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Recent results on (anti-)(hyper-)nuclei production in pp, p-Pb and Pb-Pb collisions with ALICE

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The ALICE Collaboration has collected a large data sample of Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV in 2015 at the Large Hadron Collider (LHC), which is complementary to that at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV from Run 1. In these collisions, a great variety of (anti-)(hyper-)nuclei is produced, namely deuteron, triton, ^{3}He, ^{4}He, hypertriton ($^{3}_{\Lambda}$H) and their antiparticles. Furthermore, the high quality data sample of pp collisions at $\sqrt{s}$ = 7 TeV and 13 TeV and p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, collected at the LHC, allows for a systematic study of the light (anti-)nuclei production in different collision systems.

ALICE has excellent particle identification (PID) capabilities which allow for the detection of these rarely produced particles. PID is performed using several techniques, namely by exploiting the measurement of the specific energy-loss in the Time Projection Chamber (TPC) and the information of the Time-Of-Flight (TOF) detector. In addition, the Inner Tracking System (ITS) is used to distinguish secondary vertices originating from weak decays. This is extremely important for the measurement of (anti-)hypertriton which has a decay length of several centimeters. The decay mode into 2-body ($^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$) is the one with the highest reconstruction efficiency, but the largest branching ratio is given by the 3-body decay channel ($^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$). Emphasis will be put on new results on nuclei production as a function of transverse momentum and multiplicity in all the collision systems as well as on the latest and more precise measurement of the hypertriton lifetime. The results on (hyper-)nuclei production are compared with predictions from a model based on coalescence mechanism and from statistical-thermal models. The goal is to study the (hyper-)nuclei production mechanisms in heavy-ion collisions (Pb-Pb) and to compare them to those in small collision (pp, p-Pb) systems.

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1. Introduction

In ultra-relativistic Pb-Pb collisions at the LHC, a state of matter called Quark-Gluon Plasma (QGP) is created. Among the particles produced in these collisions, (hyper-)nuclei and their anti-particles are of special interest since the production mechanism of these loosely bound states is not clear. Hypernuclei are nuclei where a nucleon is replaced with a hyperon. The hypertriton ($^{3}_{\Lambda}$H), a bound state of a proton, a neutron and a Λ, is the lightest known hypernucleus.

Two different groups of models are used to describe the production of (anti-)(hyper-)nuclei in such collisions: the thermal model [1] and the coalescence of hadrons [2, 3]. The thermal model allows to calculate the production yields of hadrons (dN/dy) created in the fireball, which is assumed to be in thermal equilibrium, when it reaches the chemical freeze-out temperature (T_{chem}), where inelastic collisions cease. The coalescence approach assumes that (anti-)baryons which are close enough in the phase-space at kinetic freeze-out, where elastic collisions cease, can form a multi-baryon state.

The study of (anti-)(hyper-)nuclei production in Pb-Pb collisions as well as in other collision systems, like pp and p-Pb, is fundamental to improve our knowledge on their production mechanism and to constrain the theoretical models. An overview of the results obtained by analysing the data sample collected during LHC Run 1 and Run 2 data taking periods is reported in this proceedings.

Moreover, the $^{3}_{\Lambda}$H lifetime is one of the open points of the hypernuclear physics, since recent more precise measurements showed a trend off from the expected value. A new and more precise lifetime measurement of the ALICE Collaboration is presented in this report.

2. Nuclei

The ALICE experiment has measured, with the LHC Run 2 data sample, the p_{T}-differential production spectra for (anti-)deuterons in pp collisions at $\sqrt{s}$ = 13 TeV as well as in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and for (anti-)^{3}He in Pb-Pb collisions at the same energy [4]. The deuteron and ^{3}He spectra exhibit a hardening with increasing centrality in Pb-Pb collisions, which can be explained by hydrodynamic models as an effect of the radial flow. In order to calculate the integrated yields (dN/dy) the spectra have been fitted with the Lévy-Tsallis [8] and the Blast-Wave [9] functions in pp and Pb-Pb analyses, respectively.

The coalescence parameters B_2 have been computed to investigate the coalescence models with the following formula

$$B_2 = E_d \frac{d^3N_d}{dp_d^3} \left(E_p \frac{d^3N_p}{dp_p^3} \right)^{-2} \tag{2.1}$$

where $E_d \frac{d^3N_d}{dp_d^3}$ and $E_p \frac{d^3N_p}{dp_p^3}$ are the invariant production spectra of deuterons and protons respectively.

Figure 1 (*left*) shows the measured coalescence parameter B_2 of deuteron as a function of p_{T} scaled by the mass number A for Pb-Pb and pp collisions. An ordering of the coalescence parameter with the centrality is clearly visible, going from the lower B_2 in the most central Pb-Pb collisions to the higher values in pp collisions. This ordering is explained in the coalescence model as a consequence of the increasing size of the emitting source volume for more central collisions.

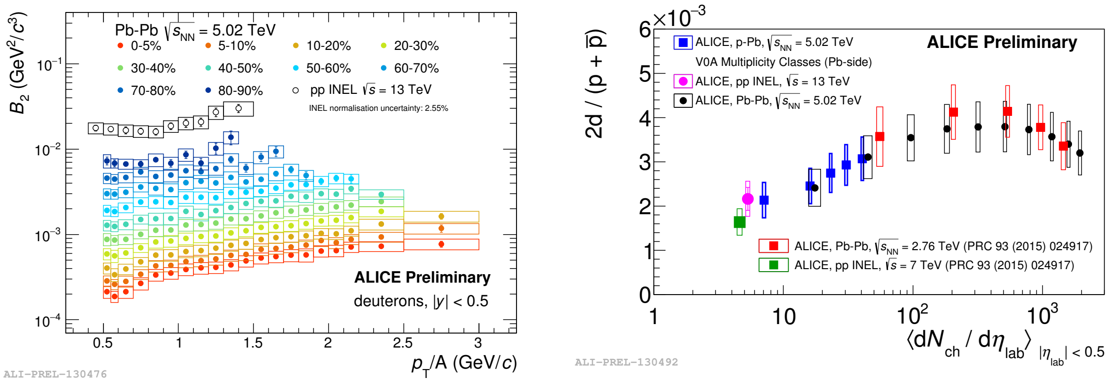

Figure 1: (*left*) deuteron coalescence parameter B_2 as function of p_T/A in Pb-Pb, for different centrality classes, and in pp collisions; (*right*) d/p ratio as a function of the charged particle multiplicity in different collision systems (pp, p-Pb and Pb-Pb) at different energies. [4]

An increasing trend of B_2 as a function of p_T/A is also visible. In the most central Pb-Pb collisions, the coalescence parameter starts rising at 0.7 GeV/c, while for the most peripheral Pb-Pb and for pp collisions it is almost flat up to 1.2 GeV/c and then it increases.

The deuteron-over-proton ratio (d/p) as a function of the charged particle multiplicity has been computed using the integrated yields of deuterons and protons. Figure 1 (*right*) shows the d/p ratio measured in the three collision systems at different energies. The thermal model predicts a constant d/p in Pb-Pb collisions since the ratio is fixed by the temperature of the source, while, according to a simple coalescence picture, d/p should increase with the number of nucleons produced in the collisions.

The d/p ratios measured in Pb-Pb collisions at 5.02 TeV are in agreement with those measured at 2.76 TeV [5] within the uncertainties and the ratio measured in pp collisions at 13 TeV [4] follows the same trend observed in pp and p-Pb collisions at 7 TeV and 5.02 TeV respectively. A possible interpretation of the data is that the increase of the d/p ratio with charged particles multiplicity from pp to the most peripheral Pb-Pb collisions ($dN_{ch}/d\eta \simeq 150$) is expected by the coalescence model since the final state nucleon density increases and with it, also the probability to form a deuteron out of them. The saturation value reached at high charged particle multiplicities is compatible with the thermal model expectation [10].

3. Hypertriton

The hypertriton has a mass of 2.99116 $\pm$0.00005 GeV/c^2 [11] and the accessible decay channels to the ALICE apparatus are the mesonic ones with charged daughters, namely ${}^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$ and ${}^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$. Figure 2 (*left*) shows the ${}^3_{\bar\Lambda}\overline{\mathrm{H}}$ invariant mass distribution from the 3-body decay reconstruction in Pb-Pb collisions at 2.76 TeV.

3.1 Production

The (anti-)hypertriton production yields were measured in Pb-Pb collisions at 2.76 TeV [6] exploiting the mesonic weak decay into two charged particles. The decay products were identified via specific energy-loss in the TPC and topological cuts were applied for the identification of secondary vertices. The signal extraction was performed by means of a fit to the invariant mass spectra with a function that includes signal and background contributions. The production yields have been measured for two different centrality classes (0-10% and 10-50%) as reported in [6]. Figure 2 (*right*) shows the comparison between the measured ${}^3_\Lambda$H dN/dy $\times$ B.R., assuming B.R. = 25% [7], and three theoretical model predictions. The measurement is in agreement with the equilibrium statistical model (T_{chem} = 156 MeV) [1] and Hybrid UrQMD model [3], while there is a discrepancy with the non-equilibrium thermal model [12].

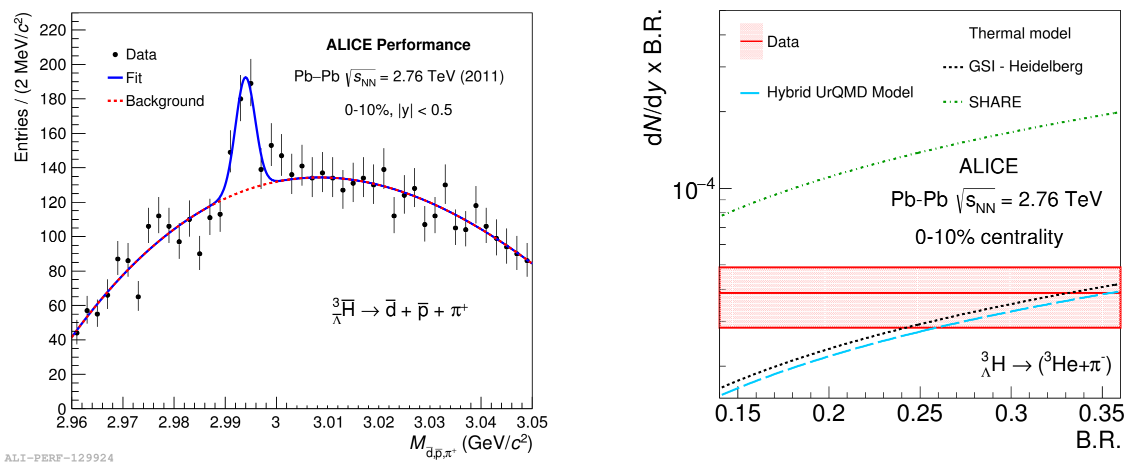

Figure 2: (*left*) Invariant mass distribution for ${}^3_\Lambda\overline{\mathrm{H}}$ reconstructed in the 3-body decay channel in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV; (*right*) Measured ${}^3_\Lambda$H dN/d$y\times$B.R. compared with three theoretical model predictions.

3.2 Lifetime

The ${}^3_\Lambda$H is a loosely bound object, with Λ binding energy E_Λ = 0.13 $\pm$ 0.05 MeV [11], and the theory predicts a value of the lifetime compatible with the free Λ lifetime [14]. However recent heavy-ion experiment results show a trend below the expected free Λ lifetime. ALICE already measured [6] a lifetime value which was in agreement with the trend and with the world average lifetime [13] τ=215^{+18}_{-16} ps, as shown in Figure 3. Now the ${}^3_\Lambda$H lifetime has been measured with higher precision analysing the data sample of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The decay products and the secondary vertices have been reconstructed using the same strategy adopted for the measurement of the production yields. Two techniques have been used for the lifetime determination. The first method consists in the exponential fit to the background subtracted ct-differential spectrum, leading to a value for the lifetime of τ = 237^{+33}_{-36}(stat.) $\pm$ 17(syst.) ps, represented by the blue marker in Figure 3 (*left*). The second approach is an unbinned fit to the 2-dimensional distribution ct vs invariant mass, with a simultaneous description of signal and background based on a double exponential. As shown in Figure 3 (*right*), a lifetime value which is in agreement with the result from the first method, but with slightly larger systematics, is obtained.

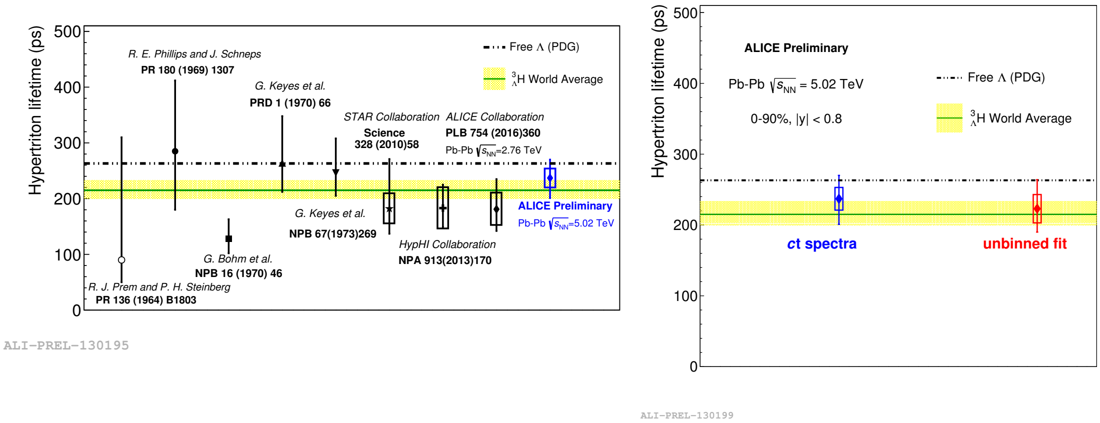

Figure 3: (*left*) Lifetime values available in literature with the new ALICE result (blue marker) obtained in Pb-Pb collisions at 5.02 TeV. The dashed line is the free Λ lifetime and the green line is the $^{3}_{\Lambda}$H lifetime world average [13]; (*right*) $^{3}_{\Lambda}$H lifetime values obtained with the two methods.

4. Conclusion

The preliminary results on nuclei and hypernuclei production, measured in the Run2 data sample of Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV and pp collisions at $\sqrt{s}$ = 13 TeV, are partially well described by thermal (Pb-Pb, p-Pb) and coalescence (pp, p-Pb) models. However a unified description of their production in all collision systems is still missing.

In particular it has been possible to measure the d/p ratio with better precision and more differential in centrality, covering also a region which has overlap with the p–Pb multiplicities. The ratio shows a rise from pp to the most peripheral Pb-Pb collisions which is in agreement with the expectation from the coalescence model, then it becomes almost flat for higher multiplicities reached in the Pb-Pb collisions at the two different energies.

The lifetime of the $^{3}_{\Lambda}$H has been measured with higher statistics and better precision and the preliminary result is closer to the expected free Λ lifetime. Future data taking in LHC Runs 2, 3 and 4 will allow to further reduce the statistical uncertainties in order to solve the puzzle on $^{3}_{\Lambda}$H lifetime.

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