CODATA Task Group on Fundamental Physical Constants (TGFC)

Report for the 26th meeting of the

Consultative Committee for Units (CCU)

The mission of the CODATA Task Group on Fundamental Physical Constants (TGFC) is to periodically provide the scientific and technological communities with a self-consistent set of internationally recommended values of the basic constants and conversion factors of physics and chemistry based on all relevant data available at a given point in time. The last regular CODATA-TGFC four-year cycle adjustment of the fundamental constants was the 2022 adjustment with a closing date of 31 December, 2022 for input data to be available for consideration. Relevant data were collected and reviewed for possible impact on the determination of the values of the fundamental constants. The results of the 2022 CODATA-TGFC adjustment are ready for release pending approval of the TGFC with the accepted input data and analysis to be published in a review article.

Major impact of the 2022 CODATA adjustment of the fundamental constants

One of the most significant impacts on the 2022 CODATA adjustment of the fundamental constants are new input data for the fine structure constant, α. There has been an updated value for the $A_1^{(10)}$ mass independent term in the theory of the electron magnetic moment anomaly, a_e, with tension between two independent evaluations,[1, 2] requiring an expansion factor of 2.1 for $A_1^{(10)}$. The shift from 2018 to 2022 value of $A_1^{(10)}$ is $-3.5 \times 10^{-11} a_e$. There is a new measurement of the electron magnetic moment anomaly[3] by the same senior researcher as the 2008 Harvard result[4] that is consistent with the previous results but with a 2.2 times smaller uncertainty. More importantly is a new atom recoil measurement by Laboratoire Kastler-Brossel, Paris, France (LKB) with new systematic effects shifting their 2011 value by 2.4 sigma. The resulting relevant input data for the determination of the fine structure constant, α, is shown in Figure 1. The change in α from 2018 to 2022 is 3.2 times the uncertainty of the difference. The impact of the change of α is shown in terms of previously exactly defined constants, the permeability of free space, μ_0, and the molar mass constant, M_u, in Table 1.

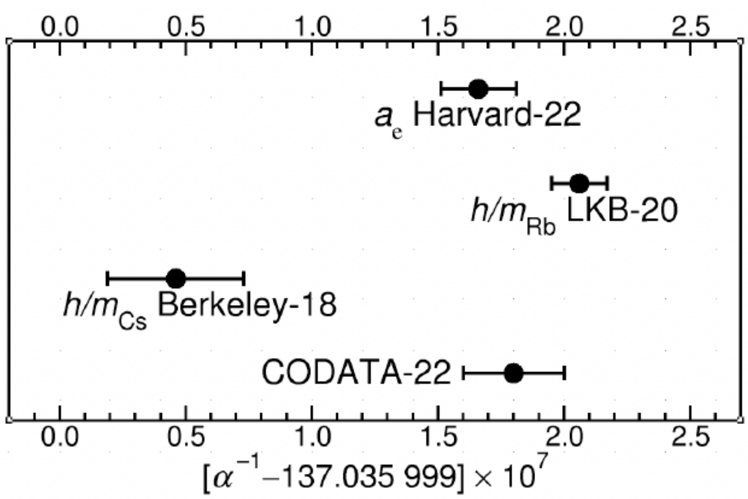

Figure 1: Determinations of the value of the fine-structure constant from atom recoil measurements and the measurement of the electron magnetic moment anomaly. An expansion factor of 2.5 is applied to the uncertainties of these data during the adjustment, so that all values lie within two (expanded) standard deviations of the CODATA value.

CODATA Adjustment	$\mu_0/(4\pi \times 10^{-7}\ \mathrm{N/A^2})$	$M_u/(1\ \mathrm{g/mol})$
2018	1.000 000 000 55(15)	0.999 999 999 65(30)
2022	0.999 999 999 87(16)	1.000 000 001 05(31)

Table 1: Relative deviation of the permeability of free space, μ_0, and the molar mass constant, M_u, with respect to their previous exact values of $4\pi \times 10^{-7}$ N/A^2 and 1 g/mol, respectively.

There are new results for the screening correction for ^{3}He atoms[5] that may be used to deduce the bare nuclear moment from measurements made on the atoms. Combining with a new measurement of the magnetic moment of the $^3He^+$ ion[6] leads to a factor of 14 reduction in the uncertainty of the bound helion magnetic moment (previously called the shielded helion magnetic moment).

Other relevant new input data for the 2022 adjustment of the fundamental constants:

Relative atomic masses

Four new results from cyclotron frequencies ratios have become available for LSA2022 for the determination of the relative atomic masses of the light nuclei particles: $\omega_c(^{12}C^{6+})/\omega_c(p)$ [7], $\omega_c(^{12}C^{6+})/\omega_c(d)$ [8], $\omega_c(H_2^+)/\omega_c(d)$ [9], and $\omega_c(^{12}C^{4+})/\omega_c(HD^+)$ [8]. Three new results from measurements[10,11,12] as well as theoretical determinations[13] of transition frequencies between rovibrational states in the molecular ion HD^+ have become sufficiently accurate to constrain the electron-to-proton and electron-to-deuteron mass ratios. This is the first time that these types of data are used in a CODATA LSA of the fundamental constants.

Atomic hydrogen and deuterium transition energies

The theory for hydrogen energy levels and for the g-factor of the bound electron keep improving. There are also two new atomic hydrogen transition measurements available for LSA2022: $1S_{1/2} - 3S_{1/2}$ [14] and $2S_{1/2} - 8D_{5/2}$ [15]

Muonic atoms and muonic atomic ions

There is a new measurement of the Lamb shift in μ^4He^+ [16,17], adding to the input data for the determination of the radii of the proton, deuteron, and α particle.

Muon magnetic-moment anomaly

There is a new measurement of the anomaly of the positively charged muon, a_μ, from the Fermilab National Accelerator Laboratory[18] that is in excellent agreement with a previous 2006 determination at Brookhaven National Laboratory using the same 1.45 T superconducting storage ring magnet, with a slightly better uncertainty.

Newtonian constant of Gravitation

The value and uncertainty for the 2022 determination of the Newtonian constant remain the same as 2018 along with the same expansion factor of 3.9 since there is no new relevant input datum for the 2022 adjustment.

2022 LSA treatment and results

The 2022 adjustment of the fundamental constants consists of 79 adjusted constants with 133 input data for 54 degrees of freedom. The initial LSA without expansion factors has $\chi^2 = 106.1$, $p(106.1|54) = 0.00003$, and $R_B = 1.40$. Expansion factors to reduce residuals to 2 or less are 1.7 for all transition energies for electronic hydrogen and deuterium; 1.7 for muonic Lamb shift data; and 2.5 for data related to the determination of α. With expansions applied the final LSA that determines the 2022 CODATA recommended values of the constants yields $\chi^2 = 49.2$, $p(49.2|54) = 0.86$, and $R_B = 0.89$.

Membership

Due to the increasing importance of simple atomic systems and fundamental particles playing a major role in the determination of the fundamental constants, the TGFC has invited the following experts to become members of the TGFC: Dr Jean-Philippe Karr, Laboratoire Kastler Brossel, Paris, France; Dr J.C.J. Koelemeij, Department of Physics & Astronomy, Vrije Universiteit Amsterdam, The Netherlands; and Prof. Dr Frédéric Merkt, Department of Physics, ETH Zurich, Switzerland.

The next CODATA-TGFC meeting will be held 10-11 September 2024 as a hybrid meeting at the BIPM, Paris with virtual attendance as an option. The meeting will last for two days with several scientific presentations on subjects of interest to the Task Group.

[1] "Theory of the Anomalous Magnetic Moment of the Electron," T. Aoyama, T. Kinoshita, and M. Nio, Atoms **7**, 00028, 27 p. (2019)

[2] "Calculating the five-loop QED contribution to the electron anomalous magnetic moment: Graphs without lepton loops," S. Volkov, Phys. Rev. D **100**, 096004, 13 p. (2019)

[3] "Measurement of the Electron Magnetic Moment." X. Fan, T. G. Myers, B. A. D. Sukra, and G. Gabrielse, Phys. Rev. Lett. **130**, 071801, 6 p. (2023)

[4] "New Measurement of the Election Magnetic Moment and the Fine Structure Constant," D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev. Lett. **100**, 120801, 4 p. (2008)

[5] "QED Effect on the Nuclear Magnetic Shielding of ^{3}He," D. Wehrli, A. Spyszkiewicz-Kaczmarek, M. Puchalski, and K. Pachucki, Phys. Rev. Lett. **127**, 263001, 6 p. (2021)

[6] "Direct measurement of the $^3He^+$ magnetic moments," A. Schneider, B. Sikora, S. Dickopf, M. Müller, N. S. Oreshkina, A. Rischka, I. A. Valuev, S. Ulmer, J. Walz, Z. Harman, C. H. Keitel, A. Mooser, and K. Blaum, Nature **606**, 878-883 (2022)

[7] "High-precision mass spectrometer for light ions," F. Heiße, S. Rau, F. Köhler-Langes, W. Quint, G. Werth, S. Sturm, and K. Blaum, Phys. Rev. A **100**, 022518, 21 p. (2019)

[8] "Penning trap mass measurements of the deuteron and the HD^+ molecular ion," S. Rau, F. Heiße, F. Köhler-Langes, S. Sasidharan, R. Hass, D. Renisch, C. E. Düllmann, W. Quint, S. Sturm, and K. Blaum, Nature **585**, 43-47 (2020)

[9] "Deuteron-to-Proton Mass Ratio from Simultaneous Measurement of the Cyclotron Frequencies of H^+_2 and D^+," D. J. Fink and E. G. Myers, Phys. Rev. Lett. **127**, 243001, 6 p. (2021)

[10] "Precise test of quantum electrodynamics and determination of fundamental constants with HD^+ ions," S. Alighanbari, G. S. Giri, F. L. Constantin, V. I. Korobov, and S. Schiller, Nature **581**, 152-158 (2020)

[11] "Proton-electron mass ratio by high-resolution optical spectroscopy of ion ensembles in the resolved-carrier regime," I. V. Kortunov, S. Alighanbari, M. G. Hansen, G. S. Giri, V. I. Korobov, and S. Schiller, Nature Phys. **17**, 569-573 (2021)

[12] "Proton-electron mass ratio from laser spectroscopy of HD^+ at the part-per-trillion level," S. Patra, M. Germann, J.-P. Karr, M. Haidar, L. Hilico, V. I. Korobov, F. M. J. Cozijn, K. S. E. Eikema, W. Ubachs, and J. C. J. Koelemeij, Science **369**, 1238-1241 (2020)

[13] "Extraction of spin-averaged rovibrational transition frequencies in HD^+ for the determination of fundamental constants," J.-P. Karr and J. C. J. Koelemeij, Mol. Phys. **121**, e2216081, 13 p. (2023)

[14] "Two-photon frequency comb spectroscopy of atomic hydrogen," A. Grinin, A. Matveev, D. C. Yost, L. Maisenbacher, V. Wirthl, R. Pohl, T. W. Hänsch, and T. Udem, Science **370**, 1061-1066 (2020)

[15] "Measurement of the $2S_{1/2}$ - $8D_{5/2}$ Transition in Hydrogen," A. D. Brandt, S. F. Cooper, C. Rasor, Z. Burkley, A. Matveev, and D. C. Yost, Phys. Rev. Lett. **128**, 023001, 7 p. (2022)

[16] "Measuring the α-particle charge radius with muonic helium-4 ions," J. J. Krauth, K. Schuhmann, M. A. Ahmed, F. D. Amaro, P. Amaro, F. Biraben, T.-L. Chen, D. S. Covita, A. J. Dax, M. Diepold, and e. al., Nature **589**, 527-531 (2021)

[17] Pachucki, K., V. Lensky, F. Hagelstein, S. S. L. Muli, S. Bacca, and R. Pohl (2022), ArXiv:2212.13782

[18] "Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm," B. Abi, T. Albahri, S. Al-Kilani, D. Allspach, L. P. Alonzi, A. Anastasi, A. Anisenkov, F. Azfar, K. Badgley, S. Baeßer, and e. al., Phys. Rev. Lett. **126**, 141801, 11 p. (2021)