Precision laser spectroscopy experiments on antiprotonic helium

Masaki Hori¹,*

¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany

Abstract. At CERN’s Antiproton Decelerator (AD) facility, the Atomic Spectroscopy and Collisions Using Slow Antiprotons (ASACUSA) collaboration is carrying out precise laser spectroscopy experiments on antiprotonic helium ($p\text{He}^+ \equiv p + \text{He}^{2+} + e^-$) atoms. By employing buffer-gas cooling techniques in a cryogenic gas target, samples of atoms were cooled to temperature $T = 1.5–1.7$ K, thereby reducing the Doppler width in the single-photon resonance lines. By comparing the results with three-body quantum electrodynamics calculations, the antiproton-to-electron mass ratio was determined as $M_p/m_e = 1836.1526734(15)$. This agreed with the known proton-to-electron mass ratio with a precision of $8 \times 10^{-10}$. Further improvements in the experimental precision are currently being attempted. The high-quality antiproton beam provided by the future Extra Low Energy Antiproton Ring (ELENA) facility should further increase the experimental precision.

1 Introduction

The metastable antiprotonic helium ($p\text{He}^+ \equiv p + \text{He}^{2+} + e^-$) atom is an exotic long-lived system made of a helium nucleus, an electron in the ground state, and an antiproton occupying a Rydberg state of principal and orbital angular momentum quantum numbers $n \sim \ell - 1 \sim 38$ [1–3]. The unusual longevity of the atom allows us to measure its transition frequencies by laser spectroscopy. By comparing the values with the results of three-body quantum electrodynamics (QED) calculations, the antiproton-to-electron mass ratio $M_p/m_e$ can in principle be determined with a relative precision of $\sim 10^{-11}$ [4–6]. This corresponds to the best determinations of the proton-to-electron mass ratio $M_p/m_e$ obtained from Penning trap experiments [7–11], or laser spectroscopy of HD+ molecular ions [12–14]. The $p\text{He}^+$ experiments also provide a consistency test of CPT symmetry [15], which may be complementary to the spectroscopy experiments on antihydrogen atoms [16–18]. It provides experimental constraints on any exotic fifth force that may exist at the $\sim 1$ Å length scale [19–22].

The atoms can be readily synthesized via the reaction, $\bar{p} + \text{He} \rightarrow \bar{p}\text{He}^+ + e^-$, by allowing an antiproton beam [23] to come to rest in a helium gas target [24–26]. The transition frequencies of $\bar{p}\text{He}^+$ spanning the infrared to ultraviolet range have been calculated [4–6] to a relative precision of $\sim 10^{-10}$ by evaluating the quantum electrodynamics (QED) corrections up to order $m_e\alpha^7$ in atomic units. Here $m_e$ and $\alpha$ respectively denote the electron mass and the fine structure constant. These calculations used the International Council for

*e-mail: Masaki.Hori@mpq.mpg.de

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).
Science Committee on Data for Science and Technology (CODATA) 2010 recommended values of the fundamental constants [27], including the fine structure constant $\alpha$, the $^3$He- and $^4$He-to-electron mass ratios, the Bohr radius, and the Rydberg constant. The corrections to the transition frequencies that arise from the finite charge radii of the helium nucleus (4 to 7 MHz) and of the antiproton [28] (< 1 MHz) are small because the spatial overlap between the Rydberg antiproton orbital and the nucleus is relatively small, and because the antiproton is polarized away from the $1s$ electron in the atom.

## 2 Buffer gas cooling of $\bar{p}$He$^+$ atoms

The thermal motions of $\bar{p}$He$^+$ in the experimental target at temperature $T$ broadens the width of the measured single-photon laser resonances by a factor, $\nu \sqrt{8k_BT \log 2/Mc^2}$. Here $\nu$ denotes the transition frequency, $k_B$ the Boltzmann constant, $M$ the atom’s mass, and $c$ the speed of light. This loss in the spectral resolution limited [29, 30] the precision of determining the resonance centroid to around $10^{-7}$–$10^{-8}$. One way to reach a precision beyond this Doppler limit was provided by two-photon spectroscopy [2, 31], in which the $\bar{p}$He$^+$ was irradiated by two counterpropagating ultraviolet laser beams.

An alternative method involved cooling some $2 \times 10^9$ $\bar{p}$He$^+$ atoms to a temperature $T = 1.5$–1.7 K, by allowing the $\bar{p}$He$^+$ to undergo elastic collisions with cryogenic helium gas [3]. This cooling behavior is in contrast to some other kinds of hadronic exotic atoms, such as pionic hydrogen [32], which was found to be heated by collisions with H$_2$ molecules that deexcite the atom. The density of the buffer gas ($T \sim 1.5$ K and $P = 40$–170 Pa) used in the experiment was carefully adjusted so that the $\bar{p}$He$^+$ atoms, once formed, rapidly underwent a
few hundred or more cooling collisions. It was then interrogated by the resonant laser beam. The 1s electron protected a significant fraction of the $\vec{p}^4$He$^+$ from annihilation during this cooling.

The experiment (Fig. 1) was carried out by utilizing the pulsed beam of AD that contained between $2 \times 10^7$ and $3 \times 10^7$ antiprotons with a kinetic energy $E = 5.3$ MeV and repetition rate $f = 0.01$ Hz. Some of the antiprotons were slowed down to $E = 75$ keV by allowing them to traverse a 3 m long radiofrequency quadrupole decelerator [29, 33]. This setup was also recently used to attempt to measure the annihilation cross sections of antiprotons that traversed some thin target foils [34–38]. The emerging 75-keV antiprotons were transported by a beamline and allowed to enter the cryogenic helium gas target. The target was in thermal contact with an open-cycle Joule-Thomson cryocooler at temperature $T = 1.3$ K. The $\vec{p}^4$He$^+$ were irradiated by $\Delta t = 40$ to 100 ns long laser pulses [39] with peak powers $P = 0.5$ to 10 kW and wavelengths $\lambda = 264$ to 841 nm, which were generated by Ti:Sapphire and dye laser systems.

The spectra in Figs. 2 (A)–(C) show the resonance profiles of the transitions $(n, \ell) = (37, 35) \rightarrow (38, 34)$, $(39, 35) \rightarrow (38, 34)$, and $(38, 35) \rightarrow (39, 34)$ of buffer-gas cooled $\vec{p}^4$He$^+$. (D) The resonance profile $(36, 34) \rightarrow (37, 33)$ of $\vec{p}^3$He$^+$. The $x$-abscissa indicates the offset of the laser frequency relative to the resonance centroid. Solid curves indicate the best fit of an ab initio model based on the optical Bloch equation. From Ref. [3].
Eight transition frequencies of $\bar{p}^4\text{He}^+$ atoms and five frequencies of $\bar{p}^3\text{He}^+$ were measured with relative uncertainties between $2.5 \times 10^{-9}$ and $15 \times 10^{-9}$. The frequencies $\nu_{\exp}$ (Fig. 3A, open circles with error bars) agree with theoretical $\nu_{\text{th}}$ values (filled squares). Due to the cooling techniques described here, this agreement is a factor of 1.4 to 10 times better than previous single-photon experiments [30] of $\bar{p}\text{He}^+$. The uncertainties for most of the theoretical frequencies $\nu_{\text{th}}$ arise from QED contributions of orders higher than $\alpha^7$ which have not been calculated yet.

When the antiproton-to-electron mass ratio $M_{\bar{p}}/m_e$ used in the calculations was changed by $1 \times 10^{-9}$, the theoretical $\bar{p}\text{He}^+$ frequencies $\nu_{\text{th}}$ changed by $2.6 \times 10^{-9}$ to $2.7 \times 10^{-9}$. The mass ratio was determined as, $M_{\bar{p}}/m_e = 1836.1526734(15)$, by minimizing the difference between the frequencies $\nu_{\exp}$ and $\nu_{\text{th}}$. The one-standard deviation uncertainty in the parenthesis includes the three contributions $9 \times 10^{-7}$, $11 \times 10^{-7}$, and $3 \times 10^{-7}$ of the experimental statistical and systematic uncertainties, and the theoretical uncertainty, respectively.

The atomic mass of the electron was recently determined [10] with a relative precision of $3 \times 10^{-11}$ by confining a $^{12}\text{C}^5+$ ion in a Penning trap. The cyclotron frequency of its motion...
in a magnetic field and the precession frequency of the electron spin was then measured, and the results compared with the latest QED calculations of its $g$-factor [40]. From this and the proton mass which was recently measured in a separate measurement involving a Penning trap [11] from the same collaboration, the proton-to-electron mass ratio was determined as, $M_p/m_e = 1836.152673346(81)$. In Fig. 3(B), the latest $M_p/m_e$ mass ratios are shown together with the previous experimental values that were determined by comparing the cyclotron frequencies of protons and electrons in a Penning trap [7], laser spectroscopy of cold HD$^+$ molecular ions [12], and the CODATA 2010 recommended value [27]. These recent high-precision values are in good agreement with the $M_p/m_e$ ratio determined from $p$He$^+$. The TRAP and BASE experiments of CERN have compared the cyclotron frequencies of antiprotons and H$^-$ ion pairs confined in a Penning trap [41–43]; a limit of $5 \times 10^{-10}$ was set [3, 44] on any deviation between the antiproton and proton masses and charges by combining the results with the $p$He$^+$ spectroscopic data.

The $p^3$He$^+$ transition $(n, \ell) = (40, 36) \rightarrow (41, 35)$ was also studied by laser spectroscopy [45]. A stimulated first-order Raman scattering process in a H$_2$ gas cell was utilized to generate the 7 ns long laser pulses of wavelength $\lambda = 1154.9$ nm needed to excite this transition. The measurements revealed that most of the metastable populations are concentrated into states of principal quantum number $n \geq 40$, whereas the states $n > 41$ contain very few antiprotons. A laser-microwave-laser triple resonance method was used to study the hyperfine structure of the $(n, \ell) = (36, 34)$ state of $p^3$He$^+$ [46].

3 Future perspectives

Currently the precision on the calculations of $p$He$^+$ energies are more than an order of magnitude higher than the experimental uncertainties. Further improvements in the theoretical precision are expected in the next 5 years. The Extra Low Energy Antiproton Ring (ELENA) facility due to begin operation in 2021 will provide a high-quality, cooled antiproton beam of energy $E = 100$ keV. Samples of $p$He$^+$ would then be formed in a smaller volume, so that lasers of lower power and higher spectral resolution could be used in the experiments. The high stability of the antiproton beam should ensure an improved signal-to-noise ratio on the $p$He$^+$ spectral lines. This may allow us to resolve weak atomic transitions between metastable states of smaller natural width, which can be measured with a higher precision. Intensive efforts are currently underway to achieve this goal.

Metastable pionic helium ($\pi$He$^+$) is a three-body atom [47–49] consisting of a helium nucleus, an electron in the $1s$ ground state, and a negative-charged pion in a Rydberg state of quantum numbers $n \sim \ell - 1 \sim 16$. The spectral lines of these atoms have never been directly observed, and so the existence of $\pi$He$^+$ is so far hypothetical. Laser spectroscopy of $\pi$He$^+$ is currently being attempted at the 590 MeV ring cyclotron facility of the Paul Scherrer Institute. By comparing the experimental frequencies with those derived from QED calculations, the $\pi^-$ mass can in principle be determined with a fractional precision of $10^{-8}$ to $10^{-6}$.

References

[1] R.S. Hayano, M. Hori, D. Horváth, E. Widmann, Rep. Prog. Phys. 70, 1995 (2007)
[2] M. Hori et al., Nature 475, 484 (2011)
[3] M. Hori et al., Science 371, 610 (2016)
[4] V.I. Korobov, L. Hilico, J.-P. Karr, Phys. Rev. Lett. 112, 103003 (2014)
[5] V.I. Korobov, L. Hilico, J.-P. Karr, Phys. Rev. A 89, 032511 (2014)
[6] M-H. Hu et al., Chem. Phys. Lett. 654, 114 (2016)
[7] D.L. Farnham, R.S. Van Dyck Jr., P.B. Schwinberg, Phys. Rev. Lett. 75, 3598 (1995)
[8] T. Beier et al., Phys. Rev. Lett. 88, 011603 (2002)
[9] J. Verdú et al., Phys. Rev. Lett. 92, 093002 (2004)
[10] S. Sturm et al., Nature, 506, 467-470 (2014)
[11] F. Heiße et al., Phys. Rev. Lett. 119, 033001 (2017)
[12] J. Biesheuvel et al., Nat. Commun. 7, 10385 (2016)
[13] J.C.J. Koelemeij, B. Roth, A. Wicht, I. Ernsting, S. Schiller, Phys. Rev. Lett. 98, 173002 (2007)
[14] S. Alighanbari, M.G. Hansen, V. Korobov, S. Schiller, arXiv:1802.03208 (2018)
[15] V.A. Kostelecký, A.J. Vargas, Phys. Rev. D 92, 056002 (2015)
[16] M. Ahmadi et al., Nature 506, 467-470 (2014)
[17] M. Ahmadi et al., Nature 548, 66 (2017)
[18] G. Gabrielse et al., Phys. Rev. Lett. 108, 113002 (2012)
[19] E.J. Salumbides, W. Ubachs, V.I. Korobov, J. Mol. Spect. 300, 65 (2014)
[20] J. Murata, S. Tanaka, Class. Quantum Grav. 32, 033001 (2015)
[21] P. Brax, S. Fichet, G. Pignol, arXiv:1710.00850 (2017)
[22] F. Ficek et al., arXiv:1801.00491 (2018)
[23] M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206 (2013)
[24] K. Sakimoto, Phys. Rev. A 91, 042502 (2015)
[25] V.I. Korobov, Z.-X. Zhong, Q.-L. Tian, Phys. Rev. A 92, 052517 (2015)
[26] A. Adamczak, D. Bakalov, Phys. Rev. A 90, 054501 (2014)
[27] P.J. Mohr, B.N. Taylor, D.B. Newell, Rev. Mod. Phys. 84, 1527 (2012)
[28] R. Pohl et al., Nature 466, 213 (2010)
[29] M. Hori et al., Phys. Rev. Lett. 91, 123401 (2003)
[30] M. Hori et al., Phys. Rev. Lett. 96, 243401 (2006)
[31] M. Hori et al., Phys. Rev. A 81, 062508 (2010)
[32] A. Badertscher et al., Phys. Lett. B 392, 278 (1997)
[33] A.M. Lombardi et al., 2001 First operating experience with the CERN decelerating RFQ for antiprotons. Proc. Part. Acc. Conf. Chicago, USA
[34] H. Aghai-Khozani et al., Eur. Phys. J. Plus 127, 125 (2012)
[35] M. Corradini et al., Nucl. Instrum. Methods A 711, 12 (2013)
[36] A. Sótér et al., Rev. Sci. Instrum. 85, 023302 (2014)
[37] K. Todoroki et al., Nucl. Instrum. Methods A 835, 110 (2016)
[38] H. Aghai-Khozani et al., Nucl. Phys. A 970, 366 (2018)
[39] M. Hori, A. Dax, Opt. Lett. 34, 1273 (2009)
[40] K. Pachucki, A. Czarnecki, U.D. Jentschura, V.A. Yerokhin, Phys. Rev. A 72, 022108 (2005)
[41] G. Gabrielse et al., Phys. Rev. Lett. 82, 3198 (1999)
[42] J.K. Thompson, S. Rainville, D.E. Pritchard, Nature 430, 58 (2004)
[43] S. Ulmer et al., Nature 524, 196 (2015)
[44] R.J. Hughes, B.I. Deutch, Phys. Rev. Lett. 69, 578 (1992)
[45] T. Kobayashi et al., J. Phys. B: At. Mol. Opt. Phys. 46, 213 (2013)
[46] S. Friedreich et al., J. Phys. B: At. Mol. Opt. Phys. 46, 125003 (2013)
[47] M. Hori, A. Sótér, V.I. Korobov, Phys. Rev. A 89, 042515 (2014)
[48] V.I. Korobov, A.K. Bakbaev, D.T. Aznabayev, S.A. Zhaugasheva, J. Phys. B: At. Mol. Opt. Phys. 48, 245006 (2015)
[49] B. Obreshkov, D. Bakalov, Phys. Rev. A 93, 062505 (2016)