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Extending the ALICE strong-interaction studies to nuclei: measurement of proton–deuteron correlations in pp collisions at $\sqrt{s}$ = 13 TeV

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The large data sample of high-multiplicity pp collisions collected by ALICE allows for the precise measurement of the size of source producing primary hadrons, opening the doors to a study of the interaction of different hadron species using femtoscopy techniques. The momentum correlation between (anti)protons and (anti)deuterons measured in pp collisions at $\sqrt{s}$ = 13 TeV with ALICE is studied here for the first time. The measured correlation function for $(\overline{\mathrm{p}})$p–$(\overline{\mathrm{d}})$d pairs is compared with theoretical predictions obtained considering Coulomb and Coulomb plus strong interactions and employing the Lednický-Lyuboshitz model with scattering parameters extracted from traditional scattering experiments for the p–d system. The measured correlation function can not be reproduced by any of the obtained predictions. This deviation can to large extent be interpreted as a demonstration of the late formation time of (anti)deuterons in hadron–hadron collisions. This observation is key for the understanding of the production mechanism of light (anti)nuclei, which is an open issue in high-energy physics and has also important consequences for the study of antinuclei formation in the interstellar medium either from collisions triggered by high-energy cosmic rays or by dark matter decays.

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1. Introduction

The formation mechanism of light (anti)nuclei in collision experiments has been of great interest over the past decades. One of the key challenges is the not yet understood formation time of light (anti)nuclei. The theoretical description of the production mechanism of (anti)nuclei is still an open problem. At present the phenomenological models, particularly the Statistical Hadronisation Model (SHM) [1] and the coalescence model [2], are used to infer the production of multi-baryon states. In the SHM, light nuclei are assumed to be effused from a common source in the local thermal and hadrochemical equilibrium and their abundances are fixed at chemical freeze-out. On the other hand the coalescence model assumes that light nuclei are formed via the process of coalescence of the nucleons which are close in phase-space at the common kinetic freeze-out surface. However, both the SHM and the coalescence model do not provide information on the time taken for the formation of light (anti) nuclei relative to the formation time of the nucleons.

Here, a new approach is proposed to probe the formation time of the (anti)deuterons via the measurement of the proton–deuteron (p–d) correlation in pp collisions at $\sqrt{s} = 13$ TeV using the femtoscopic technique at ALICE. The measurement of final-state interactions between a pair of a (anti)proton and a (anti)deuteron provides useful insight into the formation time of (anti)deuterons. The measured p–d ($\overline{\text{p}}$–$\overline{\text{d}}$) correlation function is compared with the predicted theoretical one which employs the scattering parameters measured in scattering experiments. We provide for the first time a direct comparison of theory and measurement.

2. p–d Correlation Measurement

The results presented in this contribution are obtained by analysing pp collisions at $\sqrt{s} = 13$ TeV recorded with the ALICE detector [3] during the LHC Run 2 (2015–2018). The sample was collected using the high-multiplicity trigger selection criteria adopted from the p-Σ^0 analysis [4]. For the tracking of the charged particles the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) are employed. The ITS and TPC detectors are used for particle identification (PID) via the measurement of the specific ionization energy loss (dE/dx) along the particle trajectory. The PID for particles with large momentum is accomplished by measuring their velocity β in the Time-Of-Flight (TOF) detector. The (anti)proton candidates are reconstructed following the analysis method used for high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV [4], and are selected from the charged-particle tracks reconstructed with the TPC in the kinematic range $0.5 < p_{\mathrm{T}} < 4.05\,\mathrm{GeV}/c$ and $|\eta| < 0.8$ exploiting the combined PID capabilities of TPC and TOF detectors. The (anti)deuterons are reconstructed in the kinematic range $0.5 < p_{\mathrm{T}} < 1.4\,\mathrm{GeV}/c$ and $|\eta| < 0.8$ with the combined PID capabilities of TPC and ITS detectors. (Anti)deuterons with $p_{\mathrm{T}} > 1.4\,\mathrm{GeV}/c$ are omitted due to the large contamination of the sample with other particle species.

The two-particle correlation function for ($\overline{\text{p}}$)p–($\overline{\text{d}}$)d pairs is obtained employing the following formula [5],

$$C(k^*) = \mathcal{N} \times \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} \xrightarrow{k^* \to \infty} 1\,, \tag{1}$$

The relative momentum of the pair k^* is defined as $k^* = \frac{1}{2} \times |p_1^* - p_2^*|$, where p_1^* and p_2^* are the momenta of the two particles in the pair rest frame. N_{same} and N_{mixed} are same and mixed

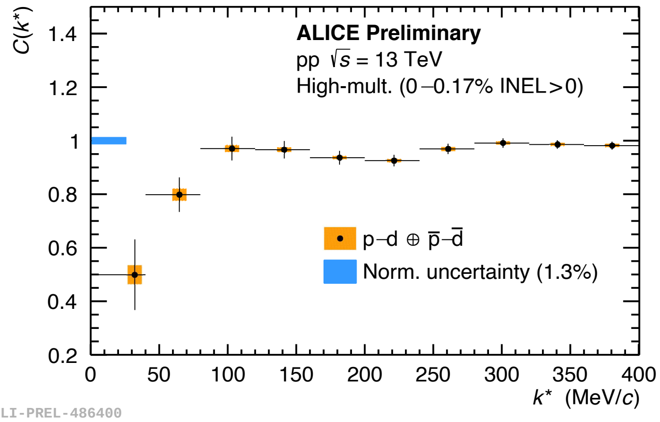

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Figure 1: Measured correlation function of p–d ⊕ $\overline{\mathrm{p}}$–$\overline{\mathrm{d}}$. Statistical (bars) and systematic uncertainties (boxes) are shown separately.

event distributions and a normalization constant $\mathcal{N}$ is obtained by requiring that the ratio is 1 in in $k^* \in [200, 500]$ MeV/c, where effects of final-state interactions are negligible and hence the correlation function approaches unity.

In the data sample, 1747(1250) p–d ($\overline{\mathrm{p}}$–$\overline{\mathrm{d}}$) pairs contribute to the respective correlation functions in the region $k^* < 200$ MeV/c. No significant differences among the p–d and $\overline{\mathrm{p}}$–$\overline{\mathrm{d}}$ correlation functions are observed. In order to enhance the statistical significance of the results, the p–d and $\overline{\mathrm{p}}$–$\overline{\mathrm{d}}$ correlations are combined and denoted as p–d ⊕ $\overline{\mathrm{p}}$–$\overline{\mathrm{d}}$. The resulting measured correlation function is presented in Fig. 1. It is flat around $C(k^*) = 1$, but exhibits a depletion below one at low k^*.

Systematic uncertainties of the measured correlation function are evaluated by simultaneously varying all (anti)proton and (anti)deuteron selection criteria by up to 20% around the nominal values. Only the variations that modify the pair yield by less than 10% are considered as systematic variations. Additionally, the uncertainties due to variations of the normalisation range within $k^* \in [100, 600]$ MeV/c are considered, which yield ~ 1.3% and are shown as blue box at $C(k^*) = 1$.

3. Theoretical p–d Correlation

The theoretical definition of the two-particle correlation function consists of a source function $S(r^*)$ and the two-particle wave function $\Psi(r^*, k^*)$ [5]

$$C(k^*) = \int \mathrm{d}^3 r^* S(r^*) |\Psi(r^*, k^*)|^2 \,, \tag{2}$$

where r^* is the relative distance between the two particles. In pp and p–Pb collisions the system size is small and therefore the correlation function becomes very sensitive to the source function $S(r^*)$ [6]. In this study, the emitting source is assumed to be spherically symmetric with a Gaussian shaped core density profile parametrised by a radius r_0 which is fixed by the transverse mass of the p–d ($\overline{\mathrm{p}}$–$\overline{\mathrm{d}}$) pairs using the transverse-mass dependence as described in [7]. In addition to the Gaussian core, collective effects collective effect such as radial and asymmetric flow and the strong decays of resonances in (anti)protons are taken into account in the evaluation of the effective source size r_{eff}. The values of r_0 and r_{eff} are determined to be 0.98 ± 0.04 fm and 1.073 ± 0.005 fm, respectively.

At present, there are no theoretical calculations available by solving the Schrödinger equation for realistic three-body potential for the p–d system. In order to compare the measured data with a model using three-body interactions for the p–d system, the wave function of two particles near threshold evaluated in the region outside the strong interaction has been used [8]. Such an approximated wavefunction is modified due to the long-range Coulomb interaction and defined as.

$$\psi_{-k^*}(r^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-ik^*r^*}F(-i\eta,1,i\xi) + f_c(k^*)\frac{\tilde{G}(\rho,\eta)}{r*}\right]. \tag{3}$$

The components of the wavefunction are given in [8]. The amplitude of the low-energy s-wave elastic scattering due to the short-range interaction renormalized by the long-range Coulomb forces is given by.

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{d_0 k^{*2}}{2} - ik^*A_c(k^*) - \frac{2h(\eta)}{a_c}\right]^{-1}. \tag{4}$$

The theoretical correlation function for p–d is obtained substituting Eq. (3) in Eq. (2) with scattering parameters for both the doublet ($^2\mathrm{S}_{1/2}$) and the quartet ($^4\mathrm{S}_{3/2}$) spin channels [9–13]. The total s-wave p–d correlation is the sum of the contributions from the doublet and quartet channels with Clebsch-Gordan coefficients 1/3 and 2/3, respectively. Contrary to the Gamow approximation applied to the wavefuction as discussed in in [14], Eq. (3) accounts for the Coulomb correction in the scattering amplitude $f_c(k^*)$. As a check, we computed the p–d correlation function using the Gamow approximation and using the Coulomb corrected wavefunction in Eq. (3) for different source sizes r_0 = 1.5, 1.73, and 2.0 fm as it is shown in Fig. 2. The p–d correlations in the right panel of Fig. 2 are identical to those shown by Mrówczyński and Słoń in [14]. In comparison to this, the Coulomb-corrected wavefunction definition exhibits a stronger peak at low k^* as presented in the left panel of Fig. 2, reflecting a larger contribution from the strong interaction part. In addition to the genuine correlation, the measured p–d correlation function contains residual correlations due to protons stemming from weak decays of Λ and Σ^+ particles and from particle misidentification.

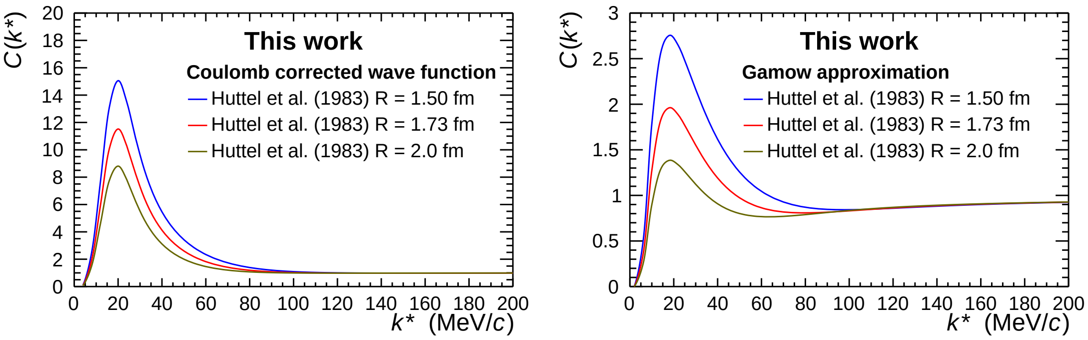

Figure 2: Theoretical p–d correlation function using a Coulomb-corrected wavefunction for Coulomb+Strong interaction (left) and a Gamow approximation (right) for soure sizes r_0 = 1.5, 1.73, and 2.0 fm.

These effects are important to be included while modeling the correlation function defined in Eq. (5), which is performed via the decomposition:

$$C_{\mathrm{model}}(k^*) = \lambda \cdot C_{\mathrm{theory}}(k^*) + (1-\lambda)\,, \tag{5}$$

where the λ parameter accounts for the genuine p–d interaction. In the case of p–d ($\overline{\mathrm{p}}$–$\overline{\mathrm{d}}$), the λ parameter for the genuine interaction is determined by the purity of the sample and contributions originating from secondary particles. The obtained values of the λ parameters are 0.81 and 0.84 for p–d and $\overline{\mathrm{p}}$–$\overline{\mathrm{d}}$ pairs, respectively. In the combined correlation function an average value of 0.83 is used for the genuine interaction. In the modelled correlation function, the effective range of expansion is varied for the doublet and the quartet within the interval $0 \leq {}^2\mathrm{d}_0 \leq 2.27$ fm, and $0 \leq {}^4\mathrm{d}_0 \leq 2.63$ fm respectively. The theoretical correlation function for Coulomb plus strong interactions with

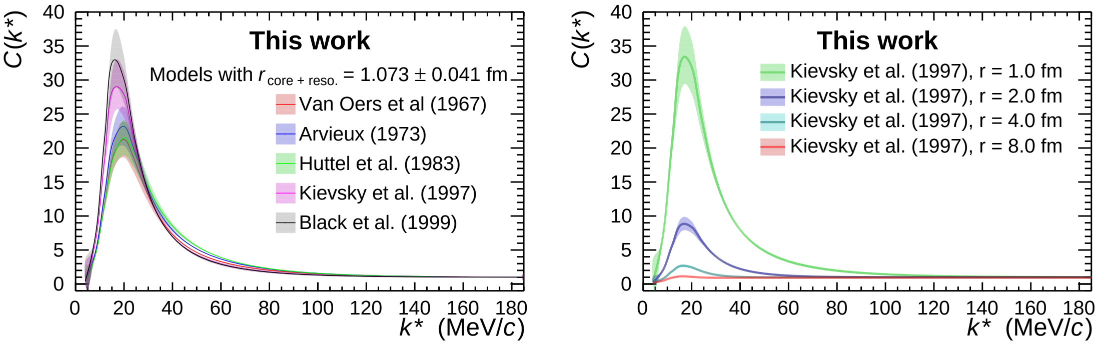

Figure 3: Theoretical p–d correlation function for Coulomb+Strong interaction for $r_{\mathrm{eff}} = 1.073 \pm 0.041$ fm (left) and for several source radii (right).

$r_{\mathrm{eff}} = 1.073 \pm 0.041$ fm corresponding to the measured one is presented in the left panel of Fig. 3. This can be compared to the measured correlation function shown in Fig. 1. Huge discrepancies are observed between the data and the theoretical models in the low k^* regime. The theoretical models for all set of scattering parameters show a very strong attractive interaction whereas the measured p–d correlation shows no strong attractive interaction, but rather exhibits a depletion at low k^* reflecting a repulsive Coulomb interaction and a possible further loss of p–d pairs. Such a large discrepancy between models and the data has not been observed in femtoscopic measurements so far. The absence of an attractive interaction in the measured correlation indicates the late formation of (anti)deuterons, which enhances the source size r_{eff}. As a result of the increased r_{eff}, the strong attractive interaction is diluted. This effect can be observed in the models performing a source radius scan, which is presented in Fig. 3 (right). The peak due to the strong attractive interaction in the modelled p–d correlations drastically diminishes with increasing source size. For a sufficiently large source size ~ 8.0 fm the modelled p–d correlation function approaches to measured p–d correlation function.

4. Conclusions

In this contribution, the first measurement of a p–d correlation function using ALICE data in high-multiplicity pp collisions is presented. A large disagreement between the modelled and the measured correlation functions is observed. The observed disagreement can be interpreted as an effect of the late formation time of (anti)deuterons. The measured p–d correlation function provides a key to unravel the production mechanism of light (anti)nuclei.

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