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

Nicole Martin for the ALICE Collaboration
Introduction

Thermal model:

Key parameter at LHC energies: chemical freeze-out temperature $T_{\text{chem}}$

Strong sensitivity of abundance of nuclei to choice of $T_{\text{chem}}$ due to:

1. large mass $m$

2. exponential dependence of the yield $\sim \exp(-m/T_{\text{chem}})$

Introduction

Coalescence model:

Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

Nuclei produced at chemical freeze-out → can break apart → created again by final-state coalescence

Analysis strategy

primary and secondary vertex separation

ITS
T0, V0

TPC

TOF

PID
**Particle identification**

**Low momenta:**
Nuclei are identified using the $dE/dx$ measurement in the Time Projection Chamber

**Higher momenta:**
Velocity measurement with the Time of Flight detector is used to calculate the $m^2$ distribution

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*ALICE preliminary*

$2.4 \text{ GeV/c} < p_t < 2.6 \text{ GeV/c}$

V0A Multiplicity
Class (Pb-Side) 0-10%

Data
- Signal
- Background
- Sig + Bkg

$\sqrt{s_{NN}} = 5.02 \text{ TeV}$

$\sqrt{s_{NN}} = 2.76 \text{ TeV}$

Pb-Pb, 2011 run, "ALICE Performance May 4th, 2012"

**Counts**

- ALICE preliminary
- Data
- Signal
- Background
- Sig + Bkg
The measured raw yields have to be corrected for efficiency and acceptance.
Nuclei and hypernuclei measurements

Deuteron

$^3$He

Hypertriton
Deuterons and $^3\text{He}$ in Pb-Pb

Spectra are fitted with blast-wave functions in different centrality bins and show radial flow.
Deuterons in p-Pb

Spectra become harder with increasing multiplicity
Deuteron to proton ratio

Rise with multiplicity
No further increase in Pb-Pb collisions within errors
**Coalescence parameter $B_2$**

First order prediction of coalescence model: $B_2$ independent of $p_T$  

$\Rightarrow$ Observed in p-Pb and peripheral Pb-Pb

\[
B_2 = \frac{E_d \frac{d^3N_d}{d\rho_d^3}}{\left(E_p \frac{d^3N_p}{d\rho_p^3}\right)^2}
\]

\[E_d \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, \text{ deuterons}\]

\[\text{ALICE preliminary}\]

\[\text{p-Pb} \]

\[\text{V0A Multiplicity Class (Pb-side)}\]

\[\text{ALICE} - \text{PREL} - 69364\]
Coalescence parameter $B_2$

In second order: $B_2$ scales like the HBT radii

$\rightarrow$ Decrease with centrality in Pb-Pb is understood as an increase in the source volume

$$B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{2m_T R^2_{\perp}(m_T) R_{\parallel}(m_T)}$$

In second order: \( B_2 \) scales like the HBT radii

\[ \rho_T \text{-slope which develops in central Pb-Pb reflects the } k_T \text{-dependence of the homogeneity volume in HBT} \]

\[ B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{2m_T R_\perp^2(m_T) R_\parallel(m_T)} \]

\[ m(\text{Hypertriton}) = 2.991 \pm 0.002 \text{ GeV/c}^2 \]

investigated decay channel:

\[ \text{Hypertriton} \rightarrow ^3\text{He} + \pi^- \]
Hypertriton

M. Petran et al. Thermal Model
\[ T = 138.3 \text{ MeV}, \quad \gamma_q = 1.63, \quad \gamma_s = 2.08 \]

A. Andronic et al. Thermal Model
\[ T = 156 \text{ MeV} \]
\[ T = 164 \text{ MeV} \]

\[ ^3\Lambda H \rightarrow ^3\text{He} + \pi \]

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\[ dN/dy \times B.R. - \text{Stat.Error} \]
\[ \text{Pb-Pb} \quad \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
Centrality 0-10%

\[ dN/dy \times B.R. - \text{Syst.Error} \]

\[ p \Lambda n \]

\text{dN/dy in good agreement with thermal model prediction from Andronic et al. for } T = 156 \text{ MeV} \]
dN/dy comparison

Not in fit

Extrapolated

ALICE Preliminary

\( \mu_B = 0 \)

Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV}, 0-10\% \)

see also poster by R. Preghenella
Searches for weakly decaying exotic bound states
H-dibaryon:
First predicted by Jaffe in a bag model calculation
(Jaffe, PRL 38, 617 (1977))

Recent lattice calculations suggest bound state or a resonance
close to the \( \Xi p \) threshold

\( \Lambda n \) bound state:
Expected H-dibaryons ($H \rightarrow \Lambda p\pi$):

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

- **events**: $1.38 \cdot 10^7$
- **eff.**: $0.0385$
- **$BR(\Lambda)$**: $0.64$
- **$dN/dy$**: $3.1 \cdot 10^{-3}$
- **dy**: $2$

**strongly bound** $H$: $2110 \cdot 0.1 = 211$

**lightly bound** $H$: $2110 \cdot 0.64 = 1350$
H-dibaryon

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

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

(events) (eff.) (BR(\Lambda)) (dN/dy) (dy)

strongly bound $H$: $2110 \cdot 0.1 = 211$

lightly bound $H$: $2110 \cdot 0.64 = 1350$

No signal visible

From the non-observation we obtain as upper limits:

For a strongly bound (20 MeV) $H$:

$$\rightarrow dN/dy \leq 8.4 \cdot 10^{-4} \text{ (99\% CL)}$$

For a lightly bound (1 MeV) $H$:

$$\rightarrow dN/dy \leq 2 \cdot 10^{-4} \text{ (99\% CL)}$$
\( \Lambda n \) bound state

Expected \( \Lambda n \) bound states \((\Lambda n \rightarrow \bar{d}\pi^+)\):

\[
N_{\Lambda n} = 1.38 \cdot 10^7 \cdot 0.0255 \cdot 0.35 \cdot 1.6 \cdot 10^{-2} \cdot 2 \approx 4000
\]

events \quad eff. \quad BR \quad dN/dy \quad dy
Expected $\bar{\Lambda}\bar{n}$ bound states ($\bar{\Lambda}\bar{n} \rightarrow \bar{d}\pi^+$):

$$N_{\bar{\Lambda}\bar{n}} = 1.38 \cdot 10^7 \cdot 0.0255 \cdot 0.35 \cdot 1.6 \cdot 10^{-2} \cdot 2 \approx 4000$$

No signal visible

From the non-observation we obtain as upper limit:

$$\Rightarrow dN/dy \leq 1.5 \cdot 10^{-3} \ (99\% \ CL)$$
Comparison to models

The $\Lambda n$ bound state and the H-dibaryon are not observed.

Different model predictions are of the same order.

Upper limits for the two particles are set, at least a factor 10 below model predictions.

→ Existence of these particles with the assumed properties (BR, mass, lifetime) is questionable.
Spectral shapes of light nuclei production can be understood based on the coalescence picture.

Also the increase of the d/p-ratio with charged particle multiplicity is consistent with this picture.
Loosely bound hypertriton is observed

Absolute yields \( \langle dN/dy \rangle \) of light nuclei and hypertriton production in \( \text{Pb-Pb} \) collisions is in good agreement with thermal model calculation

Thermal model predictions using the temperature which fits the measured nuclei and hypertriton yields are above obtained exotica limits

\[ \rightarrow \text{Existence of the } \Lambda n \text{ and } H\text{-dibaryon is doubtful} \]
Rapidity definition in p-Pb

Asymmetric energy/nucleon in the two beams

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

$y_{\text{cms},\text{NN}} = -0.465$
multiplicity classes in p-Pb

central

peripheral

Definition of seven multiplicity classes:
→ slices in VZERO-A (V0A) amplitude

Correlation between impact parameter and multiplicity is not as straight-forward as in Pb-Pb
Absorption correction

Anti-nuclei:
Additional correction for absorption
Nuclei:
Additional correction for secondaries

ALICE preliminary

p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

minimum bias

$0.8 \text{ GeV/c} < p_T < 1.0 \text{ GeV/c}$
Efficiencies exotica

\[ m_{\bar{\Lambda}n} = 2.054 \text{ GeV/c}^2 \]
\[ c\tau = 7.89 \text{ cm} \]
Branching ratios exotica

Jürgen Schaffner-Bielich, private communication

\[ \Lambda N \rightarrow N + p + \pi^- \]
\[ \Lambda n \rightarrow n + n \]
\[ \Lambda p \rightarrow n + p \]

Jürgen Schaffner-Bielich et al., PRL 84, 4305 (2000)

\[ \Lambda \Lambda \rightarrow \Lambda + p + \pi^- \]
\[ \Lambda \Lambda \rightarrow \Lambda + n + \pi^0 \]
\[ \Lambda \Lambda \rightarrow \Sigma^- + p \]
\[ \Lambda \Lambda \rightarrow \Sigma^0 + n \]

\[ \Lambda \Lambda \rightarrow \Lambda + n \]
$\rho_T$-shape of the $\Lambda n$ bound state and the H-dibaryon estimated from the extrapolation of Blast-Wave fits for $\pi, K, p$.

Normalized to unity and convoluted with Acceptance x Efficiency to get a weighted Efficiency.

Unknown $\rho_T$-shape is the main source of uncertainty: Therefore used different functions for the systematics (limiting cases: Blast-Wave of deuteron and $^3$He).
## Lifetime dependence exotica

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<th>Decay length (cm)</th>
<th>Efficiency</th>
<th>Upper limit dN/dy 99% CL</th>
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