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The CODATA 2017 Values of h, e, k, and N_A for the Revision of the SI

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Committee on Data for Science and Technology (CODATA) Task Group on Fundamental Constants (TGFC)

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Sufficient progress towards redefining the International System of Units (SI) in terms of exact values of fundamental constants has been achieved. Exact values of the Planck constant h, elementary charge e, Boltzmann constant k, and Avogadro constant N_A from the CODATA 2017 Special Adjustment of the Fundamental Constants are presented here. These values are recommended to the 26th General Conference on Weights and Measures to form the foundation of the revised SI.

I. INTRODUCTION

The International System of Units (SI) has been slowly evolving from an artifact based system to one based on values of fundamental constants and invariant properties of atoms. The quantitative limitations of the last remaining base unit of the SI defined by an artifact, the kilogram, have been known since at least the third verification of national kilogram prototypes (Girard, 1994; Quinn, 1991). As a consequence the possible role of the fundamental constants in replacing the kilogram has been discussed in earnest for nearly three decades. International consensus on the foundation of a new system of units based on exactly defined values of the Planck constant h, elementary charge e, Boltzmann constant k, and Avogadro constant N_A was reached during the 24th meeting of the General Conference on Weights and Measures (CGPM, 2011). Progress in the accuracy and consistency of the research results has enabled the 106th International Committee for Weights and Measures (CIPM) to recommend proceeding with the adoption of the revised SI (CIPM, 2017).

The Committee on Data for Science and Technology (CODATA), through its Task Group on Fundamental Constants (TGFC), periodically provides 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. Because of this role, the CGPM invited the CODATA TGFC to carry out a special least-squares adjustment (LSA) of the values of the fundamental physical constants to provide values for defining constants to form the foundation for the revised SI (CGPM, 2011). The results of that adjustment are given here, namely, the numerical values of h, e, k, and N_A, each with a sufficient number of digits to maintain consistency between the present and revised SI as proposed by the Consultative Committee for Units (CCU) and agreed to by the CIPM (CIPM, 2016). These numbers are recommended to the 26th CGPM to establish the revised SI when it convenes in November 2018.

II. THE CODATA 2017 SPECIAL ADJUSTMENT

The input data for the CODATA 2017 Special Adjustment includes the input data used in the final CODATA 2014 regular adjustment on which the 2014 recommended values are based. Of these data, which are given in Tables XV-XIX of Mohr *et al.* (2016a), the following were omitted: the four cyclotron frequency ratios, items $B8$, $B9$, $B11$, and $B12$ that have been superseded by the 2016 atomic mass evaluation (Huang *et al.*, 2017; Wang *et al.*, 2017), and all measurements of the Newtonian constant of gravitation G. Key data that were published or accepted for publication before the 1 July 2017 closing date of the CODATA 2017 Special Adjustment and have a significant impact on the determination of h, e, k, and N_A are listed in Table I. The full list of data considered for the CODATA 2017 Special Adjustment is given in Tables II - V in Mohr *et al.* (2017). Of note are data that are not included for the same reasons they were omitted from the 2014 adjustment. In particular, the measurements in muonic hydrogen and deuterium that have led to the proton radius "puzzle" were not included. These data would have no effect on the 2017 values of h, e, k, and N_A, but will be reconsidered for the next CODATA periodic adjustment.

The CODATA 2017 Special Adjustment follows the same procedures as the previous periodic CODATA adjustments of the fundamental constants (Mohr *et al.*, 2016a,b; Mohr and Taylor, 2000, 2005; Mohr *et al.*, 2008a,b, 2012a,b). Details of the Special Adjustment analysis are given in Mohr *et al.* (2017). In general, the measure the CODATA TGFC uses for consistency of an input datum is the normalized (or reduced) residual of that datum given by the LSA, that is, the difference between an input datum and its adjusted value divided by the input datum uncertainty. If a residual for an input datum is larger than two, the TGFC identifies the fundamental constant primarily influenced by that datum as well as other input data that influence the same con-

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TABLE I Key data for the determination of h, e, k, and N_{A} in the CODATA 2017 Special Adjustment. See Mohr *et al.* (2017) for a complete list of input data.

Source	Identification[a]	Quantity[b]	Value	Rel. stand. uncert u_{r}
Schlamminger *et al.* (2015)	NIST-15	h	$6.626\,069\,36(38) \times 10^{-34}$ J s	5.7×10^{-8}
Wood *et al.* (2017)	NRC-17	h	$6.626\,070\,133(60) \times 10^{-34}$ J s	9.1×10^{-9}
Haddad *et al.* (2017)	NIST-17	h	$6.626\,069\,934(88) \times 10^{-34}$ J s	1.3×10^{-8}
Thomas *et al.* (2017)	LNE-17	h	$6.626\,070\,40(38) \times 10^{-34}$ J s	5.7×10^{-8}
Azuma *et al.* (2015)	IAC-11	N_{A}	$6.022\,140\,95(18) \times 10^{23}$ mol^{-1}	3.0×10^{-8}
Azuma *et al.* (2015)	IAC-15	N_{A}	$6.022\,140\,70(12) \times 10^{23}$ mol^{-1}	2.0×10^{-8}
Bartl *et al.* (2017)	IAC-17	N_{A}	$6.022\,140\,526(70) \times 10^{23}$ mol^{-1}	1.2×10^{-8}
Kuramoto *et al.* (2017)	NMIJ-17	N_{A}	$6.022\,140\,78(15) \times 10^{23}$ mol^{-1}	2.4×10^{-8}
Moldover *et al.* (1988)	NIST-88	R	$8.314\,470(15)$ J mol^{-1} K^{-1}	1.8×10^{-6}
Pitre *et al.* (2009)	LNE-09	R	$8.314\,467(23)$ J mol^{-1} K^{-1}	2.7×10^{-6}
Sutton *et al.* (2010)	NPL-10	R	$8.314\,468(26)$ J mol^{-1} K^{-1}	3.2×10^{-6}
Pitre *et al.* (2011)	LNE-11	R	$8.314\,455(12)$ J mol^{-1} K^{-1}	1.4×10^{-6}
Pitre *et al.* (2015)	LNE-15	R	$8.314\,4615(84)$ J mol^{-1} K^{-1}	1.0×10^{-6}
Gavioso *et al.* (2015)	INRIM-15	R	$8.314\,4743(88)$ J mol^{-1} K^{-1}	1.1×10^{-6}
Pitre *et al.* (2017)	LNE-17	R	$8.314\,4614(50)$ J mol^{-1} K^{-1}	6.0×10^{-7}
Podesta *et al.* (2017)	NPL-17	R	$8.314\,4603(58)$ J mol^{-1} K^{-1}	7.0×10^{-7}
Feng *et al.* (2017)	NIM-17	R	$8.314\,459(17)$ J mol^{-1} K^{-1}	2.0×10^{-6}
Gaiser *et al.* (2017)	PTB-17	$A_{\epsilon}(^{4}\mathrm{He})/R$	$6.221\,140(12) \times 10^{-8}$ m^{3} K J^{-1}	1.9×10^{-6}
Qu *et al.* (2017)	NIM/NIST-17	k/h	$2.083\,6630(56) \times 10^{10}$ Hz K^{-1}	2.7×10^{-6}

[a] IAC: International Avogadro Coordination; INRIM: Istituto Nazionale di Ricerca Metrologica, Torino, Italy; LNE: Laboratoire national de métrologie et d'essais, Trappes and La Plaine-Saint-Denis, France; NIM: National Institute of Metrology, Beijing, PRC; NIST: National Institute of Standards and Technology, Gaithersburg, MD, and Boulder, CO, USA; NMIJ: National Metrology Institute of Japan, Tsukuba, Japan; NPL: National Physical Laboratory, Teddington, UK; NRC: National Research Council Canada, Ottawa, Canada; PTB: Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Germany

[b] h: Planck constant; N_{A}: Avogadro constant; R: molar gas constant; $A_{\epsilon}(^{4}\mathrm{He})/R$: molar polarizability of ^{4}He gas to the molar gas constant quotient; k/h: Boltzmann constant to Planck constant quotient

stant. The uncertainties of this subset of input data are multiplied by a factor that is large enough that the relevant residuals are two or less. To achieve consistency, multiplicative expansion factors were applied to the uncertainties of two subsets of input data corresponding to two adjusted constants for the 2017 Special Adjustment.

The first subset consists of the eight input data for the Planck and Avogadro constants listed in Table I, relevant to the adjusted value of the Planck constant. The uncertainties of these input data are multiplied by a factor of 1.7. With this expansion of the uncertainties of the eight data, five have relative standard uncertainties u_{r} at or below 50×10^{-9}, with two at or below 20×10^{-9}, where the latter includes results from both the Kibble balance and the x-ray crystal density (XRCD) methods.

The second subset of expanded data consists of the input data that determine the relative atomic mass of the proton: the 2016 atomic mass evaluation value of ^{1}H and the cyclotron frequency ratio of hydrogenic carbon to the proton, items $B2$ and $B12$, respectively, of Table IV in Mohr *et al.* (2017). Coincidentally, an expansion factor of 1.7 was also appropriate in this case, although its application has no effect on the 2017 values of h, e, k, and N_{A}.

III. RESULTS

Figure 1 shows values of h inferred from the key input data in Table I and the final CODATA 2017 value. The values of k inferred from the key input data in Table I and the final CODATA 2017 value are shown in Fig. 2. The final values and uncertainties of h, e, k, and N_{A} from the 2017 CODATA Special Adjustment are given in Table II.

A requirement by the CGPM (2011) is that the revised SI be consistent with the present SI. In the SI prior to redefinition, the following quantities have exactly defined values: the international prototype of the kilogram $m(\mathcal{K}) = 1$ kg, the vacuum magnetic permeability $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}, the triple point of water $T_{\mathrm{TPW}} = 273.16$ K, and the molar mass of carbon-12, $M(^{12}\mathrm{C}) = 0.012$ kg mol^{-1}. In the revised SI, these quantities are determined experimentally with associated uncertainties. As stated in the agreed upon CCU recommendation (CIPM, 2016), the number of digits for the

TABLE II The CODATA 2017 adjusted values of h, e, k, and N_A.

Quantity	Value	Rel. stand. uncert u_r
h	$6.626\,070\,150(69) \times 10^{-34}$ J s	1.0×10^{-8}
e	$1.602\,176\,6341(83) \times 10^{-19}$ C	5.2×10^{-9}
k	$1.380\,649\,03(51) \times 10^{-23}$ J K^{-1}	3.7×10^{-7}
N_A	$6.022\,140\,758(62) \times 10^{23}$ mol^{-1}	1.0×10^{-8}

TABLE III The CODATA 2017 values of h, e, k, and N_A for the revision of the SI.

Quantity	Value
h	$6.626\,070\,15 \times 10^{-34}$ J s
e	$1.602\,176\,634 \times 10^{-19}$ C
k	$1.380\,649 \times 10^{-23}$ J K^{-1}
N_A	$6.022\,140\,76 \times 10^{23}$ mol^{-1}

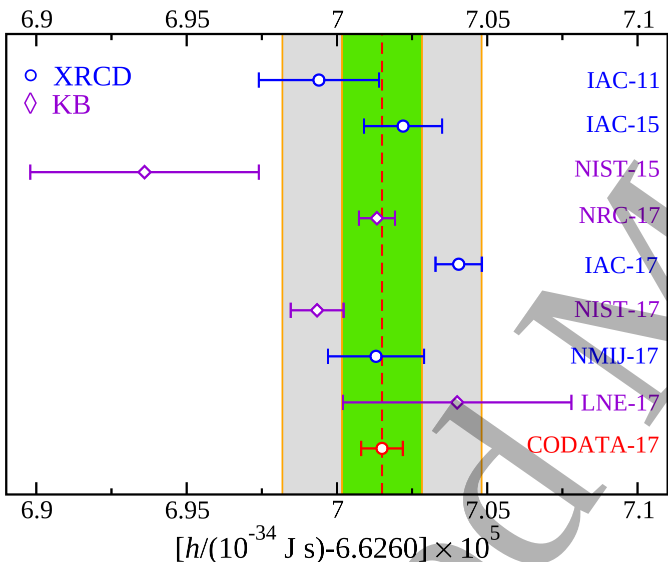

FIG. 1 Values of the Planck constant h inferred from the input data in Table I and the CODATA 2017 value in chronological order from top to bottom. The inner green band is ± 20 parts in 10^9 and the outer grey band is ± 50 parts in 10^9. KB: Kibble balance; XRCD: x-ray-crystal-density.

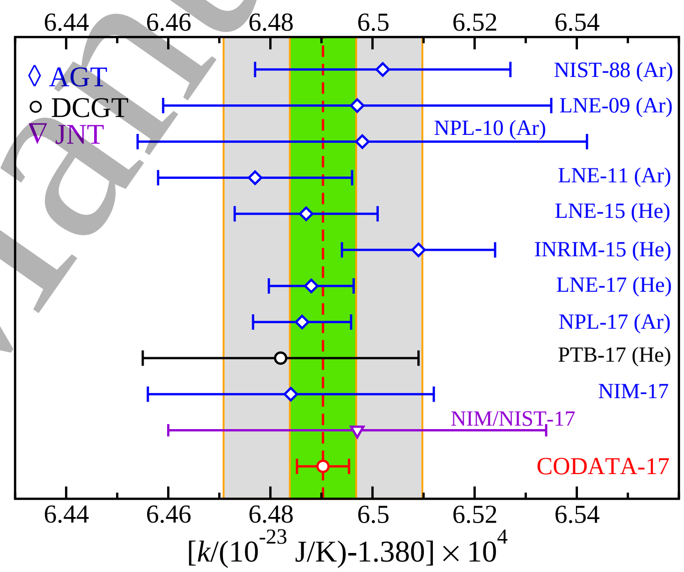

FIG. 2 Values of the Boltzmann constant k inferred from the key input data in Table I and the CODATA 2017 value in chronological order from top to bottom. The inner green band is ± 5 parts in 10^7 and the outer grey band is ± 15 parts in 10^7. AGT: acoustic gas thermometry; DCGT: dielectric constant gas thermometry; JNT: Johnson noise thermometry.

exact numerical values of h, e, and N_A to define the revised SI are determined by requiring that the numerical values of $m(\mathcal{K})$, μ_0, and $M(^{12}\mathrm{C})$ remain consistent with their previous exact values within their relative standard uncertainties given by the CODATA 2017 Special Adjustment. The number of digits for k is chosen such that T_{TPW} is equal to 273.16 K within a relative standard uncertainty at the level which T_{TPW} can be realized (CCT, 2017). The recommended exact numerical values of h, e, k, and N_A to establish the revised SI are given in Table III.

IV. SUMMARY

Sufficient progress has been achieved towards meeting the recommendations for redefining the SI in terms of exact values of fundamental constants. The recommended exact numerical values of h, e, k, and N_A to establish the revised SI based on fundamental constants are given. A detailed description of the unique 2017 CODATA special adjustment is given by Mohr *et al.* (2017). The next regular CODATA periodic adjustment of the fundamental constants, CODATA 2018, will also be unique as it will be the first one based on the exact fundamental constants of the revised SI.

Acknowledgment

The CODATA Task Group on Fundamental Constants thanks the CGPM for inviting it to play a significant role in the international effort to establish a revised SI for the 21st century, arguably the most important change to the International System of Units since its formal adoption in 1960.

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