Exotic particles and nuclei

Highlights from relativistic particle collisions

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Abstract. Light nuclei, antinuclei and hypernuclei constitute a laboratory to study the mechanisms of formation of bound states in proton-proton and nucleus-nucleus collisions over a broad range of collision energies, providing insights into the nuclear structure as well as into the strong interaction. In this contribution, a selection of the experimental results and latest developments presented at the Quark Matter 2023 conference is reviewed.

1 Introduction

Over the last few years, experiments at hadron and heavy-ion colliders have released an impressive amount of data on the production and interaction with matter of light (anti)nuclei, as well as on the production and properties of light (anti)hypernuclei. These include deuteron (d), triton (t), helium-3 (^{3}He) and helium-4 (^{4}He), hypertriton ($^3_\Lambda$H) and $A = 4$ hypernuclei as well as their antimatter counterparts. The results presented and discussed at the Quark Matter 2023 conference confirm this as a rich field of research. This summary, however, does not long to be a complete overview of the field, but rather highlight new promising developments and provide a tentative wishlist for measurements with improved precision in the near future.

2 Production of (hyper)nuclei vs models

New preliminary results presented at this conference include production yields and flow of light nuclei and hypertriton measured using the RHIC beam energy scan data at $\sqrt{s_{\mathrm{NN}}} = 3$ to 18 GeV by the STAR Collaboration [1]. Among other results, the ALICE Collaboration reported on the first $A = 4$ (anti)hypernuclei in heavy-ion collisions at the LHC, on the first ever observation of the antimatter hypernucleus $^4_{\overline{\Lambda}}\overline{\mathrm{He}}$ [2], and on the first signals of $^4\overline{\mathrm{He}}$ in pp collisions [3].

Statistical hadronisation model (SHM) calculations [4, 5] describe the collision energy dependence of the yields of light (anti)nuclei from few GeV to few TeV in $\sqrt{s_{\mathrm{NN}}}$. The best agreement is obtained for deuteron yields whereas tensions are observed for $A = 3$ (hyper)nuclei at low energy, where the (t×p)/d^2 yield ratio is overpredicted by a factor of two at RHIC [6]. A better agreement of predictions from transport models with coalescence [7] than of SHM calculations suggest that at low and intermediate collision energies, the production of light clusters at midrapidity is dominated by hadronic interactions in a dense baryon

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environment. However, nuclear fragmentation can contribute to nucleus production at target rapidities. A new measurement of the directed flow v_1 of light nuclei at $\sqrt{s_{\mathrm{NN}}} = 3$ GeV by STAR [1] shows mass number scaling at midrapidity, but breaking of such scaling in the target rapidity region, which is interpreted as a consequence of production by fragmentation.

The production of (hyper)nuclei is also affected by feeddown from excited states. Below $\sqrt{s_{\mathrm{NN}}} \sim 10$ GeV, feeddown accounts for up to the 20% and 60% of the yields for A = 2 and A = 3, 4 nuclei, respectively, whereas it contributes for few percents only to the yields at higher energies [5]. Notably, the presence of yet undiscovered excited states can be revealed by comparing precise measurements to the SHM predictions, where the yield depends on the state spin degeneracy, $\mathrm{d}N/\mathrm{d}y \sim (2J + 1)\exp(-m/\mathrm{T}_{ch})$, with J being the spin of the state, m its mass and T_{ch} the chemical freeze-out temperature. Preliminary STAR data on the ${}^{4}_{\Lambda}\mathrm{H}/{}^{4}\mathrm{He}$ ratio [8] can be reproduced by SHM only if one excited state of ${}^{4}_{\Lambda}\mathrm{H}$ is included in the calculation (Fig. 1, left [9]). Similarly, new preliminary ALICE measurements of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ yields in Pb–Pb collisions [3] suggest that the tension with SHM predictions based on ground states only can be largely recovered if excited states are accounted for (Fig. 1, right).

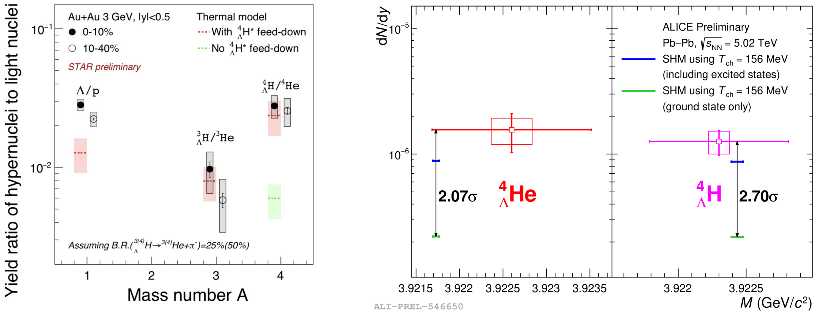

Figure 1. Yields of hypernuclei compared to thermal model predictions with and without feeddown: (left) ratio to light nuclei yields in Au–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 3$ GeV [9], and (right) yields of $A = 4$ hypernuclei in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [3].

Additional constraints to models are provided by ALICE data on the production of light (anti)(hyper)nuclei at high energy, studied as a function of p_T, rapidity, and charged-particle multiplicity, used as a proxy for the size of the system (or *source*) [10]. The multiplicity-dependent d production, measured with high precision from pp to Pb–Pb collisions, is reproduced with comparable degree of accuracy by models of coalescence [11], transport plus coalescence (hybrid UrQMD) [7], and statistical hadronisation [12, 13]. However, in central heavy-ion collisions, the latest precise data on ${}^{3}\mathrm{He}/\mathrm{p}$ and t/p from the LHC Run 2 [12] are overpredicted by a factor of ≈ 1.4 [12] by SHM and underestimated by hybrid UrQMD by a factor of ≈ 0.6. The rare ${}^{3}_{\Lambda}\mathrm{H}$ has a unique role due to its large size (see Sec. 3) compared to the typical system size [10, 11]: the first ever measurements of ${}^{3}_{\Lambda}\mathrm{H}$ production in small systems, in p–Pb and high-multiplicity pp collisions, by ALICE (Fig. 2, left) already allow us to exclude some configurations of the models [14], and justify the effort for multiplicity-differential measurements. Another stringent test for models would be a high-precision measurement of the $\mathrm{t}/{}^{3}\mathrm{He}$ yield ratio in pp collisions (see Fig. 2, right [12]). These nuclei have similar mass but different internal structure: their yield ratio is expected to be unity according to the SHM (sensitive to the mass but not on the size of the bound state) and larger than one according to coalescence (sensitive to the wavefunction and thus the nucleus size).

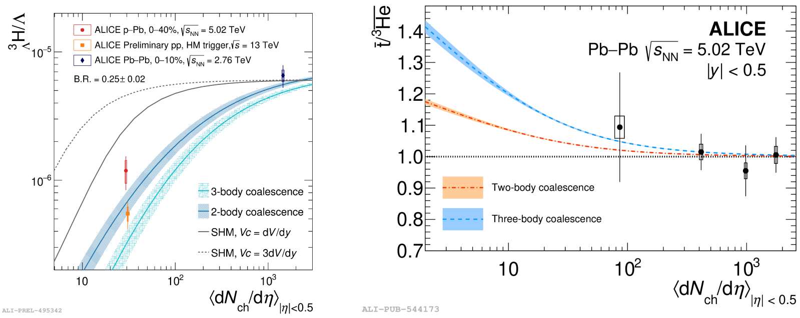

Figure 2. Charged particle multiplicity dependence of ${}^{3}_{\Lambda}$H/Λ (left) and $\bar{t}/{}^{3}\overline{\mathrm{He}}$ (right) compared to SHM and coalescence model calculations [14].

Additional insights into production via coalescence in small systems come from studies of deuteron production in jets: first results by ALICE, based on LHC Run 2 data, show an enhanced d coalescence probability in jets with respect to the underlying event in pp [15] and in p–Pb collisions [16]. This is understood as due to a reduced distance in phase space of nucleons within jets. Considering a jet as stemming from a single parton, such studies allow to test the limits of coalescence in small, nearly point-like, sources and potentially mimic the environment of e^+e^- collisions.

Motivating further the experimental characterisation of the particle source, a recent study [17] successfully demonstrated that by combining data on the proton p_T-spectrum and on the nucleon source radius measured in the same event class (there, high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV, from ALICE), a realistic simulation of the deuteron yield can be obtained using a coalescence afterburner to Monte Carlo generators on an event-by-event basis, and with no free parameters. It is noteworthy that the best agreement with data was obtained with a Wigner approach coalescence assuming realistic d wavefunctions justified by the state-of-the-art knowledge of the p–n strong interaction.

3 Hypernuclei and hadron-hadron interactions

The lifetime and binding energy of light hypernuclei are striclty linked with their internal structure and reflect the strength of the hyperon-nucleon (Y–N) interaction.

For long time, inconsistencies among world data of the ${}^{3}_{\Lambda}$H lifetime, obtained with different experimental techniques and experiments, fed the so called hypertriton lifetime puzzle, leaving open the question if the ${}^{3}_{\Lambda}$H was a weakly-bound Λ–d system as indicated by a lifetime consistent with the free Λ lifetime. In 2023, the most precise measurements to date of the ${}^{3}_{\Lambda}$H lifetime τ and Λ-separation energy (B_Λ) by ALICE [18] showed that these are compatible with predictions from effective field theories, confirming that the ${}^{3}_{\Lambda}$H is a weakly-bound system. A re-analysis of the world data with their uncertainties reveals that the tension among measurements and the updated world average (see Fig.3 left) [19] is no longer significant and hence, closes the lifetime puzzle.

A complementary approach to investigate the nuclear interaction binding baryons into (hyper)nuclei makes use of the powerful femtoscopy technique, based on measurements of the momentum correlations between two (or more) particles of interest. In a new preliminary analysis by STAR, the d−Λ correlation measured for the first time in heavy-in collisions [20] was fitted with a Lednicky-Lyuboshitz approach to determine the emission source size, the scattering lenght (f_0) and the effective range of the interaction (d_0). Notably, different spin states of d-Λ were fitted separately. The B_Λ is obtained from the measured scattering parameters and found to be consistent with world data (see Fig. 3, right), demonstrating that femtoscopic analyses provide a viable alternative way to constrain the ${}^3_\Lambda$H structure.

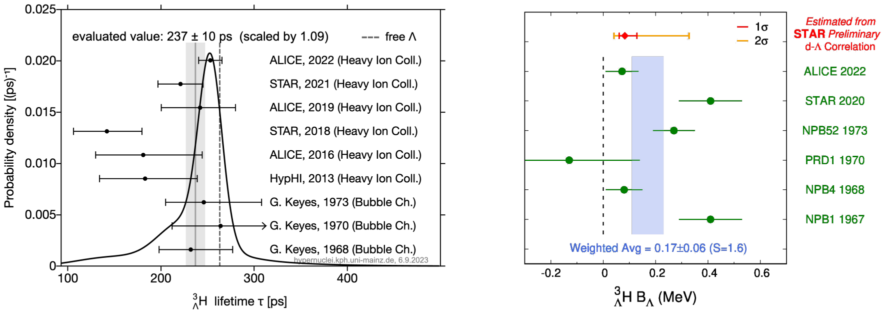

Figure 3. Left: average ${}^3_\Lambda$H lifetime (shaded band) obtained from world data compared to the free Λ lifetime (dashed line) [19]. Right: average Λ-spearation energy B_Λ in ${}^3_\Lambda$H (shaded band) obtained from world data, including the latest measurement by STAR via d$-\Lambda$ femtoscopy, in red [20].

The first ever measurement of the K$^\pm$−d scattering parameters from femtoscopy analyses in Pb–Pb [21] and in pp collisions [22] by ALICE suggest that deuterons are emitted at small distances within the source, as other hadrons. Moreover, the K−d interaction in pp collisions (Fig. 4, left) is an effective two-body interaction but the p−d correlation, also measured for the first time in pp collisions at $\sqrt{s}$ = 13 TeV (Fig. 4, right), can be modelled only by treating the d as a composite object rather than a point-like particle [22]. This further proves that femtoscopy studies can provide unique access to the genuine three-body strong interactions. Direct measurements of three-particle correlations, such as p–p–p (or p–p–Λ), require large data samples and will be accessible at the LHC Runs 3 and 4. The femtoscopy approach opens a new chapter in the study of the formation and structure of light (hyper)nuclei.

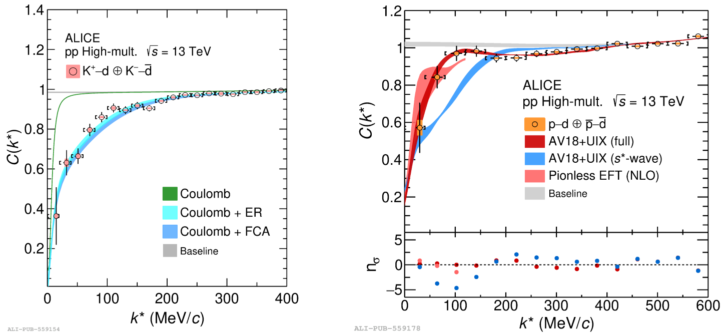

Figure 4. K−d (left) and p−d (right) correlations as a function of the pair relative momentum k*, measured in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV are shown alongside theoretical calculations [22].

4 From colliders to cosmic rays

Experiments at accelerators are in a unique position to provide input for searches for antinuclei in cosmic rays (CR) with space-based experiments such as AMS-02 and GAPS. It has been theorized that cosmic $\overline{\mathrm{d}}$ and $^{3}\overline{\mathrm{He}}$ could be produced by annihilation of dark matter particles and represent promising *smoking gun* signals due to the low background represented by secondary CR (from ordinary pp or p–A collisions of CR with the interstellar matter, mainly). Discrimination of a dark matter signal from the CR background is based on predictions for the respective fluxes. Constraints to production models come from data on $\overline{\mathrm{d}}$ and $^{3}\overline{\mathrm{He}}$ production in pp collisions discussed in Sec. 2. First ALICE analyses based on the 2022 pp data confirm that the $^{3}\overline{\mathrm{He}}$ sample is the largest collected so far, while signals of $^{4}\overline{\mathrm{He}}$ are identified for the first time in pp collisions [3]. As most flux calculations employ coalescence, the parallel developments of event-by-event afterburners based on data look promising for such applications [17]. New results of the rapidity dependence of d [16], though based on Run 2 data and limited by detector acceptance to the range $|y| \lesssim 1.7$, can provide further input to the modelling of CRs, as recent theory estimates locate most of the $\overline{\mathrm{d}}$ flux at $|y| < 2$ [23]. In LHCb, a new reconstruction strategy is proposed for the Run 3 that uses information from the tracking system to identify light nuclei at forward rapidity, allowing also for the reconstruction of the $^{3}_{\Lambda}\mathrm{H}$ decay [24]. Further studies that find application in CR physics will be performed within the LHCb SMOG-2 fixed target programme at the LHC Run 3. Further progress comes from the low energy front, where data on $\overline{\mathrm{d}}$ are scarcer or lacking. At this conference, the NA61/Shine Collaboration reported on new high precision measurement of $\overline{\mathrm{p}}$ in $|y| < 1.9$ as well as on the first $\overline{d}$ signals in pp collisions at $\sqrt{s} = 17.3$ GeV at the CERN SPS [25]. The first particle identification performance of the AMBER experiment at SPS are encouraging and pave the way for more $\overline{\mathrm{p}}$ measurements at the energies relevant for CRs [26].

5 Final remarks and outlook

A detailed comparison of theory with measurements of increased precision of light nuclear bound states in relativistic heavy-ion collisions and pp collisions over the last decade has advanced significantly formation modelling. Production can be effectively described by coalescence, transport models, and statistical hadronisation models with adjustments of assumptions and parameters. While these models were traditionally contrasted, the latest developments suggest potential convergence, offering diverse perspectives and — possibly, complementary — applications.

On the experimental side, new observables and new (hyper)nuclear species have become or will become accessibile thanks to the beam energy scan programme at RHIC and present as well as future programmes at the SPS and the LHC. Systematic and multi-differential measurements of light (hyper)nuclei as a function of p_{T}, multiplicity/centrality, collision energy and rapidity provide strong constraints to models. A still scarcely-explored avenue is the study of nucleus production in jets and at forward rapidity, which will be addressed at the LHC thanks to the expected high integrated luminosity from Runs 3 and 4. There, taking advantage of upgraded detectors and high integrated luminosities, the goal is to measure A = 3 and A = 4 (hyper)nuclei with unprecedented precision.

The latest precise measurements of the hypertriton lifetime and binding energy confirm the $^{3}_{\Lambda}\mathrm{H}$ as a weakly bound state and closes the hypertriton lifetime puzzle. The next experimental efforts could therefore focus on increasing the precision on the binding energy, extracting the still-unknown branching ratio for the hypertriton two- and three-body decays, and extending the measurements to A = 4 hypernuclei (and beyond).

In this regard, the femtoscopy technique has surfaced as an extremely powerful tool to approach the study of nuclear cluster formation from the interaction point of view. First results from p–d femtoscopy in pp collisions from ALICE showed that three-body interactions are accessible and pave the way to a whole experimental programme of femtoscopy with light (hyper)nuclei.

In addition to deepen our knowledge of the strong interaction and the emergence of nuclear structures in particle collisions, the experimental and theoretical developments in the sector of light (hyper)nuclei offer a unique contribution to neigbouring fields: in nuclear astrophysics, the understanding of strangeness in nuclear matter finds application in constraining the equation of state of neutron stars and in astroparticle physics it contributes to searches for cosmic ray antinuclei with applications to indirect dark matter searches and the quest to understanding a still big missing part of our Universe.

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