important to understand the degree of equilibration of the produced fireball. The formation of light nuclei is also crucial in the cosmological context. As an example, the generated deuterons could be dissociated into their constituent nucleons if produced in an earlier epoch. Their production could be favorable in an earlier epoch. Their production could be favorable only when photon decoupled from baryons and the process $n + p \rightarrow d + \gamma$ became dominant in the detailed balance [10].

Statistical Hadronization Model (SHM) is a standard prescription to discuss the hadronic yields of heavy-ion collision. This formalism is quite successful in explaining the final abundance of hadrons, with only a limited number of thermodynamic parameters $(T, \mu_B, \mu_Q, \mu_S, V)$ [11, 12, 13]. The surface of these parameters is known as the Chemical Freeze-out (CFO), as inelastic collision terminates and the $p_T$ integrated hadron yields are frozen onward this boundary. The contradiction arises while describing the light nuclei in this framework of this thermal model. These nuclei should not survive the chemical freezeout due to their smaller binding energy, and collisions with pions will dissociate these nuclei into constituent nucleons [14].

The Coalescence model also addresses the hadron formation of heavy-ion collisions [18–21]. In this model, depending on the momentum and spatial distribution, nearby partons confine to form a hadron. At the phenomenological level, this method relies on the momentum spectra of both the constituents and the final bound state. A complete description of local correlation and energy conservation is not possible due to the absence of experimental measurement of the parton spectra. On the other hand, the discussion of the light nuclei formation is simpler as the measured momentum spectra are available for both the light nuclei and their hadronic constituents [22]. Two or more hadrons coalesce to form the light nuclei near the kinetic freezeout surface. The momentum spectra of a light nuclei with $Z$ protons and $A-Z$ number of neutrons is proportional to, $\left( E_p \frac{dN}{dp_T} \right)^Z \left( E_n \frac{dN}{dp_T} \right)^{A-Z}$. This method has to implement several parameters to discuss the experimental data. We can calculate the hadron yield and their ratio from the thermodynamic description of the chemical freezeout. As the nucleons further coalesce to form light nuclei, a one to one mapping in chemical composition between the light nuclei and their constituents is apparent.

Despite these variations, both thermal and coalescence models make similar predictions of light nuclei yields [11, 23]. These light nuclei and hypernuclei, especially (anti-)deuterons are cleaner probes of the chemical freezeout for having a negligible decay contribution from the higher mass clusters [24, 26]. So from a parametrization of the statistical thermal models, one can directly calculate the yields of these nuclei and compare it with the experimental data.

Ref [23] analyzed the ratio of light nuclei and their constituents, assuming the Boltzman approximation and neglecting the decay feed-downs into hadrons. Though the deuteron to proton ratio was successfully reproduced in this method, the hypernuclei to light nuclei ratio did not agree with the data. With hypernuclei data from RHIC-200 GeV, it remains a challenge for thermal models to

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simultaneously describe all hadrons and hypernuclei in a single freezeout picture. Ref. [29] utilized two separate freezeout surfaces for strange and non-strange particles to address this issue. Recently, ref. [17] has shown identical production and disintegration rates for deuterons in a hydrodynamical approach, which holds even in the presence of baryon-antibaryon annihilation.

The A hypernuclei production is related to the primordial A-\(p\) phase space correlation. Referring to this, the strangeness population factor \(S_3 = \frac{3}{4} \frac{\langle p/p \rangle}{\langle p/p \rangle} \) was proposed. A multiphase transport model (AMPT) shows an enhancement of this ratio in case of a deconfined initial state, relative to a system with only a hadronic phase. This ratio is also important to investigate the strangeness baryon correlation \(C_{BS} \).

In the present work, we have reviewed the thermodynamics of the chemical freezeout and considered a uniform thermal description for the hadrons and light nuclei. We have verified the equilibration of the light nuclei in this prescription and also addressed the ratios concerning the hypernuclei and strangeness population factor \(S_3\). Our parametrization has reasonably reproduced \(S_3\) at RHIC-200 GeV and LHC-2760 GeV. As these weakly bound states are composed of hadrons, so one can ask, whether these light nuclei formation happens near the hadronic chemical freeze-out or some later times, and do these light nuclei experience a similar chemical freezeout? In a thermal model, the inclusion of resonance decay may help to investigate these light nuclei formation and freezeout.

We can represent the light nuclei ratios with their hadronic constituents e.g the ratio \(d/d\) can be approximated with \(\langle p/p \rangle^2\). If the light nuclei are produced near the chemical freezeout boundary and immediately experience the freezeout, then a hadronic description with only the primary yields of hadrons should be a reasonable representation for the phase space distribution of these nuclei and hypernuclei ratios. Whereas, if the hadrons produce these bound states long after the freezeout, then decay feed-downs from higher mass resonance will be added to the final yields of the hadrons. On this occasion, the light nuclei ratios will have a better resemblance to the ratio of total yields (primary plus decay feed-downs) of the hadronic constituents. We have tried to address these issues in our present manuscript. Though we have performed the parametrization with the proper decay contribution into final hadron states, we have found that the hadronic description provides a better estimation for the light nuclei ratios while we exclude the feed-down of higher mass resonances. This study suggests that the light nuclei yields attain an equilibrium value at freeze-out, and this formation of nuclei and hypernuclei occurs long before the decay feed-down to nucleons and hyperons take place.

The manuscript is organized as follows. In section II, we shall discuss our parametrization procedure and introduce essentials tools to discuss our findings. In section III, we shall discuss our results and summarize in section IV.

## II. FORMALISM

In this section, we shall briefly discuss our parametrization method and available experimental data of the light nuclei sector.

### A. Parametrization with hadron resonance gas

The ideal hadron resonance gas is an effective tool to describe the matter at freezeout. For the last two decades, several studies have successfully explained the bulk properties of heavy ion collision at freezeout by applying this model [12, 13, 30–35]. At the chemical freeze-out, one can associate particle density with experimentally measured yield by [36],

\[
\frac{dN_i}{dy}|_{\text{det}} = \frac{dV}{dy} n_i^{\text{Tot}}|_{\text{det}}
\]

where the subscript Det denotes the detected hadrons. The total number density of any hadron is,

\[
n_i^{\text{tot}} = n_i^{\text{primary}}(T, \mu_B, \mu_Q, \mu_S) + \sum_j n_j(T, \mu_B, \mu_Q, \mu_S) \times \text{Branching Ratio}(j \rightarrow i)
\]

where the summation runs over the heavier resonances \((j)\), which decay to the \(i^{th}\) hadron and primary denotes the thermal density of hadrons without decay contribution.

The number density \(n_i\) is calculated using Eq.3,

\[
n_i = \frac{T}{V} \left( \frac{\partial \ln Z_i}{\partial \mu_i} \right)_{V,T} = \frac{g_i}{(2\pi)^3} \int d^3p \exp[(E_i - \mu_i)/T] \pm 1
\]

For the \(i^{th}\) species of hadron, \(g_i\), \(E_i\) and \(n_i\) are respectively the degeneracy factor, energy, and mass, whereas \(\mu_B = B_i \mu_B + S_i \mu_S + Q_i \mu_Q\) is the chemical potential, with \(B_i\), \(S_i\) and \(Q_i\) denoting the baryon number, strangeness and the electric charge respectively. Though this model is commonly applied for hadrons and their resonances, we can incorporate the light nuclei states with their respective quantum numbers, mass, and degeneracy [8] [12][13].

Here we have followed our earlier introduced formalism of chemical freeze-out parameter extraction [33][38]. This approach relies on ratios of conserved current like net baryon charge and entropy and suitably parameterizes the freeze-out surface with good precision. We construct net charges and total charges, from the detected particle’s rapidity spectra. We equate the model estimation of the net baryon number normalized to the total baryon number with that of the experimental data, as in Eq.4. The other equation is constructed for detected net baryon number normalized to total particle yield as Eq.5.

\[
\sum_i^\text{Det} B_i \frac{dN_i}{dy} = \sum_i^\text{Det} B_i n_i^{\text{Tot}}
\]

\[
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\]
The extracted parameter set \((T, \mu_B, \mu_Q, \mu_S)\) has good agreement with our previous analysis, which we obtained with only hadron yields. At the LHC energy, the temperature decreases 1 MeV if we incorporate all available light nuclei yields. This variation is within the estimated variances of Ref.\([37, 38, 83]\).

It is a general exercise to reproduce particle ratios with the extracted parameter set to verify the accuracy of the fitting procedure. We used all the available light nuclei yields in our fitting procedure for the LHC energy. We have displayed the predicted ratios regarding meson, baryon, and light nuclei, alongside their experimental data in Fig.\(1\). We have successfully reproduced particle ratios with excellent precision. We reiterate that our method does not depend on individual yield ratio, so these ratios are independent predictions. The particle and anti-particle yields become identical at LHC, which demands the chemical potentials to be zero. The resemblance between \(k^+ / \pi^+\) and \(k^- / \pi^-\) is also an indication of the vanishing \(\mu_S\).

III. RESULT AND DISCUSSION

A. Light nuclei to proton ratio

Light nuclei yields are significant to review the baryon equilibrium for their high baryon content. We have normalized the light nuclei (d, \(^3\)He, \(^4\)He) yields with the proton and have examined their variation with collision energy in Fig.\(2\). Measured yields of the deuteron are available from RHIC-BES, LHC, whereas estimations for \(^3\)He are available at SPS and LHC. There is reasonable agreement between our model predictions and experimental data, which indicates the chemical equilibrium.
of these light nuclei states at freezeout.

These three ratios show a similar variation with the collision energy ($\sqrt{s_{NN}}$). They remain flat at the higher RHIC, LHC, and increase towards lower BES and AGS energies. The relative difference between LHC and AGS values increases with the mass number of light nuclei. At the lower collision energies, a finite $\mu_B$ favors the production of baryon clusters with a higher baryon number. Whereas, at the higher RHIC and LHC, the light nuclei yields are just mass suppressed. This explains the variation shown. From the parametrization, we have observed a horn in the $^3\text{He}/p$ and $^4\text{He}/p$ at lower AGS energy. This peak arises as an interplay among the thermal parameters and nucleon mass. Future data from CBM and NICA collaborations will help to investigate these claims.

\section*{B. Anti-particle to particle ratio of d and p}

In Fig. 3a, we have presented antiproton to proton and anti-deuteron to deuteron ratio. Our model estimations suitably match with the experimental data. Both of these ratios increase with the collision energy and become 1 at LHC, as the particle and antiparticle yields become equal. On the other hand, due to a large baryon stopping among the colliding nuclei (which results in a finite $\mu_B$), the baryons are more abundant than the anti-baryon at lower $\sqrt{s_{NN}}$. This demands $\bar{d}/d$ to be smaller than $\bar{p}/p$,

\begin{equation}
\frac{\bar{d}}{d} = C_2 \left( \frac{\bar{\rho}}{\rho} \right)^2 \simeq C_2 \left( \frac{\bar{\rho}}{p} \right)^2 \tag{6}
\end{equation}

We propose that, this $C_2$ helps to investigate the light nuclei formation by quantifying the similarity in chemical composition between $\bar{d}/d$ and $(\bar{p}/p)^2$. To do that we have considered the hadronic ratios from our thermal parametrization in two scenarios. First, we estimate $(\bar{p}/p)^2$ with only primary yields of (anti-)proton. A better resemblance of $\bar{d}/d$ with this primary $\bar{p}/p)^2$ will imply that the (anti-)deuteron formation happens from the primordial (anti-)protons. In the second case, we construct $(\bar{p}/p)^2$ including the decay feed-down in the (anti-)proton yields. If the (anti-)deuterons are formed long after the chemical freezeout, then the square of this total antiproton-proton ratio will be a good representation for $\bar{d}/d$.

In Fig. 3b we have plotted collision energy variation of $C_2$, for both the cases. $C_2$ increases with $\sqrt{s_{NN}}$ and saturates near 1 at RHIC and LHC. This variation is comparatively smaller (0.8 to 1) if we evaluate $(\bar{p}/p)^2$ entirely from primary density of the (anti-)proton. On the contrary, $C_2$ decreases significantly in lower $\sqrt{s_{NN}}$ with the inclusion of resonance decay. In lower AGS and BES energies, the feed-down contributions from the baryonic resonances are larger than anti-baryons due to the finite $\mu_B$, which increases the asymmetry between the total yields of proton and antiproton. The higher value of $C_2$ for the primary case denotes that $(\bar{p}/p)^2$ with the primordial yields of (anti-)proton is a better representation of $\bar{d}/d$. In this case, the little deviation from 1 at lower collision energy can be reduced by considering the isospin asymmetry and neutron yields properly. This finding means that the (anti-)deuterons are formed from the primary (anti-)nucleons, near the chemical freezeout boundary. As we have already presented a good agreement between the thermal model and experimental data for both the ratios, this finding will act as a benchmark to study the light nuclei formation.

This conclusion is in agreement with the findings of ref.\cite{17}. They have observed that the deuteron yields become fixed near the chemical freezeout, though the inelastic interactions may continue further. Here we want
pernuclei are a $\Lambda$ hypertriton ($^3\Lambda H$). In a thermal model, yields and ratios regarding this hypernuclei support to understand the phase space occupancy for strangeness at the freeze-out. For example, a hypertriton is a bound state of n, p, and $\Lambda$. On the other hand, $^3$He has two protons and one neutron. This resemblance of these two states makes their ratio important for investigating strangeness equilibration. In a coalescence picture, the ratio $^3\Lambda H/^3$He should follow the $\Lambda/p$ ratio. A ratio $S_3$, namely the strangeness population factor has been proposed \[29\], where

\[
\left(\frac{^3\Lambda H}{^3\text{He}}\right) = \left(\frac{\Lambda \text{pn}}{p \text{pn}}\right) = S_3 \left(\frac{\Lambda}{p}\right) \tag{7}
\]

and

\[
S_3 = \left(\frac{^3\Lambda H}{^3\text{He}}\right) / \left(\frac{\Lambda}{p}\right) \tag{8}
\]

In fig[15], we have displayed ratios $\Lambda/p$ and $^3\Lambda H/^3$He. Data are only available at LHC \[7\] and RHIC 200 GeV \[4\] for the hypernuclei to nuclei ratio. Our predicted $\Lambda/p$ has good agreement with experimental data. In RHIC energies, the difference between data and model prediction is an influence of the uncertainties in weak decay inclusion into the proton yield. Though we have reproduced the $^3\Lambda H/^3$He ratio in LHC energy, our prediction has slight down-shift at RHIC 200 GeV.

Alike the $C_2$, this $S_3$ is important to relate the light nuclei and hypernuclei states to their composing nucleons and hyperons. We have estimated $S_3$ with and without decay contribution in lambda and proton and have shown the variation in fig[11]. First, we shall discuss the case with the decay feed-downs and check whether it can explain the available data or not, then we shall follow up without the decay and check the similarity between the ratios $\Lambda/p$ and $^3\Lambda H/^3$He.

With the decay feed-down, the phase space occupancy factor increases from 0.6 (AGS value) to 1 at RHIC 200 GeV, and it drops to 0.6 at LHC. $S_3$ remains flat near 0.6 SPS energies, which was previously shown by \[14\]. Available data from experimental collaborations also support this non-monotonic behavior. Our prediction for AGS energy is within the uncertainty band of data. The variation with collision energies arises due to the difference in decay contribution from hyperons and non-strange baryonic resonances. Contrarily, when we consider only the primary yields of $\Lambda$ and $p$, the thermal model prediction for $S_3$ stays near 0.9 at all $\sqrt{s_{NN}}$.

As we have suitably reproduced the experimental data of $S_3$ with the total yields, the result regarding the primary density will be a guideline to investigate the $\Lambda$-hypernuclei formation. If the nuclei and hypernuclei formation occur near the hadronic chemical freeze-out and before the feed-down into $\Lambda$ and proton takes place, then there will be no significant differences between the primary $\Lambda/p$ and $^3\Lambda H/^3$He. In that case, the $S_3$ will stay

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**FIG. 3.** (Upper panel) Red and black points are data \[4\] \[9\] for $\bar{p}/p$ and $d/d$ respectively. Blue and violet points denote model estimations. (Lower panel) Variation of $C_2$ with $\sqrt{s}$. The red and blue points denote estimations with and without decay feed-down into (anti-)proton yield respectively.

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**C. Hypertriton to $^3$He ratio**

Hypernuclei are produced in high-energy interactions via hyperon capture by nuclei \[85\]. The lowest mass hypernuclei are $^6\Lambda$ hypertriton ($^3\Lambda H$). In a thermal model, yields and ratios regarding this hypernuclei support to understand the phase space occupancy for strangeness at the freeze-out. For example, a hypertriton is a bound state of n, p, and $\Lambda$. On the other hand, $^3$He has two protons and one neutron. This resemblance of these two states makes their ratio important for investigating strangeness equilibration. In a coalescence picture, the ratio $^3\Lambda H/^3$He should follow the $\Lambda/p$ ratio. A ratio $S_3$, namely the strangeness population factor has been proposed \[29\], where

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D. Tritium to $^3$He ratio

The ratio of particles related to the same isospin multiplet helps to understand the isospin variation in the heavy-ion collision. In this context, the neutron to proton and $\pi^-/\pi^+$ are the representatives of the isospin asymmetry at the hadronic sector. The detected spectra of the neutron are not available in most of the $\sqrt{s_{NN}}$, so the ratio of $\pi^-$ and $\pi^+$ represents the variation of net isospin. The neutron to proton ratio remains 1.5 in the colliding heavy-ions (Pb or Au). The initial isospin asymmetry generates net negative isospin in the final spectra, which decreases at the lower $\sqrt{s_{NN}}$. Net negative isospin will favor an abundance of $\pi^-$ than its antiparticle. This effect will decrease at higher RHIC and LHC energies and the ratio $\pi^-/\pi^+$ becomes 1. The ratio $^3H/^3He$ represents the isospin asymmetry in the light nuclei sector. Tritium ($^3H$) is composed of $n$ $p$, whereas $^3He$ is a $n$ $p$ bound state. Therefore the tritium ($^3H$) to $^3He$ ratio should reveal the neutron to proton ratio [2].

The experimental data for tritium to $^3He$ is available in SPS energy [3]. We have plotted data of $\pi^-/\pi^+$ ratio alongside tritium to Helium-3 in fig 5a. The $^3H/^3He$ ratio has a close similarity with the pion ratio. The tritium and $^3He$ differ only in isospin and charge, like the charged pions. So the isospin asymmetry of the thermal source should be observed in $^3H/^3He$.

In a thermal model, this isospin asymmetry generates a non-zero value of the corresponding chemical composition ($\mu_I$). Considering the Gell-Mann-Nishijima relation, we have used $\mu_Q$ instead of $\mu_I$. In fig 5b, we have plotted model prediction for both $\pi^-/\pi^+$ and $^3H/^3He$. The $\mu_Q$ guides the $\sqrt{s_{NN}}$ variation of these ratios. The neutron and proton asymmetry of the colliding nuclei will dynamically propagate in the final state and induce an abundance of hadrons and nuclei with negative isospin value. Baryon stopping amplifies this asymmetry via large nucleon deposition in lower $\sqrt{s_{NN}}$ and increases these ratios. It is indeed interesting to observe that both the ratio $\pi^-/\pi^+$ and $^3H/^3He$ resemble each other, though their respective masses are widely different. This behavior proposes that the light nuclei share the same chemical freeze-out surface with that of the hadrons.

Here we want to mention that, the double ratio $N_tN_p/N_d^2$ from the thermal model will be important in this context. But individual yields for tritium (t) yields in all the relevant experiments are still preliminary (HADES, STAR, ALICE).

IV. SUMMARY AND OUTLOOK

The description of light nuclei in a thermal model holds difficulties due to their small binding energy. In this manuscript, we have revisited the light nuclei equilibration at the chemical freezeout of the heavy-ion collision. We have performed the parametrization with ratios of the net baryon charge to total baryon charge and total mu-
multiplicity. We have verified the efficiency of our parameter set by comparing thermal model predictions with available experimental data.

We have addressed separate ratios to check the light nuclei equilibration in baryon, strangeness, and isospin sector. We have represented light nuclei to proton ratio to discuss the equilibrium in the baryon sector. On the other hand, a proper agreement between the thermal model and data for the ratio $^{3}\Lambda^{}/^{3}$He signifies the strangeness-baryon equilibrium in light nuclei. In the context of isospin, we have shown that the $^{3}\Lambda/H^{}/^{3}$He ratio has resemblance with $\pi^{-}/\pi^{+}$. Both these ratios carry the information of isospin asymmetry, in a thermal model prescription.

An essential outcome of the present work is a proper thermal model description of the strangeness population factor $S_{3}$. We have found a good agreement with data at both RHIC-200 and LHC-2.76 TeV. The equilibrium in the hypernuclei sector is apparent from the agreement between the thermal model and data. The successful description from the thermal model emphasizes the fact that the light nuclei exist in equilibrium with the hadrons at the chemical freezeout boundary.

We have especially examined the relationship between the light nuclei ratios and their hadronic counterpart $d/d$, $(\bar{p}/p)^{2}$ and $\Lambda/p$, $^{3}\Lambda/H^{}/^{3}$He to discuss the formation and freezeout of the light nuclei and hypernuclei. First, we have reviewed the individual ratios with the standard thermal model prescription. Then we have proposed that a better resemblance between light nuclei ratios and their hadronic counterpart can be found without the decay contribution in the final yields of hadrons. These results denote that the formation of light nuclei and hypernuclei takes place long before the decay of hadronic resonances occurs to constituting hadrons. In that case, the ratio of the primordial yields of the hadronic constituents is a good estimation of the light nuclei and hypernuclei ratios.

To summarize, in this study we have introduced a new approach to investigate the relationship among the light nuclei to their hadronic constituents at freezeout. With turning on and off the decay feed-down in the hadrons, we have shown that a better correlation between light nuclei ratios and corresponding hadronic ones can be found when we exclude the decay feed-down into hadrons. These results indicate that the light nuclei ratios are fixed near the standard chemical freezeout surface and before the decay of the hadronic resonance occurs. This method will serve as a benchmark to discuss the formation of light nuclei and the inclusion of decay into their constituents. We also want to mention that our introduced method is applicable only for the ratio of mass clusters with the same mass number. We shall address this issue with other light nuclei and hypernuclei yields from the expected results from the RHIC-BES and SPS, CBM at FAIR.

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