IL NUOVO CIMENTO **47 C** (2024) 82
DOI 10.1393/ncc/i2024-24082-3

Colloquia: IFAE 2023

Light (anti)nuclei production with the ALICE experiment at the LHC(*)

M. Rasà([1])([2])(**) on behalf of the ALICE Collaboration

([1]) *Dipartimento di Fisica e Astronomia "Ettore Majorana", Università degli Studi di Catania Catania, Italy*
([2]) *INFN, Sezione di Catania - Catania, Italy*

received 13 February 2024

Summary. — The measurement of light (anti)nuclei production in high-energy pp, p–A, and A–A collisions is a powerful tool to understand the hadronization process. The ALICE experiment, among the LHC experiments, is particularly well suited for the study of light (anti)nuclei production thanks to its excellent tracking capabilities and particle identification in a wide range of transverse momentum. Particles with mass numbers up to A=4, such as (anti)deuterons, (anti)tritons, (anti)^{3}He, and (anti)^{4}He have been successfully identified in the pseudorapidity region $|\eta| < 0.9$. In this contribution selected results on light (anti)nuclei production are presented, such as particle yields, transverse momentum distribution and comparison with hadronization models. In addition recent results on (anti)deuteron production in jets are discussed.

1. – Introduction

One of the most debated topics in the scientific community is the formation mechanism for nuclei in high-energy hadronic collisions. Currently only phenomenological models are able to describe the experimental data for light (anti)nuclei production at AGS [1-3], RHIC [4-7] and the LHC [8-15].

Typically, two different models are used to describe those results: the *Statistical Hadronization Model* (SHM) [16] and *baryon coalescence* [17]. In the first one, after the collision, all the particles are isotropically emitted by a system in both statistical and chemical equilibrium, with the particle abundance for each species fixed at the chemical freeze-out. The SHM is a macroscopic model, and it is able to reproduce the particle yields in central heavy-ion collisions with a common temperature of about 156 MeV, with an exponential dependence. However, it does not describe the hadron formation mechanism in microscopic detail.

(*) IFAE 2023 - "Energy Frontier" session
(**) E-mail: marika.rasa@ct.infn.it

The baryon coalescence model, instead, provides a description of the hadron formation. In this case, a nucleus is formed if its constituent nucleons are close in phase space and the sum of their spin states is compatible with that of the final state. The state-of-the-art model describes the coalescence picture using the Wigner formalism, where both the radial extension of the source size and the wave function of the final state are taken into account [18]. In both cases, the coalescence probability is linked to an experimental observable, the *coalescence parameter* B_A, defined as the proportionality factor between the invariant yields of the formed (anti)nucleus and the (anti)protons:

$$B_A = \left(\frac{1}{2\pi p_{\mathrm{T}}^{A}}\frac{\mathrm{d}^2N}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^{A}}\right) \Big/ \left(\frac{1}{2\pi p_{\mathrm{T}}^{p}}\frac{\mathrm{d}^2N}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^{p}}\right)^2. \tag{1}$$

In this definition A is the mass number of the final state, while the (anti)proton spectrum is evaluated at the transverse momentum of the formed nucleus divided by its mass number.

Light (anti)nuclei are identified by the ALICE experiment exploiting the information obtained by two main detectors, the Time Projection Chamber (TPC) and the Time-Of-Flight (TOF), described in detail in [19]. In particular, light (anti)nuclei are identified using the information on the specific energy loss dE/dx measured by the TPC and the velocity of the particles obtained measuring the time-of-flight by the TOF detector. In this contribution, a selection of results on light (anti)nuclei production measured by ALICE in different collision systems and energies is presented. Moreover, recent results on (anti)deuteron production in and out of jets are discussed.

2. – Light (anti)nuclei production

The production of light (anti)nuclei has been studied in depth by the ALICE experiment, in different collision systems and energies. Figure 1 shows the particle yield as a function of the mass number of the nuclei: as predicted by the SHM, this quantity has an exponential dependence with respect to the mass of the observed nuclei, and an ordering with respect to the collision system is also observed, with more nuclei are produced in Pb–Pb collisions with respect to pp collisions. Moreover, defining the *penalty factor* as the scaling factor between the production of two nuclei with mass number A and $A+1$, this value varies between 942 in pp collisions at $\sqrt{s} = 7$ TeV and 359 in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [8].

Differential studies can be carried out to examine the dependence on the collision system, such as evaluating light (anti)nucleus production as a function of charged-particle multiplicity or energy scale. In general, in pp and p–Pb collisions light (anti)nuclei up to ^{3}He can be identified [9, 10], while in Pb–Pb collisions also ^{4}He can be observed, even if its production is extremely suppressed [11]. The particle spectra, in all the collision systems and energies, have some common features, such as a hardening as a function of multiplicity. As an example, fig. 2 shows the transverse momentum spectra for protons, deuterons, and ^{3}He in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of multiplicity, where the hardening is visible. In the low and high transverse momentum regions, where no data are available, the particle production can be evaluated using the fit function, which varies from the Lévy-Tsallis in the case of lighter nuclei to an m_{T}-exponential for heavier nuclei.

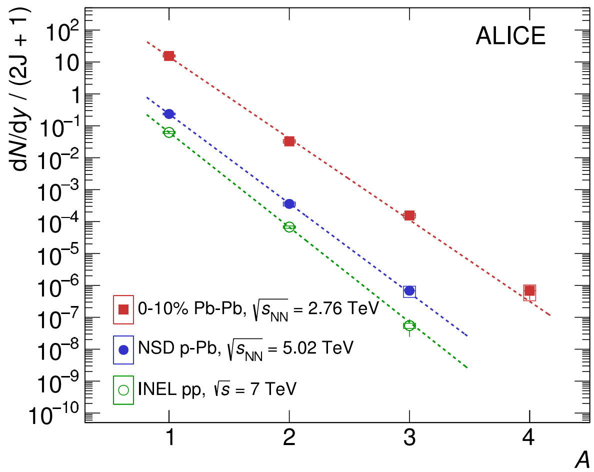

Fig. 1. – Production yield normalised by the spin degeneracy as a function of the mass number for pp collisions at $\sqrt{s} = 7$ TeV, p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, and central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The lines represent fits with an exponential function [8].

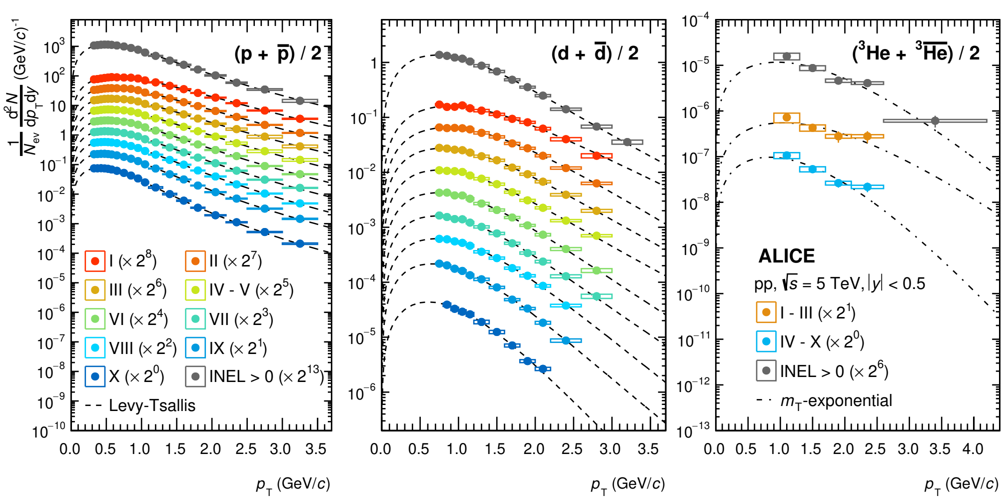

Fig. 2. – Transverse-momentum spectra of (anti)protons (left), (anti)deuterons (center) and (anti)^{3}He (right) in different multiplicity classes. Both the (anti)deuterons and (anti)protons spectra are fitted with a Lévy-Tsallis function, while (anti)^{3}He spectra are fitted with an exponential function with respect to the transverse mass m_{T} [9].

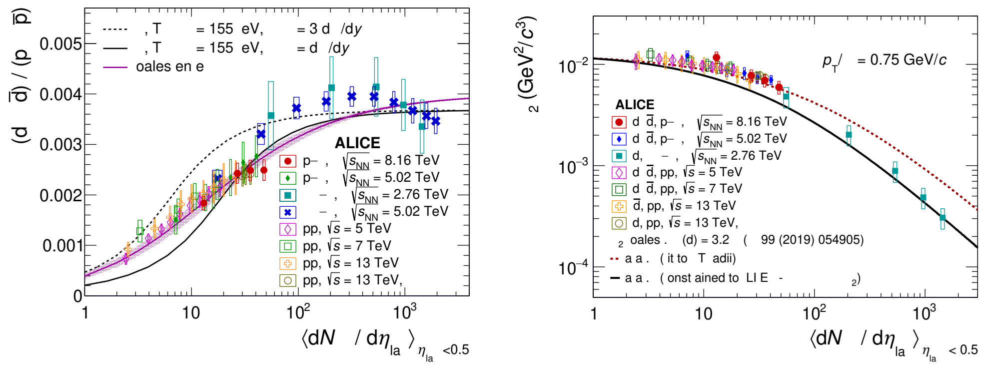

Fig. 3. – Deuteron-over-proton ratio (left) and deuteron coalescence parameter B_2 (right) as a function of the multiplicity of the collision in different systems. The lines represent the comparison with the available models [10].

The experimental data obtained by the study of light (anti)nuclei production in different collision systems available at LHC are compared with the predictions from both the SHM and the coalescence model. To make this comparison, two different observables are considered: the nuclei-over-proton ratio and the coalescence parameter B_A. Figure 3 shows both the quantities in the case of deuterons. The deuteron-over-proton ratio is compared both with the SHM (in the parametrization of Thermal-FIST CSM [20]) and the coalescence model. The data are qualitatively consistent with the the theoretical expectation, although there are some tensions at intermediate multiplicity values. For $\mathrm{dN}/\mathrm{d}\eta$ values between 90 and 500, the coalescence model underestimate the measurements, while the CSM provides a good agreement. However, at lower multiplicities this behaviour is reversed, with the coalescence model better describing the data and the CSM overestimating it. The values of the coalescence parameter, instead, are compared with the values predicted by the model considering two different parametrizations on the source dimension: in both cases the data qualitatively follow the model, with some divergence at high multiplicity [10]. Similar results are available for the ^{3}He, where there are more tensions in the helium-over-proton ratio [10, 12].

In order to further test the coalescence model, ALICE has been recently developed an innovative type of study, where the (anti)nuclei production is studied in and out of jets. According to the coalescence picture, the coalescence parameter should be enhanced inside jets with respect to the same quantity in the underlying event, due to the fact that the particles in jets are closer in phase space. This analysis has been performed both in pp collisions at $\sqrt{s} = 13$ TeV [13] and in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. To correctly identify the jets, the CDF technique [21] is used. The particle in the event with the highest transverse momentum and higher than a fixed threshold is used as a proxy for the jet axis, and an azimuthal angle $\phi = 0$ is assigned to it. Then, all the other particles are classified in three azimuthal regions, according to the $\Delta\phi$ with respect to the leading track:

- *Toward*, $|\Delta\phi| < 60°$, that contains the jet and the underlying event,
- *Away*, $|\Delta\phi| > 120°$, with the recoil jet and underlying event,
- *Transverse*, $60° < |\Delta\phi| < 120°$, characterized by the underlying event.

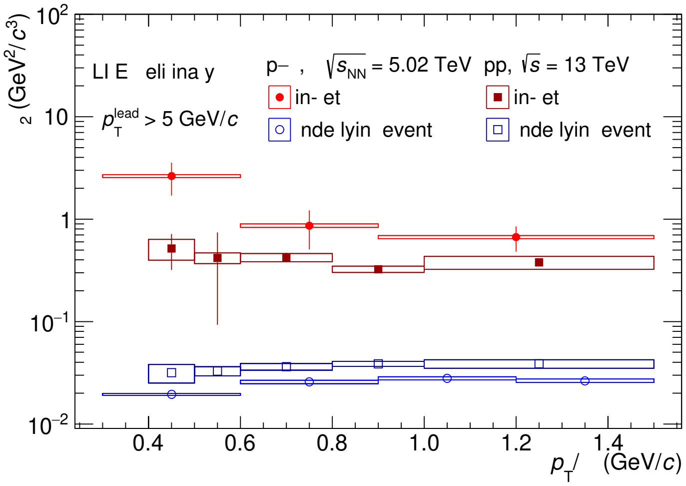

Fig. 4. – Deuteron coalescence parameter B_2 in and out of jets in pp collisions at $\sqrt{s} = 13$ TeV [13] and p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

In order to obtain the jet contribution, a difference between the Toward and Transverse spectra is taken. The coalescence parameter is then evaluated as reported in eq. (1). Figure 4 shows the value of B_2 in both pp collisions (squares) and p–Pb collisions (circles) in jets (red) and the underlying event (blue). As predicted by the coalescence model, an enhancement of B_2^{jet} with respect to B_2^{UE} is observed in both collision systems, with a larger gap in p–Pb collisions. For the UE results, they can easily be described as an effect of the source size: in fact, the pp size is slightly smaller with respect to the p–Pb size, 1 fm [22] against 1.5 fm [23], hence the coalescence parameter is expected to be smaller in p–Pb collisions. The in-jet results, instead, could be derived from nucleons closer in the phase space in jets, but the coalescence probability may also be influenced by the particle compositions inside jets.

3. – Conclusions and future perspectives

Light (anti)nuclei production has been studied in depth by the ALICE experiment in different collision systems and energies, in order to understand the hadronization process. The transverse momentum spectra of the produced nuclei have similar features ranging from pp to Pb–Pb collisions, such as a hardening of the spectra with the multiplicity. The experimental data can also be compared to the phenomenological models that describe the hadronization process, such as the SHM and the baryon coalescence model. In both cases, the models qualitatively reproduce the data, and for this reason new and innovative observables are needed. In order to constrain the coalescence model, it is possible to study the coalescence parameter in and out of jets, where an enhancement of the coalescence parameter in jets is observed, compatible with the coalescence picture. This type of measurement can be further extended with the available data sample at the end of Run 3, that will allow the observation of light (anti)nuclei at lower transverse momentum, with a larger data sample that will allow more precise measurements on particle yields and comparison with the theoretical models. For the study of the coalescence parameter in jets, instead, the improved sample will allow a multi-parametric study as a function of the jet radius, that can be fully reconstructed using jet-finder algorithms.

REFERENCES

[1] E878 Collaboration, *Phys. Rev. C*, **58** (1998) 1155.
[2] E802 Collaboration, *Phys. Rev. C*, **60** (1999) 064901.
[3] E864 Collaboration, *Phys. Rev. Lett.*, **85** (2000) 2685.
[4] STAR Collaboration, *Phys. Rev. Lett.*, **87** (2001) 2623011.
[5] PHENIX Collaboration, *Phys. Rev. Lett.*, **94** (2005) 122302.
[6] BRAHMS Collaboration, *Phys. Rev. C*, **83** (2011) 044906.
[7] STAR Collaboration,*Nature*, **473** (2011) 353; **475** (2011) 412(E).
[8] ALICE Collaboration, *Phys. Lett. B*, **800** (2020) 135043.
[9] ALICE Collaboration, *Eur. Phys. J. C*, **82** (2022) 289.
[10] ALICE Collaboration, *Phys. Lett. B*, **846** (2023) 137795.
[11] ALICE Collaboration, *Nucl. Phys. A*, **971** (2018) 1.
[12] ALICE Collaboration, *JHEP*, **01** (2022) 106.
[13] ALICE Collaboration, *Phys. Rev. Lett.*, **131** (2023) 042301.
[14] ALICE Collaboration, *Phys. Rev. C*, **101** (2020) 044906.
[15] ALICE Collaboration, *Phys. Rev. C*, **107** (2023) 064904.
[16] Andronic A. *et al*, *Nature*, **561** (2018) 321.
[17] Butler S. T. *et al.*, *Phys. Rev.*, **129** (1963) 836.
[18] Mahlein M. *et al.*, *Eur. Phys. J. C*, **83** (2023) 804.
[19] ALICE Collaboration, *JINST*, **3** (2008) S08002.
[20] Vovchenko V. and Dönigus B. and Stoecker H., *Phys. Lett. B*, **785** (2018) 171.
[21] CDF Collaboration, *Phys. Rev. D*, **65** (2022) 092002.
[22] ALICE Collaboration, *Phys. Rev. C*, **99** (2019) 024001.
[23] ALICE Collaboration, *Phys. Rev. Lett.*, **123** (2019) 112002.