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Cosmic $\overline{\mathrm{d}}$ and $\overline{\mathrm{He}}$: production mechanisms and latest constraints from ALICE at the LHC

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The formation mechanism of light (anti)nuclei in high-energy hadronic collisions remains an open question in high-energy physics. Their production mechanism is investigated by comparing experimental data with phenomenological models using statistical hadronization or a coalescence approach.

In particular, the coalescence mechanism finds an essential application in cosmic antinuclei studies for indirect dark matter searches with space-based experiments like AMS. Cosmic $\overline{\mathrm{d}}$ and $\overline{\mathrm{He}}$ are supposed to be produced via coalescence of nucleons stemming from either dark matter particle interaction or decay, or by interactions of primary cosmic rays with the interstellar matter. Constraining the formation of (anti)nuclei mechanism with experiments in controlled conditions at accelerators is essential to reduce uncertainties on cosmic antinucleus flux estimates.

Thanks to the excellent tracking and particle identification performance, the ALICE experiment has performed a broad set of precision measurements on (anti)nuclei produced in different collision systems (pp, p–Pb and Pb–Pb) since the beginning of its operations. Furthermore, the ALICE apparatus underwent a series of major upgrades to take full advantage of the luminosity increase of the LHC Run 3. The results of these latest Run 3 $\mathrm{d}(\overline{\mathrm{d}})$ and $^{3}\mathrm{He}(^{3}\overline{\mathrm{He}})$ measurements, the most recent results on the measured formation probability of bound objects as a function of the final-state charged particle multiplicity in comparison to state-of-the-art models, will be extensively discussed.

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1. Introduction

The mechanism underlying the production of light (anti)nuclei in high-energy collisions remains not fully understood. With binding energies around 1 MeV per nucleon, these (anti)nuclei have significantly lower energy compared to the chemical freeze-out temperature of temperature of the hadron gas emerging from the hadronization of the quark-gluon plasma created in heavy-ion collisions ($T_{\mathrm{ch}} \approx 155$ MeV[1]). Despite these extreme conditions, these bound states are successfully produced, survive through the hadronic phase and can eventually be detected by the ALICE detector.

The ALICE Collaboration is entering in a new era of precision studies, as the unprecedentedly large data samples collected during the LHC Run 3 high-energy collisions offer an excellent opportunity to investigate (anti)nucleus formation.

2. Cosmic antinuclei and the search for dark matter

Cosmic-ray antideuteron and antihelium nuclei have been proposed as potential signatures of dark matter (DM) candidates called Weakly Interacting Massive Particles (WIMPs), such as the neutralino χ. The antinuclei can originate from either $\chi\bar{\chi}$ pair annihilation or χ decay processes occurring within the galactic halo [2]. This production mechanism is predicted to have minimal or negligible background noise from interactions between cosmic rays and interstellar matter (ISM). As a result, the measurement of cosmic antinucleus flux is a promising path for indirect dark matter searches, actively targeted by space-based experiments like the currently operational AMS-02 and the upcoming GAPS mission, scheduled to launch at the end of 2024.

3. Antinucleus formation models

Two primary models are used to describe the production of nuclei and antinuclei: the *statistical hadronization model* (SHM) and the *coalescence* model.

Statistical hadronization model The SHM [3] is a statistical model used to describe the relative abundances of different particle species. In this model, particles emerge from an excited volume composed by all possible phase-space states, and the final particle states are constrained by quantum-mechanical conservation laws. The relative abundances of particles are mainly determined by the ratio of their masses to the chemical freeze-out temperature T_{ch} and follow an exponential dependence:

$$\mathrm{d}N/\mathrm{d}y \sim e^{-m/T_{\mathrm{ch}}}\,. \tag{1}$$

For proton–proton (pp) collisions, which are characterized by low charged-particle multiplicities, a *canonical statistical model* (CSM) is employed. This canonical-based approach enforces the local conservation of charges, such as baryon number and electric charge, in the so-called *correlation volume* V_c . In contrast, for heavy-ion collisions, a Grand-Canonical approach is used, where these charges are conserved on average rather than locally. In the latest case, due their low binding energy, the (anti)nuclei might break and reform during the hadronic phase between chemical and kinetic freeze-out.

Coalescence model In the coalescence model [4], nucleons that are produced close to one another in phase space can bind together through an attractive final-state interaction, resulting from the nuclear strong potential, to form a nucleus.

As the hadron gas expands, it undergoes kinetic freeze-out, with nucleons described by a quantum-mechanical density matrix. The projection of this matrix onto particle states provides the particle spectra, while the outgoing nuclei represent the bound-state solutions permitted by the final-state interaction.

In this model, the coalescence parameter B_A describes the formation probability of a nucleus with an atomic number A. The parameter B_A can be experimentally measured from the nucleus production yields $\frac{\mathrm{d}^3 N_A}{\mathrm{d}^3 p_A^3}$ and the nucleon production yields $\frac{\mathrm{d}^3 N_{p,n}}{\mathrm{d}^3 p_{p,n}^3}$ as

$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}^3 p_A^3} = B_A \left(E_p \frac{d^3 N_p}{d^3 p_p^3} \right)^Z \Bigg|_{\boldsymbol{p_p}=\boldsymbol{p_A}/A} \left(E_n \frac{d^3 N_n}{d^3 p_n^3} \right)^N \Bigg|_{\boldsymbol{p_n}=\boldsymbol{p_A}/A} \tag{2}$$

where Z is the number of protons in the nucleus and N is the number of neutrons.

The B_A parameter can be theoretically estimated based on the nucleus wave function and the source characteristics of the excited nucleons [5]. For instance, in the case of a deuteron, the coalescence parameter B_2 is estimated as

$$B_2 \approx \frac{2(2s_d + 1)}{m(2s_N + 1)^2} (2\pi)^3 \int d^3\boldsymbol{r} |\varphi_d(\boldsymbol{r})|^2 S_2(\boldsymbol{r}) \tag{3}$$

where m is the deuteron mass, φ_d is the deuteron internal wave-function, s_d and s_N are respectively the deuteron and the nucleon spin, $\boldsymbol{r} = \boldsymbol{r_p} - \boldsymbol{r_n}$ and $S_2(\mathbf{r})$ is the source of nucleons.

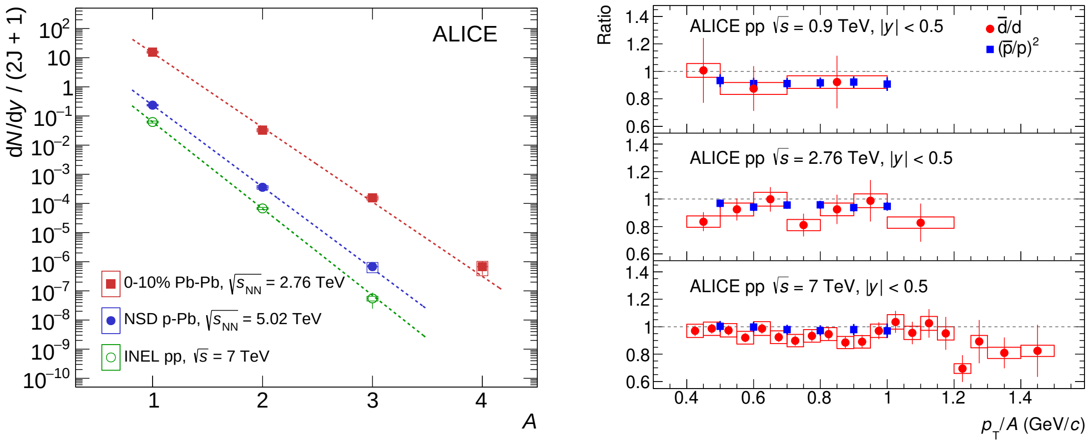

Figure 1: (Left) Production yield dN/dy normalised by the spin degeneracy as a function of the mass number for inelastic pp collisions, minimum-bias p–Pb and central Pb–Pb collisions [6]. (Right) Antideuteron-to-deuteron ratio (markers) as a function of p_T per nucleon in pp collisions compared with the $(\bar{p}/p)^2$ ratio (squares) at mid-rapidity [7].

4. Antinuclei measurements in ALICE

Due to their larger masses (see Eq.1), light nuclei are produced more rarely with respect of protons (d/p $\sim 10^{-3}$ and ^{3}He/p $\sim 10^{-6}$ in pp collisions at $\sqrt{s}$ = 7 TeV [6]). This *penalty factor* is represented in Fig. 1 (left) as a (spin degeneracy-normalised) integrated yields as a function of A. With the start of the LHC Run 3 data-taking campaign at the end of 2021, the ALICE experiment began collecting data from pp collisions at a record energy of $\sqrt{s}$ = 13.6 TeV. In 2022 alone, over 500 billion minimum-bias pp collisions were recorded, a sample far exceeding those from previous data-taking campaigns. The LHC Run 3 target luminosity and the antimatter-over-matter ratio at LHC being experimentally comparable to unity, as shown in Fig. 1 (right), make LHC the facility which provides optimal conditions for studying the mechanism of antinucleus formation.

4.1 Nucleus over protons ratio

The phenomenological models used to predict the production of nuclei in high-energy collisions (see Sec. 3) can be tested by measuring the ratio between the yields of (anti)nuclei and (anti)protons. Fig. 2 presents the ratios of (anti)deuterons to protons (left) and (anti)helium-3 nuclei to protons (right) as functions of the charged particle multiplicity at mid-rapidity. ALICE measurements of nuclei-to-proton ratios across different collision systems at the LHC [8] reveal a strong dependence on multiplicity. The coalescence model aligns well with the (anti)deuteron data, whereas both the coalescence and CSM models show a worse agreement with the (anti)helium-3 data.

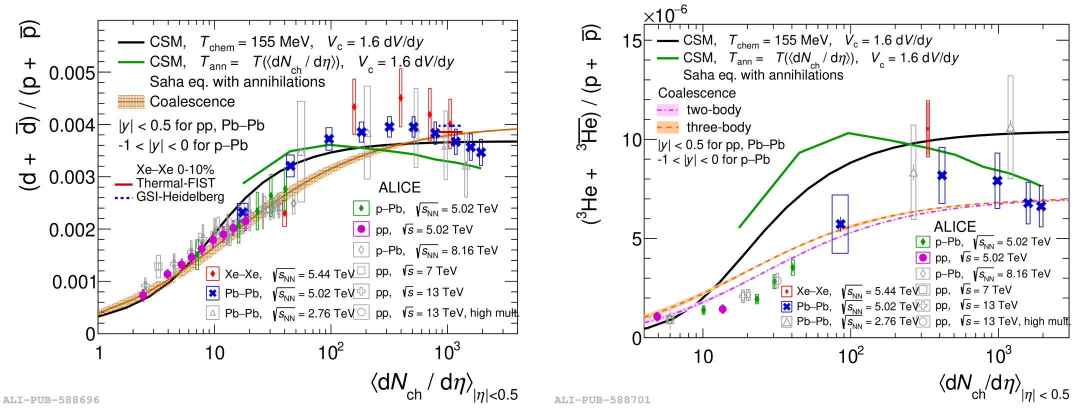

Figure 2: (Left) Deuteron-to-proton and (right) 3He-to-proton ratios shown as a function of the charged multiplicity density, measured at mid-rapidity [10]. The coalescence model predictions are shown as bands, while the black and red lines correspond to different CSM predictions.

4.2 Coalescence probability

The coalescence parameter introduced in Sec. 3 can be experimentally measured in ALICE using a formula derived from Eq. 2:

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}, \tag{4}$$

which is valid at the LHC, where protons and neutrons are expected to have approximately the same yield.

Since the beginning of LHC data collection, the ALICE collaboration has carried out various multi-differential measurements of the coalescence parameter B_A [8]. The results of these measurements are shown in Fig. 3. In high-multiplicity collisions, such as Pb–Pb, a steep decrease in the coalescence parameter with increasing charged particle multiplicity is observed. This reduction is interpreted as a consequence of the larger spatial separation of nucleons in a large source region (approximately 2–5 fm). At the same time, in low-multiplicity systems (e.g., pp or p–Pb collisions), the dependence on multiplicity is weaker, reflecting the smaller source size, with a radius around 1 fm.

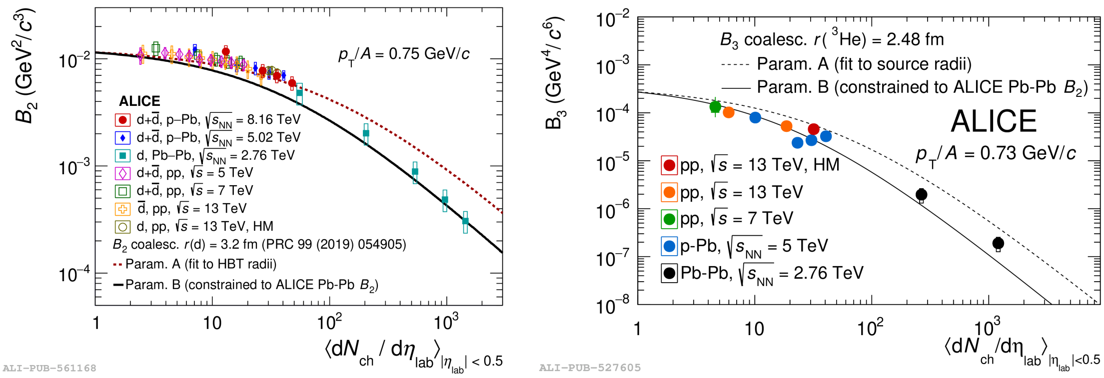

Figure 3: (Left) The coalescence parameter B_2 for at p_T/A = 0.75 GeV/c as a function of multiplicity[8]. (Right) The coalescence parameter B_3 for at p_T/A = 0.73 GeV/c as a function of multiplicity[9].

5. Antihelium measurements in the LHC Run 3

During the Long Shutdown 2 (2019–2021), the ALICE detector was upgraded [11] to improve the track reconstruction performance and to enable taking data at a higher rate during the Run 3 data taking campaign. This allows the collection of unprecedentedly large data samples (for pp $\sqrt{s}$ = 13.6 TeV up to 3250 times the integrated luminosity with respect to Run 2). For this reason, the imminent measurements in the LHC Run 3 will fully profit of the improved performance of the upgraded ALICE apparatus. The upgraded Inner Tracking System (ITS2) allows tracking at low p_T (around 100 MeV/c) with a three times improvement in pointing resolution compared to Run 2. Meanwhile, the upgraded Time Projection Chamber (TPC) supports a higher readout rate and enhanced background suppression, allowing for excellent separation of different particle species at low p_T. The Time-Of-Flight detector (TOF) now takes advantage of readout system upgrades that enable continuous readout.

In Fig. 4 (left) the performance of particle identification via the dE/dx in the TPC in Run 3 pp collision is shown. The dE/dx of (anti)nuclei is well separated with respect to lighter species. The Run 3 data campaign allowed to perform one of the first study of the production of (anti)helium-3 with increased precision and to observe (anti)helium-4 produced in pp collisions, allowing for more differential and precise data on B_3 and B_4 that will be a fundamental input to model cosmic antihelium formation. In particular, the Run 3 statistics allowed to measure the antihelium yield with a statistical uncertainty that is between 10 to 50 times smaller with respect to the previous measurements, as shown in Fig. 4 (right).

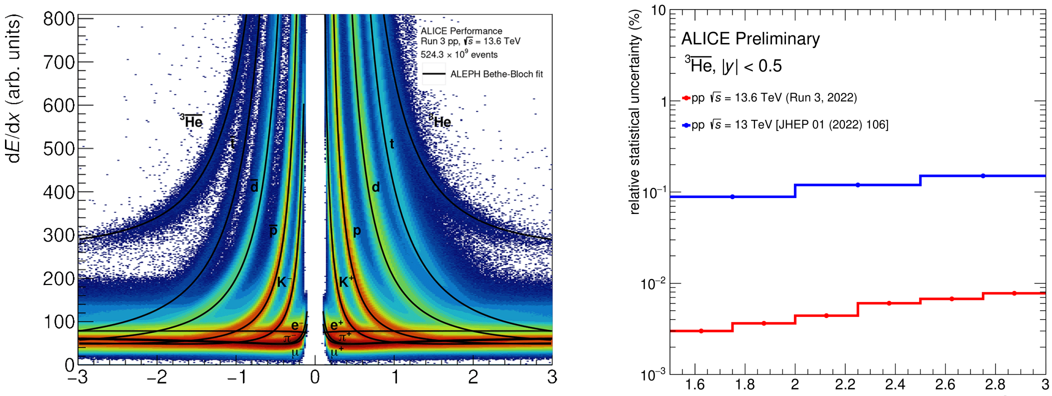

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Figure 4: (Left) ALICE TPC dE/dx particle identification performance in Run 3 pp collisions at $\sqrt{s}$ = 13.6 TeV. (Right) Relative statistical uncertainty for antihelium produced in pp collisions at $\sqrt{s}$ = 13 TeV in Run 2 (in blue) and at $\sqrt{s}$ = 13.6 TeV in Run 3 (in red).

6. Conclusions

Understanding the formation of light (anti)nuclei in high-energy collisions is a central topic for the ALICE Collaboration. At moment several multi-differential analyses are underway to explore (anti)nucleus formation within the SHM and coalescence models. These analyses fully utilise the upgraded capabilities of the ALICE apparatus, which offer an increased data-taking rate and consistently excellent PID performance. The results of these measurements are a crucial input to indirect search for DM, as the antihelium production at colliders can characterise the main background in searches for cosmic antinuclei from DM particle interactions with ISM.

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