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Strangeness and nuclei production in nuclear collisions

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Abstract

A critical review of the most recent results obtained on the study of strangeness and (anti–)nuclei production in nuclear collision at ultra–relativistic energies will be presented. Recent measurements of strangeness production at the LHC in high-multiplicity proton-proton (pp) and proton-lead (p–Pb) collisions have shown features that are reminiscent of those observed in lead-lead (Pb–Pb) collisions. These observations warrant a comprehensive measurement of the production of identified particles and are not described satisfactorily by the available Monte Carlo predictions. Another intriguing but not fully understood mechanism, in the high energy physics sector, is the one responsible for the production of light nuclei and anti–nuclei. A detailed description of the available experimental data about (anti–)matter production will be reported and compared with the available models, namely the coalescence approach and the thermal model predictions.

Keywords: (anti–)nuclei, coalescence, thermal model, strangeness enhancement, QGP in small systems

1. Introduction

The study of strange and multi–strange particle production is an important tool for the understanding of particle production mechanisms in small colliding systems like pp collisions and also for investigating the dynamics of the quark-gluon plasma (QGP) phase of nuclear collisions. The measurement of strangeness production rates relates to many signatures of this phase [1], such as strangeness enhancement and the thermalization of particle production rates. Another important goal of ultra-relativistic nuclear collision experiments is to understand how loosely bound objects, like light nuclei and anti–nuclei, could bind at the temperature reached in heavy-ion collisions. To this purpose a comparison between the measurements performed in heavy-ion collisions and those in small colliding systems are providential for a more comprehensive comparison to the models. In terms of models, the production mechanism of (anti–)nuclei is typically discussed within two different approaches. In the thermal model [2, 3] the chemical freeze–out temperature $T_{\rm chem}$ is the key parameter at LHC energies. The production yields depend exponentially on this temperature and the mass m: $dN/dy \sim exp(-m/T_{chem})$. Due to their large masses the abundance of nuclei is very sensitive to $T_{\rm chem}$. In the coalescence approach [4, 5] nuclei are formed at the kinetic freeze–out by protons and neutrons which are nearby in space and exhibit similar velocities.

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2. (Anti–)nuclei production: experimental data vs models

Most of the results discussed in this section have been obtained with the ALICE experiment [6] at the Large Hadron Collider (LHC) and with the STAR experiment [7] at the Relativistic Heavy Ion Collider (RHIC). For some of the results a comparison with lower energy experiment will be presented. The collision energy reached at RHIC and in particular at the LHC, provides the opportunity to measure nuclei and the corresponding anti–particles in unprecedented abundances, although the measurement is challenging as the production probability decreases with increasing particle mass.
One of the latest results obtained at the LHC is the measurement of the deuteron and anti-deuteron spectra in nine multiplicity classes in pp collisions at $\sqrt{s}$ = 13 TeV. The production of matter and anti-matter is found to be equal, as expected at the LHC energies and as reported in previous measurements in heavy-ion collisions [8, 9].

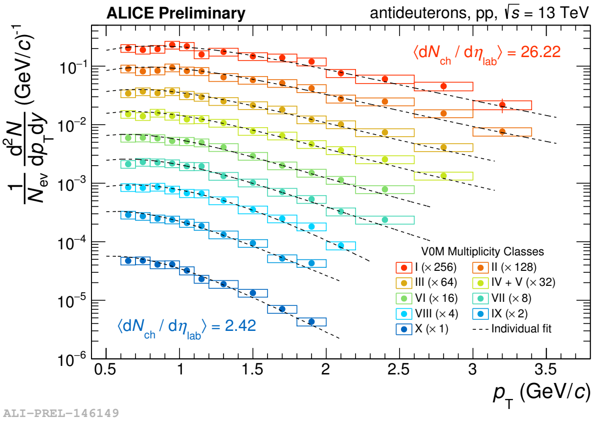

Fig. 1. Transverse momentum spectra, measured with ALICE, in different multiplicity classes for anti-deuterons in pp collsions at $\sqrt{s}$ = 13 TeV. The dotted lines superimposed to each spectrum are the fits performed by using a Levy-Tsallis function and are used to extract the production yields in the unmeasured transverse momentum region.

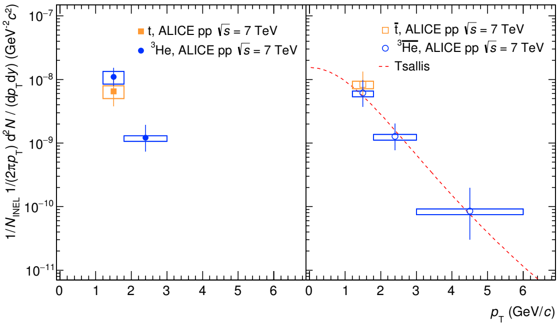

Fig. 2. Transverse momentum spectra obtained by ALICE for (left) triton and ^{3}He and (right) for their corresponding anti–particles in pp collisions at $\sqrt{s}$ = 7 TeV. The red dotted line superimposed to the spectrum is the fit performed by using a Tsallis function.

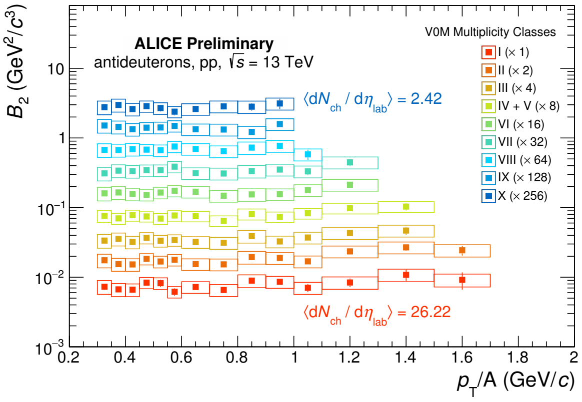

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Fig. 3. Coalescence parameter B_2 measured by ALICE as a function of the transverse momentum per nucleon (p_T/A) for different centrality classes in pp collisions at $\sqrt{s}$ = 13 TeV.

The spectra measured for anti-deuterons at $\sqrt{s}$ = 13 TeV are reported in figure 1 and they do not show the typical spectrum hardening seen in heavy-ion collisions which is a clear sign of radial flow. Furthermore a similar trend of the spectra has been observed and shown at this conference for (anti–)deuterons in pp collisions at $\sqrt{s}$ = 7 TeV.

To reproduce the hardening of the spectra measured at the LHC for central Pb–Pb collisions, a combined Blaste Wave (BW) [10] fit has been performed to the data. The data are qualitatively well described by the model and it has been also shown in [8] that the BW model predicts reasonably well the deuteron elliptic flow in a large transverse momentum range. Those results suggest that thermal model prediction works nicely for large colliding systems. The same degree of agreement of a BW model fit to the data has been presented at this conference by the High Acceptance Di-Electron Spectrometer (HADES) experiment [11] at GSI that has measured spectra of deuterons and tritons at mid–rapidity in central Au-Au collisions at 1.23 AGeV and by STAR for tritons in central Au-Au collisions at different energies going from $\sqrt{s_{NN}}$=7.7 GeV to $\sqrt{s_{NN}}$=200 GeV.

Another important piece of information about the production of matter and anti-matter has been added by measuring the production of tritons and ^{3}He and their anti–particles in pp collisions at $\sqrt{s}$ = 7 TeV [12]. To find the integrated yields, the measurements in pp collisions are usually extrapolated to the unmeasured transverse momentum region by fitting the spectra with a Tsallis [12] or Levy-Tsallis [9] function. The measurement of the integrated yields of heavier nuclei has demonstrated that the nuclei production is reduced by a factor ∼ 1000 when adding a nucleon in pp collisions and from previous measurements the reduction factor is estimated to be ∼ 300 and ∼ 600 in Pb–Pb and p–Pb collisions, respectively.

An additional observable, typically used to shed light on the production mechanism behind the (anti–)nuclei production in nuclear collisions, is the coalescence parameter B_A which provides a relation between the production rate of the nuclear cluster emitted with a certain momentum and the nucleon production rate. In this approach neutrons and protons are indistinguishable. In figure 3 the coalescence parameter measured by the ALICE collaboration for anti-deuterons as a function of the transverse momentum per nucleon (p_T/A) for different centrality classes in pp collsions at $\sqrt{s}$ = 13 TeV is shown. The B_2 measured in small colliding systems does not show a p_T dependence as suggested by simple coalescence models and the evolution of primary proton spectra across multiplicity can also explain the results without the introduction of any additional effect such as hard scattering. Extremely interesting is also the first ever measurement of the B_3 coalescence parameter in high energy physics performed with ALICE and reported on the left panel of figure 4. The figure shows the trend of the B_3 versus p_T/A obtained in pp collsions at $\sqrt{s}$ = 7 TeV for light nuclei

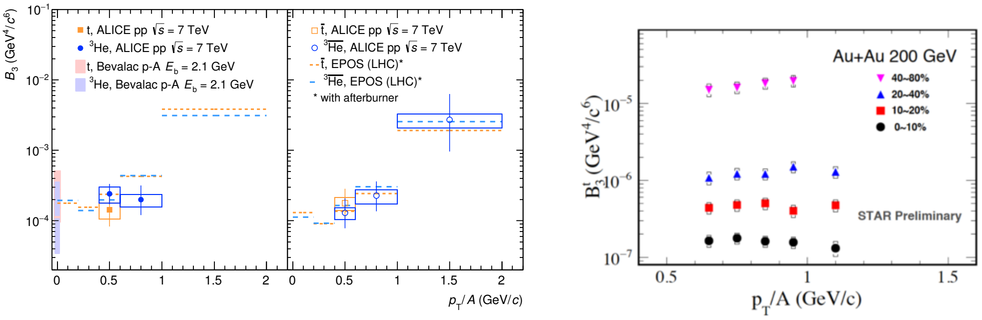

Fig. 4. (Left) Coalescence parameter B$_3$ measured by ALICE as a function of the transverse momentum per nucleon (p$_T$/A) in pp collsions at $\sqrt{s}$ = 7 TeV. The Bevalac measurements in p–C, p–Cu, and p–Pb collisions are shown as vertical bands at p$_T$/A=0 for comparison. (Right) Coalescence parameter B$_3$ measured by STAR as a function of p$_T$/A in Au-Au collisions at $\sqrt{s_{NN}}$=200 GeV for 4 different centrality classes.

and anti-nuclei with mass number A=3. Due to the limited statistics, a measurement in different multiplicity bins was not accessible but it is possible to observe that the data are well reproduced with QCD-inspired event generators with a coalescence-based afterburner and at low p$_T$ the experimental values are compatible with those obtained in p–C, p–Cu, and p–Pb collisions at Bevalac [13].

At this conference a preliminary measurement of the B$_3$ coalescence parameter for triton, in four different centrality classes, was reported by STAR at different energies and as example the values measured in Au-Au collisions at $\sqrt{s_{NN}}$=200 GeV are reported on the right panel of figure 4. The measurement of tritons in high energy experiment is quite challenging due to the contamination in terms of particle identification and the STAR measurement is available in a quite limited p$_T$ range. Nevertheless one can see how the B$_3$ decreases from peripheral to central collisions. One of the crucial point for this measurement will be the extension of the p$_T$ reach to have a better feeling about the p$_T$ dependence of the coalescence parameter.

The last point, which is worth to mention and has further hints about the (anti-)nuclei production mechanism, is the behaviour of the deuteron-to-proton ratio as a function of the charged particle multiplicity. Figure 5 shows this ratio for pp, p-Pb and Pb-Pb collisions at the different collision energies provided at the LHC. The ratio rises with multiplicity until a saturation within errors in Pb-Pb collisions is reached. The transition between the different collision systems suggests that the deuteron-to-proton ratio is in part determined by the event multiplicity, at least for smaller systems.

As already discussed, the production spectra of light nuclei can be understood based on the coalescence approach assuming that deuterons (and other light nuclei) are produced by protons and neutrons that are close in phase space. In the most naive picture, this would lead to an increased deuteron production for higher nucleon multiplicities. The increase of the deuteron-to-proton ratio with the charged particle multiplicity in figure 5 is consistent with this picture for small colliding systems like pp and p–Pb. However, the deuteron-to-proton ratio for Pb–Pb collisions is almost constant with increasing centrality, although the nucleon multiplicity increases.

A possible explanation of the Pb–Pb results can be that the increasing nucleon multiplicity is balanced out by the increasing source volume, leading to a constant nucleon density. This is also consistent with the rising deuteron-to-proton ratio with multiplicity in p–Pb collisions, if the effect of the increasing nucleon multiplicity dominates over the effect of the increasing source volume. An important question is whether the nuclei are produced at the chemical freeze-out or at a later stage via coalescence. Besides the constant deuteron-to-proton ratio a key observation is that in Pb-Pb collisions the absolute production yields (dN/dy) of light nuclei are in good agreement with thermal model calculations, as shown in [9]. On the other hand the highest deuteron-to-proton ratio obtained in pp collisions is about half the value predicted by a thermal model in central AA collisions, disfavoring the statistical description based on thermal equilibrium in small

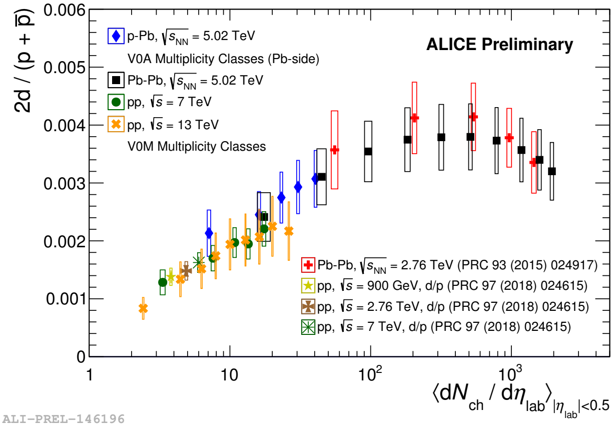

Fig. 5. Deuteron-to-proton ratio, measured by the ALICE experiment, as a function of charged-particle multiplicity at midrapidity for different colliding systems at different energies.

systems at the LHC energies. Further studies are needed to establish whether the fast expansion conserves the particle ratios and which additional conditions in the coalescence model are required to describe the constant particle ratio in Pb–Pb collisions.

3. Strangeness production and enhancement

The strangeness enhancement in heavy-ion collisions with respect to pp (p-Be) collisions, suggested as a smoking gun for QGP formation, has been observed with Pb-Pb collisions at the NA57 experiment [14], at STAR [15] with Au-Au collisions, and confirmed by ALICE in central 2.76 TeV Pb-Pb collisions [16]. The hyperon hierarchy predicted as a signature for QGP has been confirmed by the experimental data at different energy regimes and a lower enhancement has been observed when the collision energy increases.

In the last years heavy-ion experiments at RHIC and LHC have been exploited to investigate strangeness production at higher collision energies and also in small colliding systems. In figure 6 (left) the ALICE measurement of the ratio of strange and multi–strange particle yields to the pion yield is reported for pp, p-Pb and Pb–Pb collisions togheter with the comparison with the Monte Carlo predictions. One can observe that the production of strangeness is enhanced in high–multiplicity pp collisions and that the multiplicity dependence of strangeness production is strikingly similar in pp and p–Pb and follows the trend of the values corresponding to central Pb–Pb collisions.

Furthermore the models do not describe the data neither qualitatively nor quantitatively: there is a strong disagrement with PYTHIA8 [17] and also EPOS LHC [18] does not match the data straight away. A better agreement can be found when the data are compared with DIPSY [19] even if there is a deviation for the Ω particles and also the baryon production is not well reproduced.

New results have been presented at this conference by the ALICE experiment by analyzing the new data samples collected in pp collisions at $\sqrt{s}$ = 13 TeV and in Xe-Xe collisions at $\sqrt{s_{NN}}$=5.44 TeV. The wrap up of the measurements available so far from the LHC-Run 2 for the measurement of strange and multi–strange particle yields to the pion yield is reported in figure 6 (right) and confirms the trend observed at lower energies in pp collisions and in heavy-ion collisions with the measurement in Pb-Pb.

An interesting comparison is the one reported in figure 7 where the high precision measurement at the LHC is found to be in fair agreement with the STAR results at high multiplicity. The open question is if only multiplicity plays a role considering that neither energy nor system dependence is observed in the available

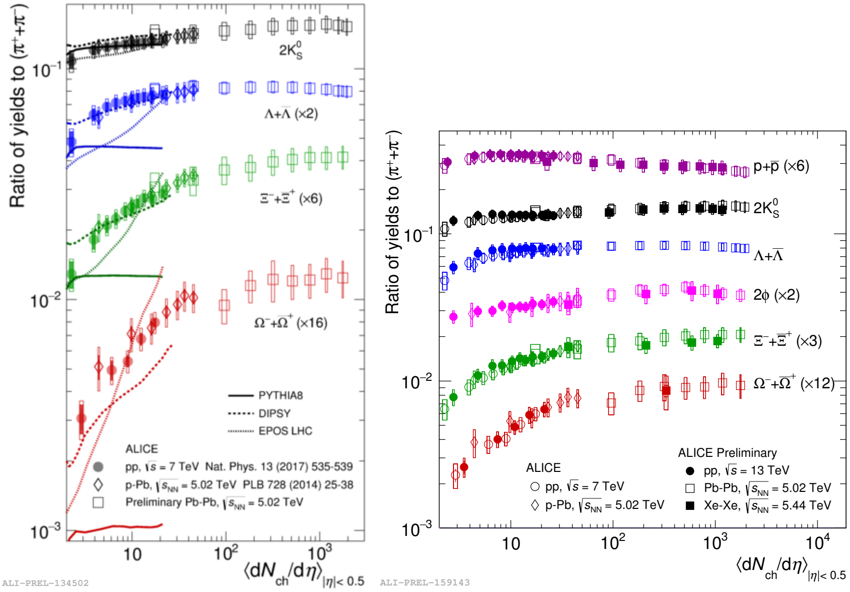

Fig. 6. (Left) Strange baryon over pion ratio as a function of the charged particle multiplicity in pp, p–Pb and Pb–Pb collisions at the LHC, compared with MC prediction from PYTHIA8 [17], EPOS LHC [18] and DIPSY [19]. (Right) Strange baryon over pion ratio as a function of the charged particle multiplicity in pp, p–Pb, Pb–Pb and Xe-Xe collisions at the LHC.

experimental data. Further measurements in small systems at RHIC and new data collected during LHC-Run 3 could help to understand the experimental hints observed so far.

4. Conclusions

The study of the production of (anti–)nuclei and multi–strange baryons and their antiparticles in high energy nuclear collisions has opened an interesting debate about the production of loosely bound objects like deuterons in a hot and dense medium as the QGP and also about the possibility to produce the QGP in small systems. Many experimental results about the production of deuteron, triton and ^{3}He show that the production in small colliding systems is well reproduced by coalescence models and the thermal model prediction works nicely for heavy-ion collisions. Quite interesting is the evolution of the experimental results as a function of the multiplicity which seems to suggest a common mechanism behind the production for different system size, that will be possible to dig out thanks to the larger statistics available during the LHC-Run 3.

About the latest results obtained on the strangeness sector, it seems that no energy or colliding system dependence is behind the experimental results and that the measurements are driven only by multiplicity. Beam Energy Scan in different colliding systems at RHIC would be beneficial in this context and also new theoretical developments in the sector of microscopic models would be necessary to have a satisfactory comparison with the precise experimental results provided at the LHC.

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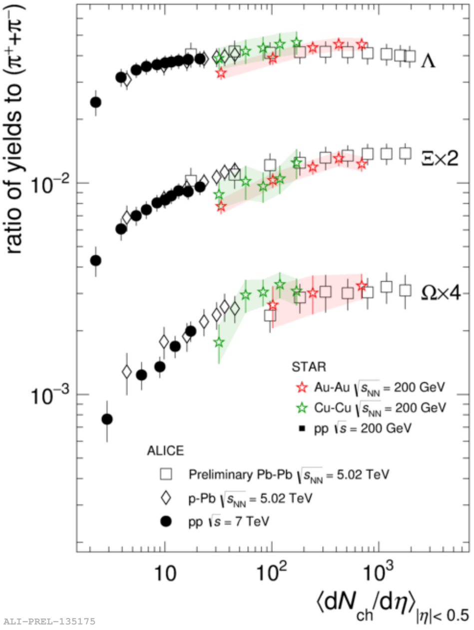

Fig. 7. Strange baryon over pion ratio as a function of the multiplicity in pp, p–Pb and Pb–Pb at the LHC compared to STAR Au-Au and Cu-Cu top energy results.

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