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RESEARCH HIGHLIGHT

Femtoscopy reveals how (anti-)deuteron is formed at the LHC

Kai-Jia Sun[1,2]

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The production of light (anti-)nuclei in high-energy collisions has long posed an apparent paradox: How can loosely bound systems such as the anti-deuteron with a binding energy of only 2.23 MeV be formed and survive in the extreme hot and dense hadronic environment emerging from proton–proton (pp) and heavy-ion collisions, where characteristic thermal energies exceed 100 MeV? A new femtoscopy analysis published on *Nature* [1] by the ALICE Collaboration at the Large Hadron Collider (LHC) delivers the clearest answer to date. By measuring pion-(anti-)deuteron momentum correlations in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV, the experiment demonstrated that most (anti-) deuterons are not produced directly at hadronization, but instead originating from meson-catalyzed reactions [2] following the decay of short-lived baryonic resonances, most notably the $\Delta(1232)$. This result provides long-sought microscopic insight into how fragile (anti-)nuclei emerge in ultra-relativistic hadronic environments, from collider events to cosmic rays.

Light nuclei and antinuclei, such as deuterons (d), tritons (^{3}H), helium-3 (^{3}He), helium-4 (^{4}He), and their antiparticles, have been measured with increasing precision across collision systems and energies, from heavy-ion collisions to pp collisions [3–11]. This phenomenon, known as 'little bang nucleosynthesis' [2, 12] or 'snowballs in hell' [13, 14], connects directly to fundamental questions about matter–antimatter symmetry [15], phase transitions in quantum chromodynamics (QCD) [16, 17], and dark-matter searches [18, 19].

While their integrated yields are often described surprisingly well by the statistical hadronization model of quark–gluon plasma [20], their microscopic formation remains far from settled [21–24]. The deuteron's binding energy is two orders of magnitude smaller than the temperature of hadronic matter produced in pp or Pb+Pb collisions. In such an environment, 'direct' emission from the hadronization of quark–gluon plasma or the chemical freeze-out hypersurface appears implausible, and any loosely bound system produced early would almost certainly be destroyed by subsequent hadronic rescatterings. Final-state coalescence models offer a different scenario in which nucleons close in phase space can merge into bound states at the very late kinetic freeze-out [25–28]. In the microscopic transport approach, it has been shown that pion-catalyzed reactions (e.g. πNN$\leftrightarrow \pi$d, πNd$\leftrightarrow \pi^3$He) do not significantly change the deuteron production in central Pb+Pb and Au+Au collisions [29], but reduce the triton and Helium-3 yield by approximately a factor of 1.8 [2]. For the forward pion-catalyzed reaction πNN $\rightarrow \pi$d, it can be viewed as a two-step process of πN $\rightarrow \Delta$ and ΔN $\rightarrow \pi$d, and a deuteron is produced via nucleon fusion following a $\Delta \rightarrow \pi$N decay. The decayed pion is kinematically correlated with the nucleon that subsequently participates in forming the deuteron. This correlation manifests as a distinct Δ resonant structure in the pion-deuteron correlation function in momentum space, as the reaction rate reaches maximum at relative momenta reflecting the Δ mass and decay kinematics [2].

The ALICE measurement exploits this signature through pion-deuteron (π-d) femtoscopy [1]. Femtoscopy analyzes momentum correlations at relative distances down to order of 1 fm (10^{-15} m) [30–33] and has become a precision tool for studying strong interactions [34–37] and exotic hadrons [38]. The new ALICE data reveal a pronounced resonance peak associated with Δ decay, providing direct evidence that (anti-)deuterons form predominantly through resonance-fed secondary processes.

The key experimental observable is the momentum correlation function,

✉ Kai-Jia Sun
kjsun@fudan.edu.cn

[1] Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China

[2] Key Laboratory of Nuclear Physics and Ion-Beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China

$$C(k^*) = \mathcal{N}\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}, \tag{1}$$

where k^* is the momentum of either particle in the pair rest frame. $N_{\text{same}}(k^*)$ denotes the distribution of relative momenta for particle pairs from the same event, while $N_{\text{mixed}}(k^*)$ provides an uncorrelated reference constructed by combining particles from different events. The factor $\mathcal{N}$ normalizes the correlation function so that $C(k^*)$ approaches unity at large k^*.

Intriguing correlations can arise from final-state strong and Coulomb interactions [39, 40], quantum statistics [39], or resonance decays [40]. In general, attractive interactions enhance $C(k^*)$ at low k^*, whereas repulsive interactions suppress it.

ALICE measures $\pi - d$ and $\pi - \bar{d}$ correlations in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV with excellent particle identification, achieving purities of 99–100%. The correlation functions shown in Fig. 1 exhibit a prominent peak associated with Δ resonance decay. The data are then modeled using

$$C_{\text{fit}}(k^*) = \epsilon(k^*) \otimes B(k^*)\left[\lambda_{\text{gen}} C_{\text{gen}}(k^*) + (1 - \lambda_{\text{gen}})\right], \tag{2}$$

where $\epsilon(k^*)$ accounts for momentum resolution, $B(k^*)$ for residual backgrounds, and λ_{gen} for the fraction of genuine pairs. The genuine correlation function $C_{\text{gen}}(k^*)$ includes Coulomb and strong interactions plus the Δ contribution and is computed via CATS [41] assuming an effective source radius $r_{\text{eff}} = 1.51 \pm 0.12$ fm.

Final-state Coulomb and strong interactions generate a monotonic enhancement (suppression) for π^--d (π^+-d) pairs at low relative momentum ($k^* < 50$ MeV/c), while the Δ resonance produces strong peaks around $k^* \approx 150$ MeV/c in both correlation functions.

By integrating the Δ peak, ALICE finds that $60.6 \pm 4.1\%$ of detected deuterons contain a nucleon produced in a Δ decay. Accounting for all short-lived resonances yields a total resonance-fed fraction of $88.9 \pm 6.3\%$. Thus, meson-catalyzed fusion with resonance-decay nucleons dominates (anti-)deuteron formation at the LHC.

This conclusion is reinforced by a recent theoretical study [42] that reproduces the observed resonant structure in both pion-proton (π-p) and pion-deuteron (π-d) correlation functions by solving relativistic kinetic equations for $\pi\text{NN} \leftrightarrow \pi\text{d}$ on an event-by-event basis. The model–data comparison further indicates a strong downward in-medium shift of the Δ(1232) mass by approximately 70 MeV/c^2 [1]. Such a reduction from $m_\Delta = 1.232$ GeV/c^2 to 1.162 GeV/c^2 may reflect strong in-medium modifications, possibly linked to partial chiral-symmetry restoration [43]. Traditional coalescence models reproduce only about half of the observed peak, and statistical hadronization fails to generate any resonance structure, highlighting the unique discriminatory power of pion-nucleus femtoscopy for unraveling (anti-)nuclei production mechanisms.

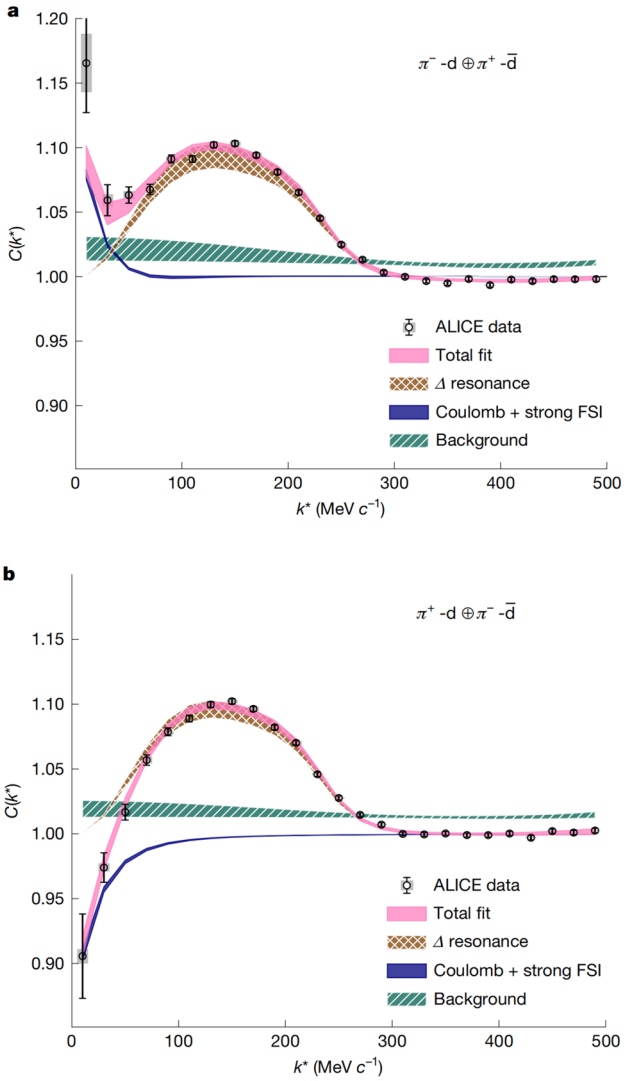

Fig. 1 (Color online) Measured π^--d (upper panel) and π^+-d (lower panel) correlation functions compared with model fits. The brown cross-hatched bands show the contributions from the Δ resonance, the blue bands the Coulomb interaction, and the teal diagonally hatched bands the residual background. The magenta bands represent the total fit. Figure taken from Ref. [1]

In summary, ALICE has uncovered the dominant mechanism of (anti-)deuteron formation at the LHC using the novel technique of pion-nucleus correlation femtoscopy. The measurement provides the first compelling evidence that most (anti-)deuterons originate from resonance decays followed by pion-catalyzed fusion rather than direct emission. This finding resolves a long-standing puzzle in light-nucleus production and establishes a clear microscopic pathway for (anti-)nucleosynthesis in high-energy collisions.

A complete understanding of these results calls for further studies on the in-medium properties of light nuclei and advances in relativistic kinetic theory that incorporate multi-body correlations and off-shell quantum effects at high temperatures [44, 45]. Extending femtoscopy measurements to heavier (hyper-)nuclei will open new opportunities to probe their formation mechanisms and may even help constrain the production of exotic hadronic states [38, 46–48] in hot and dense matter.

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