

Search for exotic hyper-matter and measurement of nuclei with ALICE at the LHC

Benjamin Dönigus (for the ALICE Collaboration)

Institut für Kernphysik, Goethe-Universität Frankfurt, Max-von-Laue-Str. 1, 60438 Frankfurt am Main

E-mail: benjamin.doenigus@cern.ch

Abstract. The high collision energies reached at the LHC lead to significant production yields of light (anti-)nuclei and hyper-matter in proton-proton and, in particular, Pb–Pb collisions. The excellent particle identification capabilities of the ALICE apparatus, in particular the specific energy loss in the Time Projection Chamber (TPC) and Time-of-Flight (TOF) measurement, allow for the detection of such rarely produced particles. Further, the Inner Tracking System (ITS) gives the possibility to separate primary nuclei from those coming from the weak decay of heavier systems. This offers the unique opportunity to search for exotica like the bound state of a Λ and a neutron which would decay into deuteron and pion, or the bound states of two Λ s. We show here the performance of the ALICE apparatus in the sector on (anti-)nuclei and in particular the results on deuteron production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. These are compared with thermal model predictions. We further present the current state of the searches, by their upper limits on the production yields, and compare the results to thermal and coalescence model expectations.

1. Introduction

The measurement of light (anti-)nuclei and search for hyper-matter, created in heavy-ion collisions, is challenging since the production probability decreases with the increasing mass of the investigated particles. The production yields of these particles can be predicted by thermal models based on an analysis of lighter particles [1, 2, 3]. The chemical freeze-out temperature T , the volume V and the baryo-chemical potential μ_B are the only three free parameters in this approach as long as one assumes an equilibrated system. To account for possible non-equilibrium effects the factors γ_s and γ_q are very often introduced (e.g. [3]). An open question in the field of heavy-ion collisions is if the production of nuclei and other multi-baryon states, such as hyper-nuclei or also hyper-matter, is entirely described by a thermal model or if those objects are formed by coalescence of hadrons or even directly from quarks.

Hyper-matter is used as a synonym of matter composed either partly or entirely by strange matter. Here we focus on exotic states like a possible Λn bound state or the H-Dibaryon. The H-Dibaryon is a bound state of $uuddss$ ($\Lambda\Lambda$) and was predicted by Jaffe in a bag model calculation [4]. Recent lattice QCD calculations [5, 6] also suggest a bound state, with binding energies in the range 13-50 MeV/ c . A chiral extrapolation of these lattice calculations to a physical pion mass resulted in a H-Dibaryon which is unbound by either 13 ± 14 MeV/ c [7] or it lies close to the Ξp threshold [8]. This renewed the interest in the experimental searches for the H-Dibaryon which were ongoing since its prediction in 1977 [4]. Details of the H-Dibaryon

analysis can be found in [9]. The results of these searches are compared to model expectations at the end of these proceedings.

2. Deuteron spectra and yields in Pb–Pb

The excellent performance of the Time-Projection Chamber (TPC) [10] and the Time-Of-Flight detector (TOF) [11] allows for the clear identification of charged stable particles over a range of 0.15 to 5 GeV/c in rigidity $R = p/z$, where p is the track momentum and z is the charge number. Combining the specific energy loss (dE/dx) in the TPC and the TOF information, anti-alpha nuclei were identified, as discussed in some more detail in [12]. The same technique is used to measure the yields of deuterons.

This measurement is affected by a huge background, as for all nuclei, coming from knockout from material. This is not relevant for the measurement of anti-nuclei, like the anti-alpha. Rejection of this background is possible by restricting the distance-of-closest-approach (dca) of the track to the primary vertex in z -direction dca_z and then fitting the dca_{xy} distribution to extract the signal in the p_T window between 0.6 and 1.9 GeV/c (technique is described in more detail in [13]). The deuterons are identified using only the dE/dx measurement in the TPC

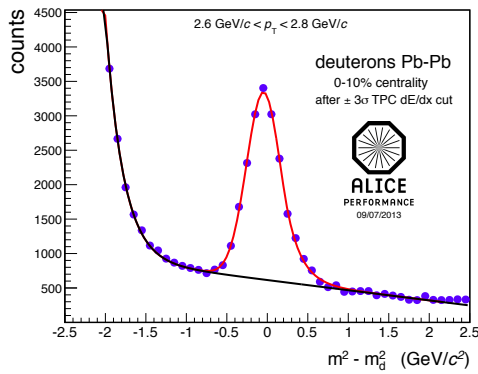


Figure 1. $m^2 - m_d^2$ distribution measured by TOF for one example p_T bin ($2.6 \text{ GeV}/c < p_T < 2.8 \text{ GeV}/c$), after preselection done by the specific energy loss measurement in the TPC of $\pm 3\sigma$ for deuterons. Fitted by a Gaussian function plus exponential tail to extract the yield.

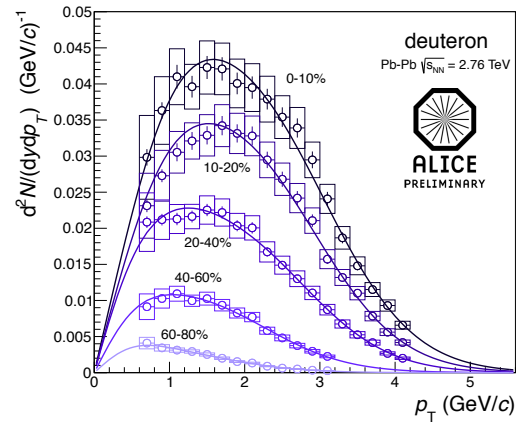


Figure 2. Measured deuteron spectra at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ for five different centralities. The lines through the measured points are individual blast-wave fits to extrapolate towards low p_T .

for $p_T \lesssim 1.5 \text{ GeV}$ and combining the TPC and TOF information for higher p_T . A sample of deuteron selected with a 3 sigma cut around the expected dE/dx value is initially used to build the $m^2 - m_d^2$ -distribution, where m is the mass measured with TOF and $m^2 = p^2/(\gamma^2 - 1)$. Then, this distribution is fitted with a Gaussian function + exponential tail in p_T intervals (shown in Figure 1). The extracted yields are then efficiency and acceptance corrected and the final spectra are shown in Figure 2 for five different collision centralities. The spectra show a characteristic hardening with increasing centrality, qualitatively similar to proton spectra. To extract p_T integrated yields the spectra in the different centrality bins are fitted by individual blast-wave distributions. The ratios of these yields with those of protons are shown in Figure 3 for five different centralities. The measured ratio agrees well with the mean of the d/p and the \bar{d}/\bar{p} from PHENIX[14], which is a fair comparison since the μ_B at the LHC is getting close to 0 MeV [2].

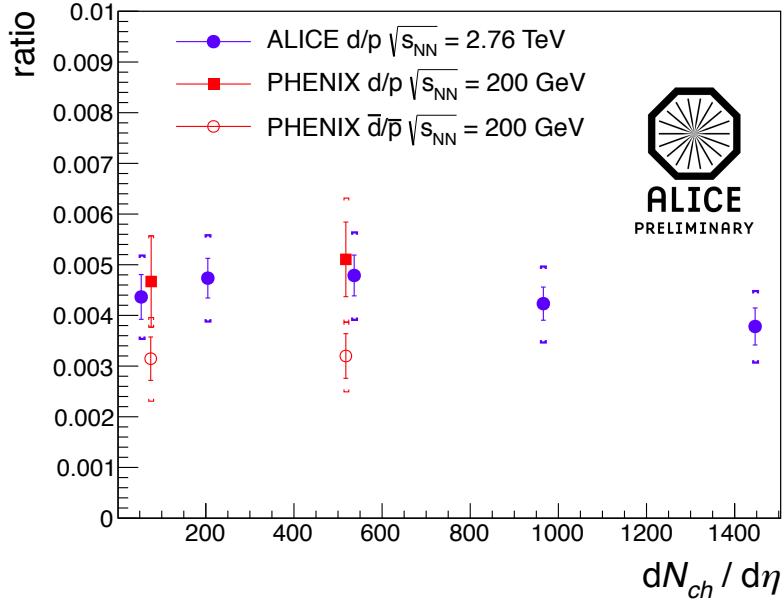


Figure 3. Deuteron-to-proton ratio over centrality compared with the PHENIX measurement [14] of deuteron-to-proton ratio and the anti-deuteron-to-anti-proton ratio at $\sqrt{s_{\text{NN}}} = 200$ GeV.

3. Search for exotica: Λn bound state

The HypHI collaboration at GSI found evidence for a possible Λn bound state, decaying into a deuteron and a pion. The signal was detected on top of a background which can be described by the mixed events technique [15]. We investigate here only the $\bar{\Lambda} n$ bound state, because of the much lower background compared to the corresponding particle (Λn) state. Monte Carlo simulations have been used to estimate the efficiency for the detection, the $\bar{\Lambda} n$ was generated flat in rapidity y and in transverse momentum p_T . We assume the lifetime to be that of the Λ particle, as suggested by the HypHI experiment. The p_T distribution of the $\bar{\Lambda} n$ was extrapolated from the blast-wave fits for π, K, p done at the same energy. The estimated efficiency \times acceptance versus p_T is convoluted with the normalised blast-wave function to get a weighted efficiency. The unknown p_T shape is the main source of uncertainty, therefore, different functions are used to study systematics (the boundary cases: blast-wave of deuteron and ${}^3\text{He}$). The analysis strategy is to search for displaced decay vertices of anti-deuterons and pions. If one of the daughter tracks is identified as an anti-deuteron and the second daughter as a pion (both via specific energy loss in the TPC), the invariant mass of these candidates is calculated. The result is shown in Figure 4 together with the systematic error as a band and the peak which we expect from the Monte Carlo estimation and its corresponding error. Since no signal is observed, an upper limit on the production of this particle was set: $dN/dy \leq 1.5 \cdot 10^{-3}$ (at 99% CL).

4. Summary and comparison with different models

The measured yield of deuterons presented here compares well with the current best equilibrium thermal model fit [16] which gives a temperature of about 156 MeV. One can now contrast the upper limits set for the exotica currently under investigation by ALICE, i.e. H-Dibaryon and Λn bound state, with different models. Figure 5 shows a comparison of the upper limits to the equilibrium thermal model [17] (164 MeV, which was the prediction for LHC and 156 MeV, the current best fit), the non-equilibrium thermal model prediction [18] from their current best fit [3]

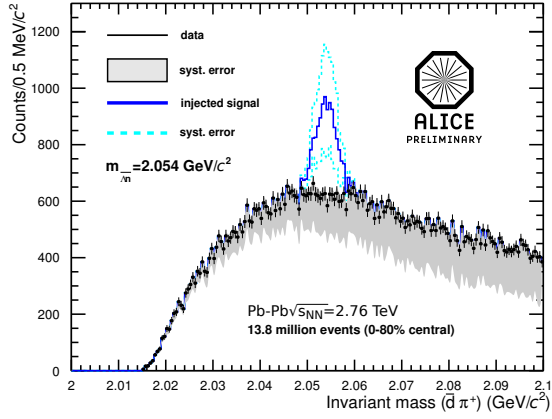


Figure 4. Invariant mass of anti-deuterons and pions. The expected signal is also shown.

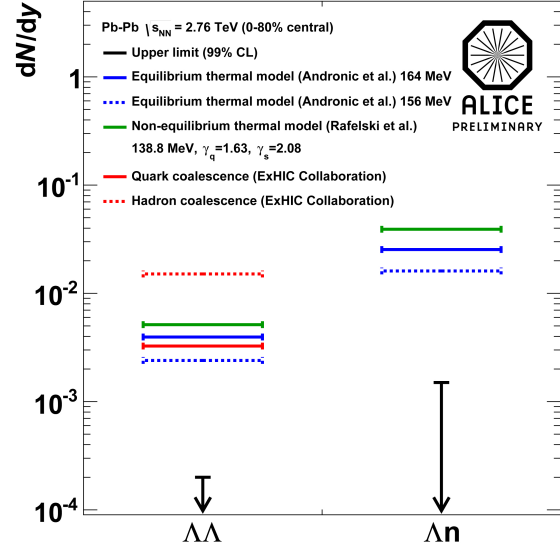


Figure 5. Upper limits of production yields for H-Dibaryon ($\Lambda\Lambda$) and Λn bound state compared with different models.

and coalescence predictions (quark and hadron coalescence) from the ExHIC collaboration [19]. All models are at least a factor 10 above the upper limits. Currently an effort continues to further reduce these upper limits by utilising more statistics than was previously used. Around 20 million central events will enhance the statistics. This will allow to make an even stricter decision about the existence of these particles.

References

- [1] Andronic A, Braun-Munzinger P, Stachel J and Stöcker H 2011 *Phys. Lett. B* **697** 203
- [2] Cleymans J, Kabana S, Kraus I, Oeschler H, Redlich K and Sharma N 2011 *Phys. Rev. C* **84** 054916
- [3] Petráň M, Letessier J, Petráček V and Rafelski J 2013 CERN-PH-TH/2012-262, arXiv:1303.2098v2 [hep-ph]
- [4] Jaffe R 1977 *Phys. Rev. Lett.* **38** 195 and erratum ibid 1977 **38** 617
- [5] Inoue T et al. (HAL QCD Collaboration) 2011 *Phys. Rev. Lett.* **106** 162001
- [6] Beane S R et al. (NPLQCD Collaboration) 2011 *Phys. Rev. Lett.* **106** 162002
- [7] Shanahan P E, Thomas A W and Young R D 2011 *Phys. Rev. Lett.* **107** 092004
- [8] Haidenbauer J and Meißner U-G 2011 *Phys. Lett. B* **706** 100
- [9] Lea R (for the ALICE Collaboration) these proceedings
- [10] Alme J et al. (ALICE TPC Collaboration) 2010 *Nucl. Instr. Meas. A* **622** 316
- [11] Aamodt K et al. (ALICE Collaboration) 2008 *JINST* **3** S08002
- [12] Dönigus B (for the ALICE Collaboration) 2013 *Nucl. Phys. A* **904-905** 457c
- [13] Abelev B et al. (ALICE Collaboration) 2013 CERN-PH-EP-2013-019, arXiv:1303.0737v2 [hep-ex]
- [14] Adler S S 2005 *Phys. Rev. Lett.* **94** 122302
- [15] <http://www.bnl.gov/hhi/files/talks/TakehikoSaito.pdf>, as shown 1.3.2012 at the Riken-BNL workshop on "Hyperon-Hyperon Interactions and Searches for Exotic Di-Hyperons in Nuclear Collisions"
- [16] Stachel J these proceedings
- [17] Andronic A private communication
- [18] Petráň M private communication
- [19] Cho S et al. (ExHIC Collaboration) 2011 *Phys. Rev. C* **84** 064910