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Light (anti-)nuclei production and elliptic flow at the LHC with ALICE

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Abstract

Results on the production of stable light nuclei, including deuterons, ^{3}He, ^{4}He and the corresponding anti-nuclei, in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV and $\sqrt{s_{\rm NN}}$ = 5.02 TeV are presented and compared with theoretical predictions and with the results in small systems to provide insight into the production mechanisms of (anti-)nuclei at colliders.

The experimental results are presented giving a critical view of their comparison to the expectations from coalescence and hydrodynamic models that aim at describing both the $p_{\rm T}$-spectra and the elliptic flow.

Keywords: Hadronisation, Nuclei, Anti-nuclei, Coalescence

1. Introduction

Thanks to the excellent performance of the LHC and ALICE experiment, it is possible to study the production of light (anti-)nuclei up to the (anti-)^{4}He in p–Pb and Pb–Pb collisions at the highest energy ever reached in a laboratory. With the high quality data collected during the LHC Run 1 and 2, the ALICE experiment is able to inquire into the phenomenology of (anti-)nuclei production with unprecedented precision. The latest results on the production spectra of (anti-)deuteron, (anti-)^{3}He and (anti-)^{4}He in p–Pb and Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV are discussed here. The results are compared with the expectations from the statistical hadronisation [1] and the hadron coalescence models [2]. Finally, the new measurements on the v_2 of (anti-)deuteron and (anti-)^{3}He in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV and $\sqrt{s_{\rm NN}}$ = 5.02 TeV are discussed and compared with the predictions from the hadron coalescence and the Blast Wave model [3] fitted on lighter hadrons.

2. Analysis details

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

Tracking and vertexing are performed using the Inner Tracking System (ITS), a silicon tracker featuring 6 cylindrical layers, and the Time Projection Chamber (TPC) [4]. Thanks to the extended lever arm and a

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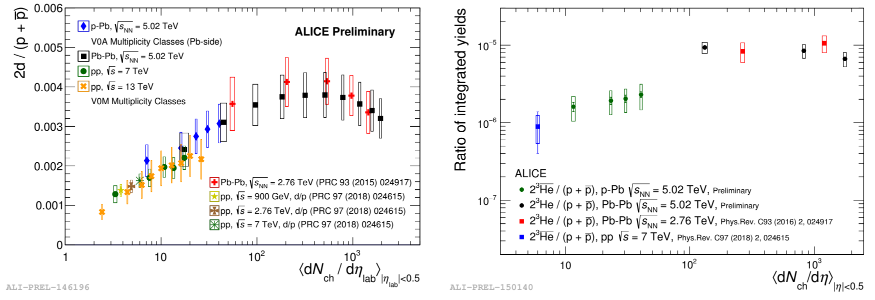

Fig. 1. Deuteron (left panel) and (anti-)^{3}He (right panel) over proton ratios as a function of the charged particle multiplicity in different collision systems. Statistical uncertainties are represented as vertical lines whereas boxes represent the systematic ones [10, 11, 12]. The V0A and V0M multiplicity classes are defined by mapping the charged particle multiplicity in the central pseudo-rapidity region to the signal in the V0 detectors, using the approaches described in [13, 14, 15].

maximum solenoidal magnetic field of 0.5 T, the momentum resolution is better than 1% for particles with $p \leq 100$ GeV/c [5]. Tracks reconstructed with points in the innermost ITS layer have a pointing resolution better than 300 μm [5].

For (anti-)nuclei identification the TPC specific energy loss signal ($\mathrm{d}E/\mathrm{d}x$) is used to clearly separate nuclei with Z=2 from the bulk of the produced charged particles in the range $2 \leq p_{\mathrm{T}} < 6$ GeV/c where the production spectra are measured. Nuclei with Z=1 can be identified clearly by means of the TPC $\mathrm{d}E/\mathrm{d}x$ only at low momenta (e.g. $p \leq 1.4$ GeV/c for deuterons), but using the Time Of Flight detector (TOF) it is possible to identify (anti-)deuterons up to $p_{\mathrm{T}} = 6$ GeV/c using a statistical unfolding technique [6].

The deuteron v_2 coefficient is measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ =2.76 TeV using the Scalar Product (SP) method [7, 8], a two-particle correlation technique, using a pseudo-rapidity gap $|\Delta\eta| > 0.9$ between the identified (anti-)deuteron and the region where the reference flow particles are measured. The applied gap reduces the non-flow effects, which are correlations not arising from the collective expansion of the system created in the collision. The (anti-)^{3}He v_2 is measured instead in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV using the event plane method [9], where the azimuthal direction of the event plane is reconstructed using forward and backward detectors and then the number of produced (anti-)^{3}He in-plane and out-of-plane are counted. The reference flow particles in the SP method and the event plane inclination are determined using the V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$) scintillator hodoscopes [4].

3. Results

As shown in [10] and at this conference, the production spectra of (anti-)deuterons and (anti-)^{3}He in p–Pb and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV has been studied with the ALICE experiment. The $\mathrm{d}N/\mathrm{d}y$ at $|y| < 0.5$ for deuterons and ^{3}He is extracted using the fit to the production spectra with the Blast Wave function [3] to extrapolate the yield in the unmeasured transverse momentum regions. The ratio between the measured $\mathrm{d}N/\mathrm{d}y$ of nuclei and protons, shown in Fig. 1, is sensitive to the light nuclei production mechanism. In small systems the simplest hadron coalescence model is able to reproduce the measured deuteron over proton ratio: 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 increases [12, 16]. However, this increase ceases in semi-central Pb–Pb collisions where the deuteron over proton ratio as a function of multiplicity becomes flatter. At very high multiplicity the measurements of the deuteron over proton ratios in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV and $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV show a hint of suppression. This kind of behaviour might point to the presence of a hadronic rescattering phase that breaks nuclei, similar to what is proposed in [17] and shown in this conference by the same authors. Nevertheless, within the current uncertainties, the measurements are compatible with a flat nucleus over proton ratio as a function of multiplicity. This flat behaviour is observed also in the case of ^{3}He

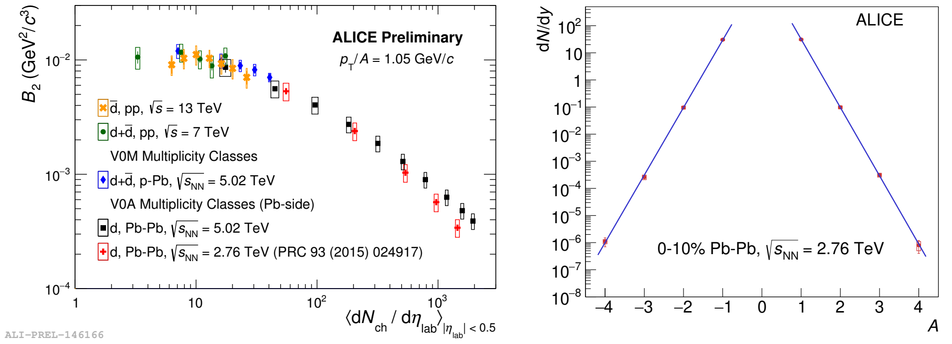

Fig. 2. Left panel: evolution of the deuteron coalescence parameter B_2 at intermediate p_T as a function of the charged particle multiplicity in different colliding systems and energies. Right panel: mass number exponential ordering (blue lines) in the production of light nuclei and anti-nuclei in Pb–Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV.

in Pb–Pb collisions, and it is expected if the statistical hadronisation is the underlying particle production mechanism in nucleus-nucleus collisions.

Furthermore, the statistical hadronisation model can describe the hierarchy of the production rates of light (anti-)nuclei in Pb–Pb collisions as shown in Fig. 2 (right): the production of (anti-)nuclei as a function of their mass number follows an exponential fall up to the heaviest (anti-)nuclei measured until now in Pb–Pb collisions [18]. However, the new measurements of (anti-)^{3}He in pp and p–Pb collisions show that also in this case the ratio with respect to the proton production increases as a function of multiplicity suggesting a simple coalescence production mechanism in small systems (Fig. 1, right panel).

The left panel of Fig. 2 shows the coalescence parameter B_2 as a function of the charged particle multiplicity. The coalescence parameter B_A is defined for a nuclide with mass number A as the ratio between the nuclide invariant production spectrum and the proton spectrum to the power of A. The decreasing trend of B_2 with increasing charged particle multiplicity suggests an interplay between the increasing size of the system produced in the collision and the width of the wave function of the produced (anti-)nuclei. Coalescence models that take into account the spatial extension of the source and the produced object show promising results in explaining the ALICE measurements [19, 20, 21].

The traditional simple coalescence picture has been further tested by measuring the v_2 coefficients of both (anti-)deuterons [6] and (anti-)^{3}He. In case of simple coalescence the expected v_2 for a nuclide X with mass number A is related to the v_2 of protons by the formula: $v_2^X(p_T) = Av_2^p(Ap_T)$. Figure 3 shows the measured v_2 of deuterons and ^{3}He compared with the expected curves by the simple coalescence model. In the case of (anti-)deuterons the measurement is not described by the coalescence prediction while it is in good agreement with the Blast Wave model fitted to lighter hadrons spectra and v_2 [6]. The v_2 of the (anti-) ^{3}He is compatible with both the Blast Wave and coalescence predictions within the large statistical uncertainties.

4. Conclusions

The harvest of results from the LHC Run 2 data in the (anti-)nuclei sector is progressing well. The new results at the current LHC top energies confirm the picture depicted by the Run 1 results [6, 11] but the understanding of this picture is evolving thanks to the renewed precision of the measurements. At the LHC energies the (anti-)nuclei production in pp, p–Pb and in Pb–Pb shows different features and traditionally there is a dichotomy between the thermal production in Pb–Pb and the simple hadron coalescence model in small systems. Simple hadron coalescence describes qualitatively the increase of the deuteron and ^{3}He over proton ratio with multiplicity but it fails to reproduce the flattening of these ratios in Pb–Pb collisions, whereas the statistical hadronisation model predicts this behaviour.

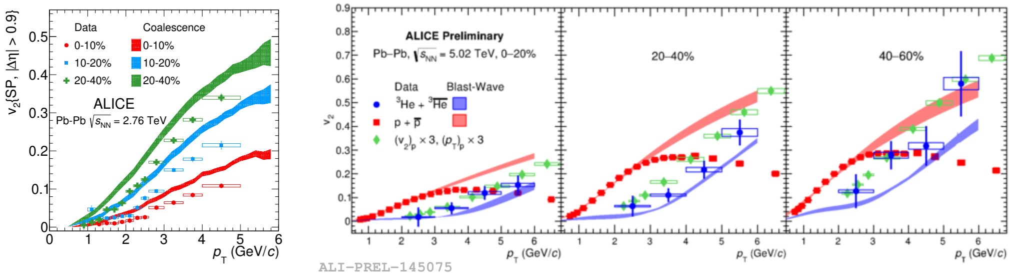

Fig. 3. v_2 of (anti-)deuterons (left panel) and ^{3}He (right panel). On the left panel: the points represent the measured v_2 while the shaded bands depict the simple coalescence expectation [6]. The different colours represent the centrality classes. On the right panel: the v_2 of protons and (anti-)^{3}He are represented in red and blue respectively. The green points represent the coalescence expectation while the blue band is the Blast Wave model prediction. In both panels the statistical and systematic uncertainties are represented with bars and boxes respectively.

Furthermore, the simple coalescence model prediction fails to reproduce the deuteron v_2, and currently the Blast Wave model gives the best description of the experimental data even if the current statistical uncertainty on the ^{3}He v_2 is limiting the constraining power of this measurement.

However, more educated coalescence models that take into account the size of the produced object and the size of the source are emerging and they describe qualitatively B_A, v_2 and nucleus over proton ratios up to central Pb–Pb collisions. The experimental challenge will be measuring more nuclear species in all possible collision systems at the LHC to test ultimately whether the source and the emitted nucleus size matter in the description of the (anti-)nuclei production. The upcoming 2018 Pb–Pb run will serve this purpose giving us the opportunity to have smaller statistical uncertainties on the ^{3}He v_2 and p_T spectra and to open the hunt to other light (anti-)nuclei like (anti-)^{3}H and (anti-)^{4}He.

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