Precision measurement of the mass difference between light nuclei and anti-nuclei

ALICE Collaboration

Abstract

The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons. The extension of such measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories, but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons ($d$) and anti-deuterons ($\bar{d}$), and $^3$He and $^3\bar{\text{He}}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment) detector in Pb-Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirm CPT invariance to an unprecedented precision in the sector of light nuclei. This fundamental symmetry of nature, which exchanges particles with anti-particles, implies that all physics laws are the same under the simultaneous reversal of charge(s) (charge conjugation C), reflection of spatial coordinates (parity transformation P) and time inversion (T).
The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons\cite{1,2}. The extension of such measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories\cite{3}, but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons (d) and anti-deuterons (\overline{d}), and $^3$He and $^3\overline{\text{He}}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment)\cite{4} detector in Pb-Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirm CPT invariance to an unprecedented precision in the sector of light nuclei\cite{5,6}. This fundamental symmetry of nature, which exchanges particles with anti-particles, implies that all physics laws are the same under the simultaneous reversal of charge(s) (charge conjugation C), reflection of spatial coordinates (parity transformation P) and time inversion (T). Heavy ions are collided at very high energies at the CERN Large Hadron Collider (LHC) to study matter at extremely high temperatures and densities. Under these conditions heavy-ion collisions are a copious source of matter and anti-matter particles and thus are suitable for an experimental investigation of their properties such as mass and electric charge. In relativistic heavy-ion collisions, nuclei and corresponding anti-nuclei are produced with nearly equal rates\cite{7}. Their yields have been measured at the Relativistic Heavy Ion Collider (RHIC) by the STAR\cite{8} and PHENIX\cite{9} experiments and at the LHC by the ALICE\cite{4} experiment. To date, the heaviest anti-nucleus which has been observed\cite{7} is $^4\overline{\text{He}}$ (anti-\alpha); meanwhile, for lighter nuclei and anti-nuclei, which are more copiously produced, a detailed comparison of their properties is possible. This comparison represents an interesting test of CPT symmetry in an analogous way as done for elementary fermions\cite{10,11} and bosons\cite{12}, and for QED\cite{13,14} and QCD systems\cite{1,2,15,16} (a particular example for the latter being the measurements carried out on neutral kaon decays\cite{15}), with different levels of precision which span over several orders of magnitude. All these measurements can be used to constrain, for different interactions, the parameters of effective field theories that add explicit CPT violating terms to the Standard Model Lagrangian, such as the Standard Model Extension\cite{19} (SME).

The measurements reported in this paper are based on the high-precision tracking and identification capabilities of the ALICE experiment\cite{20}. The main detectors employed in this analysis are the ITS\cite{21} (Inner Tracking System) for the determination of the interaction vertex, the TPC\cite{22} (Time Projection Chamber) for tracking and specific energy loss ($dE/dx$) measurements, and the TOF\cite{23} (Time Of Flight) detector to measure the time $t_{\text{TOF}}$ needed by each track to traverse the detector. The combined ITS and TPC information is used to determine the track length ($L$) and the rigidity ($p/|z|$), where $p$ is the momentum and $z$ the electric charge in units of the elementary charge $e$) of the charged particles in the solenoidal 0.5 T magnetic field of the ALICE central barrel (pseudo-rapidity $|\eta| < 0.8$). Based on these measurements, we can extract the squared mass-over-charge ratio $\mu^2_{TOF} \equiv (m/z)^2_{TOF} = (p/z)^2 [(t_{\text{TOF}}/L)^2 - 1/e^2]$. The choice of this variable is motivated by the fact that $\mu^2$ is directly proportional to the square of the time of flight, allowing to better preserve its Gaussian behaviour.

The high precision of the TOF detector, which determines the arrival time of the particle with a resolution of 80 ps\cite{20}, allows us to measure a clear signal for (anti-)protons, (anti-)deuterons and (anti-)$^3$He nuclei over a wide rigidity range ($1 < p/|z| < 4$ GeV/$c$). The main source of background, which is potentially of the same order of the signal, arises from tracks erroneously associated to a TOF hit. To reduce this contamination, a $2\sigma$ cut (where $\sigma$ is the standard deviation) around the expected TPC $dE/dx$ signal is applied. Such a requirement strongly suppresses (to below 4%) this background for rigidities below $p/|z| < 2.0$ GeV/$c$ for (anti-)deuterons and for all rigidities for (anti-)$^3$He (to below 1%). For each of the species under study, the mass is extracted by fitting the mass-squared distributions in narrow $p/|z|$ and $\eta$ intervals, using a Gaussian with a small exponential tail that reflects the time signal distribution of the TOF detector. Examples of the mass-squared distributions for (anti-)deuterons and (anti-)$^3$He candidates are reported in Fig.\cite{11} in selected rigidity intervals.
Using mass differences, rather than absolute masses, allows us to reduce the systematic uncertainties related to tracking, spatial alignment (affecting the measurement of the track momentum and length) and time calibration. Despite that, residual effects are still present, due to imperfections in the detector alignment and the description of the magnetic field, which can lead to position-dependent systematic uncertainties. In terms of relative uncertainties, the ones affecting the measurement of the momentum are the largest and independent of the mass, and are the same for all positive (negative) particles in a given momentum interval. It is therefore possible to correct the (anti-)deuteron and the (anti-)He masses by scaling them with the ratio between the (anti-)proton masses recommended by PDG[24] and the ones measured in the analysis presented here ($\mu_{\text{p}}/\mu_{\text{p}}^\text{PDG}$). The mass-squared distribution. The mass-over-charge ratio differences between the deuteron and $^3\text{He}$ masses by $\Delta\mu_{\text{d}}/\mu_{\text{d}}$ and $\Delta\mu_{^3\text{He}}/\mu_{^3\text{He}}$ are then evaluated as a function of the rigidity of the track, as shown in Fig. 2. The measurements in the individual rigidity intervals are combined, taking into account statistical and systematic uncertainties (correlated and uncorrelated), and the final result is shown in the same figure with one and two standard deviation uncertainty bands. The measured mass-over-charge ratio differences are

$$\Delta\mu_{\text{d}} = [1.7 \pm 0.9 \text{(stat.)} \pm 2.6 \text{(syst.)}] \times 10^{-4} \text{ GeV}/c^2,$$

$$\Delta\mu_{^3\text{He}}/\mu_{^3\text{He}} = [-1.7 \pm 1.2 \text{(stat.)} \pm 1.4 \text{(syst.)}] \times 10^{-3} \text{ GeV}/c^2,$$

and

$$\Delta\mu_{\text{d}}/\mu_{\text{d}} = [0.9 \pm 0.5 \text{(stat.)} \pm 1.4 \text{(syst.)}] \times 10^{-4},$$

$$\Delta\mu_{^3\text{He}}/\mu_{^3\text{He}} = [-1.2 \pm 0.9 \text{(stat.)} \pm 1.0 \text{(syst.)}] \times 10^{-3},$$

where $\mu_{\text{d}}$ and $\mu_{^3\text{He}}$ are the values recommended by CODATA[25]. The mass-over-charge differences are compatible with zero within the estimated uncertainties, in agreement with CPT invariance expectations. Given that $z_\text{d} = -z_\text{p}$ and $z_{^3\text{He}} = -z_{^3\text{He}}$ as for the proton and anti-proton[1][2], the mass-over-charge differences in Eq. 1 and Eq. 2 and the measurement of the mass differences between proton and anti-proton[1][2] and between neutron and anti-neutron[15][16] can be used to derive the relative binding...
energy differences between the two studied particle species. We obtain

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

\[
\frac{\Delta \varepsilon_{^3\text{He}^3\text{He}}}{\varepsilon_{^3\text{He}}} = 0.24 \pm 0.16 \text{ (stat.)} \pm 0.18 \text{ (syst.)},
\]

where \( \varepsilon_A = Zm_p + (A - Z)m_n - m_A \), being \( m_p \) and \( m_n \) the proton and the neutron mass values recommended by PDG\[24\] and \( m_A \) the mass value of the nucleus with atomic number \( Z \) and mass number \( A \), recommended by CODATA\[25\]. This quantity allows one to explicitly isolate possible violations of the CPT symmetry in the (anti-)nucleon interaction from the one connected to the (anti-)nucleon masses, the latter being constrained with a precision of \( 7 \times 10^{-10} \) for the proton/anti-proton system\[1, 2\]. Our results and the comparisons with previous mass difference measurements for (d-d)\[26, 27\] and (\(^3\text{He}^3\text{He}\))\[28\], as well as binding energy measurements for (d-d)\[29, 30\] are reported in Fig. 3.

We have shown that the copious production of (anti-)nuclei in relativistic heavy-ion collisions at the LHC represents a unique opportunity to test the CPT invariance of nucleon-nucleon interaction using light nuclei. In particular, we have measured the mass-over-charge ratio differences for deuteron and \(^3\text{He}\). The values are compatible, within uncertainties, with zero and represent a CPT invariance test in systems bound by nuclear forces. The results reported here (Fig. 3, left) represent the highest precision direct measurements of mass differences in the sector of nuclei and they improve by one to two orders of magnitude analogous results originally obtained more than 40 years ago\[26–28\], and precisely 50 years ago for the anti-deuteron\[26, 27\]. Remarkably such an improvement is reached in an experiment which is not specifically dedicated to test the CPT invariance in nuclear systems. In the forthcoming years the increase in luminosity and center-of-mass energy at the LHC will allow to push forward the sensitivity of these measurements, and possibly to extend the study to (anti-)\(^4\text{He}\). Given the equivalence between mass and binding energy differences, our results also improve (Fig. 3, right) by a factor two the constraints on CPT invariance inferred by existing measurements\[29, 30\] in the (anti-)deuteron system. The binding energy difference has been determined for the first time in the case of (anti-)\(^3\text{He}\), with a relative precision comparable to the one obtained in the (anti-)deuteron system.
Fig. 1: Examples of squared mass-over-charge ratio distributions for deuterons (left) and \(^3\)He (right) in selected rigidity intervals. Particle and anti-particle spectra are in the top and bottom plots, respectively. The fit function (red curve) also includes, for the (anti-)deuteron case, an exponential term to describe the background. In the rigidity intervals shown here the background is about 4% for (anti-)deuterons, while it is 0.7% for \(^3\)He and \(^3\)He.
**Fig. 2:** The $d\bar{d}$ (top) and $^3\text{He}-^3\overline{\text{He}}$ (bottom) mass-over-charge ratio difference measurements as a function of the particle rigidity. Vertical bars and open boxes show the statistical and the uncorrelated systematic uncertainties (standard deviations), respectively. Both are taken into account to extract the combined result in the full rigidity range, together with the correlated systematic uncertainty, which is shown as a box with tilted lines. Also shown are the $1\sigma$ and $2\sigma$ bands around the central value, where $\sigma$ is the sum in quadrature of the statistical and systematic uncertainties.
Fig. 3: The ALICE measurements for d-$\bar{d}$ and $^3\text{He}^\ast$-$^3\text{He}$ mass-over-charge ratio differences compared with CPT invariance expectation (dotted lines) and existing mass measurements MAS65[26], DOR65[27] and ANT71[28] (left panel). The inset shows the ALICE results on a finer $\Delta(m/z)/(m/z)$ scale. The right panel shows our determination of the binding energy differences compared with direct measurements from DEN71[29] and KES99[30]. Error bars represent the sum in quadrature of the statistical and systematic uncertainties (standard deviations).
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References


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Affiliation notes
1 Deceased
2 Also at: University of Kansas, Lawrence, Kansas, United States

Collaboration Institutes

1 A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
2 Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
3 Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
4 Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
5 Budker Institute for Nuclear Physics, Novosibirsk, Russia
6 California Polytechnic State University, San Luis Obispo, California, United States
7 Central China Normal University, Wuhan, China
8 Centre de Calcul de l’IN2P3, Villeurbanne, France
9 Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
10 Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMADEN), Madrid, Spain
11 Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
12 Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Rome, Italy
13 Chicago State University, Chicago, Illinois, USA
Precision measurement of the mass difference between light nuclei and anti-nuclei

ALICE Collaboration

14 China Institute of Atomic Energy, Beijing, China
15 Commissariat à l’Energie Atomique, IRFU, Saclay, France
16 COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
17 Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
18 Department of Physics and Technology, University of Bergen, Bergen, Norway
19 Department of Physics, Aligarh Muslim University, Aligarh, India
20 Department of Physics, Ohio State University, Columbus, Ohio, United States
21 Department of Physics, Sejong University, Seoul, South Korea
22 Department of Physics, University of Oslo, Oslo, Norway
23 Dipartimento di Elettrotecnica ed Elettronica del Politecnico, Bari, Italy
24 Dipartimento di Fisica dell’Università ‘La Sapienza’ and Sezione INFN Rome, Italy
25 Dipartimento di Fisica dell’Università and Sezione INFN, Cagliari, Italy
26 Dipartimento di Fisica dell’Università and Sezione INFN, Trieste, Italy
27 Dipartimento di Fisica dell’Università and Sezione INFN, Turin, Italy
28 Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Bologna, Italy
29 Dipartimento di Fisica and Astronomia dell’Università and Sezione INFN, Catania, Italy
30 Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Padova, Italy
31 Dipartimento di Fisica ‘E.R. Caianiello’ dell’Università and Gruppo Collegato INFN, Salerno, Italy
32 Dipartimento di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
33 Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy
34 Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
35 Eberhard Karls Universität Tübingen, Tübingen, Germany
36 European Organization for Nuclear Research (CERN), Geneva, Switzerland
37 Faculty of Engineering, Bergen University College, Bergen, Norway
38 Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
39 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
40 Faculty of Science, P.J. Šafářik University, Košice, Slovakia
41 Faculty of Technology, Buskerud and Vestfold University College, Vestfold, Norway
42 Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
43 Gangneung-Wonju National University, Gangneung, South Korea
44 Gauhati University, Department of Physics, Guwahati, India
45 Helsinki Institute of Physics (HIP), Helsinki, Finland
46 Hiroshima University, Hiroshima, Japan
47 Indian Institute of Technology Bombay (IIT), Mumbai, India
48 Indian Institute of Technology Indore, Indore (IITI), India
49 Inha University, Incheon, South Korea
50 Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
51 Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
52 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
53 Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
54 Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
55 Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
56 Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
57 Institute for Theoretical and Experimental Physics, Moscow, Russia
58 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
59 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
60 Institute of Physics, Bhubaneswar, India
61 Institute of Space Science (ISS), Bucharest, Romania
62 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
63 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
64 iThemba LABS, National Research Foundation, Somerset West, South Africa
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ALICE Collaboration

Universidade de São Paulo (USP), São Paulo, Brazil
Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
University of Houston, Houston, Texas, United States
University of Jyväskylä, Jyväskylä, Finland
University of Liverpool, Liverpool, United Kingdom
University of Tennessee, Knoxville, Tennessee, United States
University of the Witwatersrand, Johannesburg, South Africa
University of Tokyo, Tokyo, Japan
University of Tsukuba, Tsukuba, Japan
University of Zagreb, Zagreb, Croatia
Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France
V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
Variable Energy Cyclotron Centre, Kolkata, India
Vinča Institute of Nuclear Sciences, Belgrade, Serbia
Warsaw University of Technology, Warsaw, Poland
Wayne State University, Detroit, Michigan, United States
Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
Yale University, New Haven, Connecticut, United States
Yonsei University, Seoul, South Korea
Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany