LIGHT (ANTI-)NUCLEI AND (ANTI-)HYPERNUCLEI PRODUCTION WITH ALICE AT THE LHC

Stefano Piano on behalf of ALICE Collaboration
INFN sez. Trieste
MOTIVATION

- (anti-)(hyper)nuclei are good probes of coalescence mechanism
- (anti-)(hyper)nuclei yields are sensitive to the freeze-out temperature in heavy-ion collision due to their large mass (e.g. in the Thermal Model yield scales roughly $\propto e^{-M/T_{\text{chem}}}$)
- light (anti-)(hyper)nuclei have small binding energy and small $\Lambda$ separation energy, e.g. $B_{\Lambda}(^3\Lambda\Lambda H) = 0.13 \pm 0.05$ MeV [H. Bando et al., Int. J. Mod. Phys. A 5 4021 (1990)]:
  - they should dissociate in a medium with high $T_{\text{chem}}$ ($\sim 156$ MeV) and be suppressed
  - if their yields equal to thermal model prediction $\Rightarrow$ sign for adiabatic (isentropic) expansion in the hadronic phase
- $A=3$ (anti-)($^3$He, $t$, $^3\Lambda\Lambda H$), a simple system of 9 valence quarks:
  - $^3\Lambda\Lambda H$ / $^3$He and $^3\Lambda\Lambda H$ / $t$ (and anti) $\Rightarrow$ $\Lambda$-nucleon correlation (local baryon-strangeness correlation)
  - $t$ / $^3$He (and anti) $\Rightarrow$ local charge-baryon correlation
- Anti-nuclei in nature:
  - matter–antimatter asymmetry
    - [J.Adam et al. (ALICE Collaboration), Nature Phys. 11, no.10, 811 (2015)]
  - light nuclei measurements in high energy physics can be used in dark matter searches to estimate the background coming from the secondary anti-nuclei [K. Blum, Phys. Rev. D 96 (2017) 103021]
(ANTI-)(HYPER)NUCLEI PRODUCTION IN URHIC

Statistical Thermal model

- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out ($T_{\text{chem}}$)
  (hyper)nuclei are very sensitive to $T_{\text{chem}}$ because of their large mass ($M$)
- Exponential dependence of the yield $\propto e^{-\frac{M}{T_{\text{chem}}}}$

Coalescence

- If baryons at freeze-out are close enough in Phase Space an (anti-)(hyper)nucleus can be formed
- (Hyper)nuclei are formed by protons ($\Lambda$) and neutrons which have similar velocities after the freeze-out

Production yield estimate of (anti-)(hyper)nuclei in central heavy-ion collisions at LHC energy based on thermal model:

Yield/event at mid-rapidity and central collisions

- $\Lambda n$: Light nuclei
- $\Lambda\Lambda$: Hypertriton
- Search for: $\Lambda n, \Lambda\Lambda$ dibaryons

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Yield/event</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>$\sim 800$</td>
</tr>
<tr>
<td>$p$</td>
<td>$\sim 40$</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$\sim 30$</td>
</tr>
<tr>
<td>$d$</td>
<td>$\sim 0.17$</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td>$^3\Lambda$H</td>
<td>$\sim 0.003$</td>
</tr>
</tbody>
</table>

A. Andronic, private communication

ALICE particle identification capabilities are unique. Almost all known techniques are exploited: $dE/dx$, time-of-flight, transition radiation, Cherenkov radiation, calorimetry and decay topology ($V^0$, cascade)

**ITS:** precise separation of primary particles and those from weak decays (hypernuclei) or knock-out from material

K. Aamodt et al. (ALICE Collaboration), JINST 3 (2008) S08002
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ALICE is ideally suited for the identification of light (anti-)(hyper)nuclei.
NUCLEI IDENTIFICATION

Low momenta

Nuclei identification via $dE/dx$ measurement in the TPC:
- $dE/dx$ resolution in central Pb-Pb collisions: ~6.5%
- Excellent separation of (anti-)nuclei from other particles over a wide momentum range
- About 10 anti-alpha candidates identified out of $23 \times 10^6$ events by combining TPC and TOF particle identification

Higher momenta

Excellent TOF performance:
- $\sigma_{\text{TOF}} \approx 85$ ps in Pb-Pb collisions allows identification of light nuclei over a wide momentum range
- Velocity measurement with the TOF detector is used to evaluate the $m^2$ distribution and to subtract background from the signal in each $p_T$-bin by fitting the $m^2$ distribution
The precise measurement of the mass difference between nuclei and their anti-counterparts allows one to probe any difference in the interaction between nucleons and anti-nucleons.

Looking at the mass difference between nuclei and their anti-nuclei it is possible to test the CPT invariance of the residual QCD “nuclear force”

- Masses and binding energies of nuclei and anti-nuclei are compatible within uncertainties
- Measurement confirms the CPT invariance for light nuclei
DEUTERON $p_T$ SPECTRA

- Spectra become harder with increasing multiplicity in Pb-Pb and show clear radial flow.
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb.
- pp and p-Pb spectrum show no sign of radial flow.
No significant centrality dependence in Pb-Pb

Ratio in pp collisions is a factor 2.5 lower than in Pb-Pb collisions

d/p ratio increases when going from pp to p-Pb and peripheral Pb-Pb, until it reaches the grand canonical thermal model value (d/p ~ 3x10^{-3} at $T_{ch} = 156$ MeV)
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Simple coalescence works in small systems while thermal models describe better the Pb-Pb data

Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?

But … there is a change of factor 5 in the $^3$He/p between small systems and Pb-Pb
COALESCENCE PARAMETER $B_A$

- If baryons at freeze-out are close enough in phase space (i.e. geometrically and in momentum) and match spin state, a (anti-)nucleus can be formed.

- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space.

- Assuming that $p$ and $n$ have the same mass and have the same $p_T$ spectra:

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left( E_p \frac{d^3N_p}{dp_p^3} \right)^A$$

- For $A=2$:

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

Measured deuteron $p_T$-spectra

Measured proton $p_T$-spectra
COALESCEENCE PARAMETER $B_2$

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

- Coalescence parameter $B_2$ decreases with centrality in Pb-Pb and increases with $p_T$.
- Similar effect seen in p-Pb: decrease with multiplicity, but less pronounced.
- Flat behavior for pp and no dependence on multiplicity.

![Graphs showing coalescence parameter $B_2$ for Pb-Pb, p-Pb, and pp collisions.](image-url)
COALESCEENCE PARAMETER $B_2$

\[ B_2 = E_d \left( \frac{d^3N_d}{dp_d^3} \right) \left( \frac{d^3N_p}{dp_p^3} \right)^{-2} \]

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$p_T/A = 0.75 \text{ GeV/c}$
Simple coalescence model

- Flat $B_2$ vs $p_T$ and no dependence on multiplicity/centrality
- Observed “small systems”: pp, p-Pb and peripheral Pb-Pb

More elaborated coalescence model takes into account the volume of the source:

- $B_2$ scales like HBT radii (*)
- Decrease with centrality in Pb-Pb is explained as an increase in the source volume
- Increase with $p_T$ in central Pb-Pb reflects the $k_T$-dependence of the homogeneity volume in HBT
- Qualitative agreement in central Pb-Pb collisions


The coalescence parameter evolves smoothly as a function of multiplicity with no discontinuity between different colliding systems

2018 European Nuclear Physics Conference | 04-09-2018 | Stefano Piano
COALESCEANCE PARAMETER $B_3$

- $B_3$ of (t)t and (3He)3He measured in pp and Pb-Pb collisions
- First ever measurements of the $B_3$ of t and 3He in pp collisions
- Increasing trend with $p_T$ and centrality observed in Pb-Pb collision
- Present data allow to make a new estimate to assess the astrophysical secondary flux of antihelium [K. Blum, Phys. Rev. D 96 (2017) 103021]
A significant $v_2$ is observed for deuterons.

The value of $v_2(p_T)$ increases progressively from central to semi-central collisions.

Angular distribution of reconstructed charged particles can be expanded into a Fourier series w.r.t. symmetry plane:

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos (n (\varphi - \Psi_n)) \right)$$

$$v_n = \langle \cos (n(\varphi - \Psi_n)) \rangle$$

Elliptic flow ($v_2$) is sensitive to the system evolution:
It probes initial conditions and constrains particle production mechanisms.

A significant $v_2$ is observed for deuterons.

The value of $v_2 (p_T)$ increases progressively from central to semi-central collisions.

If protons have only elliptical flow.

And if the light nucleus is formed by simple coalescence, $v_2$ can be expressed as:

$$v_{2,d}(p_T) = \frac{2 v_{2,p}(p_T/2)}{1 + 2 v_{2,p}^2(p_T/2)}$$

Such a simple coalescence model is not able to reproduce the measured elliptic flow of deuterons.
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Simplified hydro model (Blast-Wave) is able to describe spectra and flow at the same time, suggesting an early “freeze out”
ANTI-ALPHA


For the full statistics of 2011 (Pb-Pb@2.76 TeV) ALICE identified 10 Anti-Alphas using TPC and TOF

TOF $\beta$ vs $p/z$ after pre-selection of 3$\sigma$ in TPC shows clear separation $\rightarrow$ Cut on Alpha’s $p/z$ needed to suppress secondary

Anti-Alpha re-measured also in the new data sample Pb-Pb@5.02 TeV
For the full statistics of 2011 (Pb-Pb@2.76 TeV) ALICE identified 10 Anti-Alphas using TPC and TOF. TOF $\beta$ vs $p/z$ after pre-selection of 3$\sigma$ in TPC shows clear separation → Cut on Alpha’s $p/z$ needed to suppress secondary Anti-Alpha re-measured also in the new data sample Pb-Pb@5.02 TeV.

Nuclei yields follow an exponential decrease with mass as predicted by the thermal model.

In Pb-Pb the penalty factor for adding one baryon is $\sim$350 (for particles and antiparticles).
NUCLEI PRODUCTION IN Pb-Pb AND IN p-Pb

For the full statistics of 2011 (Pb-Pb@2.76 TeV) ALICE identified 10 Anti-Alphas using TPC and TOF

TOF $\beta$ vs $p/z$ after pre-selection of $3\sigma$ in TPC shows clear separation → Cut on Alpha’s $p/z$ needed to suppress secondary Anti-Alpha re-measured also in the new data sample Pb-Pb@5.02 TeV

Nuclei yields follow an **exponential** decrease with mass as predicted by the thermal model

In **Pb-Pb** the penalty factor for adding one baryon is $\sim$350 (for particles and antiparticles) and in **p-Pb** it is $\sim$600
**Decay Channels**

\[
\begin{align*}
\Lambda^3 &\rightarrow ^3\text{He} + \pi^- \\
\Lambda^3 &\rightarrow ^3\text{He} + \pi^0 \\
\Lambda^3 &\rightarrow d + p + \pi^- \\
\Lambda^3 &\rightarrow d + n + \pi^0
\end{align*}
\]

New preliminary results at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)


- **Two body decay**: lower combinatorial background
- **Charged particles**: ALICE acceptance and reconstruction efficiency for charged particles higher than for neutrals

**Signal extraction:**

- **Identify** \(^3\text{He}\) and \(\pi\)
- **Evaluate** \((^3\text{He}, \pi)\) invariant mass
- **Apply** topological cuts in order to:
  - isolate secondary decay vertex and
  - reduce combinatorial background
(ANTI-)HYPERTRITON YIELDS

\[ \frac{d^2N}{dp_T^2} \times \text{B.R.} (\Lambda^3 \rightarrow 3\text{He} \pi) \]

Pb-Pb@2.76Tev:
\[ \frac{dN}{dy} \times \text{B.R.} (\Lambda^3 \rightarrow 3\text{He} \pi) \]
yield extracted in three \( p_T \) bins for central (0-10\%) events
for \( \Lambda^3 \) and \( \Lambda^3 \) separately

Pb-Pb@5.02Tev:
\[ \frac{dN}{dy} \times \text{B.R.} (\Lambda^3 \rightarrow 3\text{He} \pi) \]
yield extracted in four \( p_T \) bins for central (10-40\%) events
for \( \Lambda^3 \) and \( \Lambda^3 \) separately
This result, together with the successful Blast-Wave fit to deuteron data suggest that nuclei production happens at the hadronisation, when all the other particles are formed.
The larger data sample collected in LHC Run2 and improved reconstruction and analysis techniques reduced the uncertainties.

The preliminary data from LHC Run 2 confirm the tensions seen with data from LHC Run 1.
At the end of Pb-Pb during RUN2 (Nov. 2018) the expected statistics for A=2,3 is >2x

During the Long Shutdown 2 (2019-2020):
- **New Inner Tracking System (ITS)**
  - improved pointing precision
  - less material -> thinnest tracker at the LHC
- **Upgrade of Time Projection Chamber (TPC):**
  - new GEM technology for readout chambers
  - continuous readout
  - faster readout electronics
- **High Level Trigger (HLT):**
  - new architecture
  - on line tracking & data compression
  - 50kHz Pb-Pb event rate

At the end of RUN3 (2023):
the expected Integrated Luminosity: ~10 nb⁻¹ (~8x10⁹ collisions in the 0-10% centrality class)
OUTLOOK – ALICE UPGRADE

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At the end of RUN3 (2023):
the expected Integrated Luminosity: ~10 nb\(^{-1}\) (~8x10\(^9\) collisions in the 0-10% centrality class)

All the physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4
CONCLUSIONS

- Excellent **ALICE** performance allows for **detection of light (anti-)nuclei and (anti-)hypernuclei**

ALICE (anti-)(hyper)nuclei production measurements challenge the production models:

- Large production of nuclear clusters measured by ALICE as predicted by the thermal models
- Thermal models describe sufficiently well the nuclei production (from proton to $^4$He) in Pb-Pb
- Simple coalescence models describe the (anti-)(hyper)nuclei only in small systems (pp, p-Pb)
- Deuteron yield and $v_2(p_T)$ in Pb-Pb collisions suggest an early “freeze out”, while large effects of re-interactions (favoring late stage coalescence) should be expected
- $B_2$ coalescence parameter evolves smoothly as a function of multiplicity with no discontinuity between different colliding system

- **Future LHC runs**, RUN2 and RUN3, and ALICE upgrades will **allow for precise study** of (anti-)(hyper)nuclei production yield (and lifetime)
  - New and more precise data are expected from the LHC in the next years!
HYPERTRITON LIFETIME DETERMINATION

Direct decay time measurement is difficult (~ps), but the excellent determination of primary and decay vertex allows measurement of lifetime via:

\[ N(t) = N(0) e^{-\frac{t}{\tau}} \]

where \( t = \frac{L}{(\beta \gamma c)} \) and \( \beta \gamma c = \frac{p}{m} \) with \( m \) the hypertriton mass, \( p \) the total momentum and \( L \) the decay length.

New preliminary results at \( \sqrt{s_{NN}} = 5.02 \) TeV

Previous heavy-ion experiment results show a trend well below the free \( \Lambda \) lifetime.

ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free \( \Lambda \) lifetime.
Dashed curves represent individual Blast-Wave fits

Spectrum obtained in 3 centrality classes in Pb-Pb and for NSD collisions in p-Pb
First ever measurements of (anti-)t and (anti-)3He nuclei in pp collisions

- t and anti-t measurement difficult

- (anti-)t/(anti-)3He agrees with unity
ANTI-NUCLEI PRODUCTION

- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light flavour species)
- Ratios exhibit constant behavior as a function of $p_T$ and centrality
- Ratios are compatible with unity, in agreement with the coalescence and thermal model expectations
- Also in pp multiplicity intervals, anti-deuterons and deuterons are produced equally
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SECONDARY CONTAMINATION

- The measurement of nuclei is strongly affected by background from knock-out from material.
- Rejection is possible by fitting the DCA_{xy} distributions with templates.
SECONDARY CONTAMINATION

- The measurement of nuclei is strongly affected by background from knock-out from material
- Rejection is possible by fitting the DCA_{XY} distributions with templates
- Not relevant for anti-nuclei. However, their measurement suffers from large systematics related to unknown hadronic interaction cross-sections of anti-nuclei in material
$\Lambda n$ AND H-DIBARYON SEARCH

**H-Dibaryon:** hypothetical $udsuds$ bound state

- First predicted by Jaffe [Jaffe, PRL 38, 195617 (1977)]
- Several predictions of bound and also resonant states.
- Recent Lattice models predict weakly bound states [Inoue et al., PRL 106, 162001 (2011), Beane et al., PRL 106, 162002 (2011)]

**If H-Dibaryon is bound:** $m_H < \Lambda \Lambda$ threshold

- measurable channel $H \rightarrow \Lambda \rho \pi$ but BR depends on binding energy

**Bound state of $\Lambda n$?**

- HypHI experiment at GSI sees evidence of a new state: $\Lambda n \rightarrow d + \pi^-$ [C. Rappold et al. (HypHI collaboration), Phys. Rev. C88, 041001(R) (2013)]

```
Schaffner-Bielich et al., PRL 84, 4305 (2000)
```
No signal visible

The upper limits for exotica are lower than the thermal model expectation by a factor 20

Thermal models with the same temperature describe precisely the production yield of deuterons, $^3\text{He}$ and $^3\Lambda\text{H}$

The existence of such states with the assumed B.R., mass and lifetime is questionable
THE EXPERIMENTAL CHALLENGE

The challenge: extract the $^3\Lambda$H signal from an overwhelming background

<table>
<thead>
<tr>
<th>At $\sqrt{s_{NN}}$</th>
<th>2.76 TeV</th>
<th>5.02 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrality</td>
<td>dN$_{ch}$/d$\eta$ ($</td>
<td>\eta</td>
</tr>
<tr>
<td>0-5 %</td>
<td>1601 ± 60</td>
<td>1943 ± 54</td>
</tr>
</tbody>
</table>

Three different theoretical predictions drawn as a function of $\text{BR}(^3\Lambda H \rightarrow ^3\text{He}+\pi^-)$ after being multiplied by BR:

- **Hybrid UrQMD**: combines the hadronic transport approach with an initial hydrodynamical stage for the hot and dense medium (J. Steinheimer et al., Phys. Lett. B 714, 85 (2012))


- **SHARE**: non-equilibrium thermal model with $T_{\text{chem}}=138.3$ MeV (M. Petráň et al., Phys. Rev. C 88, 034907 (2013))

- Great sensitivity to theoretical models parameters
- Non–equilibrium statistical thermal model (Petráň-Rafelski SHARE) provides better global fitting ($\chi^2 \sim 1$) to lower mass hadrons but misses $^3\Lambda H$ and light nuclei
- Experimental data closest to equilibrium thermal model with $T_{\text{chem}} = 156$ MeV and to Hybrid UrQMD
HYPERTRITON LIFETIME DETERMINATION

Hypertriton lifetime determination

\[ \beta \tau = 5.4^{+1.6}_{-1.2} \pm 1.0 \text{ cm} \]

\[ \beta \tau = 7.10^{+1.00}_{-1.07} \text{ (stat.)} \pm 0.50 \text{ (syst.) cm} \]

\[ \tau = 181^{+54}_{-39} \text{ (stat.)} \pm 33 \text{ (syst.) ps} \]

\[ \tau = 237^{+33}_{-36} \text{ (stat.)} \pm 17 \text{ (syst.) ps} \]
HYPERTRITON LIFETIME DETERMINATION

Two methods for estimation:
• ct spectra fit (exponential fit to the differential yield in different ct bins)
• ct unbinned fit as crosscheck method

New preliminary results at $\sqrt{s_{NN}} = 5.02$ TeV

$$\begin{align*}
\beta \tau & = 7.10^{+1.00}_{-1.07} \pm 0.50 \,(\text{stat.}) \pm 0.50 \,(\text{syst.}) \,\text{cm} \\
\tau & = 237^{+33}_{-36} \,(\text{stat.}) \pm 17 \,(\text{syst.}) \,\text{ps}
\end{align*}$$
Previous heavy-ion experiment results show a trend well below the free $\Lambda$ lifetime.

ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free $\Lambda$ lifetime.

STAR result from Au-Au collision is about 50% shorter than the free $\Lambda$ lifetime.

The puzzle of the $^3\Lambda H$ lifetime is still open.

$$\tau = \left(142^{+24}_{-21}(\text{stat.}) \pm 31(\text{syst.})\right)\text{ps}$$
Nuclei are extended objects
- Geometry not directly measurable
- Centrality (percentage of the total cross section of the nuclear collision) connected to observables via Glauber model
- Data classified into centrality percentiles for which the average impact parameter, number of participants, and number of binary collisions can be determined.