Light hypernuclei in heavy-ion collisions

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Abstract. Prediction for hyper nuclei multiplicities from GSI to LHC energies from the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model combined with a final state coalescence approach is presented and compared to the thermal model. The influence of the coalescence radius on the collision energy and centrality dependence of the $^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratio is discussed.

1 Introduction

Light (hyper)nuclei production in nuclear collisions has become an active field of research in recent years. The precise understanding of the mechanisms creating those nuclei is crucial to understand the strong interaction in more detail. Furthermore, especially hypernuclei are a very important tool to investigate the nuclear Equation-of-State (EoS) at high densities. In the literature, there are basically two models frequently used to describe (hyper)nuclei production: (i) A (grand) canonical thermal model [1, 2] or (ii) a final-state coalescence approach [3]. Here, we aim to compare both methods and explore light-nuclei as well as hypernuclei production from SIS up to LHC energies.

2 Coalescence and the thermal model

Coalescence. The Ultra-relativistic Quantum Molecular Dynamics (UrQMD) [5–7] is a relativistic transport model providing an effective solution of the Boltzmann equation with hadrons as degrees of freedom. The scattering term is implemented via a geometric interpretation of the cross section, and further via string fragmentation and resonance excitation. An additional Equation-of-State can be used as well as a switch to a hybrid mode with intermediate hydrodynamic evolution suited for higher energies.

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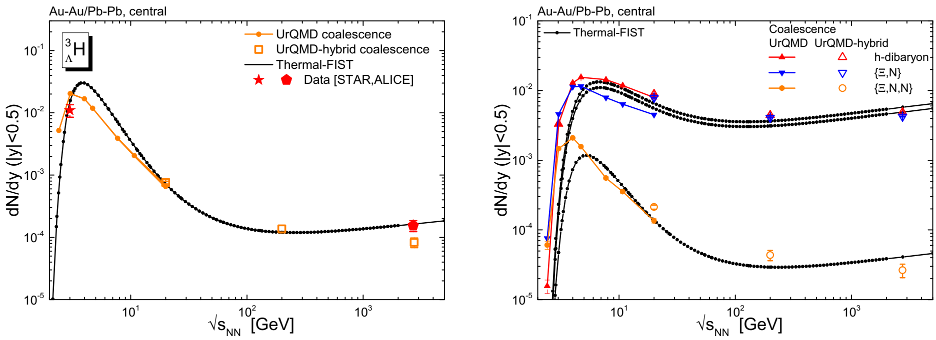

Figure 1. Mid-rapidity yields of the hyper triton (left panel) and hitherto undiscovered states (right panel) in central collisions as a function of the collision energy. The thermal model (Thermal-FIST) prediction is compared with the coalescence results of the UrQMD model and available data from ALICE [14] and STAR [15].

The coalescence approach relates the invariant momentum distribution of a cluster to the invariant spectra of its components at kinetic freeze-out (defined as last scattering point in the UrQMD simulations) via a phase-space volume $\rho_{AB}(\Delta x, \Delta p)$.

$$\frac{\mathrm{d}N}{\mathrm{d}^3k} = g \int \mathrm{d}p_1^3 \mathrm{d}p_2^3 \mathrm{d}x_1^3 \mathrm{d}x_2^3 f_A(p_1, x_1) f_B(p_2, x_2) \rho_{AB}(\Delta x, \Delta p) \delta(k - (p_1 + p_2)) \qquad (1)$$

In the following, we practically implement the phase-space coalescence volume as a box in phase-space which is defined by two parameters Δx_{max} and Δp_{max}, which have to be determined for each (hyper)nucleus. For a more detailed description of the procedure, see [8–10].

Thermal model. In the thermal model approach the light nuclei are incorporated into the partition function of hadronic matter at chemical freeze-out as separate degrees of freedom and their abundances are given by corresponding thermal distribution functions, incorporating the feed down contributions from excited nuclei. Here we employ the open source thermal model Thermal-FIST [11] to estimate the (hypernuclei) multiplicities. The thermal parameters are taken from fits to stable hadron multiplicities, the so-called freeze out curve. For small systems the Thermal-FIST model can also incorporate the canonical treatment of the baryon number, charge and strangeness within a given correlation volume V_c [12, 13].

3 Results

The midrapidity multiplicity of the hypertriton $^3_\Lambda$H, in central heavy-ion collisions, as a function of the collision energy is shown in the left panel of Fig. 1. The UrQMD model calculations are shown by orange lines and symbols, the Thermal-FIST results as a black line and the experimental data points are shown as red symbols. The parameters were fixed to describe the data points and yield $\Delta x_{\mathrm{max}}^{pn\Lambda} = 9.5$ fm (the estimated size of the wave function) and $\Delta p_{\mathrm{max}}^{pn\Lambda} = 0.135$ GeV. The same parameter set is further used to predict the multiplicity of hitherto undiscovered particles. In the right panel of Fig. 1 we show the energy dependence of the midrapidity yields of a possible H-dibaryon state (red), a bound ΞN (blue) and a bound ΞNN (orange) configuration.

Recently, it has been argued that the hypertriton multiplicity is highly sensitive to the system size due to the small Λ separation energy and therefore large spatial separation [16]. In such a scenario, the parameters Δx and Δp can be used to study the source volume at

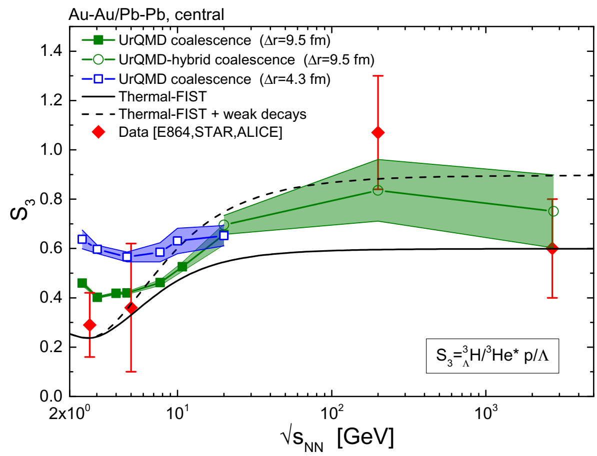

Figure 2. Energy dependence of the double ratio $S_3 = {}^3_\Lambda\mathrm{H}/{}^3\mathrm{He} \cdot p/(\Lambda + \Sigma^0)$. Here the UrQMD results are shown as green (set I) or blue (set II) lines with error bands, the thermal model (Thermal-FIST) results are shown by black lines and the available data points are shown by red symbols.

kinetic freeze out [10]. Thus, a second parameter set for the hypertriton, $\Delta x^{pn\Lambda}_{\mathrm{max}} = 4.3$ fm (same parameter as for the triton [9]), can be used to analyze the system size dependence. The differences can be clearly seen in the ratio $S_3 = {}^3_\Lambda\mathrm{H}/{}^3\mathrm{He} \cdot p/(\Lambda + \Sigma^0)$ shown as a function of energy in Fig. 2. Here, the UrQMD results are shown as green lines (parameter set I) and blue lines (parameter set II) with symbols and error bands, the Thermal-FIST results are shown by black lines and the available data points are shown by red symbols. It should be pointed out that it is not clear from the experimental results to what degree the feed down from the Λ weak decay may be taken into account. Therefore, the thermal model results are shown for two extreme scenarios, i.e. the solid line corresponds to results where feed down from the weak decay is not included in the proton number while in the dashed line it is fully included. The thermal model results with decay of excited nuclei describe the experimental data well. The UrQMD model results with parameter set I also describe the experimental data remarkably well.

In the following the centrality dependence of (hyper)nuclei at LHC energies is further discussed. Varying the centrality at fixed energy allows to analyze the volume dependence without changing the chemical composition of the system. We start with a discussion of the deuteron to proton ratio in the left panel of Fig. 3. The UrQMD model calculations are shown as green lines and the thermal model results are shown as a black line. The ALICE data points are shown as red symbols. The data clearly shows an increase of the ratio d/p from ultra-peripheral to semi-peripheral collisions and a further decrease to very central collisions (also observed in [8]). This phenomenon has been understood as an annihilation effect which affects the deuteron more pronounced, while the rest of the structure arises from volume scaling and canonical effects. One might argue that this effect should be visible for the ratio ${}^3\mathrm{He}/p$ as well. In the right panel of Fig. 3 we therefore show the ratio ${}^3\mathrm{He}/p$ from UrQMD as a green line, from Thermal-FIST as a black line and the same ratio measured by ALICE as magenta symbols. The data and both models qualitatively agree on the canonical effects visible at large centralities. For central collisions the data points do not suggest a decrease, but the available data may not be sufficient to draw final conclusions. However, the UrQMD model simulation clearly predicts a maximum at semi-peripheral collisions. Can this effect be

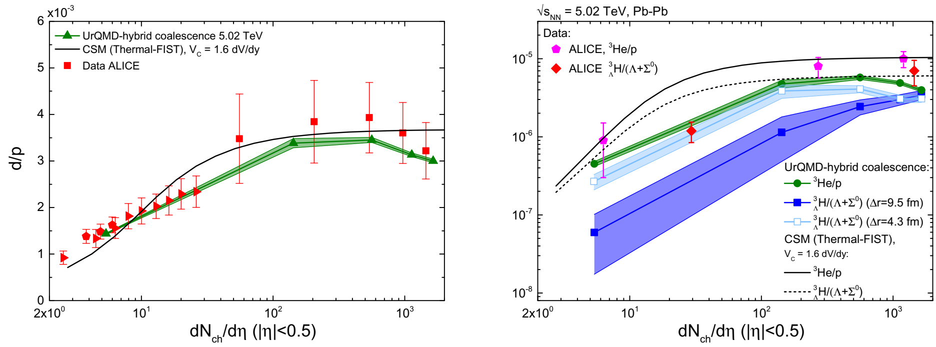

Figure 3. Left panel: Centrality dependence of the d/p ratio from models at $\sqrt{s_{NN}} = 5.02$ compared to experimental data from the ALICE experiment. Right panel: The centrality dependence of the ^{3}He to proton and $^3_\Lambda$H to Λ ratio for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. In the case of the $^3_\Lambda$H to Λ ratio we show two scenarios corresponding to two different choices of the Δr parameter ($\Delta r = 9.5$ fm or $\Delta r = 4.3$ fm). The predictions from the canonical thermal model fits are shown as black lines. ALICE data are shown as symbols [14, 17].

seen in the ratio $^3_\Lambda$H/($\Lambda + \Sigma^0$) as well? Fig. 3 also shows this ratio as a function of centrality as calculated in the UrQMD model with parameter set I (blue line) and parameter set II (light blue line), in the thermal model (dashed line) and measured by ALICE (red symbols) [14, 17]. The coalescence model using a larger coalescence parameter, motivated from the wave function, shows a much faster drop towards peripheral collisions and no peak at more central collisions. In contrast, the coalescence model using the small Δr reveals a similar drop off as the 3-Helium to proton ratio. However, more precise measurements are needed to draw a final conclusion.

4 Conclusion

We have employed the coalescence (UrQMD) and thermal (Thermal-FIST) models to predict light cluster and hypernuclei yields from SIS to LHC energies. In UrQMD, cluster production is employed via a coalescence mechanism while in the thermal model the clusters are explicitly included in the partition sum as degrees of freedom. We found a good agreement of measured multiplicities over a broad range of energies both with the transport model and the thermal model. Differences arise in the centrality dependence of the ratio $^3_\Lambda$He/($\Lambda + \Sigma^0$). Here, the UrQMD results are sensitive to the values of coalescence parameters corresponding to the coalescence source size. A larger size leads to a much faster drop towards peripheral collisions. More data is required to draw further conclusions.

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