Addressing the (anti-)hypertriton lifetime puzzle with ALICE at the LHC

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on behalf of the ALICE Collaboration

Quark Matter
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Hypernuclei

Hypernucleus:
It is a nucleus that contains at least one hyperon in addition to nucleons
First observation in 1952 by Danysz and Pniewski from cosmic ray data in photographic emulsion
Phil. Mag. 44 (1953) 348

Hypertriton (\(^3\text{H}\))

- bound state of \(p\), \(n\) and \(\Lambda\), is the lightest known hypernucleus
  - mass = 2.99131 ± 0.00005 GeV/c\(^2\) \([1]\)
  - \(\Lambda\) separation energy \(E_B = 0.13 \pm 0.05\) MeV \([1]\)
  - lifetime: world average = 216 \(^{+16}_{-19}\) ps \([2]\)
  - decay channels: 
    - Mesonic
    - Non Mesonic (B.R. < 0.02%)
- Study of the production and of the lifetime in the accessible decay channels (charged products only)
  - 2-body (B.R. = 25%)
  - 3-body (B.R. = 41%)

Mesonic channels

<table>
<thead>
<tr>
<th>Channels</th>
<th>(^3\text{He}+\pi^-)</th>
<th>d+p+\pi^-</th>
<th>n+p+p+\pi^-</th>
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Branching Ratio \([3]\) 

\(^3\text{He} = p+p+n\); \(^3\text{H} = p+p+n\)

Branching ratios (B.R.) are not precisely known.
Only few theoretical calculations available

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Hypernuclei in heavy-ion collisions

**Thermal model**

- Hadrons emitted from the interaction region in *statistical equilibrium* once the chemical freeze-out temperature is reached.
- Key parameter is chemical freeze-out temperature $T_{chem}$.
- Abundance of a species $\propto e\left(-\frac{m}{T_{chem}}\right)$
  - For hypernuclei (large $m$) strong dependence on $T_{chem}$.

**Coalescence model**

- (Anti-)baryons close in phase space at the kinetic freeze-out can form a (anti-)(hyper-)nucleus.
- (Anti-)(hyper-)nuclei formed at the chemical freeze-out:
  - might break up.
  - regenerate in the time interval between chemical and kinetic freeze-out.

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Hypertriton lifetime “puzzle”

- Very small $E_b$ ($\sim 130\text{ keV}$) led to the hypothesis that the $^3\Lambda\text{H}$ lifetime is slightly below the free $\Lambda$ lifetime ($263.2 \pm 2\text{ ps}$ [4])
- Few theoretical predictions available
  - first one by Dalitz and Rayet (1966) $\rightarrow \tau$ range $239.3 - 255.5\text{ ps}$
  - most recent by Congleton (1992) and Kamada (1998) $\rightarrow 232\text{ ps}$ and $256\text{ ps}$
- Many experiments faced this challenge with different experimental techniques

**Experimental results**

- Emulsion and bubble chamber experiment results tend to agree with free $\Lambda$ value
  - limited number of events satisfying the selection criteria $\rightarrow$ large errors
- Recent (heavy-ion) experiment results are below the expected free $\Lambda$ lifetime within the errors
A Large Ion Collider Experiment

- General purpose heavy ion experiment
- Excellent particle identification (PID) capabilities and low material budget
- Most suited detector at the LHC to study the (anti-)(hyper-)nuclei produced in the collisions

2015 data sample
- Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV
- 0-90% centrality class
- $N_{\text{ev}} = \sim 105$ M MB trigger
Hypertriton identification strategy

- $^3\text{He}$ and $\pi$ tracks identified via specific energy loss in the TPC
- Apply topological and kinematic cuts in order to
  - identify secondary vertex
  - reduce combinatorial background
- Evaluate the invariant mass and extract a signal
- Strategy adopted both for the production and the lifetime investigation

• Signal extraction with a fit to the invariant mass distribution
  - Signal: Gaussian
  - Background: 2nd degree polynomial

\[ DCA = \text{Distance of Closest Approach} \]
Hypertriton production

Transverse momentum spectra:
- Measured in semi-central collisions (10-40%) for the first time
- Fit to the spectra with the $^3\text{He}$ Blast-Wave [5] distribution obtained in the same centrality class in Pb-Pb collisions at 5.02 TeV → used for extrapolation to unmeasured $p_T$ region

Production as a function of the charged particle multiplicity:
- $dN/dy$ in three centrality classes (0-10%, 10-30%, 30-50%)
- Increasing trend can be interpreted in the thermal model as related to the volume of the created medium

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Hypertriton production

- Hypertriton decay B.R. is not precisely known, only constrained by the ratio between all charged channels containing a pion.

- Comparison of $dN/dy$ measured in 0-10% centrality class with model prediction as a function of the B.R.
  - agreement with equilibrium thermal model GSI-Heidelberg and with Hybrid UrQMD in the B.R. range between 0.24 and 0.35
  - non-equilibrium thermal model SHARE overestimates the production yields by nearly a factor 4 for B.R. = 0.25

- Improvements in the hypertriton decay B.R. knowledge expected thanks to the production measurement via 3 body decay channel.

**Particle ratios**

### $^3\text{H}/^3\text{He}$ ratio

- Ratios for most central collisions in agreement with theoretical predictions from Hagedorn resonance gas (HRG) and thermal models.
- New results at 5.02 TeV might give a hint for an evolution with the charged particle multiplicity.

### $\Lambda^3\text{H}/\Lambda^3\text{He}$

- Ratio to light hadron yields more sensitive to the chemical freeze-out temperature $T_{\text{chem}}$.
- $\Lambda^3\text{H}/\Lambda^3\text{He}$ compared with THERMUS predictions as a function of $T_{\text{chem}}$.

\[ T_{\text{chem}} = 153\text{-}165 \text{ MeV} \]

- In agreement with $T_{\text{chem}} = 156$ MeV obtained at 2.76 TeV [6].

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Strangeness population factor

Strangeness population factor $S_3$ \cite{7,8} is defined as:

$$S_3 = \frac{\lambda H}{3\Lambda} \times \frac{P}{\Lambda}$$

- It is independent on the chemical potential of the particles and any additional canonical correction factor for strangeness is cancelled.

- ALICE results obtained at 5.02 TeV (blue marker) is:
  - compatible with the published results at 2.76 TeV and with those at lower energies
  - in agreement with the prediction of the equilibrium thermal model (GSI-Heidelberg) and of the Hybrid UrQMD model.

- Coalescence predictions available only up to top RHIC energies, needed at the LHC energies.

Hypertriton in the thermal fit

- Particle production yields measured by ALICE in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Hypertriton and nuclei ($d$ and $^3He$) yields are included in the fit
- $dN/dy$ described over a wide range ($10^{-4} - 10^3$) assuming thermal equilibrium and a chemical freeze-out temperature $T_{\text{chem}} = 152-153$ MeV
- The temperature values are compatible with the chemical freeze-out temperature ranges obtained from the ratios to deuteron and proton yields
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Hypertriton in the thermal fit

- **Strangeness:** See D. Albuquerque **(Tue, 16:40) talk**
- **Nuclei:** See M. Puccio **(Wed, 18:30) talk**

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Hypertriton lifetime

The lifetime estimate is performed:

- using the full data sample of Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV collected in 2015
- selecting both hypertriton and anti-hypertriton candidates
- using two methods: “$ct$ spectra” (default) and unbinned fit (crosscheck)
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**ct spectra (default)**

- **Signal extraction** in four different ct bins
  - 4-7, 7-10, 10-15, 15-28 cm
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- Signal extraction in four different ct bins
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- Exponential fit to the corrected $dN/ct$ spectrum for the lifetime estimate
  \[ \tau = 237^{+33}_{-36} \text{(stat.)} \pm 17 \text{(syst.) ps} \]
- Result with the highest precision at the moment
  - improved resolutions with respect to the previous result at 2.76 TeV

\[\begin{align*}
\tau & = 7.10^{+0.00}_{-1.07} \text{ (stat.)} \pm 0.50 \text{ (syst.) (cm)} \\
\end{align*}\]
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- **Result** with the highest precision at the moment
  - improved resolutions with respect to the previous result at 2.76 TeV
- Lifetime estimate with an alternative method as a crosscheck

![Graph showing the lifetime estimate](image)
**Lifetime: unbinned fit method**

- Fit to the invariant mass distribution to define the *signal range* and the *sidebands*.

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**Signal range**

- $m \pm 3\sigma$

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**Sidebands**

- $[m+3\sigma, m+9\sigma]$ and $[m-3\sigma, m-9\sigma]$
Fit to the invariant mass distribution to define the **signal range** and the **sidebands**

- Fit in the **sidebands** with two exponential is performed (**background**)
- Fit in the **signal range** for the lifetime estimate
  - signal: exponential function multiplied for the efficiency
  - background: from the sidebands fit

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  **Lifetime value estimate**
  \[ \tau = 223^{+41}_{-33} \text{(stat.)} \pm 20\text{(syst.)ps} \]

- maximum-likelihood estimate

**Signal range**

\[ m \pm 3\sigma \]

**Sidebands**

\[ [m+3\sigma, m+9\sigma] \text{ and } [m-3\sigma, m-9\sigma] \]
Hypertriton lifetime (ps)

Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
0-90%, $|y| < 0.8$

$\Lambda$ (PDG)

$\bar{\Lambda}$ World Average

Lifetime value estimate

$\tau = 223^{+41}_{-33}$ (stat.) $\pm 20$ (syst.) ps

Signal range
$m \pm 3\sigma$

Sidebands
$[m+3\sigma, m+9\sigma]$ and $[m-3\sigma, m-9\sigma]$
The ALICE results, obtained by analyzing the Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV data sample, show an improved precision with respect to previous heavy ion experiment.

- It is compatible with the world average and, in particular, with the free $\Lambda$ lifetime.
- Further improvements will come:
  - from lifetime measured in the 3-body decay channel.
  - increasing the statistics → another Pb-Pb data sample will be collected in 2018 at the LHC.

$^{3}\Lambda$ lifetime estimate available in literature with new ALICE Preliminary.

- Free $\Lambda$ lifetime from PDG: 263.2 ± 2 ps.
- $^{3}H$ world average: 216 +16 -19 ps taken from [2].
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Conclusion and perspectives

- **Measurements** of the (anti-)hypertriton production and lifetime have been performed with the most recent LHC Run2 data exploiting the **excellent performance** of the ALICE detector.

- **Thermal** model can successfully describe particular aspects of the (hyper-)nuclei measurements:
  - Integrated *yields* and *ratios* are well described by thermal models.
  - Predictions at the **LHC energies** from **coalescence** models are expected.
  - Recent hypertriton **lifetime** measurement shows an improved precision and a value **closer** to the $\Lambda$ lifetime with respect to the previous heavy-ion results.
    - It will be fundamental to measure the lifetime via **3-body** decay channel.
    - New **theoretical calculations** for the lifetime are needed as well as more precise measurements of the value of $E_{B\Lambda}$.

*Thank you for your attention*
More results on (hyper-)nuclei and exotica:

Talk:

- Constraining production models with light (anti-)nuclei measurements in small systems with ALICE at the LHC
  - M. Colocci (Tue, 15:40)

- Light (anti-)nuclei production and elliptic flow in Pb-Pb collisions at the LHC with ALICE
  - M. Puccio (Wed, 18:30)

Poster:

- Search for a $\Lambda$ nn bound state in Pb-Pb collisions with ALICE at the LHC
  - A. Mastroserio (THD-12)

- Preliminary study of the (anti-)deuteron absorption in the detector material of ALICE at the LHC
  - Z. Yasin (THD-22)

- Search for the $d^*(2380)$ in p-Pb collisions at 5 TeV with ALICE at the LHC
  - P. Fecchio (THD-03)

- Measurements of (anti-)$^3$He production in p-Pb collisions and of (anti-)$^3$He elliptic flow in Pb-Pb collisions with ALICE at the LHC
  - A. Caliva (COL-06)
Backup
The coalescence parameter for the hypertriton is defined as:

\[
E_{\Lambda} \frac{d^3 N_{\Lambda}}{d^3 p_{\Lambda}} = B_3 \left( E_p \frac{d^3 N_p}{d^3 p_p} \right)^2 \left( E_{\Lambda} \frac{d^3 N_{\Lambda}}{d^3 p_{\Lambda}} \right)
\]

- It is predicted to be \( p_T \) independent in the simplest coalescence formulation.

- \( B_3 \) measured for the first time in semi-central collisions.
- It is compatible for matter and antimatter.
- The coalescence parameter shows a slight increase with the transverse momentum, as already observed for light nuclei (deuteron and \(^3\)He).
Lifetime: unbinned fit method

- This second approach has been used as a crosscheck of the result obtained with the fit to the corrected spectrum $dN/d(\text{ct})$
- It has been tested also on the data sample of Pb-Pb collisions at 2.76 TeV and the result is compatible with the published

**Data**

1\textsuperscript{st} Invariant mass distribution

- Fit
- $\sigma, N_s, N_b$

Gaussian (signal) + Pol2 (background)

**MC**

3\textsuperscript{rd} Efficiency $\times$ acceptance vs $\text{ct}$

Exponential decay 1

Exponential decay 2 (background)

Signal range

2\textsuperscript{nd} Exponential decay (signal)

Fit

lifetime
Future perspectives

**Run 3-4 (2021-2023; 2026-2029)**

- LHC will deliver more statistics
  \[ \rightarrow \text{Pb-Pb at 50 kHz collision rate} \]
- ALICE will upgrade the detectors to cope with this higher luminosity
- TPC upgrade: GEMs for continuous readout
- ITS upgrade: low material budget and more precise tracking for the identification of hyper-nuclei
- Physics analysis done for A=2 and A=3 nuclei and hyper-nuclei will be done also for A=4

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**ALICE Collaboration, ITS upgrade TDR**

ALICE Performance

Detectors used for (anti-)(hyper-)nuclei analysis:

• **ITS**
  - Separation of primary and secondary nuclei from knock-out
  - $p_T > 0.5 \text{ GeV/c} \rightarrow \sigma_{\text{DCA}_{xy}} < 100 \mu m$

• **TPC**
  - $dE/dx$ in gas (Ar-CO$_2$)
  - $\sigma_{dE/dx} \sim 5.5\%$

• **TOF**
  - Time-of flight measurement
  - $\sigma_{\text{TOF}} \sim 80 \text{ ps (Pb-Pb)}, 120 \text{ ps (pp)}$

• **V0**
  - Two arrays of 64 scintillators
  - Determination of the centrality of a collision
Centrality

Theory
The centrality of the collision is defined by the impact parameter vector $b$

Most central collision $\iff$ Smallest $b$

Experimentally
It is possible to correlate the track multiplicity to an impact parameter value by fitting data with predictions from Glauber model.

Heavy Ion collision

Theory

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