Light (hyper)nuclei production measured with ALICE at the LHC

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Alberto Calivà for the ALICE Collaboration
Outline

- Introduction and physics motivation
- Experimental techniques
- Review of experimental results
- Interpretation of the results in terms of phenomenological models of hadronization:
  - Statistical-thermal model and coalescence
In high-energy hadronic collisions multi-baryon states are produced besides other particle species

- Light (anti-)nuclei up to $A=4$ are measured
- Nuclei with strangeness (hypernuclei)

Production mechanism described by two (different) phenomenological models:

- Statistical-hadronization model
- Coalescence

Main physics motivation:

Study hadronization process for (strange) multi-baryon states

- System size dependence of (anti-)matter formation is studied using different collision systems (pp, p-Pb, Pb-Pb, Xe-Xe)
Experimental techniques
Experimental apparatus
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Inner Tracking System (ITS)
- 6 layers of silicon detectors
- Trigger, tracking, vertexing, PID (dE/dx)

Light (hyper)nuclei production
Experimental apparatus

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- Trigger, tracking, vertexing, PID \( (dE/dx) \)

**Time Projection Chamber (TPC)**
- Gas-filled ionization volume
- Tracking, vertexing, PID \( (dE/dx) \)
Experimental apparatus

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- gas-filled ionization volume
- tracking, vertexing, PID ($dE/dx$)

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**Time-Of-Flight (TOF)**
- Multi-gap resistive plate chambers
- PID via velocity ($\beta$) measurement
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**Forward detectors (V0A and V0C)**
- Forward scintillators
- Trigger, beam-gas rejection
- Multiplicity estimators
Experimental review of (anti-)nuclei measurements
Interlude: Centrality

Colliding Pb nuclei are extended objects ($R \approx 6.5$ fm)

Geometry of the collision defined by the impact parameter ($b$)

- $b \approx 0$ fm: central (head-on) collisions
- $b > 0$ fm: peripheral collisions

Centrality classes defined in terms of multiplicity percentile (measured by the V0 detectors)
(anti-)deuteron $p_T$ spectra in Pb-Pb and p-Pb collisions show clear effects of radial flow

- Described by **blast-wave** model
Deuteron spectra

(anti-)deuteron $p_T$ spectra become harder for increasing multiplicity in pp collisions

- No clear sign of radial flow (as expected)
- Spectra described by Tsallis parametrization (power law tail)
(anti-)³He $p_T$ spectra in Pb-Pb and p-Pb collisions described by blast-wave parametrization (dashed curves)

In p-Pb ³He is measured in 4 multiplicity classes (recent results)
Measurement limited by low statistics (17 $^3$He candidates) and large background from TOF mismatch for (anti-)triton $(\text{anti-})t$ / $(\text{anti})^3$He consistent with 1 (isospin symmetry)
Antinuclei/nuclei ratios consistent with 1

- matter and antimatter produced in equal amount at midrapidity (|y|<0.5)
Heaviest (anti-)nucleus observed (16 candidates in Pb-Pb at 5.02 TeV)

- Pre-selection using $dE/dx$ measured in the TPC
  - $\pm3\sigma$ from the expected value for $^4$He
- Signal extraction from mass squared distribution obtained using TOF
Yield vs. mass number

Exponential decrease of the nuclei yield with the mass number

Penalty factor for adding one baryon:
- ~300 in Pb-Pb collisions
- ~600 in p-Pb collisions
- ~1000 in pp collisions
Statistical hadronization model: thermal emission from equilibrated source

Particle abundances fixed at chemical freeze-out

\[ N_i = \frac{g_i V}{2\pi^2} \int_{0}^{+\infty} \frac{p^2 dp}{\exp \left[ - \left( \frac{E - \mu_B}{T_{\text{chem}}} \right) \right]} + 1 \]

Primordial yields modified by hadron decays:

- Contribution obtained from calculations based on known hadron spectrum

**Excellent** agreement with data with only 2 free parameters: \( T_{\text{chem}}, V \)
Nuclei which are close in space and have similar velocities can form a bound state.

Nuclei dissociate and are created again by final state coalescence after kinetic freeze-out.

\[ E_A \frac{d^3 N_A}{d^3 p_A} = B_A \left[ E_p \frac{d^3 N_p}{d^3 p_p} \right]^Z \left[ E_n \frac{d^3 N_n}{d^3 p_n} \right]^{A-Z} \quad (p_p = p_n = p_A/A) \]

**Coalescence parameter**
(defines the coalescence probability)

Neutrons are very difficult to measure:

- spectrum is assumed to be identical to proton spectrum (**isospin symmetry**)

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d/p ratio vs. multiplicity

![Graph showing d/p ratio vs. multiplicity for different collision energies and multiplicity classes.](image)

ALICE Preliminary

\[
\frac{\langle dN_{\text{ch}} \rangle}{d\eta_{\text{lab}}} \mid |\eta_{\text{lab}}| < 0.5
\]
d/p ratio vs. multiplicity

- d/p ratio increases with increasing multiplicity going from pp to peripheral Pb-Pb collisions (qualitatively described by coalescence)
**d/p ratio vs. multiplicity**

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- Plateau consistent with thermal model value ($3 \times 10^{-3}$ at $T_{chem} = 156$ MeV)
- d/p ratio increases with increasing multiplicity going from pp to peripheral Pb-Pb collisions (qualitatively described by coalescence)
- Plateau consistent with thermal model value (3×10^{-3} at $T_{\text{chem}} = 156$ MeV)
- Hint of decreasing trend at highest multiplicity (possible rescattering effect)
$B_2$ decreases with increasing volume of the emitting source.
Dark matter annihilation in the galactic halo results in matter + antimatter production:

\[ \chi \bar{\chi} \rightarrow \gamma \gamma, \; e^+ e^-, \; p \bar{p}, \; d \bar{d}, \; ^3\text{He}^3\text{He}, \ldots \]

Neutralinos (WIMPS) are the most prominent dark matter candidates

**AMS** dedicated to dark matter searches in space

**DM signal**: excess in antimatter compared to its production in collisions between cosmic rays and interstellar medium

Primary cosmic ray (>90% are protons)

Interstellar gas (mostly H)

Measurement of antimatter production in pp collisions:
- fundamental baseline
- \(^3\text{He}\) plays crucial role due to its rare production

Light (hyper)nuclei production
Coalescence parameter $B_3$ in pp collisions used to estimate the flux of secondary $^3$He for the AMS experiment

**Green band**: from pp $\rightarrow$ d$\overline{d}$ data at low energy using scaling law of coalescence
Coalescence parameter $B_3$ in pp collisions used to estimate the flux of secondary $^3$He for the AMS experiment

**Green band**: from ALICE measurement of $B_3$
$B_3$ in pp collisions

Coalescence parameter $B_3$ in pp collisions used to estimate the flux of secondary $^3$He for the AMS experiment

**Green band**: from ALICE measurement of $B_3$

Measurement will be improved using pp data at 13 TeV

- Factor $> 10$ more $^3$He candidates
Hypernuclei
Hypertriton is the lightest hypernucleus

- Possible molecular structure (d-Λ)
- Λ separation energy = 130 keV
  - Large and fragile object

Signal extracted from invariant-mass analysis

(weak) decay modes:

\[ ^3_\Lambda \text{H} \rightarrow ^3 \text{He} + \pi^- \]
\[ ^3_\Lambda \text{H} \rightarrow ^3 \text{H} + \pi^0 \]
\[ ^3_\Lambda \text{H} \rightarrow d + p + \pi^- \]
\[ ^3_\Lambda \text{H} \rightarrow d + n + \pi^0 \]
Hyper-triton lifetime puzzle

Lifetime extracted from exponential fit to ct spectrum

Lifetime of hyper-triton expected to be slightly smaller compared to that of free lambda

Data indicate a large difference (>2σ): “lifetime puzzle”

- More precise measurements are needed to clarify this aspect
Study of (anti-)(hyper-)nuclei is an important tool to study hadronization for multi-baryon systems

Thermal model successfully describes nuclei yields
- Survival of loosely bound states at $T \gg E_b$ not understood

d/p and $^3$He/p ratios:
- Increasing trend (qualitatively) described by coalescence
- Plateau consistent with thermal model value
- Information will be complemented with more measurements

$B_A$ reveals system size dependence of hadronization

Hypertriton lifetime smaller than free lambda
- Puzzle will be addressed with more precise measurement in the near future
Thank you for your attention
Nuclei identification: low momentum

Low rigidity ($p/z$):

- Identification based on the $dE/dx$ measured by the TPC

$$- \langle \frac{dE}{dx} \rangle \propto \frac{z^2}{\beta^2}$$

Excellent separation of particles with charge $z=2$ from other particle species
High rigidity ($p/z$):
- Identification based on the time-of-flight measurement of TOF

\[ m^2 = p^2 \left( \frac{t^2}{L^2} - \frac{1}{c^2} \right) \]

Mass squared distribution used for signal extraction.
Secondary nuclei from spallation

Secondary nuclei produced by spallation in interactions with the detector material

Isotropic emission of nuclear fragments:
- uniform distance-of-closest approach (DCA) to the primary vertex

Primary nucleons: DCA distribution peaked at zero

Intra-nuclear cascade

Evaporation of excited nucleus

Primary nucleons

Secondary nuclei produced by spallation in interactions with the detector material

Light (hyper)nuclei production

Anti-Triton in Pb-Pb collisions

Track-by-track identification of low-$p_T$ anti-tritons using TPC-TOF

- Background from TOF mismatch rejected by TPC only at low $p_T$

Limited range for anti-triton measurement:
$0.6 \text{ GeV/c} < p_T < 1.6 \text{ GeV/c}$

31 anti-triton candidates observed in Pb-Pb collisions at 2.76 TeV:

- consistent with expectations based on extrapolation of $^3\text{He}$ spectra and on the efficiency estimation from simulations
Hypertriton spectra

Hypertriton $p_T$ spectrum measured in 3 centrality ranges

- Blast-wave fit to extrapolate yield in unmeasured region

anti-hypertriton/hypertriton = 1 within the uncertainties

Hypertriton production yield increases with multiplicity (centrality)
$^3$He/p ratio vs. multiplicity

Similar trend observed also for $^3$He/p ratio vs. multiplicity

Factor $>10$ difference going from pp to central Pb-Pb collisions