(Hyper-)nuclei and exotica production measured with ALICE at the LHC

Stefano Trogolo

Dipartimento di Fisica, Università degli Studi di Torino, Via P. Giuria 1, 10125, Torino, Italy

E-mail: `stefano.trogolo@to.infn.it`

Abstract. The high collision energies reached at the LHC open the possibility to study extensively the production of light (anti-)(hyper-)nuclei and exotic bound states in proton-proton (pp), proton-lead (p-Pb) and lead-lead (Pb-Pb) collisions.

ALICE has excellent particle identification (PID) capability which allows the detection of these rarely produced particles. PID is perfomed using several techniques, namely by exploiting the measurement of the specific ionization energy loss in the Time Projection Chamber (TPC) and the information of the Time-Of-Flight (TOF) detector.

The transverse momentum spectra and the yields (dN/dy) of light nuclei and anti-nuclei were obtained and results are discussed here, and the first measurement of deuteron elliptic flow is presented. Furthermore, the study of the production of (anti-)hypertriton and the status of the searches for exotic bound states, i.e. Λ-Λ and Λ-n, are discussed.

Results are compared to predictions from thermal and coalescence models in order to enquire into the production mechanisms of nuclei, hypernuclei and exotic bound states.

The study of light (anti-)(hyper-)nuclei and exotic bound states in proton-proton and heavy-ion collisions is important because it allows to test production models. On one side these measurements can be useful for the comparison with QCD-inspired models which predict the existence of multi-baryon states with strangeness content. On the other hand, an open point in heavy-ion physics is whether the production of nuclei and multi-baryon states, such as hypernuclei and exotica, can be described by thermal models [1] or by coalescence [2, 3] of hadrons. The thermal model predicts that hadrons are produced in the interaction region, which is assumed to be in thermal equilibrium, when it reaches the chemical freeze-out temperature (T_{chem}). The coalescence model assumes that (anti-)baryons which are close enough in phase-space at kinetic freeze-out, can form a multi-baryon state.

1. Nuclei

The ALICE experiment has measured the p_T-differential production spectra for (anti-)deuterons in pp collisions at $\sqrt{s} = 7$ TeV, p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV and for (anti-)^{3}He in p-Pb and Pb-Pb [4]. The deuteron and ^{3}He spectra exhibit a hardening with increasing centrality in Pb-Pb collisions, which can be explained by hydrodynamic models as an effect of the radial flow. A similar behaviour with increasing multiplicity is also observed for deuteron in p-Pb. Blast-Wave (p-Pb and Pb-Pb) and Levy-Tsallis (pp) fits were used to extrapolate the spectra to the unmeasured p_T region in order to compute the integrated yields.

The integrated yields of deuteron and proton were used to compute the d/p ratio as a function of charged particle multiplicity, as shown in Fig.1 (*left*). The rise of the ratio from pp to Pb-Pb
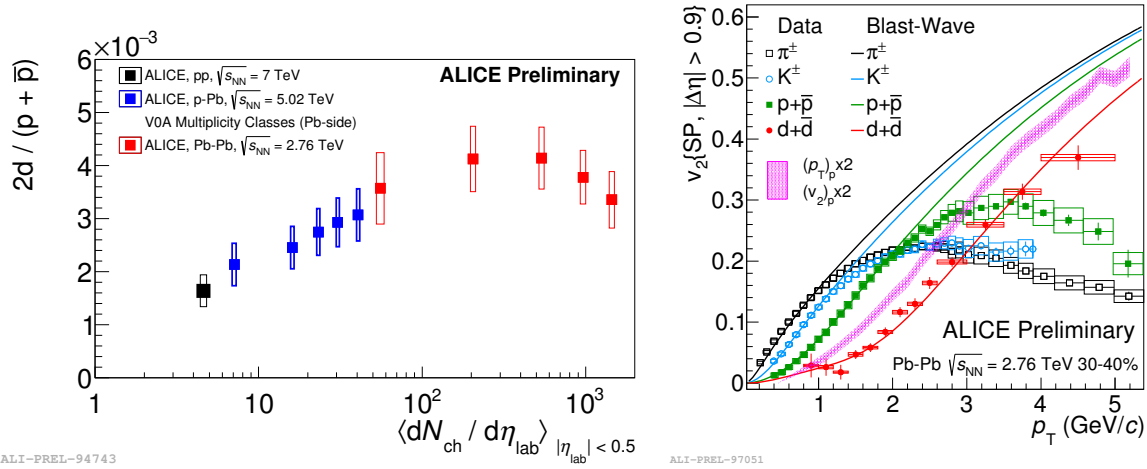
Figure 1: (*left*) d/p ratio as a function of charged particle multiplicity for pp, p-Pb and Pb-Pb collisions; (*right*) deuteron v_2 in Pb-Pb collisions for 30-40% centrality class with Blast-Wave (red line) and coalescence model (magenta band) predictions.

collisions is consistent with the coalescence model [5] which predicts an increase of deuteron production for higher nucleon densities. The flattening reached in Pb-Pb can be described in the coalescence picture assuming an increase of the size of the emitting source. This result is also consistent with thermal model expectations in which chemical freezeout is attained at a temperature of 156 MeV for all centralities.

The p_T spectra of deuteron and ^{3}He, were also used to compute the ratio between the production of anti-nuclei and nuclei [4] in the central rapidity region. These ratios are in agreement with unity within uncertainties and it is possible to conclude that, as expected, there is an equal production of matter and anti-matter in Pb-Pb collisions at the LHC energies.

Deuteron elliptic flow was measured in Pb-Pb collisions, as shown in Fig.1 (*right*), and follows the mass ordering up to $p_T = 3$ GeV/c as expected from hydrodynamics models. A Blast-Wave parameterization in Fig.1 (*right*) (red line) obtained from lower mass species can describe deuteron v_2 while the coalescence model (magenta band) is not able to reproduce it.

ALICE also studied the mass dependence of production yields in Pb-Pb and p-Pb collisions, using the measured abundances of proton, deuteron, ^{3}He and ^{4}He. From the distribution of dN/dy as a function of nucleus mass m_A, the penalty factors for adding one nucleon were extracted: they are ∼300 in Pb-Pb and ∼600 in p-Pb collisions.

2. Hypernuclei

Hypernuclei are nuclei where a nucleon has been replaced with a hyperon and the hypertriton, a bound state of a proton, a neutron and a Λ, is the lightest known hypernucleus. Its mass is 2.991 ± 0.002 GeV/c^2 [7] and its lifetime is expected to be compatible with the free Λ lifetime.

The (anti-)hypertriton production yields were measured in Pb-Pb collisions exploiting the mesonic weak decay into two charged particles [6] ($^3_\Lambda$H $\rightarrow ^3$He+π^- and $^3_{\bar\Lambda}\overline{\text{H}} \rightarrow ^3 \overline{\text{He}}+\pi^+$). The decay products were identified via specific energy loss in the TPC and topological cuts were applied for the identification of secondary vertices. The signal extraction was performed by means of a fit to the invariant mass spectra with a function that includes signal and background contributions. The measured production yields dN/dy × B.R. have been compared to different models as a function of the branching ratio (*B.R.*), as shown in Fig.2 (*left*). The result is in

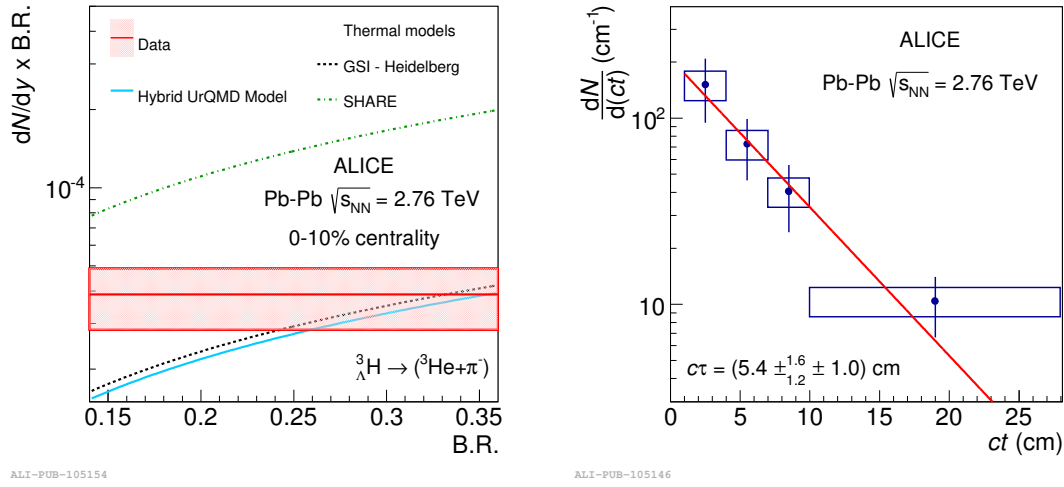**Figure 2:** (*left*) Measured $^{3}_{\Lambda}$H dN/d$y\times$ B.R. compared to three different theoretical models; (*right*) exponential fit to the ct differential spectrum to evaluate the $c\tau$ of the hypertriton.

agreement with the equilibrium thermal model (T$_{chem}$ = 156 MeV) [1] and with the Hybrid UrQMD model, if a theoretical value of $B.R.$=25% [8] is assumed.

From the ct-differential production spectrum, shown in Fig. 2 (*right*), it has been possible to compute the lifetime of the hypertriton with an exponential fit (red line). The value reported by the ALICE experiment is $\tau = 181^{+54}_{-39}(stat.)\pm33(syst.)$ ps and it is in agreement with the lifetime world average of 216^{+19}_{-16} ps [9]. However, being a loosely bound object, the theory predicts a value of the lifetime compatible with the free Λ lifetime. The fact that the ALICE value, as well as previous heavy-ion experiments results, is lower than the free Λ lifetime is still an open question. An improvement on this result might come from the study of the mesonic weak decay into three charged particles, $^{3}_{\Lambda}$H → d+p+π^{-} and $^{3}_{\Lambda}\overline{\text{H}}$ → $\overline{\text{d}}$+$\overline{\text{p}}$+π^{+}.

3. Exotica searches

The ALICE experiment is also focused on the search for exotica, such as hyperon-hyperon and hyperon-nucleon bound states. In particular the analysis looked for two particular exotic bound states in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV: the H-dibaryon and $\overline{\Lambda n}$ [10].

The H-dibaryon is a hypothetical *uuddss* bound state ($\Lambda\Lambda$) first predicted by Jaffe [11] using a bag model approach. In this analysis the $\Lambda\text{p}\pi^{-}$ decay channel of the H-dibaryon was investigated, under the assumption of a weakly-bound state. Since no evidence of a signal for the $\Lambda\Lambda$ was found in the invariant mass distribution, an upper limit (99% C.L.) on dN/dy was obtained, assuming a B.R. = 64% [12] and the free Λ lifetime. The limit dN/d$y \sim 2.0\times10^{-4}$ is a factor 30 below the values predicted by thermal models (dN/d$y \approx 6\times10^{-3}$) [10].

The $\overline{\Lambda n}$ bound state was investigated in the decay channel $\overline{\text{d}}\pi^{+}$, but no signal was found in the invariant mass distribution. Assuming a B.R. = 54% and the free Λ lifetime, this led to an upper limit (99% C.L.) on dN/d$y \sim 9.0\times10^{-4}$ that is a factor 45 below values predicted by thermal models (dN/d$y \approx 4\times10^{-2}$) [10]. The upper limits on $\Lambda\Lambda$ and $\overline{\Lambda n}$ dN/dy were compared to different thermal and coalescence (only for H-dibaryon) model predictions as a function of the branching ratio and they are below the predictions which assume the same B.R.
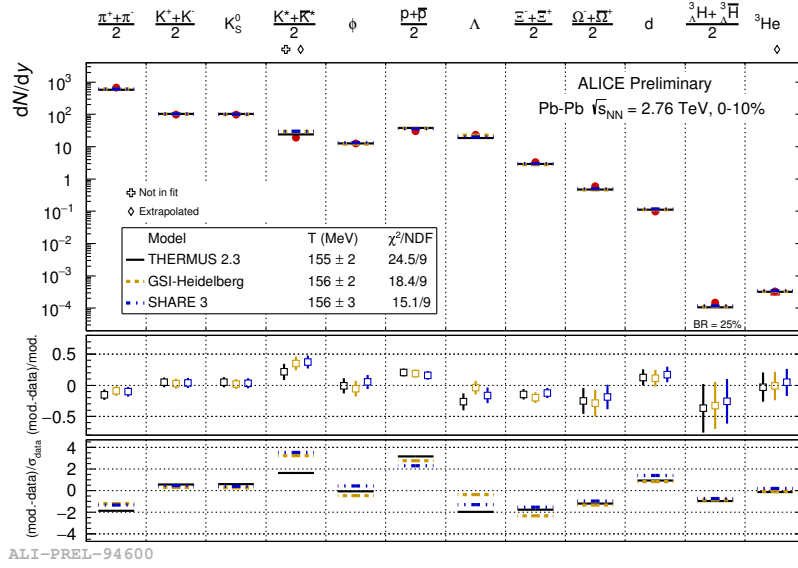
Figure 3: Grand-canonical fits to the particle yields measured in central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV.

4. Conclusion and perspective

ALICE's excellent performance in tracking and particle identification allows the detection of light (anti-)(hyper-)nuclei and the search for exotic bound states.

The results on nuclei and hypernuclei production in heavy-ion collisions can be rather well described by thermal and coalescence models. In this direction it is crucial to measure with better precision the d/p ratio. The production spectra show the effect of the radial flow due to the presence of a hydrodynamically expanding source, as already observed for lighter particles in Pb-Pb and p-Pb collisions. We also confirmed the dN/dy mass hierarchy predicted by the grand-canonical statistical model and the expected symmetry between matter and anti-matter production at the LHC. For the first time ALICE measured the elliptic flow in the nuclei sector, finding an agreement with hydrodynamic models. The thermal fits to the particle yields, shown in Fig.3, including nuclei and hypertriton, show that equilibrium thermal models with $T_{chem} = 156$ MeV are able to describe almost all the particle abundances.

Two open points are still left: the lifetime of the hypertriton, which shows a deviation from theoretical expectations, and the existence of exotic bound states. We expect to give hints on these two open points using the increased statistics (factor ~10 in Pb-Pb) of the Run 2 data taking period of LHC and improving the existing measurements.

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