Measurements of (anti)(hyper)nuclei with ALICE

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Abstract. The investigation of the production mechanism of light (anti)(hyper)nuclei in ultrarelativistic hadronic collisions is one of the main topics in modern nuclear physics. The ALICE Collaboration has significantly contributed to this specific field of research with systematic measurements of the production of (anti)(hyper)nuclei in different collision systems and centre-of-mass energies provided by the Large Hadron Collider. Measurements of the properties of hypernuclei, such as their lifetimes and binding energies, provide information on the hadronic interaction between hyperons and nucleons, which is complementary to that obtained from correlation measurements. In this contribution, recent results on the production of (anti)(hyper)nuclei measured with ALICE during the LHC Run 2 in different collision systems will be presented. These results will be discussed within the context of the statistical hadronization model and baryon coalescence. For the first time, the observations of the (anti)hyperhydrogen-4 and (anti)hyperhelium-4 in Pb–Pb collisions at 5.02 TeV will be shown. Moreover, new results on (anti)(hyper)nuclei measurements obtained using the LHC Run 3 data will be presented.

1 Introduction

Light nuclei heavier than protons (such as deuteron, triton, helium-3 and helium-4) are complex objects composed of protons and neutrons which are known since many decades. However, the details of their production mechanism in high-energy hadronic collisions are still not entirely understood. This causes debates in the scientific community. In general, theoretical phenomenological models describing the production yields of light nuclei in such collisions can be divided into two classes. In the statistical hadronisation models (SHM) [1], light nuclei are assumed to originate from a source in local thermodynamical equilibrium with the production yield following an exponential dependence as $\mathrm{d}N/\mathrm{d}y \propto e^{-m/T_{\mathrm{chem}}}$, where m is the mass of the nucleus and T_{chem} is the temperature of the system at chemical freeze-out (around 156 MeV). Such models describe very well the integrated yields of light nuclei in nucleus–nucleus collisions [2], but cannot provide detailed information such as their momentum distributions. In the coalescence models [3], nuclei are produced by coalescence of protons and neutrons which are close to each other in phase space. The simplest version of such models assumes a formation of a bound state if the nucleons are close enough in momentum space, neglecting spacial correlations between nucleons. Some of the latest state-of-the-art implementations however take into account the overlap between the phase space of the nucleons and the Wigner density function of the final bound state to calculate the coalescence probability [4].

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The antimatter partners of light nuclei such as antideuterons and antihelium nuclei in outer space have been considered since long time as a unique probe for exotic physics potentially extending beyond the Standard Model. In the low-energy range, their production cross-sections from ordinary background processes in the Universe (collisions of cosmic-ray particles with interstellar medium) are expected to be very low. At the same time, many theoretical models predict that potential signals from processes like dark-matter (DM) decays can exceed this background by several orders of magnitude [5–8]. This makes possible observations of low-energy antinuclei in space near Earth a potential breakthrough in modern physics and a smoking gun candidate for indirect DM searches. In this context, measurements of light antinuclei production at accelerator facilities, in particular in small systems as proton–proton (pp) and proton–ion (p–A) collisions, are of utmost importance for correctly interpreting the results from balloon- and space-borne experiments in the future.

Bound states of nucleons and hyperons (e.g. Λ baryon) called hypernuclei have attracted a lot of interest of the scientific community since their first observation in 1953. Such objects offer the possibility to study the hyperon–baryon and hyperon–hyperon interactions, which are of great importance for nuclear physics and nuclear astrophysics. For instance, the knowledge of hyperon–baryon interaction plays a key role in understanding and modelling of astrophysical objects like neutron stars, as the presence of hyperons as an additional degree of freedom leads to a considerable softening of the matter equation of state [9, 10]. Since hypernuclei are weakly bound systems, they are also sensitive probes to distinguish between different production scenarios of light nuclei described above and allow for testing other theories such as nuclear shell model [11].

2 Production of light (anti)nuclei across collision systems

Figure 1 summarises the measurements of production yields of light (anti)nuclei in various collision systems and at different energies performed by the ALICE Collaboration. Both deuteron-over-proton and helium-3-over-proton ratios show a smooth evolution with multiplicity and system size [12], which can possibly be explained by the same underlying mechanism of light (anti)nuclei production across the collision systems. A good description of results is achieved with coalescence-based models, whereas a tension between statistical models and experimental data for $A = 3$ nuclei is observed. The same kind of smooth evolution is also found for the B_A coalescence parameter at fixed transverse momentum [13]. The decrease of the B_2 parameter at larger multiplicities can be explained by a larger system size, which leads to spatial separation between the nucleons and to a lower coalescence probability compared to small systems. The experimental results for the B_2 coalescence parameter are compared in Fig. 1 (right) to two versions of the coalescence model [14], in which the source size is parameterised according to either HBT radii measurements in small systems or to B_2 measurements in heavy-ion collisions. More detailed studies with the larger statistics data sample collected during the ongoing LHC Run 3 will allow one to pin down the tension between various theoretical models to an unprecedented precision.

3 (Anti)hypernuclei measurements with ALICE

So far, the ALICE collaboration has measured the production and properties of (anti)hypertriton [15], the lightest (anti)hypernucelus which is a bound state of an (anti)proton, an (anti)neutron and an (anti-)Λ baryon. Figure 2 (left) shows the hypertriton-over-Λ ratio as a function of the mean charged-particle multiplicity density compared to the predictions from theoretical models. The small separation energy of the Λ hyperon in this

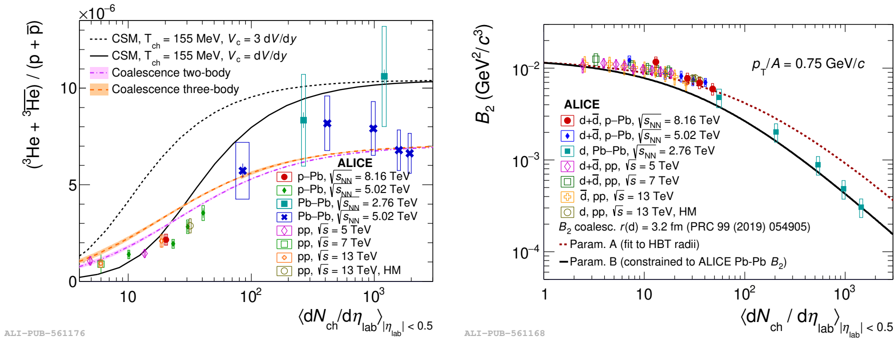

Figure 1. Left: helium-3 over proton ratio as a function of the mean charged-particle multiplicity density. Right: B_2 as a function of the mean charged-particle multiplicity density for a fixed value of p_T/A = 0.75 GeV/c.

nucleus (of about 130 keV) results in an RMS radius (average distance of the Λ to deuteron) of 10.6 fm, which is much larger than the system size created in pp and p–A collisions, making the hypertriton a very sensitive probe to test the production mechanisms in small collision systems. The latest results from the ALICE collaboration clearly favour coalescence models in small collision systems as the underlying hypertriton production mechanism.

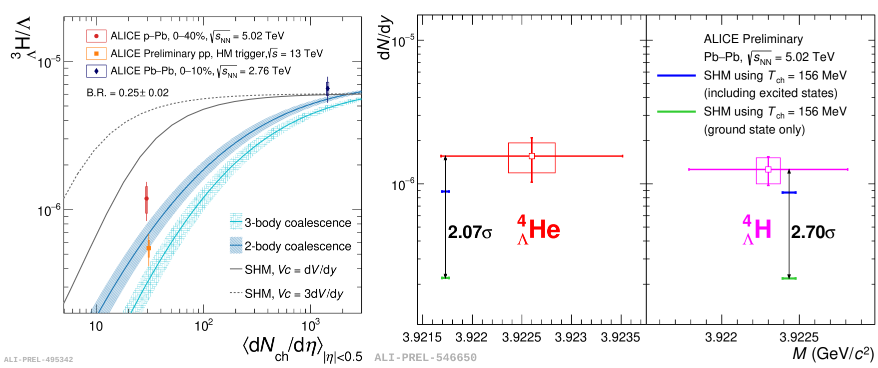

Figure 2. Left: hypertriton-over-Λ ratio as a function of the mean charged-particle multiplicity density. Right: integrated yields of hyperhydrogen-4 and hyperhelium-4 in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to the predictions from SHM.

Using careful topological selection and a machine learning approach based on the boosted desicion tree algorithm for the signal extraction, the ALICE Collaboration has observed for the first time at the LHC energies the signal of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The results (Fig. 2 right) agree with SHM predictions which take into account the feed-down from excited states for both of these hypernuclei. More detailed studies of Run 3 data with larger statistics will help to shed light on the fundamental charge symmetry breaking, which is not yet fully understood from the theoretical point of view [16].

4 First signal of $^{4}\overline{\mathrm{He}}$ in pp collisions

In the last few years, the ALICE Collaboration has successfully completed a series of upgrades for its detector, which among the other improvements allowed for the collection of an unprecedentedly large sample of pp collisions of more than 0.5×10^{12} events in 2022. The upgraded Time Projection Chamber (TPC) provided a clear identification of light (anti)nuclei over the wide momentum range using their specific energy loss $\mathrm{d}E/\mathrm{d}x$ in the TPC gas (Fig. 3 left). Such a large data sample of pp collisions together with excellent TPC $\mathrm{d}E/\mathrm{d}x$ resolution made possible the first observation of a clear $^{4}\overline{\mathrm{He}}$ signal in pp collisions (Fig. 3 right). This measurement will be of great importance for astrophysics in the context of potential $^{4}\overline{\mathrm{He}}$ events reported by the AMS-02 Collaboration [17], since so far the corresponding background from astrophysical processes has been constrained only by theoretical modelling and extrapolations from existing measurements of lighter (anti)nuclei production [18].

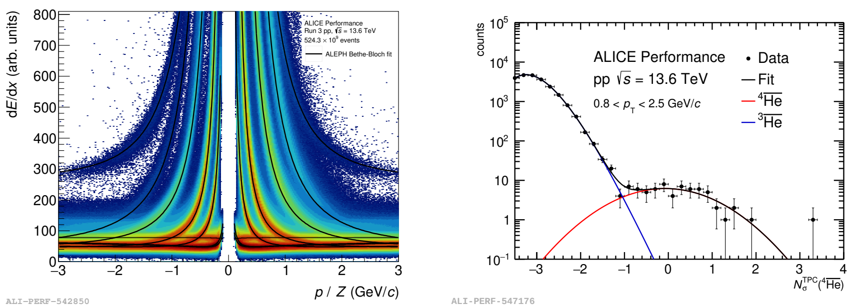

Figure 3. Left: TPC $\mathrm{d}E/\mathrm{d}x$ signal in pp collisions at $\sqrt{s}$ = 13.6 TeV. Right: $^{4}\overline{\mathrm{He}}$ signal obtained from the fit to $N_{\sigma}^{\mathrm{TPC}}$ distribution in $0.8 < p_{\mathrm{T}} < 2.5$ GeV/c momentum range.

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