NAS Reproducibility in Science Committee Meeting

April 18, 2018

Evolution of Physical Constants Over Time

Peter Mohr
National Institute of Standards and Technology
Gaithersburg, MD, USA

Some Fundamental Constants

- **Newtonian constant of gravitation:**
  $G = 6.674\,08(31) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$ $[4.7 \times 10^{-5}]$

- **Avogadro constant:**
  $N_\mathrm{A} = 6.022\,140\,857(74) \times 10^{23}\ \mathrm{mol^{-1}}$ $[1.2 \times 10^{-8}]$

- **electron mass:**
  $m_\mathrm{e} = 9.109\,383\,56(11) \times 10^{-31}\ \mathrm{kg}$ $[1.2 \times 10^{-8}]$

- **Planck constant:**
  $h = 6.626\,070\,040(81) \times 10^{-34}\ \mathrm{J\ s}$ $[1.2 \times 10^{-8}]$

- **fine-structure constant:**
  $\alpha = 1/137.035\,999\,139(31)$ $[2.3 \times 10^{-10}]$

- **electron mass (in u):**
  $m_\mathrm{e} = 5.485\,799\,090\,70(16) \times 10^{-4}\ \mathrm{u}$ $[2.9 \times 10^{-11}]$

- **Rydberg constant:**
  $R_\infty = 10\,973\,731.568\,508(65)\ \mathrm{m^{-1}}$ $[5.9 \times 10^{-12}]$

CODATA

- **Committee on Data for Science and Technology (CODATA)** – was established in 1966 - is an interdisciplinary committee for ICSU, which works to improve the quality, reliability, management, and accessibility of data of importance to all fields of science and technology.

- **CODATA Task Group on Fundamental Constants** - established in 1969 - "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 of the relevant data available at a given point in time."

- The Task Group sanctions the data selection and methodology of the adjustment of the recommended values of the constants.

Publications

"CODATA recommended values of the fundamental physical constants: 2014," P. J. Mohr, D. B. Newell, and B. N. Taylor, *Rev. Mod. Phys.* **88**, 035009, 73 p. (2016).

"The CODATA 2017 values of h, e, k, and N_{A} for the revision of the SI," D. B. Newell, F. Cabiati, J. Fischer, K. Fujii, S. G. Karshenboim, H. S. Margolis, E. d. Mirands, P. J. Mohr, F. Nez, K. Pachucki, T. J. Quinn, B. N. Taylor, M. Wang, B. M. Wood, and Z. Zhang *Metrologia* **55**, L13-L16 (2018).

"Data and analysis for the CODATA 2017 special fundamental constants adjustment," P. J. Mohr, D. B. Newell, B. N. Taylor, and E. Tiesinga *Metrologia* **55**, 125-146 (2018).

CODATA recommended values of the fundamental physical constants: 2014*

Peter J. Mohr,† David B. Newell,‡ and Barry N. Taylor§

National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8420, USA

(published 26 September 2016)

This paper gives the 2014 self-consistent set of values of the constants and conversion factors of physics and chemistry recommended by the Committee on Data for Science and Technology (CODATA). These values are based on a least-squares adjustment that takes into account all data available up to 31 December 2014. Details of the data selection and methodology of the adjustment are described. The recommended values may also be found at physics.nist.gov/constants.

DOI: 10.1103/RevModPhys.88.035009

CONTENTS

The NIST Reference on Constants, Units, and Uncertainty

Information at the foundation of modern science and technology from the Physical Measurement Laboratory of NIST

CODATA Internationally recommended 2014 values of the Fundamental Physical Constants

physics.nist.gov/constants

Constants Topics:
- **Values**
- Energy Equivalents
- Searchable Bibliography
- Background

—

Constants Bibliography

—

Constants, Units & Uncertainty home page

Version history and disclaimer

(e.g., **electron mass**, most misspellings okay)

Search by name [ ] Search

Display alphabetical list, table (image), or table (pdf)

by clicking a category below

Universal	Adopted values	Frequently used constants
Electromagnetic	Non-SI units	Extensive listings
Atomic and nuclear	Conversion factors for energy equivalents	All values (ascii)
Physico-chemical	X-ray values	

Find the correlation coefficient between any pair of constants

See also

Article on the 2014 adjustment of the values of the constants
Wall Chart and Wallet Card of the 2014 constants
Background information related to the constants
Links to selected scientific data
Previous Values (2010) (2006) (2002) (1998) (1986) (1973) (1969)

DEADLINE NOTICES (UPDATED)!

There will be an adjustment of the constants to provide the values for a revision of the International System of Units (SI) expected to take place in 2018. To be considered for use in this adjustment, new results must be **accepted for publication by 1 July 2017**.

The 2018 CODATA adjustment of the fundamental constants will be based on the revised SI, which will significantly affect the uncertainties of many constants. For data to be considered for use in this adjustment, they must be **discussed in a publication preprint or a publication by 31 December 2018**.

Volume 1. *July, 1929* *Number 1.*

THE

PHYSICAL REVIEW
SUPPLEMENT

PROBABLE VALUES OF THE GENERAL PHYSICAL CONSTANTS

(as of January 1, 1929)

By Raymond T. Birge
University of California, Berkeley

Table of Contents

Introduction

Some of the most important results of physical science are embodied, directly or indirectly, in the numerical magnitudes of various universal constants, and the accurate determination of such constants has engaged the time and labor of many of the world's most eminent scientists. Some of these constants can be evaluated by various methods. Each has been investigated by various persons, at various times, and each investigation normally produces a numerical result more or less different from that of any other investigation. Under such conditions there arises a general and continuous need for a searching examination of the *most probable* value of each important constant. The need is general since every physical scientist uses such constants.

Last Paragraph of Birge (1929)

It must be admitted that this is a very unsatisfactory way to leave the situation in the case of the most important constants known to science. It is to be hoped that before another year has passed, some if not all of these difficulties will have been removed.

Some Fundamental Constants 2014 values Compared to Birge 1929 values

- **Newtonian constant of gravitation:**

  $G = 6.674\,08(31) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$ [4.7×10^{-5}]

  $G = 6.664(2) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$ [3×10^{-4}]

- **Avogadro constant:**

  $N_A = 6.022\,140\,857(74) \times 10^{23}\ \mathrm{mol^{-1}}$ [1.2×10^{-8}]

  $N_A = 6.064(6) \times 10^{23}\ \mathrm{mol^{-1}}$ [1×10^{-3}]

- **Planck constant:**

  $h = 6.626\,070\,040(81) \times 10^{-34}\ \mathrm{J\ s}$ [1.2×10^{-8}]

  $h = 6.547(8) \times 10^{-34}\ \mathrm{J\ s}$ [1×10^{-3}]

- **fine-structure constant:**

  $\alpha = 1/137.035\,999\,139(31)$ [2.3×10^{-10}]

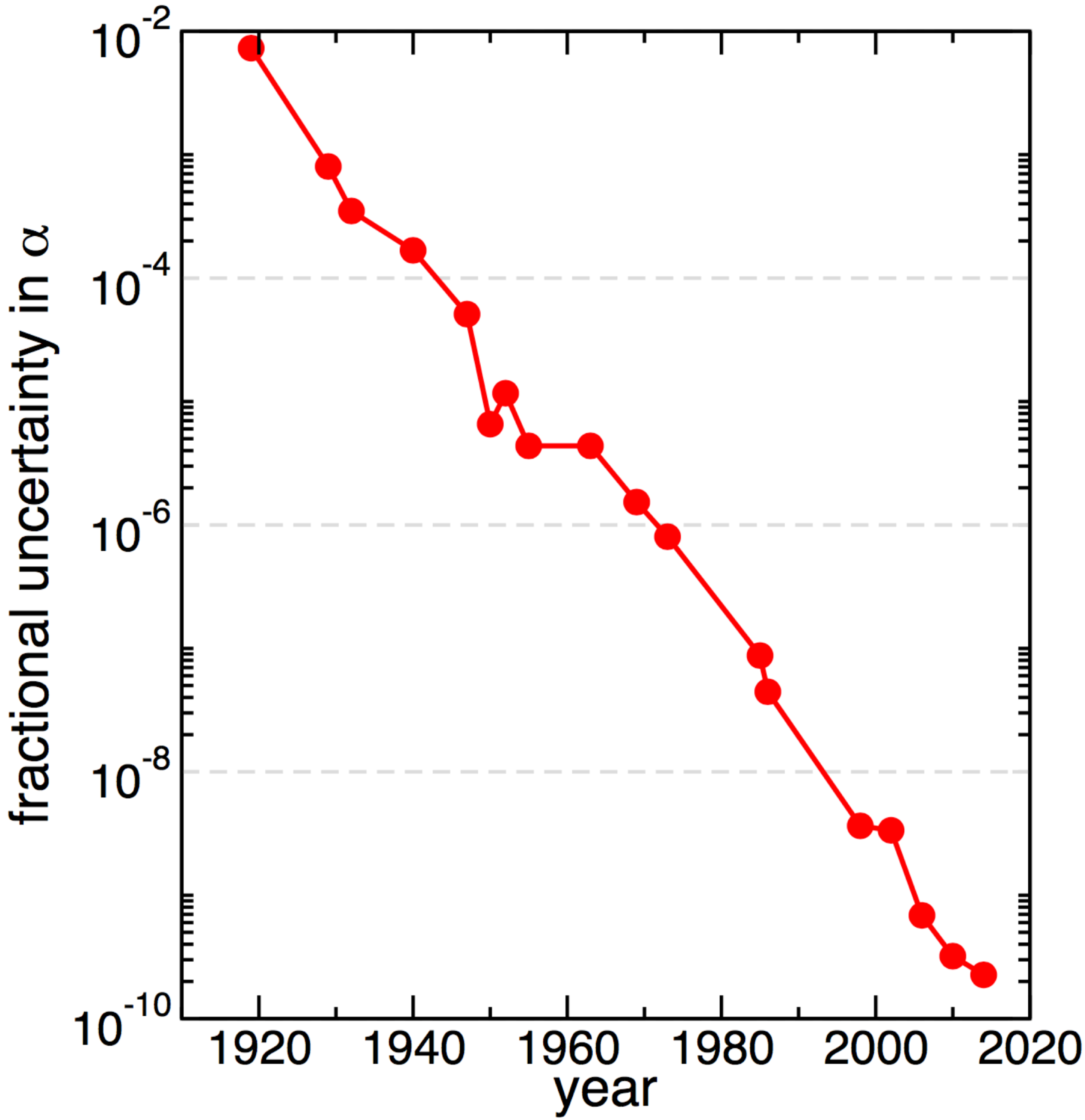
  $\alpha = 1/137.29(11)$ [8.0×10^{-4}]

- **Rydberg constant:**

  $R_\infty = 10\,973\,731.568\,508(65)\ \mathrm{m^{-1}}$ [5.9×10^{-12}]

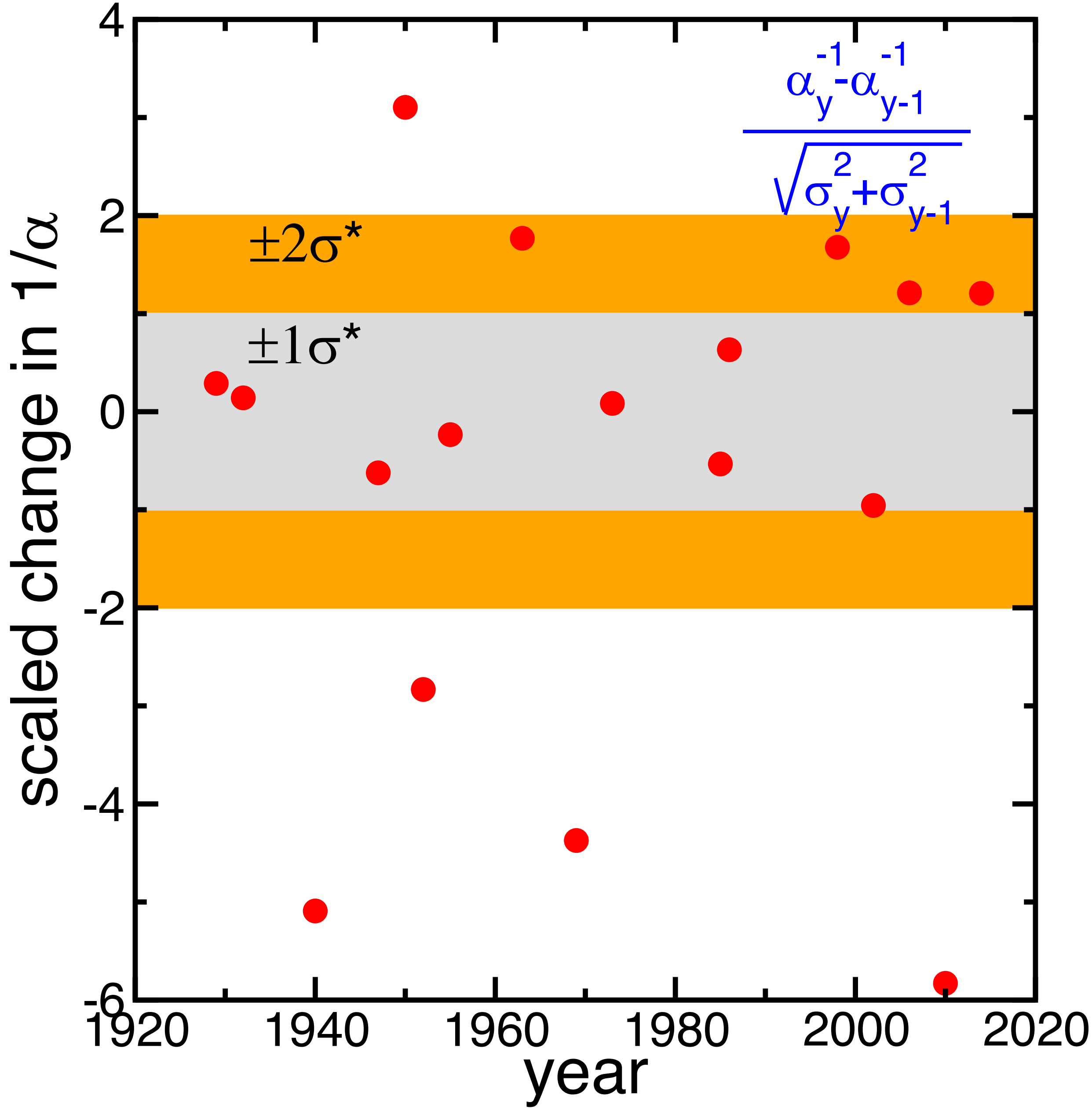
  $R_\infty = 10\,973\,742(6)\ \mathrm{m^{-1}}$ [6×10^{-7}]

History of the fine-structure constant α

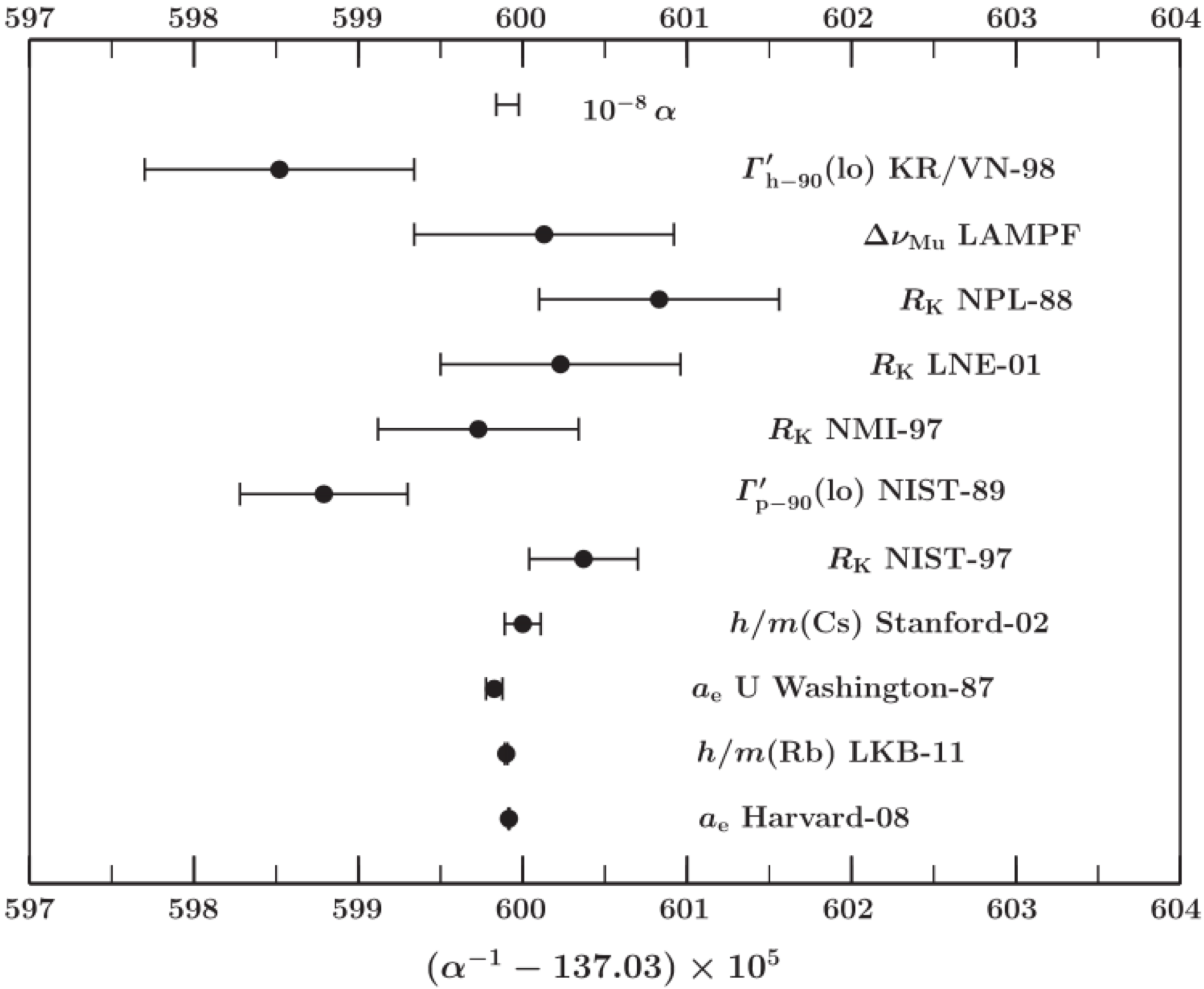


by Eite Tiesinga

History of the fine-structure constant α



by Eite Tiesinga


597
598
599
600
601
602
603
604
$10^{-8}\,\alpha$
$\Gamma'_{\rm h-90}$(lo) KR/VN-98
$\Delta\nu_{\rm Mu}$ LAMPF
$R_{\rm K}$ NPL-88
$R_{\rm K}$ LNE-01
$R_{\rm K}$ NMI-97
$\Gamma'_{\rm p-90}$(lo) NIST-89
$R_{\rm K}$ NIST-97
h/m(Cs) Stanford-02
$a_{\rm e}$ U Washington-87
h/m(Rb) LKB-11
$a_{\rm e}$ Harvard-08
$(\alpha^{-1} - 137.03) \times 10^5$

How are the most precise values determined?

- **Fine-structure constant $\boldsymbol{\alpha}$** $[2.3 \times 10^{-10}]$:
  - anomalous magnetic moment of the electron experiment/theory $[2.4 \times 10^{-10}]$

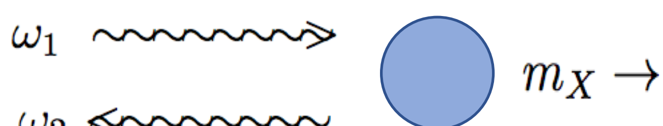
$$\omega_\mathrm{s} = \frac{\Delta E}{\hbar} = 2\,(1 + a_\mathrm{e})\;\frac{eB}{2m_\mathrm{e}} \qquad\qquad \omega_\mathrm{c} = \frac{eB}{m_\mathrm{e}}$$

$$\frac{\omega_\mathrm{s} - \omega_\mathrm{c}}{\omega_\mathrm{c}} = a_\mathrm{e}(\mathrm{exp})$$

$$a_\mathrm{e}(\mathrm{th}) = a_\mathrm{e}(\mathrm{QED}) + a_\mathrm{e}(\mathrm{weak}) + a_\mathrm{e}(\mathrm{had})$$

$$a_\mathrm{e}(\mathrm{QED}) = C_\mathrm{e}^{(2)}\left(\frac{\alpha}{\pi}\right) + C_\mathrm{e}^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + C_\mathrm{e}^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + C_\mathrm{e}^{(8)}\left(\frac{\alpha}{\pi}\right)^4 + C_\mathrm{e}^{(10)}\left(\frac{\alpha}{\pi}\right)^5 + \dots$$

  - atom recoil measurement $[6.4 \times 10^{-10}]$



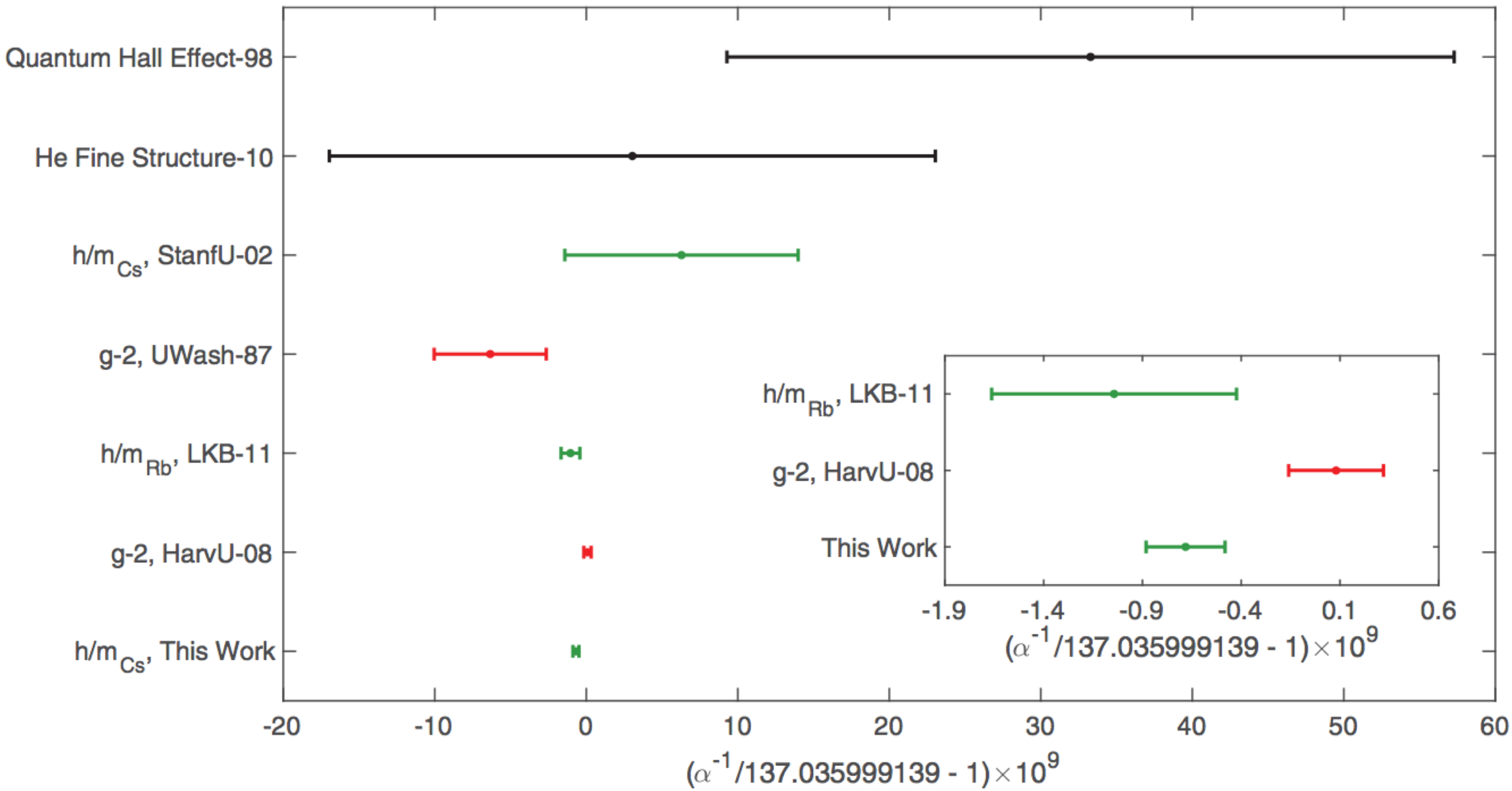
$$\frac{\omega_1 - \omega_2}{\omega_1^2} = \frac{2\hbar}{m_X c^2} = \frac{2}{c^2}\,\frac{m_\mathrm{e}/m_\mathrm{u}}{m_X/m_\mathrm{u}}\,\frac{\hbar}{m_\mathrm{e}} \qquad\qquad R_\infty = \frac{\alpha^2 m_\mathrm{e} c}{2h}$$

METROLOGY

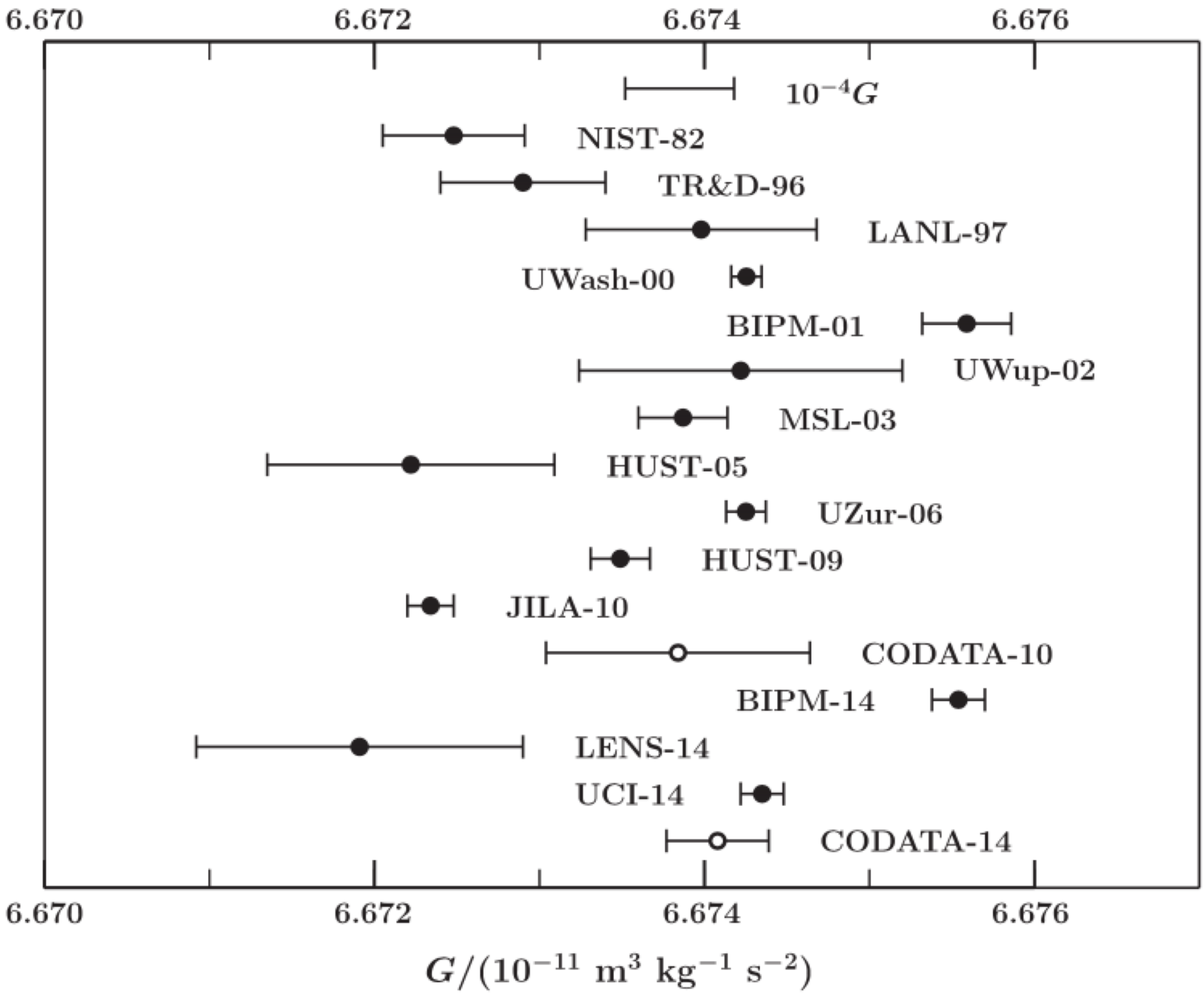
Measurement of the fine-structure constant as a test of the Standard Model

Richard H. Parker,[1*] Chenghui Yu,[1*] Weicheng Zhong,[1] Brian Estey,[1] Holger Müller[1,2]†

Parker *et al.*, *Science* **360**, 191–195 (2018) 13 April 2018



Newtonian constant of gravitation G



Newtonian constant of gravitation G

- Measurements show a serious disagreement
- The International Union of Pure and Applied Physics (IUPAP) has formed a Working Group of experts to advise future experiments and to attempt to explain the discrepancies.
- The National Institute of Standards and Technology (NIST) has taken on a project to repeat the two most discrepant experiments (JILA and BIPM). This work is in progress.

Speed of light c

$$
\begin{aligned}
c &= 2.997\,96(4) \times 10^8 \text{ m/s} && \text{Birge (1929)} \\
c &= 2.997\,924\,58 \times 10^8 \text{ m/s} && \text{Current SI}
\end{aligned}
$$

- In 1983, the SI was redefined so that the meter is the distance traveled by light in 1/299792458 s.
- As a consequence, the speed of light is exactly 299792458 m/s.
- A similar redefinition is expected to soon extend to other units in the SI by an international agreement.
- This will have a significant impact on the values of the physical constants in the future.

The International System of Units (SI) is expected to undergo a revolutionary change on May 20, 2019. After then, it will be defined by the statement:

The International System of Units, the SI, is the system of units in which

- the unperturbed ground state hyperfine splitting frequency of the caesium 133 atom ν_{Cs} is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s,
- the elementary charge e is $1.602\,176\,634 \times 10^{-19}$ C,
- the Boltzmann constant k is $1.380\,649 \times 10^{-23}$ J/K,
- the Avogadro constant N_{A} is $6.022\,140\,76 \times 10^{23}$ mol^{-1},
- the luminous efficacy K_{cd} of monochromatic radiation of frequency 540×10^{12} hertz is 683 lm/W.

Why change SI units?

- The kilogram artifact is unstable.
- “Conventional” electrical units are not presently SI units.
- Current kelvin definition is based on isotope-dependent triple point of water.
- New SI definitions of the kilogram and kelvin are scalable.
- Fundamental constants have smaller uncertainties in the new SI.

Web resources

NIST SI Redefinition Portal, US National Institute of Standards and Technology: https:/www.nist.gov/pml/productsservices/si-redefinition-portal

BIPM Revised SI Download Area: https://www.bipm.org/en/si-download-area/

Publications

"An Introduction to the New SI," Sandra Knotts, Peter J. Mohr, and William D. Phillips, *Phys. Teach.* **55**, 65 (2017).

"Towards a new SI: a review of progress made since 2011," M. J. T. Milton, R. Davis, and N. Fletcher, *Metrologia* **51**(3), R21-R30 (2014).

"A more fundamental International System of Units," D. B. Newell *Phys. Today* **67**(7), 35-42 (2014).

"Adapting the International System of Units to the twenty-first century," I. M. Mills, P. J. Mohr, T. J. Quinn, B. N. Taylor, and E. R. Williams, *Phil. Trans. R. Soc. A* **369**(1953), 3907-3924 (2011).

"Defining units in the quantum based SI," P. J. Mohr, *Metrologia* **45**(2), 129-133 (2008).

Improved values of constants

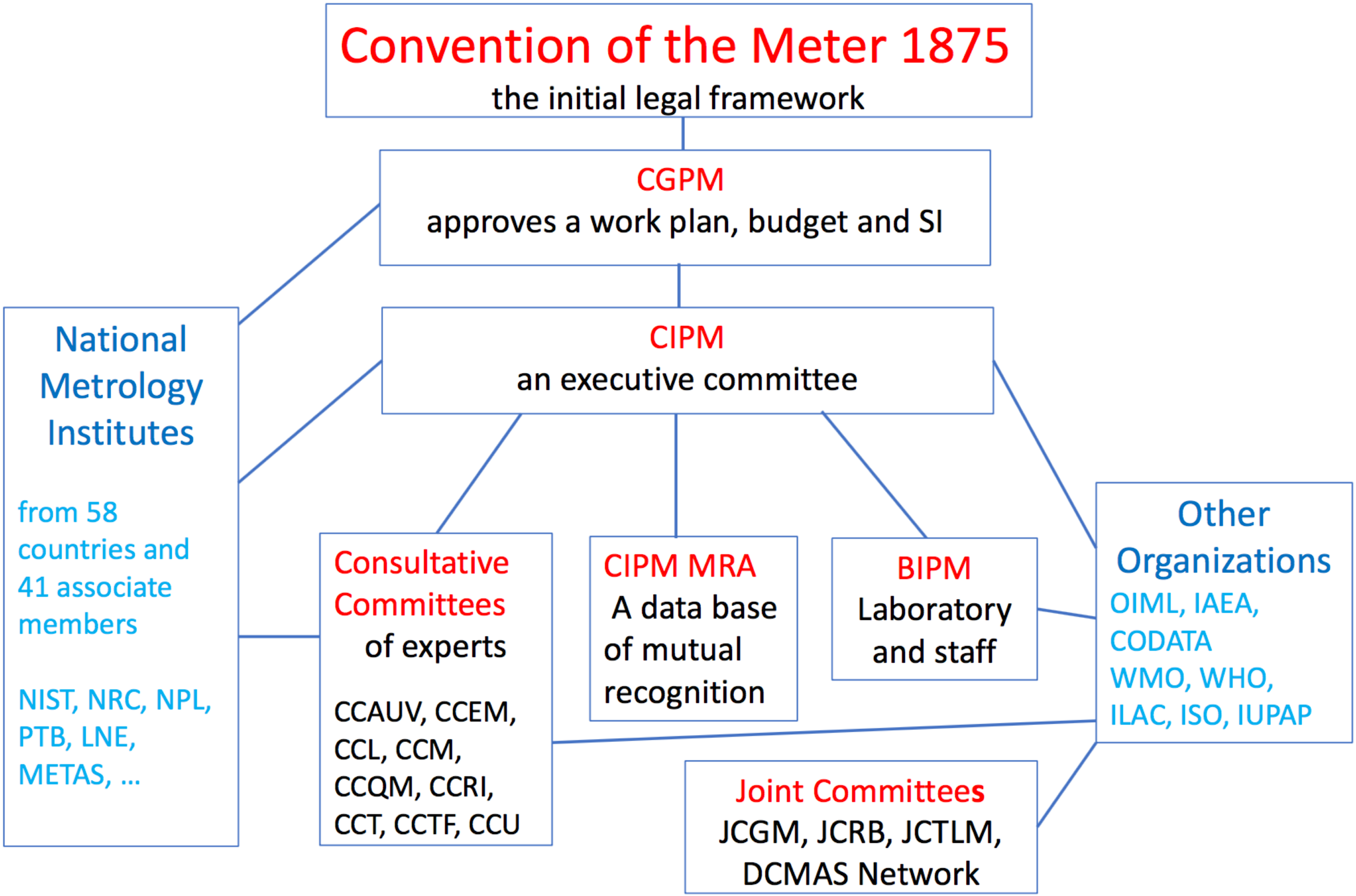
Quantity	Symbol	Present SI $u_r \times 10^9$	New SI $u_r \times 10^9$
Planck constant	h	12	0
Elementary charge	e	6.1	0
Boltzmann constant	k	570	0
Avogadro constant	N_A	12	0
Josephson constant	K_J	6.1	0
von Klitzing constant	R_K	0.23	0
Electron mass	m_e	12	0.46
Atomic mass unit	m_u	12	0.46
Mass of carbon-12	$m(^{12}C)$	12	0.46
Molar gas constant	R	570	0
Faraday constant	F	6.2	0
Stefan-Boltzmann constant	σ	2300	0
Fine-structure constant	α	0.23	0.23

No uncertainty in energy conversions

Quantity	Symbol	Present SI $u_r \times 10^9$	New SI $u_r \times 10^9$
Planck constant	h	12	0
Elementary charge	e	6.1	0
Boltzmann constant	k	570	0
Avogadro constant	N_A	12	0
$E=mc^2$ energy equivalent	J ↔ kg	0	0
$E=hc/\lambda$ energy equivalent	J ↔ m^{-1}	12	0
$E=h\nu$ energy equivalent	J ↔ Hz	12	0
$E=kT$ energy equivalent	J ↔ K	570	0
1 J =1 (C/e) eV energy equivalent	J ↔ eV	6.1	0

Timeline

- Data to determine values of the defining constants was due (published) by 1 July 2017.
- The CODATA Task Group on Fundamental Constants did a special least-squares adjustment to provide values for the defining constants.
- In August 2017, the Consultative Committee on Units recommended going ahead with the redefinition based on those constants.
- The International Committee on Weights and Measures met in October 2017 and decided to recommend going forward with the redefinition.
- Ratification to redefine expected at the General Conference on Weights and Measures, Versailles, France, November of 2018.
- Effective date expected to be 20 May 2019.



Convention of the Meter 1875
the initial legal framework
CGPM
approves a work plan, budget and SI
CIPM
an executive committee
National Metrology Institutes
from 58 countries and 41 associate members
NIST, NRC, NPL, PTB, LNE, METAS, …
Consultative Committees
of experts
CCAUV, CCEM, CCL, CCM, CCQM, CCRI, CCT, CCTF, CCU
CIPM MRA
A data base of mutual recognition
BIPM
Laboratory and staff
Other Organizations
OIML, IAEA, CODATA
WMO, WHO, ILAC, ISO, IUPAP
Joint Committees
JCGM, JCRB, JCTLM, DCMAS Network

J. C. Maxwell, 1870

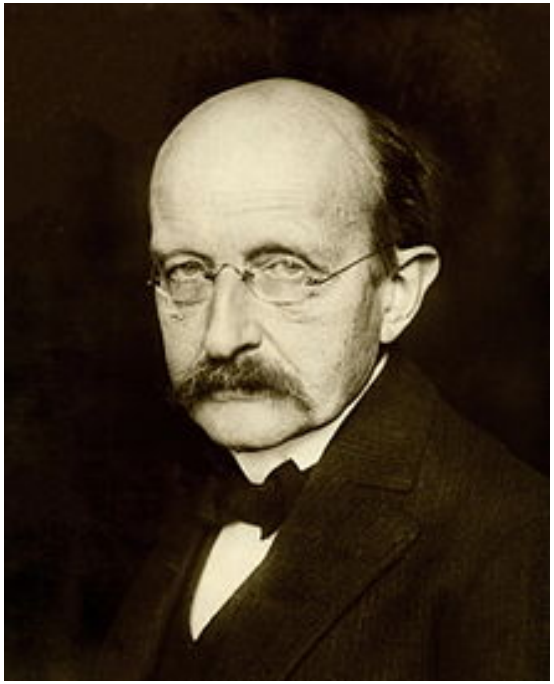
Yet, after all, the dimensions of our earth and its time of rotation, though, relatively to our present means of comparison, very permanent, are not so by physical necessity. The Earth might contract by cooling, or it might be enlarged by a layer of meteorites falling on it, or its rate of revolution might slowly slacken, and yet it would continue to be as much a planet as before. But a molecule, say of hydrogen, if either its mass or its time of vibration were to be altered in the least, would no longer be a molecule of hydrogen. If, then we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.

Maxwell, J. C. 1870 Report of the 1870 BA Meeting, Notices and Abstracts of Misc. Comm., Mathematics and Physics, pp. 1-9

Max Planck, 1900

The two constants [*h,k*]… which occur in the equation for radiative entropy offer the possibility of establishing a system of units for length, mass, time, and temperature which are independent of specific bodies or materials and which necessarily maintain their meaning for all time and for all civilizations, even those which are extraterrestrial and non-human.

-- Max Planck, 1900



"Einstein and the Quantum," A Douglas Stone, Princeton Univ. Press (2013)

Thank you for your attention.