Recent results on light (anti-)nuclei production with ALICE at the LHC

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Abstract. The high-statistics and high-quality data samples in pp, p–Pb and Pb–Pb collisions at various collision energies collected by the ALICE Collaboration, and the excellent tracking and particle identification capabilities of the Inner Tracking System, the Time-Projection Chamber and the Time-of-Flight detector allow for the detection of rarely produced light (anti-)(hyper-)nuclei. The first (anti-)triton \(p^T\) spectra in Pb–Pb at the LHC as well as the first (anti-)\(^4\)He \(p^T\) spectra are presented. Moreover, the \(p^T\)-integrated production yield ratios of deuteron over proton as well as \(^3\)He and triton over proton as a function of charged-particle multiplicity are shown. In addition coalescence parameters \(B_2\) and \(B_3\) as a function of \(p^T/A\) and charge particle multiplicity for several collision systems and energies are discussed. Furthermore, light-nuclei radial and elliptic flow are presented and compared to the flow of lighter particles. These various results are compared with statistical hadronization and coalescence model predictions to provide insight in the production mechanism of light (anti-)nuclei in heavy-ion collisions.

1. Introduction

In ultrarelativistic heavy-ion collisions at the Large Hadron Collider (LHC) a state of deconfined strongly interacting matter consisting of quarks and gluons, called the quark-gluon plasma (QGP), is created. Afterwards, the QGP expands and cools down. When the chemical freeze-out temperature is reached, hadronization takes place and from then on the hadron yields are fixed, but there can still be elastic interactions between the particles. After the kinetic freeze-out the momentum spectra of the particles also do not change anymore. The abundances of different particle species after hadronization provide information about their production mechanism. Among these particles, light (anti-)(hyper-)nuclei are of special interest since they are loosely bound objects. Their binding energies are very small compared to the chemical and kinetic freeze-out temperatures and their production mechanism is still not completely understood. There are two classes of models available to describe nuclei production: the statistical hadronization model and the coalescence model (see for instance [1] and [2], respectively).

In the statistical hadronization or thermal model, the production of nuclei happens at the chemical freeze-out in statistical equilibrium with all other hadrons and scales with the particle mass. In heavy-ion collisions, the system can be described by a grand-canonical ensemble where the free parameters are the average particle number \(\langle N \rangle\), the volume \(V\) and the temperature \(T\) at chemical freeze-out. As the system exchanges particles, the baryochemical potential \(\mu_B\) has to be introduced to ensure the average conservation of particle numbers. For a certain
collision energy, a fit to the measured particle yields can be performed to determine $V$, $T$ and $\mu_B$. However at LHC energies $\mu_B$ is zero. For small systems, i.e. pp and p-Pb, a canonical approach is used, where the quantum numbers are locally conserved rather than on average.

In the coalescence model nuclei are produced at the kinetic freeze-out and the production depends on the wave functions of the nucleus’ species. A phenomenological parameter of the coalescence model is the coalescence parameter $B_A$, which is related to the probability to form a nucleus with mass number $A$ via coalescence. It is calculated by the ratio of the invariant yield of a given nucleus to the nucleon invariant yield to the power of $A$, where the nucleon yield is measured at the corresponding fraction of the nucleus momentum.

Light (anti-)(hyper-)nuclei are produced at the LHC in pp, p–Pb and, in particular, Pb–Pb collisions. The large high-quality data samples in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as well as in pp and p–Pb collisions at several collision energies collected by the ALICE Collaboration provide a unique opportunity to study the production mechanism of these loosely bound objects. This is shown in these proceedings exemplarily for the transverse momentum spectra of (anti-)triton ($t, \bar{t}$) and (anti-)$^4$He, and the elliptic-flow coefficient of (anti-)$^3$He.

Furthermore, charged-particle multiplicity dependences of $p_T$-integrated production yields over the proton yield and coalescence parameters $B_A$ for $A=2$ and $A=3$ nuclei for different collision systems and energies are presented.

2. Light nuclei spectra and production yields

The first (anti-)triton transverse-momentum ($p_T$) spectra in Pb–Pb collisions at the LHC were obtained from the high-statistics data set from 2018 at $\sqrt{s_{NN}} = 5.02$ TeV. The nuclei were identified using the energy-loss measurement in the ALICE TPC, combined with the time-of-flight information provided by the TOF detector. The (anti-)triton spectra were measured in four centrality intervals (see Fig. 1), where an ordering of the yields can be observed. As there are many knocked-out tritons at low $p_T$, emerging from spallation processes in the beam pipe or the detector material, the triton spectra were only extracted above 2.4 GeV/$c$ (or 2 GeV/$c$ in the most peripheral centrality interval). In the overlap region, the measured $t$ and $\bar{t}$ yields are compatible. The difference in the last two $p_T$ bins of the 0-10% centrality interval is less than 2$\sigma$. The spectra exhibit an increase of the average $p_T$ with increasing centrality.

In the same data set, the first (anti-)$^4$He $p_T$ spectra were measured (see Fig. 2). These were obtained in the 0-10% most central collisions in four $p_T$ bins from 2 to 6 GeV/$c$ for $^4$He and in three $p_T$ bins from 3 to 6 GeV/$c$ for $^3$He. The $^4$He spectrum is starting at higher $p_T$ for the same reason as for the tritons. The difference between $^4$He and $^3$He for $4 < p_T < 5$ GeV/$c$ is about 2$\sigma$.

In Fig. 3 the $p_T$ spectra of $\pi$, K, p, d, $^3$He, $\bar{t}$ and $^4$He in the 0-10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown and simultaneously fitted with a Blast-Wave function [3]. The fit describes all particles quite well, the spectra show clear radial flow with a common flow velocity $\langle \beta \rangle$ and kinetic freeze-out temperature $T_{kin}$. One can also see that the $^3$He and $\bar{t}$ spectra are compatible. Although these two different particle species are treated separately, the fitted curves lie on top of each other. At higher $p_T$, the spectra are not expected to be described by the Blast-Wave fit as the shape is dominated by high-$p_T$ processes, like jets.

From individual Blast-Wave fits the $p_T$-integrated production yield $dN/dy$ was extracted for several particles [4] including light (anti-)(hyper-)nuclei and compared to different variants of the thermal model (see Fig. 4) [5, 6, 7, 8, 9, 10]. Although the newly measured $\bar{t}$ and $^4$He are not yet included in the fit, the yield is in good agreement with the model predictions from the fit to the other light-flavoured particles.

In addition, the ratio of the $p_T$-integrated yield $dN/dy$ for deuterons (see Fig. 5) as well as $^3$He and tritons (see Fig. 6) relative to the proton yield has been studied as a function of charged particle multiplicity $\langle dN_{ch}/d\eta \rangle$ for different collision systems and center-of-mass energies.
universal trend can be observed, showing an increase of the ratio with increasing multiplicity from pp to p–Pb and a saturation in Pb–Pb collisions. This trend is rather well described by the canonical statistical [11] as well as the coalescence [12] models. The canonical statistical model is shown for two different volumes $V_c$ (dotted and solid black lines). In Fig. 6, two-body and three-body coalescence is shown (magenta and orange lines, respectively). In two-body coalescence, the coalescence happens between a deuteron and a proton or neutron forming a $^3$He or t, respectively. In the case of three-body coalescence, the coalescence takes place between two protons and one neutron or two neutrons and one proton.

3. Coalescence parameters
As already mentioned, the probability to form a nucleus via coalescence can be quantified by the coalescence parameter $B_A$, where $A$ is the mass number of the respecting nucleus. It can be
\[ \textbf{Figure 4.} \] \( p_T \)-integrated production yield \( dN/dy \) fitted with three thermal model implementations in the 0-10% centrality interval.

\[ \textbf{Figure 5.} \] Ratio of the \( p_T \)-integrated production yield of deuterons over the proton production yield versus multiplicity compared to theoretical model predictions.

\[ \textbf{Figure 6.} \] Ratio of the \( p_T \)-integrated production yield of \( A = 3 \) nuclei over the proton production yield versus multiplicity compared to theoretical model predictions.

The invariant yield of a given nucleus (in the following d and \(^3\)He) is divided by the invariant proton yield to the power of \( A \). It is assumed that neutron and proton yields are the same. The proton yield is measured at the corresponding fraction \( \frac{1}{2} \) for d, \( \frac{1}{3} \) for \(^3\)He of the nucleus momentum.

\( B_2 \) and \( B_3 \) is measured versus \( p_T/A \) for various collision systems and energies. Exemplarily, the \( B_2 \) of deuterons in Pb–Pb collisions and the \( B_3 \) of (anti-\(^3\)He in p–Pb collisions, both at \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV, are shown in Fig. 7 and 8, respectively. The \( B_2 \) is measured in several

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\[ B_A = \frac{1}{2p p_T^2} \frac{d^2 N_A}{dy dp_T^2} / A \] with \( p_T = \frac{p}{A} \) \hspace{1cm} (1)
centrality intervals. It shows a rise with \( p_T \) that becomes milder going from central to more peripheral collisions. The \( B_2 \) in inelastic pp collisions at \( \sqrt{s} = 13 \) TeV is also shown in Fig. 7 (black data points). Like for peripheral Pb–Pb collisions, a mild rise is visible with \( p_T \). The \( B_3 \) (see Fig. 8) was measured in different possible multiplicity intervals and also in p–Pb collisions at \( \sqrt{s} = 5.02 \) TeV verses \( p_T \).

To further investigate the production mechanism, it is for instance possible to study, for a certain value of \( p_T/A \), the evolution of \( B_2 \) and \( B_3 \) versus charged-particle multiplicity \( \langle dN_{ch}/d\eta \rangle \) as various collision systems and centre-of-mass energies have been studied. This is shown for \( B_2 \) at \( p_T/A = 0.75 \) GeV/c and for \( B_3 \) at \( p_T/A = 0.9 \) GeV/c in Fig. 9 and 10, respectively. Both plots show a smooth evolution with multiplicity across different collision systems. Therefore the production mechanism seems to depend only on the system size, which can be expressed in terms of the charged-particle multiplicity. At lower multiplicities, where the system size is smaller than the nucleus, a flat behaviour is observed, slightly decreasing going from pp to p–Pb collisions, when the system size becomes larger. At higher multiplicities, where the system size is larger than the nucleus, a decreasing trend is observed. The overall trend is described by the coalescence model [13], where two different parametrizations of HBT (Hanbury-Brown, Twiss) radii have been used to define the source dimension (dotted and solid lines). The \( B_3 \) (Fig. 10) is also compared to predictions of the canonical and grand-canonical statistical hadronization model (blue and red dashed lines, respectively). It appears that no model can describe the values of \( B_2 \) and \( B_3 \) in the full range of multiplicities studied.

4. Light-nuclei elliptic flow

The observation of radial flow for light nuclei motivates the study of elliptic flow \( (v_2) \). Therefore, the (anti-\(^3\)He) elliptic flow has been measured in Pb–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV [15]. It was extracted in three centrality intervals (0-20\%, 20-40\% and 40-60\%). The \( v_2 \) shows to be larger in semi-peripheral collisions, where the eccentricity of the system is higher, and features an increase with \( p_T \).

The \( v_2 \) of (anti-\(^3\)He) was compared in all three centrality intervals to the \( v_2 \) of \( \pi \), K and p at the same center-of-mass energy (see Fig. 11). A clear mass ordering is observed, i.e. the maximum of the distribution is shifted to higher \( p_T \) with increasing mass, as expected from hydrodynamics.
Figure 9. Multiplicity dependence of $B_2$ for different collision systems and energies, compared to two coalescence model variants.

Figure 10. Multiplicity dependence of $B_3$ for different collision systems and energies, compared to two coalescence model variants and canonical and grand-canonical thermal model curves.

Figure 11. $v_2$ of (anti-)$^3$He compared to the $v_2$ of $\pi$, K, and p at the same center-of-mass energy for three centrality intervals.

Furthermore, the data in the 0-20% and 20-40% centrality intervals were compared to a more sophisticated coalescence model (iEBE-VISHNU hybrid model with AMPT initial conditions [16]), where the phase-space distribution of protons and neutrons is taken into account. The hybrid model includes viscous hydrodynamics and the nuclei are formed by final-state coalescence. As seen in Fig. 12 the data and the model are in good agreement in both centrality intervals.

5. Conclusion
Among other collision systems and energies, new results from the high-quality Pb–Pb data sets at a center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV, collected in 2015 and 2018, have been presented. The first $p_T$ spectra of $t$ and $\bar{t}$ as well as of $^3$He and $^4$He in Pb–Pb at the LHC were shown. The light nuclei exhibit a significant radial and elliptic flow, consistent with the flow of the
lighter particles. The production yields of light nuclei as well as the lighter particles are well described by the thermal model. The production yield ratios of d as well as $^3$He and t over proton versus multiplicity show an increasing trend going from pp to p–Pb collisions with a saturation in Pb–Pb collisions. This trend is rather well described by the canonical statistical as well as the coalescence models. The coalescence parameters $B_2$ and $B_3$ in Pb–Pb and p–Pb collisions exhibit a rise versus $p_T/A$. In Pb–Pb collisions, this rise becomes milder going from central to more peripheral collisions. Looking at $B_2$ and $B_3$ versus multiplicity, which is related to the system size, a clear trend can be observed. At low multiplicities a more flat and slightly decreasing trend going from pp to p–Pb collisions, and at higher multiplicities a more pronounced decreasing trend is seen. The overall behaviour is described by the coalescence model. Future data taking periods in 2021-2024 and 2027-2030 will increase the statistics significantly and will hopefully help to solve the current ambiguity between the discussed production models.

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