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Overview and new directions about light (anti)nuclei measurements with ALICE

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*

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Summary. — The production of light (anti)nuclei has been measured by the ALICE experiment in the last decade. Despite the abundance of experimental results, the production mechanism of light (anti)nuclei is still mysterious and under intense debate in the scientific community. The experimental data are typically described using two different phenomenological models: the statistical hadronization model and the baryon coalescence. In this contribution, an overview of recent ALICE results on light (anti)nuclei production measurements will be presented. The global picture emerging from these measurements will be discussed in the context of the available phenomenological models. Recently, ALICE has performed pioneering measurements of the (anti)deuteron coalescence parameter in and out of jets in small collision systems where unexpected and intriguing results were obtained. These will be presented along with perspectives for further developments of this research line in the LHC Run 3.

1. – Introduction

Light (anti)nuclei production has been extensively studied by the ALICE experiment [1-6], considering different collision systems and energies, in order to understand the hadronization process. In fact, even if a considerable amount of experimental results are available, the formation process of light (anti)nuclei is still mysterious and is a highly debated topic in the scientific community. To describe this process two phenomenological models are commonly used: the Statistical Hadronization Model (SHM) [7] and the baryon coalescence [8].

In the SHM the hadrons are isotropically emitted from a system in statistical and chemical equilibrium, with the abundances of the species fixed at the chemical freeze out. The particle yield is described by the relation $\mathrm{d}N/\mathrm{d}y \propto \exp(-m/T_{\mathrm{chem}})$, where m

([*]) E-mail: `marika.rasa@ct.infn.it`

is the mass of the selected particle and T_{chem} is a common freeze out temperature of about 156 MeV.

In the coalescence model, if the nucleons are close in the phase space and their spin state is compatible with the one of the final state, they can bind and form an (anti)nucleus. In this model, the key observable is the coalescence parameter B_A. If A is the mass number of the formed nucleus, this parameter is defined as

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

where the invariant spectrum of (anti)protons is evaluated at the reduced transverse momentum $p_{\mathrm{T}}^p = p_{\mathrm{T}}^A / A$. In this model, since protons and neutrons belong to the same isospin doublet, their production spectra are assumed to be the same. The state-of-the-art coalescence model uses the Wigner formalism, where both the source size and the dependence on the wave function of the final state are taken into account [9].

In this paper, an overview of recent ALICE results on light (anti)nuclei production measurements will be presented, comparing them to the model predictions available. The light (anti)nuclei are identified using the Time Projection Chamber (TPC) and Time-Of-Flight (TOF) detectors of the ALICE apparatus, described in detail in ref. [10].

2. – Experimental results and comparison with models

The light (anti)nuclei production has been studied in different collision systems and energies, considering its dependency on the multiplicity [1-6].

In Pb–Pb collisions, it is possible to study the nuclei formation up to ^{4}He. The measurements on heavy-ion central collisions are crucial for the comparison with the SHM. As reported in fig. 1, the particle yields, ranging from pions to ^{4}He, are well described by a common freeze out temperature of about 156 MeV in central (0–10%) Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, but for protons, charged kaons, charged Ξ and

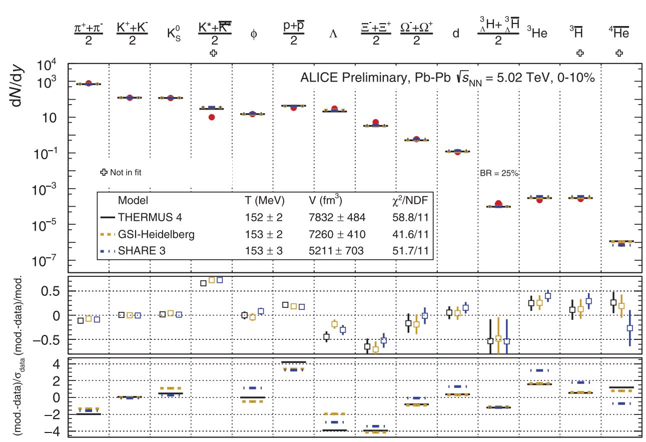

Fig. 1. – Particle yield in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV compared to the prediction from three different implementations of the SHM.

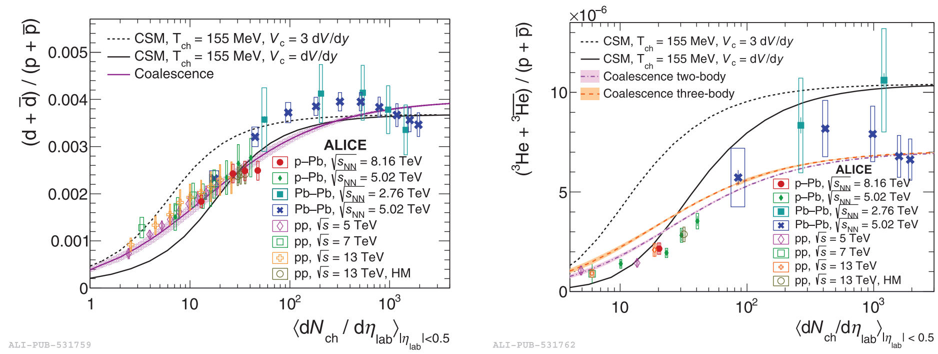

Fig. 2. – d/p (left) and ^{3}He/p (right) ratios as a function of the multiplicity in different collision systems. The lines correspond to different model parametrization, both for Thermal-Fist CSM and coalescence [3].

Λ there is a discrepancy between the expected and measured yields of about 4σ. In pp and p-Pb collisions, instead, it is possible to identify up to ^{3}He nuclei, and the obtained results are useful to constrain the coalescence model in different ways.

A useful observable to compare with the prediction from the models is the yield ratio of the produced nuclei and the protons as a function of the multiplicity, as reported in fig. 2. These ratios evolve smoothly with the multiplicity, and there is a saturation for multiplicity values typical of Pb–Pb collisions. The ratios are compared with both predictions from the Thermal-Fist Canonical Statistical Model (CSM) and the coalescence model, which give similar predictions for the deuteron, while they diverge for the ^{3}He, with the data better described by the coalescence model, even if there are some tensions at intermediate multiplicity [3].

The coalescence parameter can be calculated as a function of the multiplicity, as reported in fig. 3. It evolves smoothly with the multiplicity, and two different parametrizations of the source size as a function of the particle multiplicity are available. The experimental results are consistent with both models at low multiplicity, while they diverge at high multiplicity [2, 3].

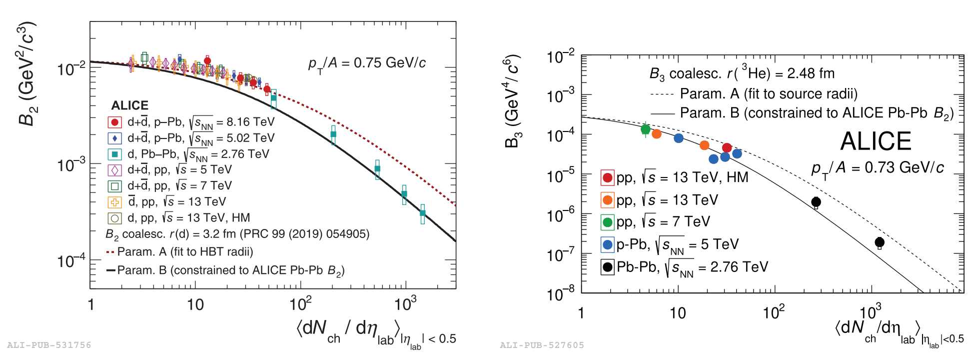

Fig. 3. – Coalescence parameter for deuteron (left) and ^{3}He (right) as a function of the multiplicity in different collision systems. The lines correspond to different model parametrization for the source size [2, 3].

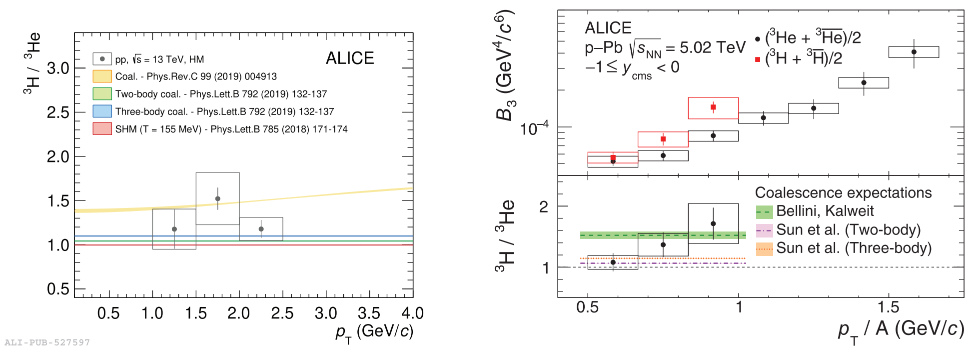

Fig. 4. – ^{3}H/^{3}He in pp high multiplicity collisions at $\sqrt{s} = 13$ TeV (left) and p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (right) as a function of the reduced transverse momentum [2, 4].

In order to constrain the coalescence model, two other observables can be discussed: the ^{3}H/^{3}He ratio and the coalescence parameter in and out of jets. In the case of ^{3}H/^{3}He ratio, according to the coalescence model, this value is expected to be greater than unity, since ^{3}H and ^{3}He have different source sizes due to the breaking of the isospin symmetry by the Coulomb repulsion. In the SHM, instead, this ratio is expected to be consistent with unity. The models predict the largest difference in systems with low multiplicity: for this reason the ^{3}H/^{3}He has been studied both in high multiplicity pp collisions at $\sqrt{s} = 13$ TeV [2] and p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [4]. The ratio, reported in fig. 4, is greater than unity in both systems, as predicted by the coalescence model, but the precision of the present data is not enough to distinguish between the models.

The other way to constrain the coalescence model is to study the coalescence parameter in small systems in and out of jets. In fact, in this case, the nucleons in jets are closer in the phase space with respect to larger systems like Pb–Pb: for this reason the coalescence model predicts an enhanced coalescence parameter in jets with respect to the underlying event. The particle with the highest p_{T} and higher than a fixed threshold (in this case $p_{\mathrm{T}} > 5$ GeV/c) is used as a proxy for the jet axis and, adopting the CDF tech-

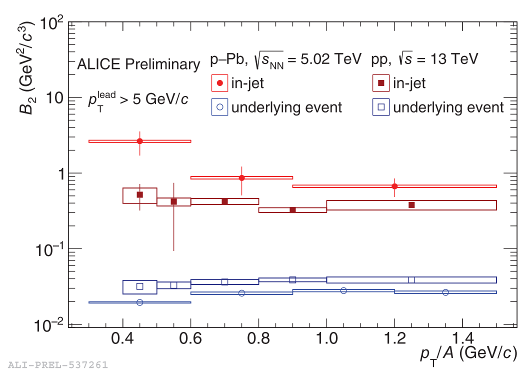

Fig. 5. – Coalescence parameter B_2 in and out of jets in pp collisions at $\sqrt{s} = 13$ TeV (darker points) [6] and p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (brighter points) as a function of the reduced transverse momentum.

nique, three azimuthal regions of equal width are identified: the *Toward*, that contains the jet and the underlying event; the *Away*, with the recoil jet and the underlying event; the *Transverse*, dominated by the underlying event. The jet contribution is then obtained as a subtraction of spectra between the Toward and Transverse regions. The results obtained for the deuteron coalescence parameter in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ [6] and p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02\,\text{TeV}$ are reported in fig. 5. An enhancement of the B_2^{jet} with respect to B_2^{UE} is observed in both pp and p–Pb collisions, with the gap between the two larger in p–Pb system. The underlying event results can be easily interpreted with the coalescence model: since the p–Pb system has a source size larger with respect to pp, 1.5 fm [11] against 1 fm [12], the coalescence parameter in p–Pb is expected to be smaller with respect to the same quantity in pp. For the in-jet part a possible explanation is that in p–Pb jets the particles are closer in the phase space with respect to the pp system, hence the larger B_2, but more studies are needed, since the particle composition of jets could also affect the coalescence probability.

3. – Conclusions and outlooks for Run 3 measurements

In this contribution, an overview of the recent ALICE results on light (anti)nuclei measurements has been presented and discussed in the context of the available phenomenological models that describe the hadronization process, *i.e.*, the Statistical Hadronization Model and the baryon coalescence. In both cases, the models qualitatively reproduce the data, and for this reason new sets of observables are needed. To further test the coalescence model it is possible to study the coalescence parameter in and out of jets, where enhanced values in jets are observed with respect to the same quantity in the underlying event. With the Run 3 data, this type of study can be further extended: first of all, thanks to the high integrated luminosity that will be collected, a more precise determination of the coalescence parameter could be performed. Moreover, a multi-differential approach can be adopted, where the jet can be reconstructed with jet finder algorithms and the coalescence parameter could be studied as a function of the jet radius and particle multiplicity.

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