MEASUREMENT OF THE HYPERTRITON PROPERTIES AND PRODUCTION WITH ALICE*

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The hypertriton ($^3_\Lambda$H) is a bound state of a proton, a neutron, and a Λ baryon. Studying its internal structure is crucial to investigate the hyperon–nucleon (Y–N) strong interaction and offers insights into the inner core of neutron stars, where Λ production is favoured. Measuring precisely the $^3_\Lambda$H lifetime, $\tau_{^3_\Lambda\mathrm{H}}$, and Λ separation energy, B_Λ, provide a powerful tool for constraining the parameters of the Y–N potential, as $\tau_{^3_\Lambda\mathrm{H}}$ and B_Λ directly reflect the strength of the Y–N interaction. The most precise measurements to date of $\tau_{^3_\Lambda\mathrm{H}}$ and B_Λ are obtained by the ALICE Collaboration, using the data sample of Pb–Pb collisions at a centre-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. These measurements strongly support the loosely-bound nature of $^3_\Lambda$H and shed light on the Y–N interaction. Furthermore, the weakly bound nature of the $^3_\Lambda$H has important implications on our understanding of the nucleosynthesis mechanism in hadronic collisions. Indeed, the large size of the $^3_\Lambda$H wave function determines a large separation between the nuclei production models at low charged-particle multiplicity. For this reason, the first measurement of the production of $^3_\Lambda$H in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV performed by ALICE represents an ideal probe for discriminating between the nuclei production mechanisms in high-energy hadron–hadron collisions.

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1. Introduction

The hypertriton ($^3_\Lambda$H) is the lightest known hypernucleus composed of a proton, a neutron, and a Λ baryon. This state is characterised by a very small Λ separation energy, of the order of a few hundred of keV, and consequently a wide wave function that can extend up to a radius of ≈ 10 fm [1]. In recent years, measurements of the hypertriton production and lifetime have

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stimulated an interesting debate in the high-energy physics community. The knowledge of the Y–N interaction has become more relevant recently due to its connection to the modelling of dense astrophysical objects such as neutron stars. Indeed, many theoretical models predict the production of Λ hyperons in the inner core of the neutron stars, leading to a softening of the matter equation of state [2]. As a consequence, the formation of large-mass neutron stars, such as those discussed in [3], should be suppressed, constituting what is referred to as the "hyperon puzzle". Many attempts were made to solve this puzzle, *e.g.* by introducing three-body forces leading to an additional repulsion that can counterbalance the large gravitational pressure and allow for larger star masses [4]. Detailed knowledge of the Y–N interaction and of the three-body Y–N–N interaction is fundamental for testing the robustness of these models. Numerous particle-correlation analyses [5] directly contribute to the determination of such interactions. In a complementary approach, the lifetime and the binding energy of a hypernucleus reflect the strength of the Y–N interaction [6, 7]. Previous measurements of the lifetime $\tau_{^3_\Lambda\mathrm{H}}$ [8, 9] and B_Λ [10] of $^3_\Lambda$H in heavy-ion collisions have still quite large uncertainties.

Furthermore, the weakly-bound nature of the hypertriton has important implications on our understanding of the nucleosynthesis mechanism in hadronic collisions. Currently, two models describe successfully the nuclear production in hadronic collisions using completely different approaches: one is based on coalescence [11], the other on statistical hadronisation model (SHM) [12]. Assuming a weakly-bound hypertriton, these two models show a large separation at low charged-particle multiplicity density. The reason is that the hypertriton yield predicted by the coalescence model, where the ratio of nucleus size to source size directly influences yields, is suppressed with respect to the SHM expectations, where the nuclear size does not enter explicitly. Hence, the first measurement of the production of $^3_\Lambda$H in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV performed by ALICE provides an ideal probe for discriminating between the different nucleosynthesis mechanisms in hadronic collisions.

2. $^3_\Lambda$H reconstruction and selection

The measurements presented in this contribution are performed using both Pb–Pb ($\tau_{^3_\Lambda\mathrm{H}}$ and B_Λ) and p–Pb (production) data at $\sqrt{s_{NN}} = 5.02$ TeV, collected by ALICE during the LHC Run 2. The $^3_\Lambda$H reconstruction is performed analysing its two-body mesonic charged decay channel $^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$ (and the related charge conjugated particles for $^3_{\bar\Lambda}\bar{\mathrm{H}}$). Pions and (anti-)^{3}He are identified using the measured energy loss in the Time Projection Chamber (TPC) [13], which has excellent particle identification capabilities. Then a vertexing algorithm performs the secondary vertex reconstruction, in which all the ^{3}He and π tracks satisfying loose topological requirements are matched. Finally, the $^3_\Lambda$H selection is entrusted to a Boosted Decision Trees classifier (BDT) [14] trained on a dedicated Monte Carlo (MC) simulated event sample. The signal extraction is performed by fitting the invariant-mass spectra using a Kernel Density Estimator (KDE) function [15], constructed using the MC sample to describe the signal and a linear function to describe the background. The KDE is used to model the non-Gaussian behaviour of the signal shape observed in the simulation by means of a superposition of Gaussian functions. An example of invariant-mass spectrum is shown in Fig. 1.

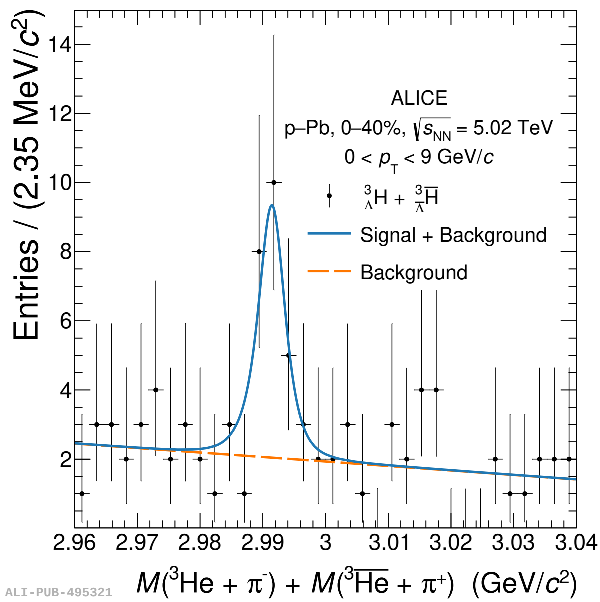

Fig. 1. (Colour on-line) Invariant mass distribution of the ^{3}He + π^- and charge conjugate pairs in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Vertical lines represent the statistical Poissonian uncertainties. The invariant-mass spectrum is fitted with a two-component model: the blue solid line represents the total fit, while the orange dashed line shows the background component only.

3. $\tau_{^3_\Lambda\text{H}}$ and B_Λ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

For both measurements, the selected $^3_\Lambda$H candidates are first divided into nine mean proper length (ct) intervals from 1 to 35 cm. Then $\tau_{^3_\Lambda\text{H}}$ is obtained by fitting, with an exponential function, the corrected ct spectrum. B_Λ is extracted starting from a fit with a constant function to the reconstructed mass values as a function of ct. Then B_Λ is computed as $B_\Lambda = m_d + m_\Lambda - m_{^3_\Lambda\mathrm{H}}$, where $m_{^3_\Lambda\mathrm{H}}$ is the $^3_\Lambda$H mass extracted from the fit, m_d is the deuteron mass taken from CODATA [16], and m_Λ is the Λ mass taken from the PDG [17]. The values of $\tau_{^3_\Lambda\mathrm{H}}$ and B_Λ are shown in Fig. 2, together with previous measurements obtained with different experimental techniques. Recent and past theoretical predictions are included too: models assuming $^3_\Lambda$H as an extreme weakly-bound state with an halo structure are clearly favoured by both the ALICE measurements.

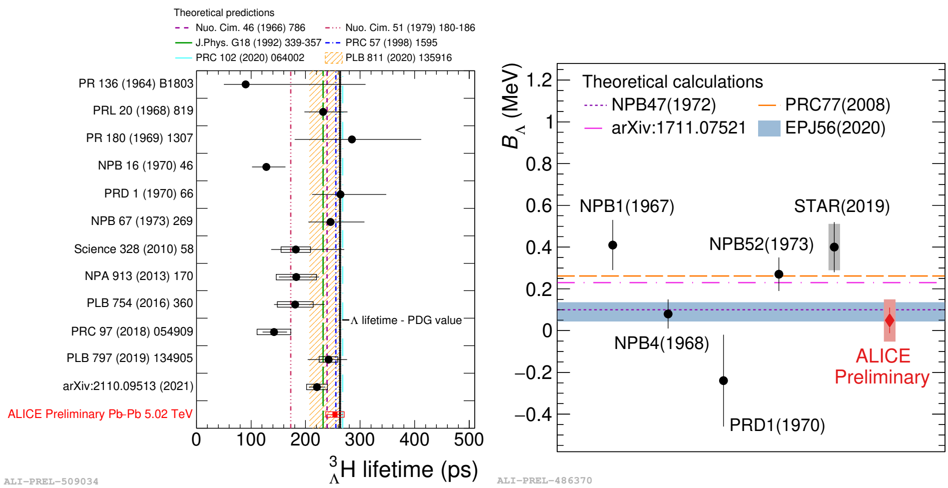

Fig. 2. Collection of the $^3_\Lambda$H lifetime (left) and B_Λ (right) measurements obtained with different experimental techniques. The markers lines and boxes are the statistical and systematic uncertainties, respectively. The dash-dotted lines are the corresponding theoretical predictions.

4. $^3_\Lambda$H production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The $^3_\Lambda$H production yield in p–Pb collisions [18] is obtained by correcting the extracted signal for the reconstruction and the selection efficiency, the number of analysed events, the branching ratio (BR) of the $^3_\Lambda$H in the two-body decay channel [7], and the fraction of $^3_\Lambda$H that are absorbed in the ALICE detector. The $^3_\Lambda\mathrm{H}/\Lambda$ ratio and the strangeness population factor $S_3 = (^3_\Lambda\mathrm{H}/^3\mathrm{He})/(\Lambda/p)$ in p–Pb collisions are computed and compared with the theoretical predictions, as shown in Fig. 3. The measured $^3_\Lambda\mathrm{H}/\Lambda$ ratio excludes, with high significance, canonical versions of the SHM with correlation volume $V_c \geq 3\mathrm{d}V/\mathrm{d}y$ to explain the (hyper)nuclei production in p–Pb collisions. Both the ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratio and the S_3 are described by the 2-body coalescence prediction while the 3-body formulation is slightly disfavoured by our measurements.

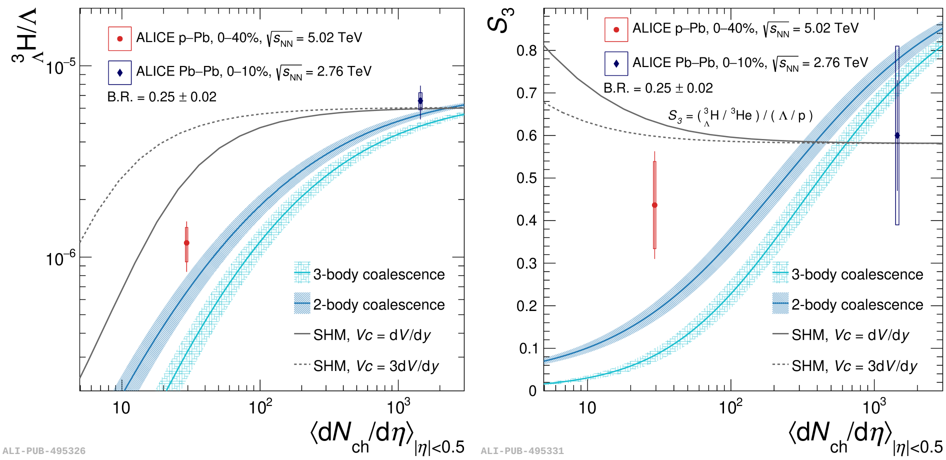

Fig. 3. ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ (left) and S_3 (right) measurements in *p*–Pb (circle) and Pb–Pb collisions [19] (diamond) as a function of mean charged-particle multiplicity. The vertical lines and boxes are the statistical and systematic uncertainties (including the uncertainty on the BR), respectively. The expectations for the canonical statistical hadronization [12] and coalescence models are shown [11].

5. Summary and conclusions

The most precise measurements to date of the ${}^{3}_{\Lambda}\mathrm{H}$ lifetime and B_Λ strongly support the loosely-bound nature of ${}^{3}_{\Lambda}\mathrm{H}$ and contribute significantly to the understanding of the Y–N interaction. An important consequence of the ${}^{3}_{\Lambda}\mathrm{H}$ weakly-bound structure is that the (hyper-)nuclei production models give well-separated predictions at low charged-particle multiplicity for ${}^{3}_{\Lambda}\mathrm{H}$. Hence, the first measurements of ${}^{3}_{\Lambda}\mathrm{H}$ yield in *p*–Pb collisions provide an opportunity to discriminate between nucleosynthesis models in hadronic collisions. The ALICE results are in agreement with the 2-body coalescence predictions and exclude with high significance a few configurations of the SHM. With the upgraded ALICE apparatus and the upcoming LHC Run 3 and Run 4, it will be possible to reduce both the statistical and the systematic uncertainties of the ${}^{3}_{\Lambda}\mathrm{H}$ yield measurements in *pp* and *p*–Pb collisions and to explore the $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ dependence of the ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratio, in order to decisively distinguish between the two production models.

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