Preliminary Physics Summary:
Deuteron and anti-deuteron production in pp collisions at $\sqrt{s} = 13$ TeV
and in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Abstract

The mechanism which is behind the production of light (anti–)nuclei in ultra-relativistic collisions is one of the open questions in high-energy physics. We present the preliminary results obtained from the analyses of the (anti-)deuteron production for two different data samples collected in the LHC run 2: pp collisions at $\sqrt{s} = 13$ TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. In particular, the production yields, the ratio between the productions of anti–matter and matter, the d/p ratio and the coalescence parameter $B_2$ are compared for the two colliding systems and discussed in the context of thermal and coalescence models.
1 Introduction

Collisions of ultra-relativistic heavy ions create suitable conditions for the production of light (anti-)nuclei, because a high-energy density is reached over a large volume. Under these conditions, hot and dense matter, which contains approximately equal numbers of quarks and anti-quarks at mid-rapidity, is produced for a short duration (a few $10^{-23}$ s). After a possible de-confined Quark Gluon Plasma (QGP) phase, the system cools down and undergoes a transition to a hadron gas. While the hadronic yields are fixed at the moment when the rate of inelastic collisions becomes negligible (chemical freeze–out), the transverse momentum distributions continue to change until also elastic interactions cease (kinetic freeze-out).

The production of light nuclei and anti-nuclei has already been measured in many experiments at lower energies in heavy–ion collisions at the AGS, SPS, and RHIC [1–9] and in smaller collision systems [10–16]. The production of light nuclei is usually discussed within two theoretical approaches: the hadron–coalescence model [17] and the thermal–statistical approach [18]. Hadron–coalescence models explain the light nuclei production as the result of the coalescence of protons and neutrons that, at the kinetic freeze–out, are nearby in space and have similar velocities. A quantitative description of this process is typically based on the coalescence parameter $B_2$ and it has been applied to many collision systems at various energies.

The nuclei abundance is very sensitive to the chemical freeze-out conditions as well as to the dynamics of the emitting source. In the thermal–statistical approach the key parameter is the chemical freeze-out temperature. This approach has been successful in describing particle yields over a wide range of energies in A–A collisions [19, 20]. Thus, the measurement of light nuclei integrated yields in different colliding systems and particle ratios such as the deuteron-to-proton ratio serve as a test for a thermal-statistical behaviour. Moreover, since the binding energy of light nuclei is very small (around few MeV) with respect to the typical temperature of the medium during the hadronic phase (around 100 MeV), the study of the deuteron-to-proton ratio might help to understand the interactions occurring in the hadron gas phase.

2 Experimental apparatus and data sample

The results presented in this document are based on the data sets of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV collected in 2015 and on the pp minimum bias data sample collected during the $\sqrt{s} = 13$ TeV run of 2015. The ALICE detector [21, 22] has excellent particle identification and vertexing capabilities. The (anti-)nuclei were measured using the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Time-Of-Flight detector (TOF). All the detectors are located inside a solenoidal magnetic field with a maximum strength of 0.5 T and cover the full azimuthal acceptance and the pseudo-rapidity range $|\eta| < 0.9$.

The ITS [23] consists of six cylindrical layers of position-sensitive detectors, covering the central rapidity region for vertices located in $|z| < 10$ cm, where $z$ is the distance from the nominal interaction point along the particle beam direction. The ITS allows the reconstruction of the primary and secondary vertices and it is also used to separate primary nuclei from secondary nuclei via the determination of the distance of closest approach of the track to the primary vertex. The TPC [24] is the main tracking device of the experiment with a low material budget to reduce multiple scattering and secondary particle production. The TPC measures the particle momentum and provides the identification via the specific energy-loss $dE/dx$. The TOF detector [25] allows for the light (anti-)nuclei identification by means of the velocity determination. Its total time resolution for tracks from Pb–Pb collisions corresponds to about 80 ps which is determined by the intrinsic time resolution of the detector and the resolution of the event collision time measurement. In pp collisions the total time resolution is about 120 ps. By a combined analysis of TPC and TOF data, (anti-)deuterons are identified up to 6 GeV/$c$ in Pb–Pb collisions and up to 3 GeV/$c$ in the case of pp collisions.
Finally, a pair of forward/backward scintillator hodoscopes (2.8 < η < 5.1 and −3.7 < η < −1.7), the V0 detectors [26], measures the arrival time of particles with a resolution of 1 ns and it is used for triggering purposes in both pp and Pb–Pb collisions. Furthermore it provides the centrality determination in Pb–Pb collisions.

3 Data analysis

3.1 Event and track selection

The data samples used for the presented analyses consist of approximately 60 million pp events and 90 million Pb–Pb events. In pp and Pb-Pb collisions, the data were collected using a minimum-bias trigger requiring at least one hit in both the V0 detectors. Moreover, in both pp and Pb–Pb events, the timing information of the V0 scintillator arrays is used to reject offline the events triggered by the interactions of the beam with the residual gas in the LHC vacuum pipe. In Pb–Pb collision a further selection using the Zero Degree Calorimeter is applied in order to reject the electromagnetic beam–beam interactions and beam–satellite bunch collisions.

The production of primary (anti-)deuterons is measured at mid-rapidity. In order to provide optimal particle identification by reducing the difference between transverse and total momentum, the spectra are provided within a rapidity window of |y| < 0.5. Only those tracks in the full tracking acceptance of |η| < 0.8 are selected. In order to guarantee a good track momentum and TPC dE/dx resolution in the relevant p_T ranges the selected tracks are required to have at least 70 reconstructed points in the TPC and two points in the ITS (out of which at least one in the Silicon Pixel Detector, SPD). The requirement of at least one point in the SPD assures a resolution better than 300 µm on the distance of closest approach to the primary vertex in the plane perpendicular (DCA_xy) and parallel (DCA_z) to the beam axis for the selected tracks [27]. Furthermore, it is required that the χ² per TPC reconstructed point is less than 4 and tracks of weak-decay products are rejected as they cannot originate from the tracks of primary nuclei.

3.2 Particle Identification

The TPC allows for a clean identification of deuterons and anti-deuterons up to p_T ~ 1 GeV/c and for higher transverse momenta the specific energy-loss information is combined with the TOF mass determination. Figure 1 shows the TPC specific energy-loss as a function of rigidity (p/z) in pp collisions at √s = 13 TeV. The solid curves represent a parametrization of the Bethe-Bloch function for the different particle species. In practice, it is required that the measured energy-loss signal of a track lies in a 3σ window around the expected value for a given mass hypothesis. The same approach is used for the analysis in Pb-Pb collisions.

In order to extend the p_T reach of the measurement it is additionally requested that the track is matched to an hit in the TOF detector. Based on the time-of-flight measurement the mass of the particle is determined in different p_T bins and the distributions are then fitted using a Gaussian function with an exponential tail for the signal. The background mainly originates from two components, namely wrong associations of a track with a TOF hit and the non-Gaussian tail of lower mass particles. This background is described with the sum of two exponential functions. The same procedure for signal extraction and background subtraction is applied in the analysis of Pb-Pb collisions.

3.3 Background rejection

One of the main sources of background in the analysis of the primary deuteron production is the detection and reconstruction of nuclei originating from secondary interactions. These secondary nuclei come mostly from the interactions of other primary particles with the detector material. In some of these interactions, a light nucleus can be produced by knock–out processes. The baryon number conservation sets a very high energy threshold for the production of secondary anti–nuclei with similar processes,
thus in the following only the case of nuclei will be discussed. Other processes, such as the decay of (anti-)hypernuclei, represent a negligible contamination to the observed (anti-)deuterons.

To remove the background from secondary deuterons the DCA$_{xy}$ of the deuteron candidates is studied. The distribution of primary particles is expected to be peaked at DCA$_{xy} = 0$ cm, whereas secondary particles are expected to exhibit a flat DCA$_{xy}$ distribution to first order. In second order the tracks originating from secondary particles may be associated to a wrong hit in the SPD. If the latter belongs to a primary particle, the extrapolation of the secondary particle track will wrongly point to the primary vertex, as the track pointing is mostly driven by the SPD hits. For this reason, in both analyses presented in this paper, a fit to the observed DCA$_{xy}$ distribution is performed to extract the primary fraction of deuterons. The DCA$_{xy}$ distributions of primary and secondary deuterons in each transverse momentum interval are extracted from Monte Carlo (MC) events and they are used as templates to fit the measured DCA$_{xy}$ distribution. An typical example of a fit to the DCA$_{xy}$ distribution in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for most central events is shown in Figure 2. The fit is done in a range of DCA$_{xy}$ wider than the actual track selection criterion to better constrain the fit of the secondary particle component, that populates mostly the tails of the DCA$_{xy}$ distribution. The contamination from deuterons produced in the interactions with the detector material is less than 1.4 GeV/$c$.

3.4 Corrections to the spectra

The $p_T$-differential-production spectra of (anti-)deuterons are obtained by correcting the raw spectra for tracking efficiency and acceptance based on MC generated events. The MC samples used to compute the efficiency and the acceptance corrections for the Pb–Pb (pp) analysis were generated using the HIJING event generator [28] (PYTHIA6-Perugia2011 [29]). Since neither HIJING nor PYTHIA provide light (anti-)nuclei, an ad–hoc generator that injects particles on top of these event generators was used. The kinematics of the injected nuclei is chosen randomly by picking their transverse momentum from a flat distribution in the range between 0 and 10 GeV/$c$, their azimuthal angle from a distribution between 0 and $2\pi$ radians, and their rapidity from a flat distribution in the range $|y| < 1$. All particles are transported with GEANT 3 [30] through a full simulation of the ALICE detector. The GEANT3 version used in ALICE software framework has been modified to use an empirical model [31] in order to describe the
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Figure 2: Fit to the DCA$_{xy}$ distribution of deuteron candidates in Pb-Pb collisions (black points). The blue line is the fit result and it represents the sum of the primary particle component (green shaded area) and secondary particle one (red shaded area).

(anti-)nuclei hadronic interaction in the detector material.

In addition to GEANT3, the GEANT4 transport code [32] was also used in order to estimate the systematic uncertainty related to the different implementations of the (anti-)nuclei hadronic interactions with the detector material.

Furthermore, for the Pb-Pb analysis it has been verified that the trend of efficiency × acceptance as a function of $p_T$ is not centrality dependent. For this reason the minimum bias (MB) efficiency × acceptance is used to correct the Pb-Pb raw spectra in all the centrality classes in order to profit from better statistical uncertainties in the determination of the correction.

Finally, pp spectra have been corrected for the inefficiency of the MB trigger in detecting an inelastic pp collision (INEL). This correction has been computed by dividing the total pp inelastic cross section by the V0 detector visible cross section. The uncertainty on this ratio is considered as a systematic uncertainty of the $p_T$-differential spectra.

4 Systematic uncertainties

The sources of systematic uncertainty affecting these measurements have been studied as follows:

1. the amount of material budget employed in the MC simulation of the ALICE apparatus has been increased and decreased by 4.5%, corresponding to the uncertainty on the ALICE material budget determination;

2. as an alternative to GEANT3, GEANT4 was considered as the transport code to simulate the passage of particles through the detector material;

3. track selection criteria have been varied as done for previous analyses;

4. variation of the the fit functions used for the signal extraction.
The largest contribution to the systematic uncertainties is given by differences between the efficiency and acceptance evaluated with GEANT3 and GEANT4. In general, the accuracy of the transport codes is limited by the available data for nuclei and especially (anti-)nuclei hadronic interaction cross sections which have been measured in energy ranges far from the typical momenta of light (anti-)nuclei produced in heavy ion collisions [33-36]. The choice of the transport code results in a 8% (12%) systematic uncertainty. The variation of the material budget results in a systematic uncertainty smaller than 2% at low $p_T$ and vanishing at high $p_T$. All the other systematic uncertainties in the Pb-Pb analysis were estimated for each centrality class: particle identification and analysis selection criteria contribute by less than 3% and the signal extraction by less than 2%. The discrepancy between the data and MC description of the ITS-TPC and the TPC-TOF matching efficiencies is accounted for by adding two systematic uncertainties of 3.5% and 2.5%, respectively. For the pp results the systematic uncertainty on the tracking efficiency is estimated to be about 5%. The TOF particle identification and matching efficiency contribution to the systematic uncertainty up to 10% at high $p_T$. The background rejection using the secondary correction for the deuteron leads to a systematic uncertainty of 5% at low $p_T$ and the TPC particle identification systematic uncertainty is estimated to be 4%.

5 Results

The production spectra of (anti-)deuterons have been extracted in Pb–Pb and pp collisions at the unprecedented energies of $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s} = 13$ TeV. The spectra are shown in Figure 3 for the Pb-Pb and inelastic pp collisions.

![Deuteron spectra measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for different centrality classes reported with different colours and in pp collisions at $\sqrt{s} = 13$ TeV reported in black. The boxes represent the systematic uncertainties while the vertical lines are the statistical ones. The dashed lines represent the individual Blast Wave fit to the spectra in the Pb-Pb case and the LévRy-Tsallis fit in the pp analysis.](ALICE Preliminary)

To calculate the integrated yield ($dN/dy$) in the pp analysis at $\sqrt{s} = 13$ TeV the spectra have been fitted with the Lévy-Tsallis function [37] [38]. The systematic uncertainty of the integrated yield is obtained by shifting the spectrum within its systematic errors and adding an additional uncertainty quadratically to account for the extrapolation to low and high $p_T$. The latter is estimated by using different fit functions such as $m_T$ exponential, Boltzmann, Fermi-Dirac and Bose-Einstein functions. The extrapolation accounts for 32% of the total yield. The statistical uncertainties are calculated by shifting the spectra.
randomly with a Gaussian distribution within the statistical uncertainties of each $p_T$ bin. The resulting yield distribution is fitted with a Gaussian and the width of this distribution is taken as the statistical uncertainty.

In order to measure the total yield per rapidity unit in Pb-Pb collisions, the spectra were fit with the Blast-Wave function which describes the measured spectra assuming a thermal production of particles from an expanding source [39]. Since the production of nuclei and anti–nuclei are compatible within uncertainties and since the anti–nuclei spectra are affected by larger systematic uncertainties, the measurement of the yield is performed using the nuclei spectra only. The procedure to extract the statistical and systematic uncertainties of the $dN/dy$ was the same as used for the pp analysis. The extrapolation in this case accounts for 9% and 60% of the total integrated yield in the most central and in the most peripheral events, respectively.

In pp and Pb-Pb the $\bar{d}/d$ ratio was determined as the ratio between anti-matter and matter yields in each of the measured $p_T$ bins. Results are shown in Figure 4 for the pp collisions and for all the studied centrality classes of the Pb-Pb analysis. The ratios are found to be compatible with unity as expected by coalescence and thermal models.

![Figure 4: Ratio between the anti–deuteron and the deuteron spectra for pp collisions at $\sqrt{s} = 13$ TeV (open symbols) and in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV data sample.](image)

The coalescence models can be further investigated by computing the coalescence parameter $B_2$:

$$B_2 = E_d \frac{d^3N_d}{dp_d^3} \left( \frac{E_p d^3N_p}{dp_p^3} \right)^{-2},$$

where $E_d \frac{d^3N_d}{dp_d^3}$ and $E_p \frac{d^3N_p}{dp_p^3}$ are the invariant production spectra of deuterons and protons, respectively. Figure 5 shows the measured coalescence parameter $B_2$ as a function of the transverse momentum scaled by the mass number $A$ for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and for pp collisions at $\sqrt{s} = 13$ TeV. An ordering of the coalescence parameters with centrality, going from higher $B_2$ values in pp and peripheral collisions to lower $B_2$ values in the central ones is clearly visible in the Pb-Pb result. This trend with centrality is explained in the coalescence model framework as a consequence of the increasing volume $V_{eff}$ of the source going from peripheral to central events. The extracted $B_2$ for pp collisions is mainly flat in the low $p_T$ region and an increasing trend as function of $p_T/A$ starts to be visible above 1 GeV/c.
Figure 5: Coalescence parameters $B_2$ measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the transverse momentum scaled by the mass number of the nucleus. Each colour corresponds to a different centrality class. See the text for details. In black the $B_2$ measured in pp collisions at $\sqrt{s} = 13$ TeV is reported.

According to the thermal-model interpretation, the deuteron-over-proton ratio (d/p) is fixed by the temperature of the source, thus it is expected to stay constant as a function of charged particle multiplicity. On the other hand, in a naive coalescence picture d/p should increase with the number of nucleons produced in the collision. Figure 6 shows the d/p measured by the ALICE Collaboration for different colliding systems at different energies. The preliminary 5.02 TeV Pb-Pb ratios are consistent within uncertainties with the results in Pb-Pb collisions at 2.76 TeV and follow the trend observed from pp to p-Pb collisions as a function of multiplicity. A possible interpretation of the data is, that the rise of the ratio with charged particles multiplicity in p-Pb collisions points to an increased deuteron production with a rising proton and neutron density as expected in the coalescence picture. For high charged particle multiplicities as reached in semi-central and central Pb-Pb collisions, the ratio reaches a saturation, which is compatible with the thermal model description.

6 Summary

We have shown the preliminary results for (anti-)deuteron production in inelastic pp collisions at $\sqrt{s} = 13$ TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in ten different centrality classes. The results match the trends observed in previous analyses in pp, p–Pb and Pb–Pb collisions at lower energies. In particular the coalescence parameter $B_2$ is decreasing strongly in Pb–Pb collisions when going from peripheral to central events. The d/p ratios and $B_2$ values in pp and Pb–Pb presented here confirm the trend as a function of multiplicity already measured by ALICE [16].

References

Figure 6: Integrated deuteron yield over integrated proton yield as a function of charged particle multiplicity \(\langle dN/d\eta_{ch} \rangle\) for pp, p–Pb and Pb–Pb collisions measured by the ALICE Collaboration.


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