A thermal model study of the formation of nuclei and hypernuclei

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The recent findings from Ref.[1] have been reported, where we have verified the equilibration of the light nuclei and introduced a new method to investigate their formation timeline. By studying the similarity between the phase space density of ratios concerning the nuclei(hyper) and their hadronic constituents e.g $\bar{d}/d$, $(\bar{p}\bar{n}/pn)$ and ${}^{3}_{\Lambda}\mathrm{H}{}^{3}\mathrm{He}$, Λ/p, we have found that the exclusion of the decay feed-down from the hadronic yield results into an excellent agreement between the pairs. We have also addressed the puzzle regarding strangeness population factor S_3. Our result indicates that the nuclei(hyper) formation may occur at the standard chemical freeze-out and before the resonances decay.

Introduction

Yields of light nuclei (d,^{3}He,^{4}He) and hypernuclei (${}^{3}_{\Lambda}$H) are clean probes to understand the freeze-out and equilibration in the heavy-ion collision, for having negligible decay contribution from higher massive states. In this context, a thermal model representation with a handful of thermodynamic parameters (T, μ_B, μ_Q, μ_S, V) helps to directly calculate the yields of these nuclei and compare those with the experimental data [2]. The existence of these nuclei(hyper) at the freeze-out boundary possesses an intrinsic puzzle due to their relatively lower binding energy(few MeV). We have proposed a novel phenomenological study by modifying resonance decay into these nuclei states and addressed the issues regarding their formation. This study has also helped to understand the uncertainty concerning the strangeness population factor S_3 by investigating hypernuclei ${}^{3}_{\Lambda}$H yield [1].

Formalism

Measured yields of hadrons and nuclei(hyper) can be connected to the thermal model estimation via, $\frac{dN_i}{dy} = \frac{dV}{dy} n_i^{Tot}$. Here the thermal model estimation of number density for any final state is,

$$n_i^{Tot} = n_i^{primary} + \textstyle\sum_j n_j \times \mathrm{B.R}(j \to i) \quad (1)$$

where the summation runs over the heavier resonances (j), which decay to the i^{th} hadron(nuclei) with branching ratio $B.R$ and *primary* denotes the thermal density of hadrons(nuclei) without decay contribution. The number density n_i is calculated using Eq.[2].

$$n_i = \frac{g_i}{(2\pi)^3} \int \frac{d^3p}{\exp[(E_i - \mu_i)/T] \pm 1}. \quad (2)$$

g_i, E_i and m_i are respectively the degeneracy factor, energy, and mass, whereas $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$ is the chemical potential, with B_i, S_i and Q_i denoting the baryon, strangeness, electric charge respectively. It is worth mentioning that yields of nuclei(hyper) are mainly consist of their primary densities.

Parameters are extracted Ref.[2], where two main equations are

$$\frac{\sum_i^{Det} B_i \frac{dN_i}{dY}}{\sum_i^{Det} |B_i| \frac{dN_i}{dY}} = \frac{\sum_i^{Det} B_i n_i^{Tot}}{\sum_i^{Det} |B_i| n_i^{Tot}} \quad (3)$$

$$\frac{\sum_i^{Det} B_i \frac{dN_i}{dY}}{\sum_i^{Det} \frac{dN_i}{dY}} = \frac{\sum_i^{Det} B_i n_i^{Tot}}{\sum_i^{Det} n_i^{Tot}} \quad (4)$$

We solve these two equations alongside two constraints of the colliding nuclei, i.e net electric charge to net baryon and strangeness neutrality.

Results an discussions

In Fig.[1] we have plotted collision energy variation of the ratio of the yields of light nuclei (d, ^{3}He, ^{4}He) to proton. The reasonable

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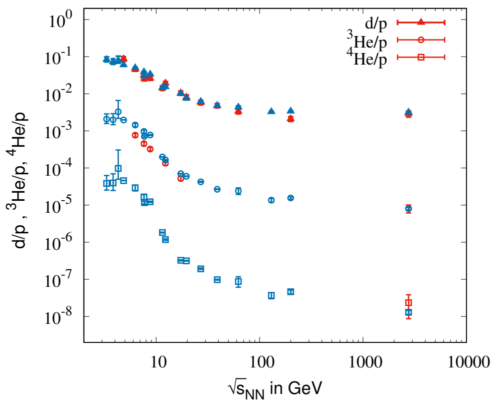

FIG. 1: Variations of light nuclei to proton ratio with $\sqrt{s}$. The red points are the data and blue points are the model predictions.

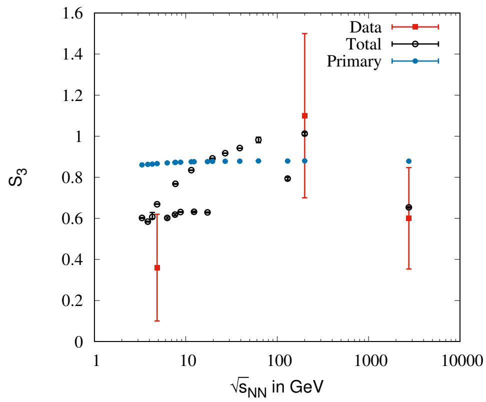

FIG. 2: Variation of S_3 with $\sqrt{s}$. Black(blue) points are estimations with(out) the decay. Red points are the experimental data.

agreement between our model predictions and experimental data indicates the chemical equilibrium of these light nuclei states at freeze-out. At AGS, large μ_B favors the production of baryon clusters with a higher baryon number which is reflected in the relative variation of these ratios. Our parametrization has observed a horn in the ^{3}He/p and ^{4}He/p at lower AGS energy, which is an artifact of the variation of μ_B and nuclei masses.

Hypernuclei are generally formed via hyperon capture by nuclei. The lowest mass hypernuclei are Λ hypertriton ($^3_\Lambda$H), a bound state of n, p, and Λ. Whereas ^{3}He has two protons and one neutron. The strangeness population factor (S_3) quantifies the relative abundances of these two massive states with that of lambda to the proton, where

$$S_3 = \left(\frac{^3_\Lambda\mathrm{H}}{^3\mathrm{He}}\right) / \left(\frac{\Lambda}{\mathrm{p}}\right) \quad (5)$$

We have estimated S_3 both with and without decay contribution in the lambda and proton. In Fig[2], we have found that the decay feed-down produces a large variation in S_3, from 0.6 (AGS value) to 1 at RHIC 200 GeV, and again drops to 0.6 (LHC). This variation is also present in the available data from experimental collaborations, which arises due to the difference in decay contribution from hyperons and non-strange baryonic resonances. On the other hand, considering only the primary yields of Λ and p, the predictions from the thermal model stay near 0.9 at all $\sqrt{s_{NN}}$.

If the nuclei and hypernuclei formation occur near the hadronic chemical freeze-out and before the feed-down into Λ and proton takes place, then there will be no significant differences between the *primary* Λ/p and $^3_\Lambda$H/^{3}He. In that case, the S_3 will stay near 1 at all $\sqrt{s_{NN}}$. We have observed this flatness of S_3 in our thermal model predictions. This close resemblance between primary Λ/p and $^3_\Lambda$H/^{3}He indicates that the hypernuclei formation occurs from the primordial nuclei and hyperons.

Acknowledgments

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References

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