# Editorial: Proceedings of the 2015 Workshop on the Determination of the Fundamental Constants

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# Editorial: Proceedings of the 2015 Workshop on the Determination of the Fundamental Constants

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## 1. Overview of the Workshop and Proceedings

The *Workshop on the Determination of the Fundamental Constants* was held on February 1–6, 2015, at the Hotel Frankenbach in Eltville, Germany.[1] The workshop involved approximately 70 presentations (talks and posters); the 15 papers submitted as part of the proceedings covered a wide range of fundamental constants, including the Rydberg constant $R_\infty$, fine-structure constant $\alpha$, Avogadro constant $N_A$, proton charge radius $r_p$, bound-electron $g$ factor, heliocentric gravitational constant $GM_{Sun}$, anomalous magnetic moment of the muon $a_\mu$, hyperfine splitting of positronium, root mean square (rms) nuclear charge radii $R = \langle r^2 \rangle^{1/2}$, and nuclear magnetic dipole $\mu$ and electric quadrupole $Q$ moments of various nuclei. No papers were submitted for two of the most basic fundamental constants: the Boltzmann constant $k_B$ and the Planck constant $h$. [Note: We have included the program for the workshop as the supplementary material[91]].

The proceedings can be considered as supporting information for the report "Committee on Data for Science and Technology (CODATA) Recommended Values of the Fundamental Physical Constants: 2014," which will be published simultaneously in the *Journal of Physical Chemical Reference Data* and the *Review of Modern Physics* in 2016. The report—which updates the earlier CODATA 2010 recommendations[2,3]—is a product of the *CODATA Task Group on Fundamental Constants*.[4]

Similar to the previous reports, the 2014 CODATA report will summarize the available data related to each of the fundamental constants and provide an overview of the new experimental techniques and computational methods used to produce the data that determine values for the fundamental constants. The report provides an analysis of the available data, evaluates an uncertainty for each datum, and when necessary determines weighting factors to account for possible unknown systematic uncertainties. It also considers and evaluates correlations between fundamental constants that are interdependent and coupled. Because of the volume of data considered in the fundamental constants evaluation, the report provides only a brief overview about the background and motivation of the various experimental and computational efforts. In addition, the report only briefly summarizes the physical theory, numerical calculations, uncertainty analysis, and other factors pertaining to each measurement or calculation.

Each article in these proceedings provides supporting information to the fundamental constants report. These articles provide much more detail regarding uncertainty analysis and other considerations needed to produce a self-consistent set of best values. A more extensive overview of the proceedings and presentations at the Workshop can be found in an Introductory Paper in this issue entitled "Advances in determination of fundamental constants" by Karshenboim, Mohr, and Newell.[5]

## 2. Overview of the Fundamental Constants

The fundamental constants of physics and chemistry are an internationally accepted, self-consistent set of best values (and their uncertainties) used by scientists and engineers in quantifying and reporting measurements and calculations of physical phenomena. Accurate fundamental constants are necessary to compare different types of related observations. Many of the fundamental constants are basic constants of proportionality between units of measurement and physical quantities. For example, the Boltzmann constant $k_B$ provides the relationship between temperature and the energy of a particle through $E = k_B T$, while Planck's constant $h$ provides the relationship between the frequency of light and the energy of a photon through $E = h\nu$. A number of other fundamental constants, however, characterize complicated interactions. For example, the fine-structure constant $\alpha$ characterizes the electromagnetic interactions of charged particles and is related to other constants by $\alpha = e^2/2\varepsilon_o hc$, where $e$, $\varepsilon_o$, and $c$ are the elementary charge, electric constant (vacuum permittivity), and speed of light, respectively.[2,3]

Measurement technology has advanced to a state where many of the fundamental constants are known to great accuracy.[2,3] For example, the meter, the unit of length, is now defined[6,7] in terms of an exact value for the speed of light $c$ in the SI system of units ($c$ = 299 792 458 m/s).[8,9] The Rydberg

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constant $R_\infty$ and the fine-structure constant $\alpha$ have very small relative standard uncertainties of about $5 \times 10^{-12}$ and $3 \times 10^{-10}$, respectively. Many of the fundamental constants[2,3]—including the Planck constant $h$, elementary charge $e$, electron mass $m_e$, proton mass $m_p$, and Avogadro's number $N_A$—have somewhat higher, but still small, relative standard uncertainties of about $(2–4) \times 10^{-8}$. The relative standard uncertainty of the Boltzmann constant $k_B$ is substantially higher at about $1 \times 10^{-6}$.

There are two fundamental constants that each have significant unresolved discrepancies, where different types of measurements produce values that differ by many times their standard deviations.[2,3] The accepted value of the Newtonian constant of gravitation $G$ has a high relative standard uncertainty of about $1.2 \times 10^{-4}$, because several measurements differ by about (10–15)σ of their individual standard uncertainties. Similarly, the proton rms charge radius $r_P$ has a high relative standard uncertainty of about $6 \times 10^{-3}$ with two types of measurements differing by about (5–7)σ of their individual standard uncertainties. This tension in the $r_P$ values is termed the "proton radius puzzle." In both cases, $G$ and $r_p$, the question remains: are there unidentified systematic errors in some of the measurements, or is the physics of these phenomena not sufficiently understood?

## 3. History of Evaluations of the Fundamental Constants

Compilations and evaluations of the fundamental constants date to the 1920s. Overviews of the history of this effort have been given previously by Rossini (Chair of the International Union of Pure and Applied Chemistry (IUPAC) Task Group on Fundamental Constants) in 1964[10] and in a report by the U.S. National Research Council (NRC) Committee of Fundamental Constants in 1983.[11] We update and expand on this history here.

In 1919, the IUPAC approved a project called the "International Critical Tables (ICT)," which was to provide recommended values for a wide range of properties in physics, chemistry, and technology. The ICT Advisory Committees were established several years later in 1922. The values for the fundamental constants in the ICT were prepared under the direction of Frederick E. Fowle of the Smithsonian Institution based on information obtained from various laboratories throughout the world. These values were adopted in 1923 and then published as a table in the first volume of the "International Critical Tables of Numerical Data, Physics, Chemistry and Technology" in 1926.[12] No references, evaluation, or discussion were provided for the recommended values.

In 1926, Henning and Jaeger[13] published a chapter in the "Handbuch der Physik" entitled "The General Physical Constants" that provided some discussion of the selected values and references. Also in 1926, Birge published an article in *Science* entitled "The most probable value of certain basic constants" discussing the recommended values from the *International Critical Tables*, pointing out inconsistencies, sources of error, and the interdependencies of many of the fundamental constants.[14]

In 1928, the U.S. National Research Council Division of Physical Sciences established the "Committee on Physical Constants." The stated purpose of the committee was "to encourage the preparation of papers on the general physical constants and derived constants whenever a significant change amounting to more than the probable error of a new value is reported." Raymond Birge was the chair of the committee and largely responsible for its output—working for the most part independently.

In 1929, the first comprehensive review of the fundamental constants was published by Birge as the first article in the first volume of *Reviews of Modern Physics*.[15] (About a dozen fundamental constants' updates have been published in *Reviews of Modern Physics*). In 1932, Birge reevaluated a number of the fundamental constants using a self-consistent least squares analysis[16] but found little statistical differences with his 1929 initial evaluation. The next major update to the fundamental constants by Birge was published in two papers in 1941.[17,18] He also published an extensive set of papers regarding evaluations of the fundamental constants in general[19–22] and for specific subsets of fundamental constants.[23–33]

During the 1930–1940s, a number of authors published compilations and evaluations of various subsets of the fundamental constants, including Born (1930),[34] Millikan (1930,1938),[35,36] Bond (1936),[37] von Friesen (1937),[38] Dunnington (1939),[39] Wensel,[40] and Stille (1943 and 1948).[41,42]

In 1939, DuMond published a paper in *Physical Review* discussing the interdependencies of the fundamental constants.[43] The following year, the National Research Council established the "Committee of Fundamental Constants and Conversion Factors" for the "purpose of ascertaining and publishing from time to time the best and most generally acceptable values of the physical constants."

Working under the auspices of the U.S. NRC Subcommittee on Fundamental Constants, Dumond and Cohen produced major updates to the fundamental constants (and associated intermediate discussion papers) in 1947,[44–47] 1950,[48,49] 1952,[50,51] 1955,[52–55] 1959,[56] and 1965.[57,58] During this time period, Bearden and coworkers also contributed to the work of this NRC subcommittee and published a series of papers making recommendations for some of the fundamental constants and providing some discussion about inconsistencies, uncertainties, and evaluation methods.[59–64] A summary report by the NRC committee was published in 1952.[65]

In 1966, the CODATA was established by the International Council of Science, and in 1969, the CODATA Task Group on Fundamental Constants was formed. Also in 1969, Taylor, Parker, and Langenberg published an update to the fundamental constants[66] based upon a new determination of $e/h$ by Taylor *et al.* in 1967.[67] In 1973, Cohen and Taylor produced the first CODATA recommended values for the fundamental constants[68] followed by an update in 1986.[69–72] Mohr and Taylor at the National Institute of Standards and Technology (NIST) revised the CODATA recommended values with the 1998[73,74] and 2002[75] updates, followed by Mohr, Taylor, and Newell with the 2006[76,77] and 2010[2,3] updates. These updates are now published every 4 year. The 1973, 1986, 1998, 2006, and 2010 CODATA updates were jointly published in *Reviews of Modern Physics* and the *Journal of Physical and Chemical Reference Data*, as will be the 2014 update (in preparation).[78,79]

It is important to note the efforts by others who have worked both independently and in cooperation with the NRC and CODATA committees over the years to make recommendations and provide helpful discussions and debate over evaluation of the fundamental constants, including Gorbatesvich and coworkers (1967 and 1970),[80,81] Levyleblond (1977),[82] Pipkin and Ritter (1983),[83] Petley and coworkers (1989 and 2001),[84,85] Delaeter (1994),[86] Uzan (2003),[87] Conroy (2003),[88] and Karshenboim (2005 and 2013).[89,90]

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