**PRECISION COMPARISON OF LIGHT NUCLEI AND ANTI-NUCLEI MASS-TO-CHARGE RATIO WITH ALICE AT THE LHC**

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Outline

• Physics motivations
• The ALICE experiment
• Analysis strategy
• Results
• Conclusions and outlook

http://www.nature.com/nphys/journal/v11/n10/full/nphys3432.html

more details can be found in ALICE-PUBLIC-2015-002
https://cds.cern.ch/record/2033777
Introduction

• In the today’s Universe we observe only ordinary matter but... the Standard Model predicts that in the primordial Universe there should have been equal amounts of matter and anti-matter → CPT violation? See e.g. Rev. Mod. Phys. 53 (1981) 141, Phys. Lett. B 725 (2013) 407

• The CPT theorem demonstrates that CPT symmetry is guaranteed within a RQFT description of interactions constructed in a flat space-time (1), based on Lorentz invariance (2) and on the locality of the interactions (3)

→ if some of the conditions which back-up the CPT theorem are not satisfied, the symmetry is no longer guaranteed (see e.g. Phys. Rev. D 92 (2015) 056002)

• Many experimental tests based on one important consequence of CPT symmetry: mass, lifetime, charge, magnetic moment of a particle equal to those of the corresponding anti-particle
From (anti-)baryons to (anti-)nuclei

- $\Delta(q/m)$ for systems bound by the strong force has reached a very high precision with protons and anti-protons

- (anti-)baryons → (anti-)nuclei: **binding energy** $\varepsilon_A$

\[
m_A = Zm_p + (A - Z)m_n - \varepsilon_A
\]
\[
m_A^{-1} = Zm_{\bar{p}} + (A - Z)m_{\bar{n}} - \varepsilon_A^{-1}
\]

→ The extension of such measurement to (anti-)nuclei allows to probe any matter/anti-matter asymmetry in nucleus-nucleus interactions, today described only by effective theories

\[\frac{(q/m)_{\bar{p}}}{(q/m)_p} - 1 = 1(64)(26) \times 10^{-12}\]

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Manuel Colocci – 13th September 2017 – EXA2017
LHC as an (anti-)nuclei factory

In high energy Pb-Pb collisions at LHC

1. large number of matter and anti-matter particles are produced: \( dN/d\eta \approx 10^3 \) in central collisions \( \rightarrow \) (anti-)nuclei production via coalescence of (anti-)nucleons

2. high temperature (\( \approx 156 \) MeV) and energy density (\( \approx 1 \) GeV/fm\(^3\)) in the primary interaction \( \rightarrow \) thermal production of (anti-)nuclei

\( \rightarrow \) Pb-Pb collisions are an abundant source of nuclei and anti-nuclei allowing to study their properties

[CERN Courier, Sept. 2015]
LHC as an (anti-)nuclei factory

Many results at LHC exclusively by ALICE During this conference:

- Production of (anti-)nuclei in pp, p-Pb, Pb-Pb
  → for small systems, see B. Döngus’s Talk

- (Anti-)hypernuclei production in Pb-Pb
  → see S. Piano’s Talk

- Searches for exotic QCD bound states
  → see A. Mastroserio’s Talk

- CPT test with light (anti-)nuclei
  → this contribution

Central Pb-Pb collision in ALICE at LHC

[CERN Courier, Sept. 2015]
LHC as an (anti-)nuclei factory

- $^4\overline{\text{He}}$ is the heaviest anti-nucleus observed until today
  10 candidates in ALICE
LHC as an (anti-)nuclei factory

- $^4\text{He}$ is the heaviest anti-nucleus observed until today 10 candidates in ALICE

- Lighter (anti-)nuclei more abundantly produced
  The yield is reduced by a factor $\approx 300$ by adding one nucleon, as extracted by fitting the experimental data:

  (yields of nuclei and corresponding anti-nuclei are very similar at LHC energies [ALICE Coll. PRC 93 (2015) 024917])
LHC as an (anti-)nuclei factory

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  \[ \text{yields of nuclei and corresponding anti-nuclei are very similar at LHC energies [ALICE Coll. PRC 93 (2015) 024917]} \]
Detectors involved in the analysis

**VZERO** for triggering

**Inner Tracking System** for triggering and charged particles tracking

**Time Projection Chamber** for charged particles tracking and PID based on dE/dx measurement

**Time Of Flight** for the mass/charge reconstruction based on time of flight measurement

**DATA set:**

\[ \text{Pb-Pb @ } \sqrt{s_{_{\text{NN}}}} = 2.76 \text{ TeV (2011 data taking: 67M events)} \]

Trigger selection: enriched in central and semi-central collisions
Particle Identification with TPC

- *(anti-)*d identified at rigidities $p/z<2 \text{ GeV}/c$

- *(anti-)*$^3\text{He}$ well separated from lighter particles in the full $p/z$ range thanks to its double charge ($z=2$)

- $\bar{\tau}$ is much more difficult to measure than $^3\text{He}$ even if they have a similar mass
Particle Identification with TOF

- (anti-)d identification until higher p/z thanks to a time resolution of 80 ps [EPJ Plus 128 (2013) 44]

- (anti-)\(^3\)He also well separated (between proton/deuteron band) but under the background coming from track-TOF hit time misassociation (see the next slide too)

- The background (B) is significantly reduced requiring:

\[
n_{\sigma}^{TPC} = \left| \frac{(dE/dx) - (dE/dx)_{exp}}{\sigma_{TPC}} \right| < 2
\]

\[\rightarrow B/S < 4\% \text{ at } p/z < 2 \text{ GeV/c (for deuteron) and } B/S < 1\% \text{ (for } ^3\text{He)}\]

\[\rightarrow \approx 10^6 \text{ (anti-)deuterons and } \approx 2 \times 10^3 \text{ (anti-)}^3\text{He are selected for the analysis}\]
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Rejection of secondaries

- The nuclei sample at low p/z may include secondaries originating from the interactions of primary particles with the detector material.

- This source of background is strongly suppressed:
  - $|DCA_{xy}| < 0.1$ cm
  - restricting the analysis to $p/z > 1.5$ GeV/c (deuteron) and $p/z > 1$ GeV/c ($^3$He)

→ contamination from secondary nuclei reduced to a level below 3%
Mass/charge reconstruction

- Squared mass-over-charge ratio reconstructed following:
  \[
  \mu_{\text{TOF}}^2 = \left(\frac{p}{z}\right)^2 \left[\left(\frac{t_{\text{TOF}}}{L}\right)^2 - \frac{1}{c^2}\right]
  \]
  \[
  \mu_{\text{TOF}}^2 \equiv (m/z)_{\text{TOF}}^2
  \]

- For each particle species the corresponding distribution is fitted in each p/z and η interval

- The fit function has two terms, signal + background:
  - signal: **gaussian** distribution **with an exponential tail** (right) according to the TOF time response
  - background: **exponential distribution** (in the deuteron case only)
Improving the mass difference determination

- The difference of masses ($\Delta \mu_{\text{TOF}}$) reduces significantly the syst. uncertainties affecting tracking and time calibration.

- The mass independent residual effects (mainly affecting the measurement of the rigidity) are significantly reduced via a correction based on the (anti-)proton mass:

$$\mu_{A(\bar{A})} = \mu_{A(\bar{A})}^{\text{TOF}} \times \frac{\mu_{p(\bar{p})}^{\text{PDG}}}{\mu_{p(\bar{p})}^{\text{TOF}}}$$

- Upon inversion of the magnetic field $\vec{B}$ of the experiment the remaining effects (mainly affecting the precision on the determination of the track length) are inverted:
  - the average of the two $\vec{B}$ polarities ($\pm 0.5$ T) is the best estimate
  - the half-difference represents the corresponding systematic uncertainty on $\Delta \mu$ (see also Tab. next slides)
    - $7 \times 10^{-5}$ for (anti-)deuteron
    - $7 \times 10^{-4}$ for (anti-$^3$He)
Other sources of syst. uncertainties

- **TPC dE/dx cut** \( (n_\sigma^{TPC}) \)
  - other cuts (tighter and looser: from 1 to 4) scanned to probe the sensitivity of the fit result on the residual background

- **Fit of \( \mu_{TOF}^2 \) distributions**
  - assumptions on the fit functions and the range of the fit varied

- The rigidity entering the mass formula is a **mean rigidity** (the particles slow down due to ionization energy loss during their propagation) → dedicated parameterization from Monte Carlo simulations is used to derive it from the rigidity at the IP
  - measurements repeated with/without such correction

- From the **contamination from secondary nuclei**
  - tighter and looser DCA\(_{xy}\) cuts varied to evaluate its impact on the final measurement
# Summary of syst. uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
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<th>$\Delta\mu_{3\text{He}^{3\text{He}}}/\mu_{3\text{He}}$ ($\times10^{-3}$)</th>
</tr>
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![Graph showing systematic uncertainties for $d-d$ collision](image)

**ALICE**
Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
Summary of syst. uncertainties

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The final measurement is obtained from the weighted average over all rigidity intervals.
Results

\[ \frac{\Delta \mu}{\mu} = \left[ -1.2 \pm 0.9 \text{ (stat.)} \pm 1.0 \text{ (syst.)} \right] \times 10^{-3} \]
\[ \frac{\Delta \mu}{\mu} = \left[ 0.9 \pm 0.5 \text{ (stat.)} \pm 1.4 \text{ (syst.)} \right] \times 10^{-4} \]

- Highest precision direct measurements of mass differences in the sector of nuclei
- Improvement by 1 to 2 orders of magnitude compared to previous measurements obtained more than 40 years ago

Results

\[ \Delta \varepsilon_{A\bar{A}} = Z \Delta m_{p\bar{p}} + (A - Z) \Delta m_{n\bar{n}} - \Delta m_{A\bar{A}} \]

\( \Delta m_{p\bar{p}} < 7 \times 10^{-10} \text{ GeV (CL=90\%)} \)


\( \Delta m_{n\bar{n}} = [0.85 \pm 0.51 \text{ (stat.)} \pm 0.29 \text{ (syst.)}] \times 10^{-4} \text{ GeV} \)


\[ \frac{\Delta \varepsilon}{\varepsilon} = -0.04 \pm 0.05 \text{ (stat.)} \pm 0.12 \text{ (syst.)} \quad \text{d-\bar{d}} \]

\[ \frac{\Delta \varepsilon}{\varepsilon} = 0.24 \pm 0.16 \text{ (stat.)} \pm 0.18 \text{ (syst.)} \quad \text{\textsuperscript{3}He-\textsuperscript{3}He} \]

- Constraint improved by a \textbf{factor 2} for (anti-)deuteron case
- \( \Delta \varepsilon \) determined for the \textbf{first time} in (anti-)\textsuperscript{3}He case

\[ \Delta \varepsilon \leq 7 \times 10^{-10} \text{ GeV (CL=90\%)} \]

[\textit{Nature}, 475 (2011) 484]

\[ \Delta m_{n\bar{n}} = [0.85 \pm 0.51 \text{ (stat.)} \pm 0.29 \text{ (syst.)}] \times 10^{-4} \text{ GeV} \]


Experimental limits are also used to constrain some CPT violating terms added to the SM lagrangian in the Standard Model Extension (SME) 


These tests independently verify each distinct prediction of CPT symmetry 

**More recent CPT tests**

  → experimental bound on the antihydrogen charge, $Q_e$, of $|Q| < 0.71 \times 10^{-9}$
- Observation of the 1S–2S transition in trapped antihydrogen [ALPHA Coll., Nature 541 (2017) 506] 
  → result consistent with CPT invariance at a relative precision of about $2 \times 10^{-10}$
CPT experimental tests

More recent CPT tests

  → scattering length $f_0$ and effective range $d_0$ of antiproton-antiproton interaction consistent with antiparticle counterpart at a relative precision of $5 \times 10^{-2}$ and $6 \times 10^{-1}$, respectively

Experimental limits are also used to constrain some CPT violating terms added to the SM lagrangian in the Standard Model Extension (SME)


These tests independently verify each distinct prediction of CPT symmetry

https://cds.cern.ch/record/2033777
Looking forward: Run 3+4

More statistics is a necessary condition to increase the precision of our measurements:


→ very significant improvement of the int. luminosity (100 times more than RUN 1 i.e. \( L_{\text{int}} = 10 \text{ nb}^{-1} \)) expected for the Run 3+4 of LHC (2020-2028) + ALICE upgrade

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Table 3: Expected yields for light (hyper)nuclear states (and their antiparticles) for central Pb–Pb collisions (0–10%) at \( \sqrt{s_{\text{NN}}} = 5.5 \text{ TeV} \). From left to right: (hyper)nuclear species, production yield from the statistical hadronization model [396], branching ratio (only for hypernuclei and exotica states), rapidity interval, and number of expected reconstructed particles for \( L_{\text{int}} = 10 \text{ nb}^{-1} \) [245] and reference for the estimation of the average acceptance-times-efficiency \( \langle \text{Acc.} \times \epsilon \rangle \) for \( p_T > 0 \).

| State                | dN/dy | B.R. | \(|y| < \) | Yield             | Ref. |
|----------------------|-------|------|---------|-------------------|------|
| d (TPC)              | 5 \times 10^{-2} | -    | 0.5     | 3.1 \times 10^8   | [388] |
| d (TPC+TOF)          | 5 \times 10^{-2} | -    | 0.5     | 1.4 \times 10^8   | [388] |
| \(^3\text{He} \) (TOF) | 3.5 \times 10^{-4} | -    | 0.5     | 2.2 \times 10^6   | [388] |
| \(^4\text{He} \) (TOF) | 7.0 \times 10^{-7} | -    | 0.5     | 1.5 \times 10^3   | [388] |
| \(^3\Lambda\)        | 1.0 \times 10^{-4} | 0.25 | 1       | 4.4 \times 10^3   | [396] |
| \(^4\Lambda\)        | 2.0 \times 10^{-7} | 0.50 | 1       | 1.1 \times 10^2   | [396] |
| \(^4\Lambda\) He     | 2.0 \times 10^{-7} | 0.54 | 1       | 1.3 \times 10^2   | [396] |
| \(\Lambda n\)        | 3.0 \times 10^{-2} | 0.35 | 1       | 2.9 \times 10^7   | [397] |
| \(\Lambda\Lambda\)   | 5.0 \times 10^{-3} | 0.064| 1       | 1.9 \times 10^5   | [397] |
| \(\Lambda\Lambda\)   | 5.0 \times 10^{-3} | 0.41 | 1       | 1.2 \times 10^6   | [397] |

[arXiv:1602.04120v1, February 2016]
Summary

• The abundant production of (anti-)nuclei in ultra relativistic heavy-ion collisions combined with the unique tracking/PID capability of the ALICE experiment allowed to report on rare quantitative verification of the matter/anti-matter symmetry in the context of the nuclear forces

• The measurements of Δμ between d and $\bar{d}$, and $^3$He and $\bar{^3}$He have been obtained, improving by 1 to 2 orders of magnitude existing results

• The results are also expressed in terms of Δε; for the (anti-)d it improves by a factor 2 the constraints on CPT invariance inferred by existing measurements; for the (anti-)$^3$He it has been determined for the first time, with a relative precision comparable to the one obtained in the (anti-)deuteron system

• Remarkably, these improvements are reached in an high energy experiment not specifically designed/built for that

• Significant improved precisions are expected at Run 3+4 of LHC with the upgraded ALICE detector
Backup
Thanks for the attention !!
Mean rigidity correction

\[ \mu^2_{\text{TOF}} = \left( \frac{p}{z} \right)^2 \left[ \left( \frac{t_{\text{TOF}}}{L} \right)^2 - \frac{1}{c^2} \right] \]

- rigidity at the primary vertex 
  \((p/z)_{\text{vtx}}\) provided by track reconstruction
  \(\rightarrow (p/z)_{\text{vtx}}\) adjusted to the mean one \((p/z)\) by a correction calculated via a Monte Carlo simulation
About the absolute deuteron mass

• After correcting the deuteron mass for the proton one we are able to measure even the absolute mass with an unexpected good precision for a high energy experiment (with other purposes e.g. tracking, PID, ...)

• Caveat: in the mass difference most of the syst. uncertainties cancel!
On the tracking uncertainties

On the mass difference the uncertainties related to the particle tracking have to be accounted for. → they correspond to an error on the rigidity (1) and on the track length (2):

\[ \frac{\delta \mu_{\text{TOF}}}{\mu_{\text{TOF}}} = \frac{\delta (p/z)}{p/z} \oplus \gamma^2 \frac{\delta L}{L} \]

\( \oplus L - p/z \) corr. term (negl.)

(1) is the largest one (≤ 1%) and mass independent in a p/z interval

\[ \mu_{A(A)} = \mu_{A(A)}^{\text{TOF}} \times \frac{\mu_{p(\bar{p})}}{\mu_{p(\bar{p})}^{\text{TOF}}} \]

(1) now negligible; indeed it propagates in \( \Delta \mu/\mu \) as

\[ \frac{\Delta \mu}{\mu} \times \left[ \frac{\delta (p/z)}{p/z} \right]^2 \]

where the 1° term can be consider a suppression factor and the 2° term is O(10^{-4})
On the mass difference the uncertainties related to the particle tracking have to be accounted for. → they correspond to an error on the rigidity (1) and *on the track length (2)*:

\[
\frac{\delta \mu_{\text{TOF}}}{\mu_{\text{TOF}}} = \frac{\delta (p/z)}{p/z} \oplus \gamma^2 \frac{\delta L}{L} \oplus L - p/z \text{ corr. term (negl.)}
\]

(2) is mass dependent via \( \gamma^2 \) factor.

\[
\mu_{A(\bar{A})} = \mu_{A(\bar{A})}^{\text{TOF}} \times \frac{\mu_{p(\bar{p})}^{\text{PDG}}}{\mu_{p(\bar{p})}^{\text{TOF}}}
\]

(2) propagates in \( \Delta \mu/\mu \) as

\[
\left( \frac{\delta L}{L} - \frac{\delta \bar{L}}{L} \right) \times (\gamma_A^2 - \gamma_p^2)
\]

then inverting the magnetic field polarity \( \delta L/L \leftrightarrow \delta \bar{L}/\bar{L} \ldots \)