Multiplicity Dependence of (Anti-)Deuteron Production in p–Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV
Measured with ALICE

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Abstract. The measurement of the (anti-)deuteron production as a function of transverse momentum and event multiplicity in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is presented here. (Anti-)deuterons are identified via their energy loss $dE/dx$ in the time projection chamber and via their time-of-flight. Their production will be discussed within the context of thermal and coalescence models.

1. Measurement of (Anti-)Deuterons
The (anti-)deuteron production has been measured with the minimum-bias trigger data recorded by ALICE [1] during the 2013 p–Pb run at $\sqrt{s_{NN}} = 5.02$ TeV at the LHC. The event selection is done as in [2] and the sample is divided in five multiplicity classes according to the multiplicity of the VZERO-A detector, which is located in the Pb-going direction at $2.8 < \eta < 5.1$.

Figure 1: (Anti-)deuteron identification with the TPC and TOF. On the left the energy loss per path-length as a function of momentum is shown. On the right an example of the fit to the squared TOF mass to reduce the remaining background is shown.

Fig. 1 on the left shows the specific energy loss of particles in the time projection chamber (TPC) [3] for p–Pb data. At low momenta ($< 1$ GeV/c) a clean identification of (anti-)deuterons...
is achieved by a symmetric 3σ cut around the expected energy loss. At higher momenta the particle bands cross and the mass measured with the time-of-flight detector (TOF) [4] is used in addition. Here, the cut of 3σ on the TPC dE/dx signal reduces the amount of the TPC-TOF mismatched tracks and the remaining background is removed with a fit to the squared mass. This is shown for deuterons with 2.4 GeV/c < p_T < 2.6 GeV/c in Fig. 1 on the right.

The tracking efficiency and the TOF matching efficiency for deuterons and anti-deuterons is shown in Fig. 2. The efficiencies also account for particles that are absorbed by the detector material, which is negligible for deuterons, but sizeable for anti-deuterons. In addition, only very little data is available for the hadronic cross-section of anti-deuterons and different transport models give different results. For this work the efficiencies have been calculated with Geant 4 [5] and have been compared to results from Geant 3 [6] to estimate the systematic uncertainty. It amounts to about 15%.

![Figure 2: Tracking and TOF matching efficiencies for deuterons and anti-deuterons.](image)

2. Results

The (anti-)deuteron transverse momentum distributions for different charged-particle multiplicities are shown in Fig. 3. Also shown are individual Blast-Wave fits (black lines) used to extrapolate to low and high p_T and to calculate the integrated yields dN/dy. A hardening of the spectra from low to high multiplicity is visible, which is also observed for light-flavor hadrons [7]. In heavy-ion collisions this hardening is commonly attributed to radial flow [8].

A central result of the deuteron measurement is the deuteron to proton ratio. It is shown in Fig. 4 for p-Pb and Pb-Pb collisions as a function of multiplicity and for minimum bias pp collisions. At low multiplicity the d/p ratio in p-Pb is consistent with the pp data. The ratio rises with multiplicity reaching the value of peripheral Pb-Pb collisions, where it saturates. The smooth transition between the different systems suggests that the d/p ratio is governed by the event multiplicity. Please note, that the uncertainties for p-Pb are largely correlated across multiplicity bins.

The deuteron production in ultra-relativistic particle collisions is commonly discussed within coalescence [9, 10] and thermal models [11, 12, 13]. Thermal models describe the particle abundance with the chemical freeze-out temperature T_ch, the baryo-chemical potential \( \mu_B \) and the source volume V. The chemical freeze-out marks the point in the evolution of particle collisions, where all inelastic processes cease and the chemical composition is fixed. They are very successful in describing not only the hadron production, but also the light nuclei production of heavy-ion collisions [14, 15, 16]. This is unexpected, because in thermal models the nuclei yield is fixed at T_ch \( \approx 150 \) MeV and deuterons can hardly remain intact in this hot environment,
because of their low binding energy $E_B = 2.2 \text{ MeV}$ [17]. On the other hand, the quality of current thermal model fits to high multiplicity p-Pb collisions is poor [18].

In coalescence models deuterons (and other light nuclei) are produced by protons and neutrons, that are close in phase space. In the most naive way, this would lead to an increased deuteron production for higher nucleon multiplicities. However, the d/p ratio for Pb-Pb collisions is constant with increasing centrality, although the nucleon multiplicity increases. Models, which take the source volume into account, i.e. are sensitive to the nucleon density, are therefore clearly favored. Here, the increasing nucleon multiplicity is cancelled by the increasing source volume, leading to a constant nucleon density. This is also consistent with the rising d/p ratio with multiplicity in p-Pb, where the effect of the increasing nucleon multiplicity probably dominates over the effect of the increasing source volume.

Within coalescence models the coalescence parameter for deuterons $B_2$ is defined as

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

where $p_d = 2p_p$. Fig. 3 shows the resulting $B_2$ as a function of $p_T$ and multiplicity for p-Pb and Pb-Pb collisions. Within the systematic uncertainties it is flat over the measured $p_T$-range in p-Pb collisions and peripheral Pb-Pb collisions, which is in agreement with the

Figure 3: The deuteron (left) and anti-deuteron (right) transverse momentum distributions as a function of multiplicity.

Figure 4: Deuteron over proton ratio as a function of charged-particle multiplicity at mid-rapidity ($|\eta| < 0.5$) for pp, p-Pb and Pb-Pb collisions at the LHC.
coalescence picture. In addition, a decreasing $B_2$ for increasing multiplicity is observed, which can be attributed to the increasing source volume. In fact, $B_2$ could be governed by the same homogeneity volume as HBT [19]. For $p_T > 2.0$ GeV/c and centralities $> 40\%$ of Pb-Pb collisions $B_2$ increases with the transverse momentum, which could be due to the collectivity of the emerging particles.

3. Summary
The transverse momentum distributions of (anti-)deuterons as a function of multiplicity in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been measured with ALICE. The deuteron over proton ratio rises with multiplicity and is consistent with pp and Pb-Pb collisions at low and high multiplicities, respectively. This favors coalescence models, that are based on the nucleon density. The coalescence parameter $B_2$ is flat over the measured $p_T$-range, which is in agreement with the expectation. Thermal models successfully describe the particle production including the light nuclei production in Pb-Pb collisions, but current fits to high multiplicity p-Pb collisions [18] are less successful.

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