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Constraining the formation mechanisms of light (anti)nuclei at the LHC and applications for cosmic ray physics

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Summary. — The formation mechanism of light (anti)nuclei produced in high-energy hadronic collisions is an open question that is being addressed both theoretically and experimentally. Moreover, the study of (anti)nuclei production at particle accelerators is relevant to model the flux of antinuclei produced in cosmic ray interactions, which represents the dominant background for dark matter searches. According to the most accredited theoretical models, dark matter particles in the galactic halo could annihilate and produce ordinary matter-antimatter pairs. Thanks to its excellent particle identification capabilities, ALICE measured (anti)nuclei in all the collision systems and energies provided by the LHC. Measurements of transverse momentum distributions, ratios of integrated yields, and coalescence probabilities are discussed in these proceedings in comparison with two phenomenological models used to describe the production of nuclei. The performance of the upgraded ALICE detector during the proton proton data taking in Run 3 is discussed together with perspectives on new applications to indirect dark matter searches by the AMS experiment.

1. – Introduction

The production mechanism of light (anti)nuclei in high-energy collisions is not fully understood. The binding energy of (anti)nuclei is of the order of 1 MeV per nucleon, an extremely low value compared to the the chemical freeze-out temperature of a heavy-ion collision ($T_{ch} > 150\,\mathrm{MeV}$). Nevertheless, these bound states are produced in those extreme conditions, survive, and then can be detected by the ALICE apparatus. At present, ALICE is entering a new precision era as the LHC Run 3 high-energy collisions unprecedentedly large-data samples provide very good conditions for studying the formation of (anti)nuclei.

Two different models are used for describing the nuclei production: the statistical hadronization (SHM) and the coalescence model.

2. – (Anti)nuclei production models

2˙1. *Statistical hadronization models.* – The SHM [1] is an implementation of statistical model for particle formation. In the SHM, particles originate from an excited volume that is occupied by all the possible states in the phase space: the final state is composed by the particle states allowed by the quantum-mechanical conservation laws. The abundances depend on the ratio between particle masses and the chemical freeze-out temperature, as $\mathrm{d}N/\mathrm{d}y \sim e^{-m/T_{ch}}$.

To describe pp collisions (characterized by low charged-particle multiplicities) a Canonical Statistical Model (CSM) approach is used, which requires the local conservation of charges (baryon number, electric charge, ...). Whereas, in heavy-ion collisions a Grand-Canonical approach is applied, which only conserves these charges on average.

2˙2. *Coalescence model.* – In the coalescence model [2] the nucleons which are produced close to each other in phase space can bind to each other thanks to an attractive final-state interaction (due to the nuclear strong potential) and form a nucleus. State-of-the-art models take into account the quantum-mechanical nature of the nucleons, and the phase space of the nucleus is replaced by its Wigner function. The expansion of highly excited state leads to kinetic freeze-out with nucleons, which is described by a QM density matrix. The projection onto particle states gives the particle spectra. The outgoing nuclei are the bound-state solutions allowed by the final-state interaction. The formation probability in the coalescence model is described by the coalescence parameter B_A. This parameter can be theoretically predicted knowing the wave function of the nucleus and the source of excited nucleons [3]. For a deuteron, *e.g.*, the coalescence parameter B_2 is estimated as

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

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

The coalescence parameter can be experimentally measured as

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

3. – (Anti)nuclei measurements

3˙1. *Nuclei over p ratio.* – The measurement of the ratio between (anti)nuclei and (anti)protons produced in high-energy collisions is a test for predictions of the phenomenological models. Figure 1 shows the ratio of (anti)deuterons over protons and (anti)helium-3 nuclei over (anti)protons, as a function of the charged particle multiplicity at mid-rapidity. ALICE measurements of nuclei over proton ratio in different collision systems at the LHC [4] show a strong multiplicity dependence and a colliding system dependency. In particular, coalescence model is in good agreement with the (anti)deuteron data, while both coalescence and CSM show a weaker agreement with the (anti)helium-3 data.

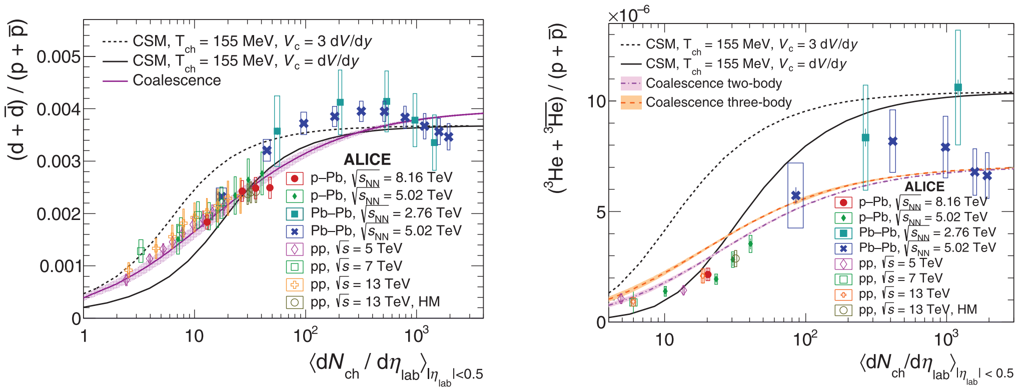

Fig. 1. – Ratio of (anti)deuterons over protons and (anti)helium-3 nuclei over protons [4].

3·2. *Coalescence probability.* – The ALICE Collaboration performed several multi-differential measurements of the coalescence parameter B_A [4], starting from the very beginning of the LHC data-taking operations. A significant drop of the coalescence parameter as a function of charged particle multiplicity is visible in high-multiplicity collisions (*e.g.*, Pb-Pb): this effect is due to larger space separation of the nucleons in a large source (∼2–5 fm). A weaker dependence on multiplicity is visible in low-multiplicity systems (as pp or p-Pb collisions), due to the smaller sources dimension (∼1 fm radius).

4. – Light antinuclei as smoking guns for Dark Matter

Cosmic ray antideuteron and antihelium nuclei have been suggested as possible smoking guns for dark matter WIMPs, χ. The antinuclei could be produced as a result of $\chi\bar{\chi}$ pair annihilation or χ decay in the galactic halo [5]. This mechanism is expected to have low or no background from interactions of cosmic rays (CR) with interstellar matter (ISM). The cosmic antinuclei flux is therefore a subject for indirect DM searches with space-based experiments such as AMS-02 (ongoing) or GAPS (planned at the end of 2023). One of the key ingredients to predict the cosmic antinuclei flux is the measurement of the inelastic cross-section to account for (anti)nuclei absorption by ISM. This measurement has been recently performed by the ALICE Collaboration [6]. The (anti)helium inelastic cross-section has been measured using the ALICE apparatus as an absorbing medium. The measurement has been performed with two different methods: the antimatter-to-matter ratio and the TOF-to-TPC ratio method. Both measurements have been compared with Monte Carlo simulations: the data shows a 2σ compatibility with GEANT4 simulations. Furthermore, ALICE estimated the transparency of the Galaxy to antihelium-3 as the ratio between cross-sections with and without inelastic scattering (fig. 2). For low kinetic energy Dark Matter originated candidates, the transparency is around 50%: half of the antinuclei due to Dark Matter annihilation or decay would travel through the Galaxy without being absorbed.

5. – The upgraded ALICE

The (anti)nuclei measurements shown in this proceedings have been possible thanks to the unique tracking and particle identification (PID) capabilities of the ALICE apparatus.

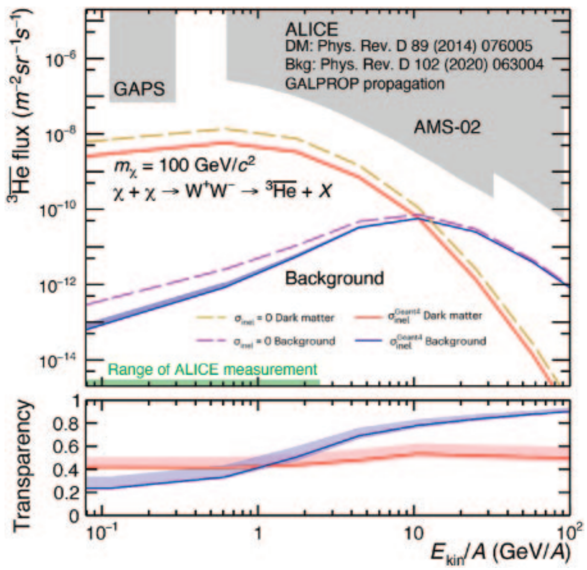

Fig. 2. – ALICE measurements of $^3\overline{\mathrm{He}}$ flux as a function of E_{kin}/A [6]. The full lines correspond to results obtained using GEANT4 parameterizations, while the dashed lines show the fluxes obtained with $\sigma_{\mathrm{inel}}(^3\overline{\mathrm{He}})$ set to zero. The shaded areas, in grey, show the expected sensitivity of the GAPS and AMS-02 experiments.

The upcoming measurements in the LHC Run 3 will benefit from the improved capabilities of the upgraded ALICE apparatus. The upgraded Inner Tracking System (ITS2) allows for excellent tracking down to low p_{T} ($\sim$100 MeV/c) with a 3-times improved pointing resolution with respect to Run 2, while the upgraded Time Projection Chamber (TPC) allows for an increased readout rate and an improved background suppression, providing an excellent separation of different particle species at low p_{T}. To perform the PID of higher p_{T} particles, the Time-Of-Flight detector (TOF) now benefits from the upgrades of the readout systems, allowing for continuous readout. In fig. 3 the response

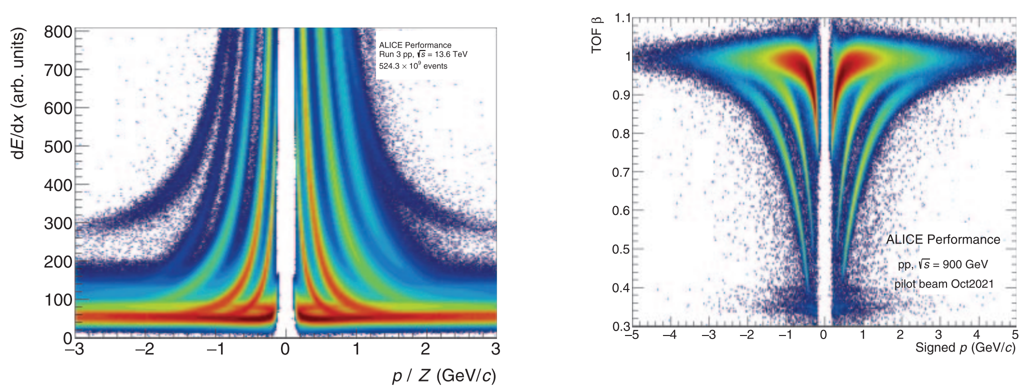

Fig. 3. – (Left) ALICE TPC dE/dX PID performance in Run 3 pp collisions at $\sqrt{s} = 13.6$ TeV. (Right) ALICE TOF β PID performance in Run 3 pp collisions at $\sqrt{s} = 900$ GeV.

of ALICE TPC and TOF in Run 3 pp collision is shown: (anti)nuclei responses are well separated with respect to lighter species. These upgrades will allow to improve multi-differential (anti)nuclei analyses taking advantage of the unprecedentedly large data samples to be collected during the LHC Run 3.

6. – Conclusions

The search to understand the formation of light (anti)nuclei produced in high-energy collisions is a pivotal topic addressed by the ALICE Collaboration. At the moment, several multi-differential analyses are being performed to better understand the (anti)nuclei formation taking into account the SHM and coalescence models, taking full advantage of the upgraded ALICE apparatus features, allowing for an increased data-taking rate, as well as of the confirmed excellent PID performance.

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