Recent results for the (anti-)(hyper-)nuclei production and searches for exotica by ALICE at the LHC

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Abstract. The excellent tracking and particle identification capabilities of the ALICE apparatus combined with the high particle production rates reached at the LHC in pp, p–Pb and in particular in Pb–Pb collisions allow for detailed study of the production of (anti-)nuclei and searches for exotica, like dibaryons. In this report, we present recent results on the production of the (anti-)deuteron and (anti-)helium. Further, we discuss recent results on the production and the lifetime of the (anti-)hypertriton. In addition, results from the searches for the weakly-decaying exotic nuclear bound states H-dibaryon and Λn are shown. The results are compared with the expectations from statistical (thermal) particle production and coalescence models.

1. Introduction

Collisions of ultra-relativistic heavy ions are an efficient tool for producing (anti-)(hyper-)nuclei because a high energy density is reached over a large volume. The measurements presented here, have been performed in pp collisions at \( \sqrt{s} = 7 \) TeV, in Pb–Pb collisions at \( \sqrt{s_{\rm NN}} = 2.76 \) TeV as a function of collision centrality and in p–Pb collisions at \( \sqrt{s_{\rm NN}} = 5.02 \) TeV as a function of charged-particle multiplicity.

The excellent particle identification capabilities of the ALICE detector system [1–4] is suited to measure the production of (anti-)nuclei and to search for exotic bound states like \( \Lambda n \) and the H-dibaryon. The formation of (anti-)nuclei is very sensitive to the chemical freeze-out conditions, to the dynamics of the emitting source as well as to the final-state effects. The production mechanisms of these particles are typically discussed within two approaches: the thermal-statistical model and the coalescence model. In the thermal model [5–7] the chemical freeze-out temperature \( T_{\rm chem} \) (predicted around 160 MeV) acts as the key parameter at LHC energies. The strong sensitivity of the nuclei production to the choice of \( T_{\rm chem} \) is caused by the large mass \( m \) and the exponential dependence of the yield given by the factor \( \exp(-m/T_{\rm chem}) \).

In the coalescence model, nuclei are formed by protons and neutrons which are nearby in space and exhibit similar velocities [8,9]. A quantitative description of this process, applied to many collision systems at various energies [10–17], is typically based on the coalescence parameter \( B_A \) (see Section 2). The two mechanisms give very similar predictions [18].
2. Nuclei

Nuclei and anti-nuclei such as (anti-)deuterons, (anti-)tritons, and (anti-)³He are identified using the specific energy loss measurement in the TPC. The final spectra of deuterons obtained in Pb–Pb and in pp collisions [19] are shown in Figure 1. The \( p_T \)-distributions in Pb–Pb show a clear evolution, becoming harder as the centrality increases, a behaviour similar to that of the protons which exhibit a significant radial flow [20]. The spectra obtained in Pb–Pb collisions are individually fitted with the blast wave model for the determination of \( p_T \)-integrated yields. Figure 2 shows the deuteron-to-proton ratio as a function of the multiplicity in pp, p–Pb and in Pb–Pb collisions. The p–Pb ratio rises with multiplicity (higher nucleon multiplicities would lead to an increased deuteron production) until a saturation (within the achieved experimental precision) is reached for Pb–Pb collisions: the increasing nucleon multiplicity is balanced by the increasing source volume, leading to a constant density. The observed value of about 3.6 \( \times 10^{-3} \) for the \( d/p \) ratio in Pb–Pb collisions is in agreement with the expectation from the thermal-statistical models (with \( T_{\text{chem}} = 156 \) MeV) [19].
In the coalescence approach, light nuclei are formed at kinetic freeze-out via coalescence of protons and neutrons which are close to each other in space and momentum phase space. In this mechanism, the spectral distribution of the composite nuclei is related to the one of the primordial nucleons via the following relationship:

\[ E_i \frac{d^3 N_i}{(dp_i)^3} = B_A \left( E_p \frac{d^3 N_p}{(dp_p)^3} \right)^A \]  

assuming that protons and neutrons have the same momentum distribution. \( B_A \) is the coalescence parameter of particle \( i \) with mass number \( A \) and a momentum of \( p_i = A_p p_p \).

Figure 3 shows the obtained \( B_2 \) values for deuterons for Pb–Pb and p–Pb (right) collisions. A clear decrease with increasing centrality is observed for Pb–Pb collisions. In the coalescence picture, this behaviour is explained by an increase in the source volume \( V_{\text{eff}} \). \( B_2 \) also shows an increasing trend with the transverse momentum for central collisions, in contrast with the most simple coalescence models. This behaviour can be qualitatively understood by position-momentum correlations which are caused by a radially expanding source. In p–Pb collisions the \( B_2 \) is slightly decreasing with multiplicity, again in contrast with the most simple coalescence model, that represents a solid ground for further studies.

3. (Anti-)hypertriton

The production of hypertriton \( \Lambda^3 \text{H} \) and \( \Lambda^3 \overline{\text{H}} \) has been measured in Pb–Pb collisions via invariant mass reconstruction in the weak decay channel \( \Lambda^3 \text{H} \rightarrow \Lambda \pi \pi^0 \) and \( \Lambda^3 \overline{\text{H}} \rightarrow \Lambda \pi^+ \pi^- \), respectively [21]. The daughter tracks of the (anti-)hypertriton candidates are required to originate from a secondary vertex and identified as a \( 3\Lambda \) (\( \Lambda^3 \text{He} \)) and a pion via TPC dE/dx. The total yield for the hypertriton, \( dN/dy \times B.R. = (3.86 \pm 0.77 \text{ (stat)} \pm 0.68 \times 10^{-5} \) in the 0–10% most central collisions, is consistent with the predictions from a statistical model using the same temperature as for the light hadrons (\( T_{\text{chem}} = 156 \pm 2 \text{ MeV} \)). Also the measured lifetime of the hypetriton (\( \tau = 181^{+54}_{-39} \) (stat.) \pm 33 (syst.) ps) is compatible with the world average value [21].

4. Exotica bound states

Searches for two hypothetical strange dibaryon states, i.e. the H-dibaryon and the \( \Lambda n \) bound state is performed in 0–10% most central Pb–Pb collisions, by invariant mass analysis in the decay modes H-dibaryon \( \rightarrow \Lambda p \pi^- \) and \( \Lambda n \rightarrow d \pi^+ \) [22]. No signal in the invariant mass
distributions is observed. The analysis provides stringent upper limits at 99% confidence level for the production of H-dibaryon and $\Lambda n$ bound state, significantly below the thermal model prediction [22]. The upper limits are obtained for different lifetimes: the values are significantly below (about a factor 20) the model predictions when realistic branching ratios (64% for the H-dibaryon and 54% for $\Lambda n$) and reasonable lifetimes are assumed.

5. Summary and conclusions
The most recent results of the ALICE experiment on the (anti-)deuteron production in pp, p–Pb and Pb–Pb collisions have been reported. The deuteron spectra in Pb–Pb collisions exhibit a significant hardening with increasing centrality. The d/p ratio, in Pb–Pb collisions, is found to be constant (within the achieved experimental precision) as a function of $dN_{\text{ch}}/d\eta$ which is in agreement with the thermal-statistical interpretation. The rising d/p ratio with the charged particle multiplicity in p–Pb is consistent with the coalescence approach: higher nucleon multiplicities would lead to an increased deuteron production. However, the d/p ratio for Pb–Pb collisions is constant with the increasing centrality: the increasing nucleon multiplicity is balanced by the increasing source volume, leading to a constant density. Extrapolations and model predictions based on the thermal-statistical or coalescence approach are, therefore, a solid ground for further studies. Measurements of hypertriton and anti-hypertriton in Pb–Pb collisions have been also presented. In addition, a search for the existence of loosely bound strange dibaryon has been discussed and no signals are observed.

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