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 $T_{\text{chem}}$
  - Nuclei abundance strongly depends on the value of $T_{\text{chem}}$
    - Large mass
    - Exponential dependence of the yield $\sim \exp(-m/T_{\text{chem}})$

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecher, Phys. Lett. B697, 203 (2011), 1010.2995

- **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

J.I. Kapusta, Phys. Rev. C21, 1301 (1980)
ALICE is ideally suited for the identification of light (anti-)nuclei and hyper-nuclei;

**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)

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

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$$\cos\theta_{Cherenkov} = \frac{1}{n\beta} \quad \Rightarrow \quad m^2 = p^2(\frac{n^2\cos^2\theta_{Cherenkov}}{n^2\cos^2\theta_{Cherenkov}} - 1)$$
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

E. Schnedermann et al., Phys. Rev. C48, 2462 (1993)
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.

E. Schnedermann et al., Phys. Rev. C48, 2462 (1993)
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
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 $B_A$.

\[
B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_P \frac{d^3N_P}{d^3p_P}\right)^A}
\]

\[
\rightarrow \text{deuterons}
\]

\[
B_2 = \frac{E_d \frac{d^3N_d}{d^3p_d}}{\left(E_P \frac{d^3N_P}{d^3p_P}\right)^2}
\]

- 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

R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)
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

R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)
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: 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 Jaffe in a bag model calculation
    \( \text{R.L. Jaffe, PRL 38, 195 (1977)} \)
  - Recent lattice calculations suggest a bound state or a resonance close to the \( \Xi p \) threshold
  - Renewed interest in experimental searches
    \( \text{Inoue et al., PRL 106, 162001 (2011)} \)
    \( \text{Beane et al., PRL 106, 162002 (2011)} \)
- Bound state of \( \Lambda n \) ?
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 (H0 → Λ p π⁻):
  \[ N_{H^0} = \frac{1.38 \times 10^7 \cdot 0.0385 \cdot 0.64 \cdot 3.1 \times 10^{-3} \cdot 2}{\text{events eff. BR(Λ) dN/dy dy}} \approx 2110 \]

- Strongly bound: 2110 x 0.1 = 211

- Lightly bound: 2110 x 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)
    \[ H: dN/dy \leq 8.4 \times 10^{-4} \text{ (99\% CL)} \]
  - For a lightly bound (1 MeV)
    \[ H: dN/dy \leq 2 \times 10^{-4} \text{ (99\% CL)} \]
\( \Lambda n \) bound state

Assuming a V0 type decay topology

- Expected \( \bar{\Lambda}n \) bound states (\( \bar{\Lambda}n \rightarrow \bar{d} \pi^+ \)):
  \[ N_{\bar{\Lambda}n} = 1.38 \times 10^7 \times 0.0255 \times 0.35 \times 1.6 \times 10^{-2} \times 2 \approx 4000 \]
- Efficiency estimation from MC simulation
- No signal visible
  - From the non-observation we obtain as upper limits:
    - \( dN/dy \leq 1.5 \times 10^{-3} \) (99% CL)
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 $\Lambda n$ 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 \(\rightarrow\) excellent PID needed. The ALICE detectors is a dedicated heavy-ion experiment at the LHC.

Heavy Ion collisions dynamical evolution

- Initial interaction
- Hydrodynamic flow (radial and elliptic flow)
- Chemical freezeout (particle ratios)
- Kinetic freezeout (momentum distribution)

Time

Initial state

Energy Stopping Hard Collisions

Hydrodynamic Evolution

Hadron Freezeout
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 $\rightarrow$ cms moves with rapidity $y_{\text{cms}} = -0.465$

$y_{\text{cms},\text{NN}} = -0.465$
Absorption correction

Anti-nuclei: additional correction for absorption
**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 (H0 → Λ p π⁻):
  
  \[ N_{H^0} = 1.38 \times 10^7 \cdot 0.0385 \cdot 0.64 \cdot 3.1 \times 10^{-3} \cdot 2 \approx 2110 \]

  - Strongly bound: 2110 x 0.1 = 211
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Andronic, private communication

Shaffner-Bielich et al., PRL 84, 4305 (2000)
H-dibaryon

Two cases:
- \( m_H < \Lambda \Lambda \) threshold
  \( \rightarrow \) 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
  \( \rightarrow \) resonant state
  measurable channel
  \( H \rightarrow \Lambda \Lambda \)
  \( m_H > 2.231 \text{ GeV}/c^2 \)
Hypertriton

- $m(\text{Hypertriton}) = 2.991 \pm 0.002$ GeV/c$^2$
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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;
Efficiency correction

- After subtraction of secondaries, the measured raw yields have to be corrected for efficiency and acceptance;
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 $y_{CMS} = -0.465$ in the direction of the proton beam

Centrality/Multiplicity selection:

- In pp collisions:
  - tracklets + tracks estimator
- In Pb-Pb collisions:
  - VZEROOM (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)
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  - 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)
- 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)