Light (Hyper-)Nuclei production at the LHC measured with ALICE

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Outline

• Introduction

• The ALICE detector
  • Detector performance and analysis strategy

• Results
  • d and $^3$He spectra and d/p ratio
  • Coalescence parameter B2
  • Thermal model fit to the data
  • Hypertriton
  • Searches for exotic bound states

• Conclusions
Introduction

**Thermal model:**
- The key parameter at the LHC energies is the $T_{chem}$
- Nuclei abundance strongly depends on the value of $T_{chem}$
  - Large mass
  - Exponential dependence of the yield $\sim \exp(-m/T_{chem})$


**Coalescence model:**
- Nuclei are formed by protons and neutrons which are nearby and have same velocity (after kinetic freeze-out)
- Nuclei produced at chemical freeze-out
  - Can break apart
  - Created again by final-state coalescence

ALICE detector

ALICE is ideally suited for the identification of light (anti-)nuclei and hyper-nuclei;

Central barrel
- $2\pi$ tracking and PID
  - $|\eta| < 0.9$
  - $B = 0.5$ T
- EM cal. ($|\eta| < 0.7$, $\Delta \phi = 107^\circ$)
- RICH ($|\eta| < 0.5$, $\Delta \phi = 57.6^\circ$)

ALICE subdetectors used for the results in this talk:
- **ITS** tracking + vertexing + PID ($dE/dx$)
- **TPC** tracking + vertexing + PID ($dE/dx$)
- **TOF** PID (time-of-flight)
- **HMPID** PID (ring imaging Cherenkov)

ALICE is ideally suited for the identification of light (anti-)nuclei and hyper-nuclei;
Particle identification via $dE/dx$

- At low momenta, nuclei are identified using the $dE/dx$ measurement in the TPC
- About 7% resolution in central Pb-Pb collisions
Particle identification via TOF

- Velocity measurement with the TOF detector is used to calculate the $m^2$ distribution
- Excellent TOF performance ($\sigma_{\text{TOF}} = 85$ ps time resolution in Pb-Pb collisions)
- $3\sigma$-cut around expected TPC $dE/dx$ for deuterons reduces drastically the background from TOF and TPC track mismatch
- Raw yields extraction from a fit of gaussian function + exponential tail to the $m^2$ distribution
Particle identification in HMPID

At higher momenta, deuterons, in central Pb-Pb collisions, are identified based on Cherenkov radiation (HMPID).

Excellent agreement with the nominal value of the deuteron mass ($m^2$).

- At higher momenta, deuterons, in central Pb-Pb collisions, are identified based on Cherenkov radiation (HMPID)

\[
\cos \theta_{\text{Cherenkov}} = \frac{1}{n\beta} \quad \Rightarrow \quad m^2 = p^2 (n^2 \cos^2 \theta_{\text{Cherenkov}} - 1)
\]
Deuterons and $^3$He in Pb-Pb

A hardening of the spectrum with increasing centrality is observed → expected in a hydrodynamic description of the fireball as a radially expanding source

Deuterons and $^3$He in Pb-Pb

- Spectra are fitted with the blast-wave function (simplified hydro model) in different centrality bins.
- These fits are used for the extrapolation of the yield to the unmeasured region at low and high $p_T$.
- A hardening of the spectrum with increasing centrality is observed → expected in a hydrodynamic description of the fireball as a radially expanding source.

Deuterons in p-Pb

- Pb-Pb: spectra are fitted with the blast-wave functions in different centrality bins
- p-Pb: spectra become harder with increasing multiplicity
Deuteron to proton ratio

- An increasing trend with multiplicity in p-Pb data is observed
- Possible saturation in Pb-Pb collisions within the errors
- Ratio in pp collisions is a factor 2.5 lower than in Pb-Pb collisions
Coalescence parameter $B_2$

- Coalescence model. In this picture the nuclei are formed in the last stage of the collision (after kinetic freeze-out) by protons and neutrons which are close in position and momentum space.

- The formation probability of nuclei can be quantified through the coalescence parameter $B_A$

$$B_A = \frac{E_A \frac{d^3N_A}{d\vec{p}_A}}{(E_p \frac{d^3N_p}{d\vec{p}_p})^A} \rightarrow \text{deuterons}$$

$$B_2 = \frac{E_d \frac{d^3N_d}{d\vec{p}_d}}{(E_p \frac{d^3N_p}{d\vec{p}_p})^2}$$

- To first order, $B_2$ is expected to depend only on the maximum difference in the momentum of the two constituents ("pure nuclear physics")
  - $B_2$ should be flat vs. $p_T$ and should not dependent on multiplicity/centrality
  - The $d/p$ ratio should strongly increase with multiplicity/centrality
Coalescence parameter $B_2$

- $B_2$ is flat vs. transverse momentum in p-Pb and peripheral Pb-Pb
- p-Pb:
  - $d/p$ shows increasing trend in p-Pb
  - $B_2$ is slightly decreasing with multiplicity
- Pb-Pb:
  - $B_2$ is strongly decreasing with centrality in Pb-Pb collisions
  - $d/p$ shows no significant dependence with centrality

Coalescence parameter $B_2$

- $B_2$ is flat vs. transverse momentum in p-Pb and peripheral Pb-Pb
- Pb-Pb:
  - $B_2$ is strongly decreasing with centrality in Pb-Pb collisions

$B_2$ scales like the HBT radii. The strong decrease of the $B_2$ with centrality can be naturally explained as an increase in the emitting volume


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Thermal model fit to the ALICE data

- The $p_T$-integrated yields and ratios can be interpreted in terms of statistical (thermal) model
- Measured absolute yields ($dN/dy$) of light nuclei production in Pb-Pb collisions are in good agreement with thermal model calculation
- Temperature $T = 156 \pm 2$ MeV

Talks: D. Elia - G. Volpe
Hypertriton

- $m(\text{Hypertriton}) = 2.991 \pm 0.002 \text{ GeV/c}^2$
- Investigated decay channel: $\text{Hypertriton} \rightarrow ^3\text{He} + \pi^-$
- Yields can be extracted in two centrality bins
- $dN/dy$ in good agreement with thermal model prediction from Andronic et al. for $T = 156 \text{ MeV}$
Searches for exotic bound states

• H0-dibaryon:
  • Hypothetical bound state of uuddss (ΛΛ)
  • First predicted by Jaffee in a bag model calculation
    R.L. Jaffe, PRL 38, 195 (1977)
  • Recent lattice calculations suggest a bound state
    or a resonance close to the Ξp threshold
  • Renewed interest in experimental searches
    Inoue et al., PRL 106, 162001 (2011)
    Beane et al., PRL 106, 162002 (2011)

• Bound state of Λn ?
**H-dibaryon**

- The thermal model describes the production rates of strange hadrons, light nuclei and hypernuclei → baseline for the expected rates in exotica searches
- Expected H-dibaryons ($H^0 \rightarrow \Lambda p \pi^-$): 
  \[ N_{H^0} = 1.38 \times 10^7 \times 0.0385 \times 0.64 \times 3.1 \times 10^{-3} \times 2 \approx 2110 \]
  - Strongly bound: $2110 \times 0.1 = 211$
  - Lightly bound: $2110 \times 0.64 = 1350$ where 0.64 BR(H-dibaryon)

- **No signal visible**
- From the non-observation we obtain as upper limits:
  - For a strongly bound (20 MeV) $H$: $dN/dy \leq 8.4 \times 10^{-4}$ (99% CL)
  - For a lightly bound (1 MeV) $H$: $dN/dy \leq 2 \times 10^{-4}$ (99% CL)
Λn bound state

Assuming a V0 type decay topology

- Expected Λn bound states (Λn → d π⁺):
  - Efficiency estimation from MC simulation
  - No signal visible
  - From the non-observation we obtain as upper limits:
    - dN/dy ≤ 1.5 x 10⁻³ (99% CL)

\[N_{Λn} = 1.38 \times 10^7 \times 0.0255 \times 0.35 \times 1.6 \times 10^{-2} \times 2 \approx 4000\]
Comparison to models

- Extracted upper limits for exotica are lower than expected from thermal model calculation;
- At the same time, the thermal model with the same temperature describes precisely deuteron, $^3$He nuclei and hypertriton;
- Existence of those particles with the assumed proprieties (BR, mass, lifetime) is questionable.
Conclusions

- ALICE at the LHC offers unique experimental possibilities for the study of light (hyper-)nuclei

- Coalescence and thermal (statistical) models describe different aspects of the data:
  - production rates (light nuclei and hypertriton) in Pb-Pb collisions are in agreement with thermal model expectation

- d/p ratio in pp collisions is a factor 2.5 lower then in Pb-Pb. The p-Pb results connect the pp and Pb-Pb results

- Existence of Λn and H-dibaryon is doubtful
  - Upper limits have been set (significantly lower than thermal model prediction)
Nuclear matter under extreme conditions can be investigated in ultra-relativistic heavy-ion collisions.

Collective and thermal properties of the Quark Gluon Plasma inferred from transverse momentum ($p_T$) distributions and integrated yields of identified particles → excellent PID needed

The ALICE detectors is a dedicated heavy-ion experiment at the LHC
Introduction (2)

- Particle production in pp, p-Pb and Pb-Pb collisions shows an equal abundance of matter and anti-matter in central rapidity region;
- A large number of particle are produced in every collision \( \frac{dN}{d\eta} \approx 1600 \) for central Pb-Pb collision
  - \( \approx 80\% \) of charged particles are pions, \( \approx 5\% \) of all the charged particles are protons
- ALICE is ideally suited for these studies thanks to its particle identification capabilities and efficient reconstruction down to low momenta
Rapidity definition in p-Pb

Asymmetric energy/nucleon in the two beams → cms moves with rapidity $y_{\text{cms}} = -0.465$
Absorption correction

Anti-nuclei: additional correction for absorption
The thermal model describes the production rates of strange hadrons, light nuclei and hypernuclei → baseline for the expected rates in exotica searches

- Expected H-dibaryons ($H^0 \rightarrow \Lambda p \pi^-$):

  \[
  N_{H^0} = 1.38 \cdot 10^7 \cdot 0.0385 \cdot 0.64 \cdot 3.1 \cdot 10^{-3} \cdot 2 \approx 2110
  \]

  - Strongly bound: $2110 \times 0.1 = 211$
  - Lightly bound: $2110 \times 0.64 = 1350$ where 0.64 BR(H-dibaryon)
H-dibaryon

Two cases:

- $m_H < \Lambda \Lambda$ threshold
  - weakly bound measurable channel
  - $H \rightarrow \Lambda p \pi$
  - $2.2 \text{ GeV}/c^2 < m_H < 2.231 \text{ GeV}/c^2$

- $m_H > \Lambda \Lambda$ threshold
  - resonant state measurable channel
  - $H \rightarrow \Lambda \Lambda$
  - $m_H > 2.231 \text{ GeV}/c^2$
Hypertriton

- $m(\text{Hypertriton}) = 2.991 \pm 0.002 \text{ GeV/c}^2$
- Investigated decay channel: $\text{Hypertriton} \rightarrow ^3\text{He} + \pi^-$
- $dN/dy$ in good agreement with thermal model prediction from Andronic et. al. for $T = 156 \text{ MeV}$;
Secondaries

- The measurement of nuclei is strongly affected by background from knock-out material;
- Rejection is possible by fitting the DCAxy distribution;
- Not relevant for anti-nuclei. However, their measurement suffers from large systematics related to unknown hadronic interaction cross section of anti-nuclei in material;
After subtraction of secondaries, the measured raw yields have to be corrected for efficiency and acceptance.

![Graph showing acceptance vs. transverse momentum](image-url)
pp, p-Pb and Pb-Pb details

- $\sqrt{s_{pp}} = 7$ TeV (2010, 2011)
- $\sqrt{s_{Pb-Pb}} = 2.76$ TeV (2010, 2011)
- $\sqrt{s_{p-Pb}} = 5.02$ TeV (2012, 2013)
- Asymmetric energy/nucleon in the beams → the nucleon-nucleon center-of-mass system was moving in the laboratory frame with a rapidity of $y_{LAB}^{CMS} = -0.465$ in the direction of the proton beam.

Centrality/Multiplicity selection:

- In pp collisions:
  - tracklets + tracks estimator

- In Pb-Pb collisions:
  - VZEROM (VZERO-A + VZERO-C) (ALICE arXiv:1301.4361)

- In p-Pb collisions:
  - correlation between impact parameter and multiplicity is not as straightforward as in Pb-Pb (VZERO-A chosen)
Centrality/Multiplicity selection:

- In pp collisions:
  - tracklets + tracks estimator

- In Pb-Pb collisions:
  - VZEROM (VZERO-A + VZERO-C) (ALICE arXiv:1301.4361)

- In p-Pb collisions:
  - Seven p-Pb multiplicity event classes based on the amplitude of the signal of the VZERO-A detector (A is the direction of Pb beam)

Asymmetric energy/nucleon in the beams → the nucleon-nucleon center-of-mass system was moving in the laboratory frame with a rapidity of $y_{CMS} = -0.465$ in the direction of the proton beam.

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$\sqrt{s_{Pb-Pb}} = 2.76$ TeV (2010, 2011)
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Asymmetric energy/nucleon in the beams → the nucleon-nucleon center-of-mass system was moving in the laboratory frame with a rapidity of $y_{LAB} = -0.465$ in the direction of the proton beam.
- **ITS: inner tracking system**
  - 2 layers of Silicon Pixel Detector (SPD)
  - 2 layers of Silicon Drift Detector (SDD)
  - 2 layers of Silicon Strip Detector (SSD)