Fundamental Physical Constants 1986 Adjustments

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Over the past twenty years a surprisingly strong link has developed between the applied science of metrology and atomic, molecular and solid state physics. The techniques of frequency multiplication, and the precise measurement of frequency at infrared and visible wavelengths, have reached such a level of development that the metre has been redefined in terms of the distance travelled by light in a given time [1, 2]). The direct linking of atomic lattice spacings to optical wavelengths has produced a significant improvement in the determination of the Avogadro constant [3, 4]). Impressive progress has been made in the precision of measurement of the electron anomalous magnetic moment [5]) as well as the numerical evaluation of the associated sixth- and eighth-order Feynman diagrams [6]). The most striking metrological advance occurred when K. von Klitzing in 1980 observed the quantization of electrical conductance [7]) and achieved not only a direct macroscopic measurement of the fine-structure constant, but the 1985 Nobel Prize in Physics as well [8]).

The CODATA Task Group on Fundamental Constants has recently completed a new evaluation of the fundamental physical constants [9]) taking into account the truly extraordinary amount of experimental and theoretical work that has become available since the previous adjustment in 1973 [10]).

Because of past problems associated with the statistical treatment of such a diverse set of experimental and theoretical data, increased attention was directed in the 1986 analysis to questions of statistical validity. The least-squares approach to the analysis of such data has been described in detail in previous reviews [11, 12, 13], but in brief, each experimental result with its estimated uncertainty represents a constraint on the values of a set of physical quantities, expressed as an algebraic relationship involving the auxiliary constants, the unknown stochastic data and their unknown experimental and theoretical errors. The least-squares solution determines the "best" values of these unknown quantities by finding the weighted mean of the observational equations that gives the smallest statistical variances consistent with the constraints.

Table 1. 1986 Adjustment of the fundamental constants.
Comparison of the initial and final stages of the multivariate analysis.

	Initial (least-squares, external error)	Final (extended least-squares)
N	35	22
ν	30	17
χ^2	106.6	17.01
R_B	1.89	1.00
α^{-1}	137.035 996(11)	137.035 9895(61)
K_V	$1-7.24(54)\times10^{-6}$	$1-7.59(30)\times10^{-6}$
K_Ω	$1-1.524(92)\times10^{-6}$	$1-1.563(50)\times10^{-6}$
d_{220}	192.015 553(74) pm	192.015 540(40) pm
μ_μ/μ_p	3.183 345 71(87)	3.183 345 47(47)

The weight ω_i associated with each experimental datum is the reciprocal of the variance, or statistical mean square error, σ_i^2 which is however only available as an *a priori* estimate s_i^2 and is itself uncertain. The usual least-squares procedure multiplies the calculated uncertainties of an adjustment by the Birge ratio, $R_B = (\chi^2/\nu)^{1/2}$, to rescale the weights and give a value of χ^2 equal to its expectation value ν. This is equivalent to an *a posteriori* evaluation of the 'error associated with unit weight' and is valid if the assigned uncertainties have only relative significance, or if the systematic errors of all input data are roughly similar. However, when the data come from different and unrelated sources with broadly different physical content, a uniform expansion of all uncertainties can hardly be justified. In such a case, any rescaling of the assigned weights should consider all other information that may be available concerning the uncertainty assignment of each individual datum. In analyzing the 1986 input data we have considered not only the usual least-squares algorithm, but also the algorithm proposed by Tuninskii and Kholin in 1975 [14]) of the Mendeleyev Institute of Metrology in Leningrad, as well as a modification of it suggested by Taylor in 1982 [15]), and the extended least-squares algorithms described by Cohen in 1976 [16]), 1978 [17]) and 1980 [18]). These algorithms use the consistency of the data to provide additional information with which to improve these *a priori* estimates of the variances.

Input Data

As in previous adjustments, the data are divided into two categories:

a) the more precise data (auxiliary constants) that are not subject to adjustment because of their relatively low uncertainties, and

b) the less precise or stochastic data that are subject to adjustment.

There is no formal basis for separation into these two categories except that a variable with an uncertainty much smaller than that of other variables to which it is connected will be only slightly altered by the adjustment and can hence be treated as a constant. The uncertainty of an auxiliary constant is typically one twentieth the uncertainty of the stochastic datum with which it appears. All the auxiliary constants have uncertainties not greater than 0.02 ppm while the 38 items of stochastic data have uncertainties in the range 0.05 ppm to 10 ppm

On the basis of a preliminary screening, three of the 38 items were identified as inappropriate for further consideration in the adjustment: one because it represented an uncompleted measurement; a second because it had recently been shown to be in error; and the third because it required for its interpretation an inadequately developed theoretical expression. The remaining 35 items formed the basis for an analysis with five unknowns. These unknowns were the inverse fine-structure constant α^{-1}, the ratio of the standard volt (defined and maintained by the Josephson effect) to the SI volt K_V, the ratio of the standard ohm (maintained in terms of a set of standard resistance coils, corrected for drift to the value on 1 Jan, 1985) to the SI ohm K_Ω, the lattice spacing of the silicon lattice (at 22.5°C in vacuum) d_{220}, and the ratio of the muon magnetic moment to the proton magnetic moment, μ_μ/μ_p. The multivariate analysis was carried out using the several algorithms mentioned above; the details are given in *CODATA Bulletin* No. 63 [9]).

From the results of applying the various algorithms to the data and from a consideration of the effects on consistency produced by eliminating data, we deleted 11 observations of very low weight and two other older observations which were of low weight and somewhat discrepant relative to their claimed precision. As a result, 22 items of stochastic data remained to define the data set for the 1986 recommended values of the fundamental physical constants. This final solution is compared with the initial adjustment with 35 observations in Table 1. The uncertainties given for the initial adjustment (with $\chi^2 = 106.6$ and $R_B = 1.89$) are computed from external consistency. These uncertainties, which are expanded by the factor R_B from the internally computed values, are still significantly smaller than the corresponding uncertainties of the 1973 adjustment. Even though this solution contains some discordant data, none of these quantities differs from its final recommended value by more than 0.7 standard deviations of that difference, and only K_V differs from the final recommended value by more than one standard deviation of that value.

Table 2 gives a selected list of values of the fundamental constants of physics and chemistry; Table 3 presents a set of related values, such as the quantities V_{BI-76}, Ω_{BI85} and d_{220} that are a necessary part of the data of the adjustment, but cannot be considered as fundamental in the same sense as the quantities of Table 2.

Comparisons and Discussion

The precision of the 1986 recommended values is roughly an order of magnitude better than that of their 1973 counterparts; the precision of the Rydberg constant R_∞ is improved by a factor of 60 while that of m_p/m_e and α, by factors of approximately 20. The most significant revision is the change in K_V and the resultant 7.75 ppm change

Table 2. Summary of the 1986 recommended values of the fundamental physical constants.

A list of some fundamental constants of physics and chemistry based on a least-squares adjustment with 17 degrees of freedom. The digits in parentheses are the one-standard-deviation uncertainty in the last digits of the given value. Since the uncertainties of many of these entries are correlated, the full covariance matrix must be used in evaluating the uncertainties of quantities computed from them.

Quantity	Symbol	Value	Units	Relative uncertainty (ppm)
speed of light in vacuum	c	299 792 458	$\mathrm{m\,s^{-1}}$	(exact)
permeability of vacuum	μ_o	$4\pi\times10^{-7}$	$\mathrm{N\,A^{-2}}$	
		=12.566 370 614...	$10^{-7}\,\mathrm{N\,A^{-2}}$	(exact)
permittivity of vacuum	ϵ_o	$1/\mu_o c^2$		
		=8.854 187 817...	$10^{-12}\,\mathrm{F\,m^{-1}}$	(exact)
Newtonian constant of gravitation	G	6.672 59(85)	$10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$	128
Planck constant	h	6.626 0755(40)	$10^{-34}\,\mathrm{J\,s}$	0.60
$h/2\pi$	$\hbar$	1.054 572 66(63)	$10^{-34}\,\mathrm{J\,s}$	0.60
elementary charge	e	1.602 177 33(49)	$10^{-19}\,\mathrm{C}$	0.30
magnetic flux quantum, $h/2e$	Φ_o	2.067 834 61(61)	$10^{-15}\,\mathrm{Wb}$	0.30
Josephson frequency–voltage ratio	$2e/h$	4.835 9767(14)	$10^{14}\,\mathrm{Hz\,V^{-1}}$	0.30
quantized Hall resistance, $h/e^2 = \mu_o c/2\alpha$	R_H	25 812.8056(12)	Ω	0.045
electron mass	m_e	9.109 3897(54)	$10^{-31}\,\mathrm{kg}$	0.59
		5.485 799 03(13)	$10^{-4}\,\mathrm{u}$	0.023
in electron volts, $m_e c^2/\{e\}$		0.510 999 06(15)	MeV	0.30
electron specific charge	$-e/m_e$	−1.758 819 62(53)	$10^{11}\,\mathrm{C\,kg^{-1}}$	0.30
muon mass	m_μ	1.883 5327(11)	$10^{-28}\,\mathrm{kg}$	0.61
		0.113 428 913(17)	u	0.15
in electron volts, $m_\mu c^2/\{e\}$		105.658 389(34)	MeV	0.32
muon–electron mass ratio	m_μ/m_e	206.768 262(30)		0.15
proton mass	m_p	1.672 6231(10)	$10^{-27}\,\mathrm{kg}$	0.59
		1.007 276 470(12)	u	0.012
in electron volts, $m_p c^2/\{e\}$		938.272 31(28)	MeV	0.30
proton-electron mass ratio	m_p/m_e	1836.152 701(37)		0.020
neutron mass	m_n	1.674 9286(10)	$10^{-27}\,\mathrm{kg}$	0.59
		1.008 664 904(14)	u	0.014
in electron volts, $m_n c^2/\{e\}$		939.565 63(28)	MeV	0.30
neutron–electron mass ratio	m_n/m_e	1838.683 662(40)		0.022
neutron–proton mass ratio	m_n/m_p	1.001 378 404(9)		0.009
fine-structure constant, $\mu_o ce^2/2h$	α	7.297 353 08(33)	10^{-3}	0.045
inverse fine-structure constant	α^{-1}	137.035 9895(61)		0.045
Rydberg constant, $m_e c\alpha^2/2h$	R_∞	10 973 731.534(13)	$\mathrm{m^{-1}}$	0.0012
Bohr radius, $\alpha/4\pi R_\infty$	a_o	0.529 177 249(24)	$10^{-10}\,\mathrm{m}$	0.045
Compton wavelength, $h/m_e c$	λ_C	2.426 310 58(22)	$10^{-12}\,\mathrm{m}$	0.089
$\lambda_C/2\pi = \alpha a_o = \alpha^2/4\pi R_\infty$	λ_C	3.86 159 323(35)	$10^{-13}\,\mathrm{m}$	0.089
classical electron radius, $\alpha^2 a_o$	r_e	2.817 940 92(38)	$10^{-15}\,\mathrm{m}$	0.13
Thomson cross section, $(8\pi/3)r_e^2$	σ_e	0.665 246 16(18)	$10^{-28}\,\mathrm{m^2}$	0.27
Bohr magneton, $e\hbar/2m_e$	μ_B	927.401 54(31)	$10^{-26}\,\mathrm{J\,T^{-1}}$	0.34
nuclear magneton, $e\hbar/2m_p$	μ_N	0.505 078 66(17)	$10^{-26}\,\mathrm{J\,T^{-1}}$	0.34
electron magnetic moment	μ_e	928.477 01(31)	$10^{-26}\,\mathrm{J\,T^{-1}}$	0.34
in Bohr magnetons	μ_e/μ_B	1.001 159 652 193(10)		1×10^{-5}
in nuclear magnetons	μ_e/μ_N	1838.282 000(37)		0.020
proton magnetic moment	μ_p	1.410 607 61(47)	$10^{-26}\,\mathrm{J\,T^{-1}}$	0.34
in Bohr magnetons	μ_p/μ_B	1.521 032 202(15)	10^{-3}	0.010
in nuclear magnetons	μ_p/μ_N	2.792 847 386(63)		0.023
diamagnetic shielding correction for protons in pure water, spherical sample, 25 °C, $1-\mu_p'/\mu_p$	σ_{H_2O}	25.689(15)	10^{-6}	–
shielded proton moment (H_2O, sph., 25 °C)	μ_p'	1.410 571 38(47)	$10^{-26}\,\mathrm{J\,T^{-1}}$	0.34
in Bohr magnetons	μ_p'/μ_B	1.520 993 129(17)	10^{-3}	0.011
in nuclear magnetons	μ_p'/μ_N	2.792 775 642(64)		0.023
proton gyromagnetic ratio	γ_p	26 752.2128(81)	$10^4\,\mathrm{s^{-1}\,T^{-1}}$	0.30
	$\gamma_p/2\pi$	42.577 469(13)	$\mathrm{MHz\,T^{-1}}$	0.30
uncorrected (H_2O, sph., 25 °C)	γ_p'	26 751.5255(81)	$10^4\,\mathrm{s^{-1}\,T^{-1}}$	0.30
	$\gamma_p'/2\pi$	42.576 375(13)	$\mathrm{MHz\,T^{-1}}$	0.30
muon–proton magnetic moment ratio	μ_μ/μ_p	3.183 345 47(47)		0.15
neutron magnetic moment	μ_n	0.966 237 07(40)	$10^{-26}\,\mathrm{J\,T^{-1}}$	0.41
in Bohr magnetons	μ_n/μ_B	0.001 041 875 63(25)		0.24
in nuclear magnetons	μ_n/μ_N	1.913 042 75(45)		0.24

Table 2. Summary of the 1986 recommended values of the fundamental physical constants (continued).

Quantity	Symbol	Value	Units	Relative uncertainty (ppm)
neutron–electron magnetic moment ratio	μ_n/μ_e	0.001 040 668 82(25)		0.24
neutron–proton magnetic moment ratio	μ_n/μ_p	0.684 979 34(16)		0.24
Avogadro constant	N_A, L	6.022 1367(36)	10^{23} mol^{-1}	0.59
Faraday constant, $N_A e$	F	96 485.309(29)	C mol^{-1}	0.30
electron molar mass	$M(e), M_e$	5.485 799 03(13)	10^{-7} kg/mol	0.023
muon molar mass	$M(\mu), M_\mu$	1.134 289 13(17)	10^{-4} kg/mol	0.15
proton molar mass	$M(p), M_p$	1.007 276 470(12)	10^{-3} kg/mol	0.012
Hartree energy, $e^2/4\pi\epsilon_0 a_0 = 2R_\infty hc$	E_h	4.359 7482(26)	10^{-18} J	0.60
in eV, $E_h/\{e\}$		27.211 3961(81)	eV	0.30
molar gas constant	R	8.314 510(70)	J mol^{-1}K^{-1}	8.4
Boltzmann constant, R/N_A	k	1.380 658(12)	10^{-23} J K^{-1}	8.5
first radiation constant, $2\pi hc^2$	c_1	3.741 7749(22)	10^{-16} W m^2	0.60
second radiation constant, hc/k	c_2	0.014 387 69(12)	m K	8.4
Wien displacement law constant, $b = \lambda_{max}T = c_2/4.965\,114\,23\ldots$	b	2.897 756(24)	10^{-3} m K	8.4
Stefan–Boltzmann constant, $(\pi^2/60)k^4/\hbar^3c^2$	σ	5.670 51(19)	10^{-8}W m^{-2} K^{-4}	34

Table 3. Maintained units and standard values.

A summary of 'maintained' units and 'standard' values and their relationship to SI units, based on a least-squares adjustment with 17 degrees of freedom. The digits in parentheses are the one-standard-deviation uncertainty in the last digits of the given value. Since the uncertainties of many of these entries are correlated, the full covariance matrix must be used in evaluating the uncertainties of quantities computed from them.

Quantity	Symbol	Value	Units	Relative uncertainty (ppm)
electron volt, (e/C) J $= \{e\}$ J	eV	1.602 177 33(49)	10^{-19} J	0.30
(unified) atomic mass unit, $1\,u = m_u = \frac{1}{12}m(^{12}C)$	u	1.660 5402(10)	10^{-27} kg	0.59
standard atmosphere	atm	101 325	Pa	(exact)
standard acceleration of gravity	g_n	9.806 65	m s^{-2}	(exact)
'As-Maintained' Electrical Units				
BIPM maintained ohm, Ω_{69-BI} $\Omega_{BI85} \equiv \Omega_{69-BI}$(1 Jan 1985)	Ω_{BI85}	$1 - 1.563(50)\times10^{-6}$	Ω	
		$= 0.999\,998\,437(50)$	Ω	0.050
Drift rate of Ω_{69-BI}	$\frac{d\Omega_{69-BI}}{dt}$	−0.0566(15)	μΩ/a	—
BIPM maintained volt, $V_{76-BI} \equiv 483\,594$ GHz$(h/2e)$	V_{76-BI}	$1 - 7.59(30)\times10^{-6}$	V	
		$= 0.999\,992\,41(30)$	V	0.30
BIPM maintained ampere, $A_{BIPM} = V_{76-BI}/\Omega_{69-BI}$	A_{BI85}	$1 - 6.03(30)\times10^{-6}$	A	
		$= 0.999\,993\,97(30)$	A	0.30
X-Ray Standards				
Cu x-unit : $\lambda(CuK\alpha_1) \equiv 1537.400$ xu	xu($CuK\alpha_1$)	1.002 077 89(70)	10^{-13} m	0.70
Mo x-unit : $\lambda(MoK\alpha_1) \equiv 707.831$ xu	xu($MoK\alpha_1$)	1.002 099 38(45)	10^{-13} m	0.45
Å* : $\lambda(WK\alpha_1) \equiv 0.209\,100$ Å*	Å*	1.000 014 81(92)	10^{-10} m	0.92
lattice spacing of Si (in vacuum, 22.5 °C), +	a	0.543 101 96(11)	nm	0.21
$d_{220} = a/\sqrt{8}$	d_{220}	192.015 540(40)	pm	0.21
molar volume of Si, $M(Si)/\rho(Si) = N_A a^3/8$	V_m(Si)	12.058 8179(89)	cm^3/mol	0.74

+ The lattice spacing of single-crystal Si can vary by parts in 10^7 depending on the preparation process. Measurements at PTB indicate also the possibility of distortions from exact cubic symmetry of the order of 0.2 ppm.

in the recommended value of $2e/h$: the 1986 value is higher than the 1973 value by three times the standard deviation of the latter. The Josephson frequency-voltage ratio (483 594.0 GHz/V) adopted by the Consultative Committee on Electricity in 1972, which was intended to reproduce the SI value and which forms the basis of the legal representation of the volt in many countries, is too small by about 8 ppm. This unsatisfactory situation is undergoing international review and will be rectified in the near future [19,20].

Since the fine-structure constant α, which is proportional to $e(e/h)$, has changed by only 0.37 ppm, the increase in $2e/h$ is strongly correlated to an approximately equal fractional decrease in e. If e^2/h is almost unchanged and e decreases, the fractional decrease in h must be twice as great. Furthermore, the quantity $N_A h$ is proportional to α^2; a decrease in h is coupled with an increase in N_A and with an increase (approximately half as large) in F. The changes from the 1973 values of many quantities are thus strongly correlated, and all of the large changes can be directly linked to the change in K_V. This is seen in the comparison of the 1973 and 1986 recommended values of several constants shown in Table 4.

A major part of the difference between 1973 and 1986 may be traced to the deletion, in 1973, of two Faraday determinations which seemed to be discrepant with the remaining data. In hindsight this 'discrepancy' was not that severe. Adjustment No. 40 in that analysis [13], which differs from the 1973 recommended set (No. 41) only in its retention of the two Faraday determinations, gives a value for $2e/h$ that is 5.3 ppm higher than the 1973 recommendation and only 2.5 ± 2.0 ppm lower than the present value. It is important to recognize, however, that there are no similar data discrepancies in the present analysis; the deleted data have been either extremely discrepant or of very low weight (or both). Thus, it is improbable that any future reassessment of the current data could change the recommendations of the present analysis by as much as two standard deviations.

The 1986 analysis does not separately consider those data that are independent of quantum electrodynamics (WQED data), as was done in 1969 and 1973. If the measurements that depend on QED information (the electron anomalous moment and the muonium hyperfine-structure) are deleted, the remaining 20 items give α^{-1} = 137.035 9846(94). This differs from the

Table 4. Comparison of 1973 and 1986 adjustments

quantity	change from 1973 recommended value (ppm)	uncertainties of recommended values (ppm) 1973	1986
α^{-1}	−0.37	0.82	0.045
e	−7.4	2.9	0.30
h	−15.2	5.4	0.60
m_e	−15.8	5.1	0.59
N_A	+15.2	5.1	0.59
m_p/m_e	+0.64	0.38	0.020
F	+7.8	2.8	0.30
$2e/h$	+7.8	2.6	0.30

recommended value by 0.036 ± 0.059 ppm. The WQED value of K_V differs from the recommended value by 0.01 ± 1.03 ppm. There is clearly no basis for any distinction between QED and WQED data.

By deleting the quantum Hall effect (QHE) data from the analysis one may investigate the validity of the theoretical relation $R_H = h/e^2$. If the QHE data are deleted, the value of α^{-1} becomes 137.0359884(79); the difference from the recommended value is −0.009 ± 0.071 ppm. A value of α^{-1} from the Hall resistance data and the direct ohm determinations yields 137.0359943(127). This differs by only 0.043 ± 0.085 ppm from the value above. Thus, based on the presently available observational data, there is no evidence of any discrepancy in the QHE theory at the current levels of precision.

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International Cooperation Strengthens European Optics

Two events, of considerable importance to the future of optical technology in Europe, marked the opening of the recent Fourth International Symposium on Optical and Optoelectronic Applied Science and Engineering, arranged by SPIE/ANRT at the Hague in the Netherlands. These were the creation of a new association of West European Optical Societies called EUROPTICA, and the declaration of a Memorandum of Understanding (MOU) between EUROPTICA, EPS (European Physical Society) and SPIE — The International Society for Optical Engineering based in the USA.

In recent years, as the pace of developments in optical science and engineering has increased, and more European countries have formed their own Optical Societies, and also as a result of the now established trend, led by SPIE, for the organization of large multidisciplinary conferences, the need has arisen for the creation of a focal point through which future major international events could be channelled. As a start, the partners of the MOU have agreed to collaborate in the organization of one major meeting in Europe each year to be known as the **International Conference on Optical Science and Engineering.** This title has been chosen to reflect the interests of EPS in optical science, those of EUROPTICA in the industrial application of new developments in optics technology and the professional interests of optical engineers through their membership of SPIE. Plans are already well advanced for the first such meeting to be held from 19-23 September 1988 at the Hamburg Conference Centre (CCH). The second meeting will be in Paris from 24-28 April 1989 at the Palais des Congrès de la Porte Maillot.

This new partnership of non-profit bodies representing the interests of over 20,000 scientists, engineers and technologists in optics is expected to develop, in the course of time, to encompass other services to the optical community in the fields of education, exhibitions and publishing. The partnership will have the additional benefit of speeding up the transfer of technology into industry and helping to promote international trade. These activities will be managed by an appointed Joint Policy Committee (JPC) with the following representation:

EPS — European Physical Society
H.A. Ferweda, Universiteit Groningen
G. Thomas, EPS, Secretary of JPC
H. Tiziani, Universität Stuttgart, Institut für Technische Optik, Vice-chairman of JPC

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