# Production of (anti-)(hyper-)nuclei at LHC energies with ALICE

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**Abstract.** The ALICE experiment at the LHC has measured a variety of (anti-)(hyper-)nuclei produced in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and at 2.76 TeV. In addition, a large sample of high quality data was collected in pp collisions at $\sqrt{s}$ = 7 TeV and 13 TeV and in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. These data are used to study the production of different (anti-)(hyper-)nuclei in the collisions, namely (anti-)deuteron, (anti-)$^3$He, (anti-)alpha and (anti-)$^3_\Lambda$H. The identification of these (anti-)(hyper-)nuclei is based on the energy loss measurement in the Time Projection Chamber and the velocity measurement in the Time-Of-Flight detector. In addition, the Inner Tracking System is used to distinguish secondary vertices originating from weak decays from the primary vertex. New results on deuteron production as a function of multiplicity in pp, p–Pb and Pb–Pb collisions will be presented, as well as the measurement of $^3$He in p–Pb and Pb–Pb collisions. Special emphasis will be given to the new results of the (anti-)$^3_\Lambda$H in its charged-two-body decay mode. The large variety of measurements at different energies and system sizes constrains the production models of light flavour baryon clusters, in particular those based on coalescence and the statistical hadronisation approaches.

## 1 Introduction

The nuclei, anti-nuclei and hyper-nuclei formation mechanism in high energy collisions is still unknown. Thanks to the LHC which provides pp, p–Pb and Pb–Pb collisions at the highest energy ever reached in the laboratory, the ALICE experiment is able to shed light on the phenomenology of (anti-)(hyper-)nuclei production. The latest results on the production spectra of (anti-)deuteron and (anti-)$^3$He in pp collisions at $\sqrt{s}$ = 13 TeV and Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV will be discussed here. The results are compared with the expectation from the statistical hadronisation and the hadron coalescence models. Finally the new measurement of the (anti-)$^3_\Lambda$H lifetime by the ALICE experiment, which is the most precise ever performed, will be discussed.

## 2 Analyses details

The key features that allow ALICE to measure (anti-)(hyper-)nuclei are the precise vertexing, tracking capabilities and the redundancy of particle identification detectors.

Tracking and vertexing are performed using the Inner Tracking Systems (ITS), a silicon tracker featuring 6 cylindrical layers, and the Time Projection Chamber (TPC) [1]. Thanks to the extended
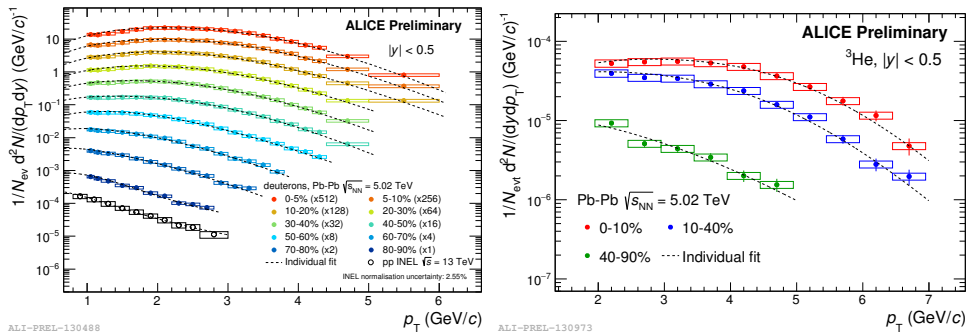
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**Figure 1.** Transverse momentum spectra of deuterons (on the left) and $^3$He (on the right) in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The $p_T$ production spectrum of deuterons in pp at $\sqrt{s}$ = 13 TeV is also reported in the left panel. Statistical uncertainties are represented as vertical bars whereas boxes represent the systematic ones. The dashed lines represent the fit to the individual spectra (Blast Wave function in Pb–Pb [8] and the Lévy-Tsallis in pp [9]) to extrapolate the production yield in the unmeasured $p_T$ regions.

lever arm and a maximum solenoidal magnetic field of 0.5 T, the momentum resolution is better than 1% for particles with $p \leq$ 100 GeV/$c$ [2]. Tracks reconstructed with points in the innermost ITS layer have a pointing resolution better than 300 $\mu$m [2]. For (anti-)(hyper-)nuclei identification the TPC specific energy loss signal (d$E$/d$x$) is used to clearly separate nuclei with Z=2 over the full measured momentum range from the bulk of the produced charged particles. Lighter nuclei with Z=1 can be identified clearly by means of the TPC d$E$/d$x$ only at low momenta (e.g. $p \leq$ 1.4 GeV/$c$ for (anti-)deuterons), but thanks to the Time Of Flight detector (TOF) it is possible to identify, for instance, (anti-)deuterons up to $p_T$ = 6 GeV/$c$ using a statistical unfolding technique [3]. In order to identify (anti-)$^3_\Lambda$H decaying in (anti-)$^3$He and $\pi^{-(+)}$ it is necessary to reconstruct its decay vertex. For each possible pair of (anti-)$^3$He and $\pi^{-(+)}$ the point of closest approach between the two tracks is computed and a set of topological selection is applied. A pair of (anti-)$^3$He and $\pi^{-(+)}$ that passes all these selections is considered to be a (anti-)$^3_\Lambda$H candidate. Finally a two components fit is performed to extract the yield of (anti-)$^3_\Lambda$H, similarly to what is illustrated in [4].

## 3 Results

The production spectra of deuterons in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and in pp collisions at $\sqrt{s}$ = 13 TeV are shown in Figure 1 (left). The typical hardening of the spectra with increasing centrality, already observed for lighter particles [5, 6] and for deuterons [3, 7] at lower energies, is visible here and in the $^3$He spectra (right panel of Figure 1): this pattern suggests an increasing radial flow with increasing centrality. Moreover, the ratio between the production spectra of nuclei and their anti–matter partners is compatible with unity [10], like for the other baryon over anti-baryon ratios at the LHC energies. This observation is compatible with expectations from the statistical hadronisation [11] and the hadron coalescence models [12]. In both approaches the abundances of a (anti-)nuclide $X$ with mass number $A$ are coupled to those of (anti-)protons according to the following relation: $\overline{X}/X \approx (\overline{p}/p)^A$. This expectation for the coalescence model holds only if the spectra of (anti-)neutrons are compatible with those of (anti-)protons. Under this assumption it is also possible to compute the coalescence parameter $B_A$ which is defined for a nuclide with mass number $A$ as the
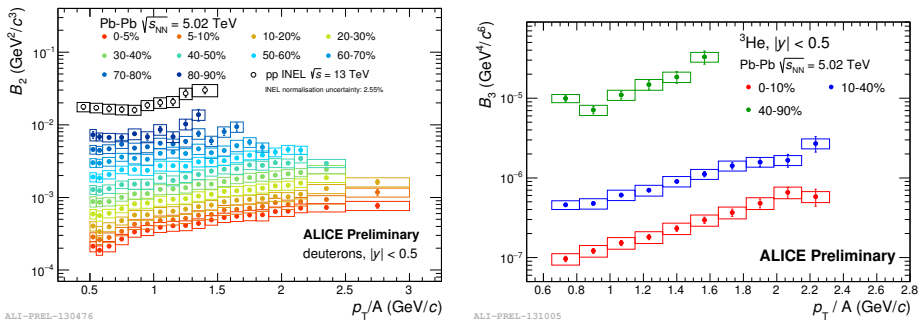
**Figure 2.** Coalescence parameters of deuterons ($B_2$, left panel) and $^3$He ($B_3$, right panel) measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The $B_2$ measured in pp collisions at $\sqrt{s} = 13$ TeV is also shown in the left panel. Statistical uncertainties are represented as vertical bars whereas boxes represent the systematic ones. The ALICE preliminary proton $p_T$-production spectra [6] are used to compute the coalescence parameters.

ratio between the nuclide invariant production spectrum and the proton spectrum to the power of $A$. Figure 2 shows the coalescence parameters for deuterons and $^3$He. In the simple hadron coalescence approach the coalescence parameter is assumed to be momentum independent. However, the presence of correlations in the proton and neutron initial emission, such as jets or common emission radius from the thermal source [13], can introduce a momentum dependence similar to the measured $B_A$.

Another observable qualitatively described by the simple hadron coalescence is the deuteron over proton ratio as a function of multiplicity in small systems, see Figure 3. As more protons and neutrons are created in events with increasing multiplicities, the probability of finding two nucleons close in momentum space and consequently the probability of forming a deuteron increase in small systems. However, this scaling breaks in semi-central Pb–Pb collisions where the deuteron over proton ratio as a function of multiplicity becomes flatter. A flat nucleus over proton ratio as a function of multiplicity, observed also in the case of $^3$He shown in Figure 3, is expected if the statistical hadronisation is the underlying production mechanism in nucleus nucleus collisions. At very high multiplicity the measurements of the deuteron over proton ratios in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV show a hint of suppression. This kind of behaviour might point to the presence of a hadronic rescattering phase that might break nuclei, similar to what is proposed in [14].

Finally, the ALICE collaboration has been able to perform one of the most precise measurements of the $^3_\Lambda$H lifetime using the Pb–Pb data sample at $\sqrt{s_{NN}} = 5.02$ TeV collected in 2015. The lifetime was measured analysing the $^3_\Lambda$H $\rightarrow ^3$He $+ \pi^-$ and the $^3_\Lambda\overline{\text{H}} \rightarrow ^3\overline{\text{He}} + \pi^+$ decays in different $ct$ intervals and performing an exponential fit to the obtained d$N$/d($ct$) distribution, similarly to what has been done in [4]. The preliminary measured value $\tau = 237^{+33}_{-36}$ (stat.) $\pm$ 17 (syst.) ps is compatible with both the previously computed world average ($\tau = \left(216^{+18}_{-16}\right)$ ps, [4]) and with the free $\Lambda$ lifetime.

## 4 Conclusions

The harvest of results from the LHC Run 2 data in the (anti-)nuclei sector just started. The new results at the current LHC top energies confirm the picture depicted by the Run 1 results [3, 7]: at the LHC energies the nuclei production mechanisms in small systems and in Pb–Pb seem to be different. On one hand the simple hadron coalescence describes qualitatively the measurements of deuteron over proton ratio and $B_2$ up to peripheral Pb–Pb collisions. On the other hand the steady rise of the $B_2$ with
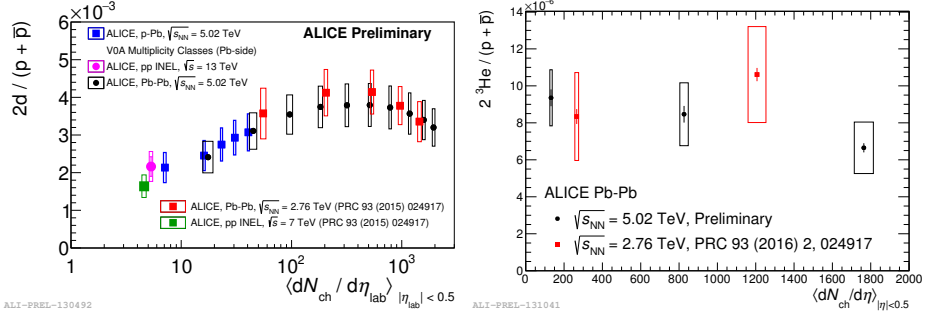
**Figure 3.** Deuteron (left panel) and $^3$He (right panel) over proton ratios as a function of the charged particle multiplicity in the laboratory in different collision systems. Statistical uncertainties are represented as vertical lines whereas boxes represent the systematic ones.

momentum and the flattening of the deuteron over proton ratio in mid-central and central Pb–Pb collisions require additional assumptions to reconcile the coalescence expectations with ALICE results. The larger data sample expected in the upcoming 2018 Pb–Pb run will help to refine the results for $^3$He and possibly extend the measurements to heavier nuclei to test the model predictions with increased precision. However, hadron coalescence might not be the production mechanism of (anti-)nuclei in Pb–Pb collisions: the flat d/p ratio starting from mid-central collisions is in agreement with the expectations of the statistical hadronisation model. Further studies on the systematic uncertainties will help to establish whether the decrease of the d/p ratio in very central Pb–Pb collision is significant.

In the strange nuclear sector, the new ALICE measurement of the $^3_\Lambda$H lifetime is compatible with both the current world average and with the theoretical expectation (i.e. the free $\Lambda$ lifetime [15]).

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