

METHODOLOGICAL NOTES

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New recommended values of the fundamental physical constants (CODATA 2006)

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Contents

Abstract. **Up-to-date data on the fundamental physical constants are briefly reviewed, as are the results of their combined analysis, namely, the new recommended values of the fundamental physical constants [Mohr P J, Taylor B N, Newell D B, "CODATA recommended values of the fundamental physical constants: 2006"** ***Rev. Mod. Phys.*** **80 633 (2008)]. Following an approach presented previously (*Usp. Fiz. Nauk* 175 271 (2005) [*Phys. Usp.* 48 255 (2005)]), the author divides the data into blocks. The same block approach is used to discuss new theoretical and experimental results and their implications for the new recommended values of the constants. A comparison with the previous (1998 and 2002) sets of the recommended values of the constants is given.**

1. Introduction

Research in the field of fundamental physical constants plays an important role in physics and metrology and finds diverse applications. For the general public, these constants primarily serve as a universal component of reference data, where very high accuracy is not really important, but what is important is that different researchers use the same values of the constants. In other studies, high accuracy of values at hand is important, because this makes it possible to verify modern highly accurate methods of measurements and calculations and models used in such studies, while in some cases this provides the means for a search of what is referred to as 'new physics'. On a more practical scale, implementation of most accurate methods of measurements and calculations as standards is essential.

In all these applications, the key role is played by what is known as adjustment of the fundamental physical constants, a procedure carried out on a regular basis by the Task Group on Fundamental Constants of the Committee on Data for Science and Technology (CODATA) of the International Council for Science (ICSU, formerly the International Council of Scientific Unions) [1 – 5]. To a certain extent, the Russian texts of these papers have been published in Refs [6 – 9]. Recently, this topic was studied in Ref. [10] in connection with the recommendations of 2002 [4], while in the present work I discuss the results of the 2006 CODATA adjustment [5]. Notice that the years do not refer to the dates of publication but the period during which the data was gathered. The 2002/2006 recommendations are based on the data published prior to December 31, 2002/2006. Thus, below I discuss only the data used in the most recent adjustment, which led to issuing a new set of recommended values (2006) [5], while the more recent data obtained in 2007 and 2008 are not discussed here.

2. What does adjustment of fundamental constants mean?

Let us briefly discuss what adjustment really means in context and why it seems necessary. The adjustment of values of the fundamental physical constants amounts to combined processing of data of different measurements and calculations in a very specific way. Usually the data that are processed form a kind of homogeneous arrays, such as the different values of the frequency f as a function of the laser power P. In order to find the unperturbed value of the frequency we must extrapolate $f(P)$ to zero power. Many points of the sought dependence are measured by similar methods and have roughly the same uncertainties, more or

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less understandable correlations of various systematic effects, etc.

The situation is quite different with adjusting the values of the fundamental constants. Here, the data are obtained by very different methods and, moreover, methods belonging to different areas of physics. Suppose we managed to measure such quantities as e^2/h, h, e/h, $eN_{\rm A}$, $hN_{\rm A}$, and e. Obviously, all these quantities can be expressed in terms of three independent quantities, say e, h, and $N_{\rm A}$. Here, the obtained data are linked through nontrivial correlations related, for instance, to the fact that in some cases the same standards were used in measuring very different quantities. One must check the consistency of the findings used as initial parameters in further calculations and the methods by which they were obtained, as well as the consistency of the standards used in the process.

The obtained results must also be adjusted. For instance, although the above combinations of quantities can be expressed in terms of three physical quantities, e, h, and $N_{\rm A}$, this does not mean that by knowing only the values of these constants we can calculate any their combination, say e^2/h. Only the central value can easily be found, but not its uncertainty. To find the latter, we must know the correlations between the constants. In particular, the combination e^2/h is known with a much higher accuracy than e and h separately. Hence, the result of adjustment consists not of the minimal set of independent constants but of a broad spectrum of different (redundant, so to say) combinations whose determination uncertainties are found with allowance for correlations between the recommended values of the fundamental constants from a minimal independent set.

Thus, the adjustment procedure includes the verification of the consistency of all the data at the entrance to the data processing system, while at the exit it produces a large self-consistent set of values. The first part is implemented during a detailed discussion of the input data, while the second part is implemented in the tables of values. Both these parts are extremely important.

Another essential feature of adjustment is the employment of theory. The reader will recall that often different data stem from studies conducted in different areas of physics, with the result that the theoretical justification of an experimental 'point' may differ essentially from point to point. Of course, an 'ordinary' extrapolation also requires theoretical substantiations, but these are highly restricted, solved by using models or phenomenologically, e.g., by introducing additional terms with unknown coefficients into the extrapolation formulas. A fundamental theory is needed in order to be able to compare results from different areas of physics.

3. Structure of data and the adjustment procedure

The presence of entirely different data must irrevocably generate a certain structure determined by very practical aspects — the accuracy of the data related to a particular constant. All the data can be roughly divided into various accuracy classes (for more details see Refs [10, 11]).

- First, there are data whose accuracy is much higher than that of all other data (to be exact, data whose uncertainties are negligible compared to those that occur in calculating other constants; in particular, in addition to the highly accurate values of the ratio of particle masses and the Rydberg constant, there is the electroweak coupling constant which is known not to a very high accuracy but contributes to small corrections and, therefore, has really no effect on anything). These data are known as auxiliary and can be found before the main adjustment procedure comes into effect.
- Then there are the data whose accuracy is somewhat lower. They form two blocks. The fine-structure constant α belongs to one block with more precise data, while the other is related to the Planck constant h and the elementary charge e. Operations involving these two blocks constitute an adjustment in the narrow sense of the word. It is at this stage that dissimilar measurements appear, standards are used, etc. First, the data from the first block are processed, and then from the second.
- There is also a group of data for quantities that formally may be related through various ratios with auxiliary constants or constants from the two blocks mentioned above. However, the accuracy of the direct measurements of such quantities is extremely low. One example is the electron mass expressed in kilograms. Such data are not included in the adjustment procedure, and the respective quantities are calculated after the main procedure has been completed. Here, we will not single out these constants individually; rather we give their values in those blocks where the results depend on them.
- Obviously, there are always some physical constants, such as the Newtonian constant of gravitation G and the Boltzmann constant k, that are determined in experiments fully independently from measurements of other quantities. They are not involved in the adjustment procedure proper, and their values in the tables of recommended values of constants are calculated independently from the main procedure.

It should be noted that there is no way in which the main procedure and the processing of the remaining data can be formally divided. All the data are processed simultaneously, but their statistical weights are organized in such a way that the processing is actually done block-by-block. The results of processing the block with the more precise data impose constraints on the less precise data, while the blocks with less precise data have no effect on the processing of the more precise data. Data processing in which the separation into classes and blocks is done in the very calculation algorithm differs marginally from the processing of all the data at once. Here, irrespective of the choice of the uncertainty minimization algorithm, analysis of the input data is always done block-by-block.

4. Auxiliary data

The block of auxiliary constants is formed by constants whose values are known exactly (by definition) and those measured with high accuracy, such as the Rydberg constant

$$R_\infty = \frac{\alpha^2 m_{\rm e} c}{2h} \tag{1}$$

or various ratios of particle masses. Auxiliary constants also include quantities that are needed for allowance for small theoretical corrections to various quantities, usually calculated in quantum electrodynamics. The respective results are listed in Table 1. [1]

[1] Here and in what follows we list, as an example, only the values of a few constants of this or that type. The complete set of recommended values can be found on the Web at http:/physics.nist.gov/cuu/Constants/index.html [the National Institute of Standards and Technology (NIST), Gaithersburg, MD] [5].

Table 1. Auxiliary physical constants (cf. Tables 3–5 in review [10]). The exactly known values are listed in the upper half of the table, while the other values of auxiliary constants are listed in the lower half; u_r is the relative standard uncertainty.

Quantity	Symbol	Value and unit	u_r
Speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Magnetic constant	μ_0	$4\pi \times 10^{-7}$ N A^{-2}	(exact)
Electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817\ldots \times 10^{-12}$ F m^{-1}	(exact)
Mass of ^{12}C atom	$m(^{12}\mathrm{C})$	12 u	(exact)
Rydberg constant	R_∞	10 973 731.568 527(73) m^{-1}	6.6×10^{-12}
Proton–electron mass ratio	m_p/m_e	1836.152 672 47(80)	4.3×10^{-10}
Proton mass	m_p	1.007 276 466 77(10) u	1.0×10^{-10}
Electron mass	m_e	5.485 799 094 3(23) $\times 10^{-4}$ u	4.2×10^{-10}

On the whole, in the latest adjustment [5] only a few auxiliary physical constants have slightly different values than those in the earlier adjustment [4].

5. Block of data related to the fine-structure constant *α*

The block related to the fine-structure constant incorporates the set of various data and is formed on the basis of the following relations:

- The Rydberg constant (1) is known with an accuracy much higher than that of the data in the α-block. This sets a direct relation between measurements of α and h/m_e (and the electron Compton wavelength).
- The ratio of electron mass to proton mass is also known with a very high accuracy (see Table 1), with the result that in h/m_e we can replace the electron mass with the proton mass.
- The proton mass is known with a high accuracy in atomic mass units (see Table 1), just as other masses of atoms and nuclei, with the result that there is a relation between measurements of α and h/m for a broad spectrum of objects.
- The electric constant ϵ_0 for a vacuum is known in the SI exactly, so that the fine-structure constant

$$\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} \tag{2}$$

is related to the von Klitzing constant

$$R_K = \frac{h}{e^2} \,. \tag{3}$$

The latter is present in many measurements that involve the use of one or the other of standards of electrical quantities.

The situation with determination of the fine-structure constant through various methods is illustrated by Fig. 1. Fourteen different values of this constant are presented with six very different ways of determining it. Two of these rely on electric standards, while one requires studies of the properties of matter with metrological accuracy. The remaining three use no standards nor metrological measurements and are based entirely on quantum mechanics and quantum electrodynamics, as well as on 'ordinary' measurements. [2] Notice also that a major part of points in Fig. 1 are not determined by one measurement but by a series of measurements of very different quantities whose combination is needed to determine α.

In recent years, the consistent value of α has been determined almost entirely by the contribution from data obtained through studies of the anomalous magnetic moment of the electron. However, over the years the situation has markedly improved. In 1998, the accuracy with which this quantity was determined exceeded that of all other methods. In 2002, the accuracy achieved by Raman spectroscopy of cesium atoms came close to the one achieved by anomalous magnetic moment measurements. In both adjustments, the quantity $\alpha(a_e)$ was determined only by one measurement, while the theory was developed by a single group. [3]

In the 2006 adjustment, the theory was determined (just as it was in previous adjustments) by the works of T Kinoshita and collaborators. This group of theorists was able to increase the accuracy of calculations from $u_r = 9.9 \times 10^{-10}$ in 2002 to $u_r = 2.4 \times 10^{-10}$ in 2006 [12]. There also emerged a new experimental result from measurements of the anomalous electron magnetic moment [13], while the Raman spectroscopy method (in a much modified form) was successfully applied to rubidium atoms [14].

Acknowledging the progress in refining the value of $\alpha(a_e)$ and in obtaining independent verifications of this most precise value of α, we should nevertheless bear in mind that the considerable gap between the accuracy of the most precise value and those of independent verifications still remains, which to a certain extent raises a query about the reliability of the recommended result.

The values of the main constants related to the fine-structure constant are listed in Table 2. The molar Planck constant hN_A plays an important role in forming the other block of data related to h, so its presence in this table should be briefly explained. There are several microscopic units in which the masses of particles and atoms are measured with high accuracy. In particular, this is true of units of frequency (i.e., mc^2/h is measured instead of m) and atomic mass units. It is the value of hN_A that determines the conversion factor. This stems from the following reasoning. The relationship

$$\frac{mc^2}{h} = \frac{1}{(hN_A)}\,\frac{m}{m(^{12}\mathrm{C})/12}\,c^2\left[N_A m(^{12}\mathrm{C})/12\right] \tag{4}$$

[2] Here, the frequency is measured in absolute or relative units, but the measurements themselves are done with an accuracy much lower than the standard, or metrological, accuracy. Hence, the problems that occur in connection with the reproduction of the unit, characteristic of measurements involving standards, have no effect here. In this (and only this) meaning the measurements are not related to standards.

[3] Here, we give references only to some recent works. The other references can be found in the respective papers on the adjustments: 1998 [3], 2002 [4], and 2006 [5]. The number of references in each paper amounts to several hundred, so we do not think it proper to list them here.

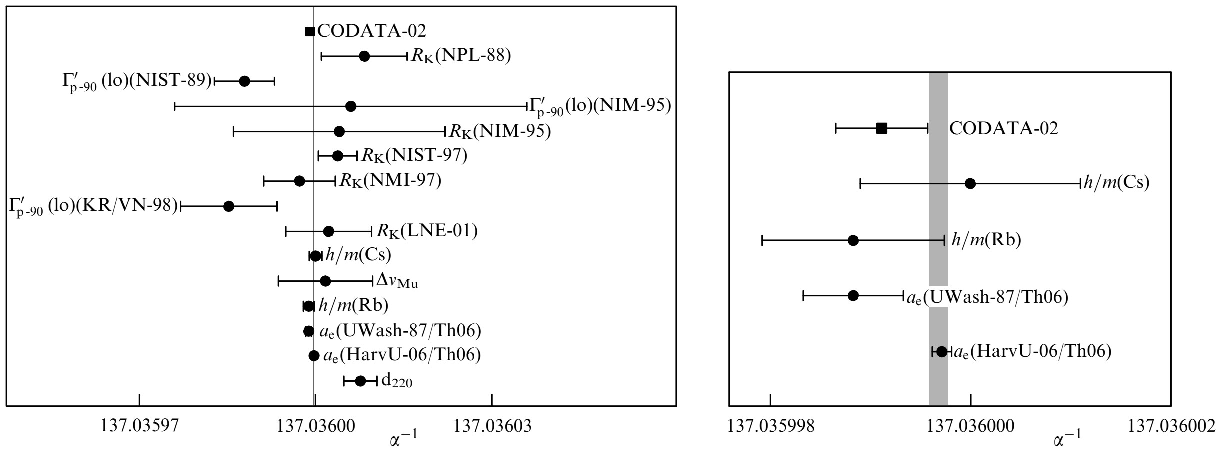

Figure 1. Results of precise measurements of the fine-structure constant α (according to the data of the 2006 adjustment [5]). The notation is the same as in Ref. [5], where the interested reader can find all necessary references. The vertical band corresponds to the value recommended by the results of data adjustment. The most precise data (obtained through studies of the anomalous electron magnetic moment and by Raman spectroscopy methods) are magnified in the right half of the figure.

Table 2. Values of constants related to α [5] (cf. Table 6 in review [10]); u_r is the relative standard uncertainty.

Quantity	Symbol	Value and unit	u_r
Inverse fine-structure constant	α^{-1}	137.035 999 68(9)	6.8×10^{-10}
Molar Planck constant	hN_A	$3.990\,312\,6821(57) \times 10^{-10}$ J s mol^{-1}	1.4×10^{-9}
Quantum of circulation	$h/2m_e$	$3.636\,947\,5199(50) \times 10^{-4}$ m^2 s^{-1}	1.4×10^{-9}
Electron Compton wavelength	$\lambda_C = h/(m_e c)$	$2.426\,310\,2175(33) \times 10^{-12}$ m	1.4×10^{-9}
Von Klitzing constant	$R_K = h/e^2$	25 812.807 557(18) Ω	6.8×10^{-10}

links the mass (of an atom) measured in frequency units on the left-hand side to the molar Planck constant and the numerical value of the mass of an atom in atomic mass units (the first two factors on the right-hand side). The last two factors on the right-hand side of the equality are known exactly in the SI, with $N_A m(^{12}C/12) = 1$ g mol^{-1}.

As noted earlier, measurements of mass in frequency units (which coincides in accuracy with measurements of h/m) are closely related to determining α.

6. The Planck constant *h* and the related data

As in the previous case, this block of data is formed by the values of the involved constants linked by relations whose accuracy is greater than that of the values of the constants themselves. The block incorporates such physical constants as the Planck constant h, the electron (or elementary) charge e, the Josephson constant $K_J = 2e/h$, the Avogadro constant N_A, the Faraday constant $F = eN_A$, and various combinations of quantities that incorporate the electron mass and charge and other constants, such as the ratio e/m_e, the Bohr magneton μ_B, and the nuclear magneton μ_N in SI units. Some are measured directly, while others in combinations with auxiliary and more accurately known constants from the α-block.

The interrelation in defining the above-mentioned constants is determined by the fact that the fine-structure constant α, the molar Planck constant hN_A, and the electron Compton wavelength λ_C (see Table 1) are known with a higher accuracy than the characteristic accuracy in the h-block, whose data are listed in Fig. 2, while the results for the constants [5] are summarized in Table 3.

The nine experimental points presented in Fig. 2 have been found by five very different methods. The predominant results are those obtained through the use of what is known as the watt balance. The principal transformation compared to the 2002 result consists in the emergence of a new and more accurate result from NIST [15]. The watt-balance results contradict the value based on the fabrication and investigation of an 'ideal' silicon crystal for determining the Avogadro constant. The average over all the other values is somewhat less accurate than the value obtained for silicon crystal but is in perfect agreement with the watt-balance result.

The discrepancies in this block of data have a long history and, to make a long story short, stem from the fact that the block is always linked to complex macroscopic devices and chemical technologies, which makes the experimental techniques less transparent, to put it mildly, than many experiments related to determining α. In 1998, the announced accuracy in determining the Planck constant was higher than in 2002, since at that time the international collaboration dealing with measurements of the Avogadro constant refused, temporarily, to supply a result of any kind and was involved in a verification process. In 2002, it insisted on its result, and the uncertainty in the recommended value was somewhat widened and was determined not by the accuracy of the existing particular values but by their spread. In 2006, an extended uncertainty was also adopted due to differences in opinion concerning the data, but the statistical weight of the silicon value diminished.

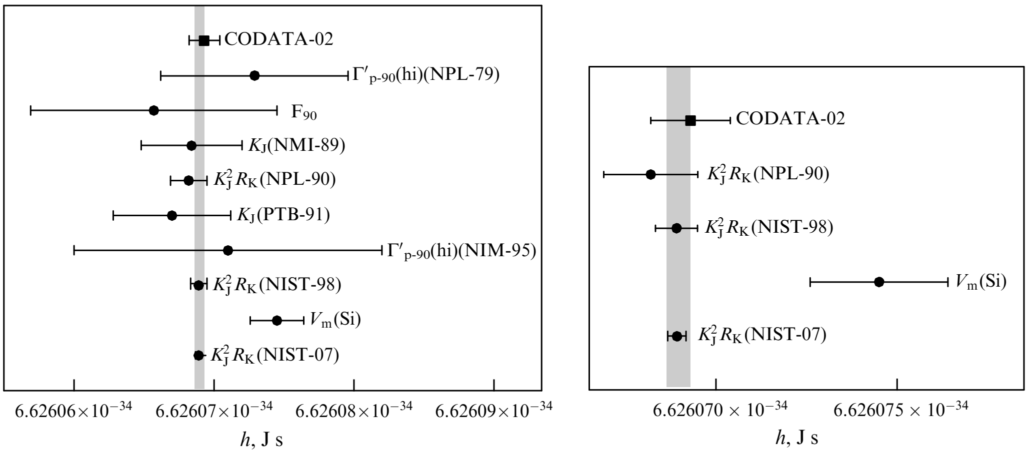

Figure 2. Determining the Planck constant h in the 2006 adjustment [5]. The notation is the same as in Ref. [5]; the vertical band corresponds to the recommended value of the constant. The most precise results, obtained by applying the watt-balance method and in the project of determining the Avogadro constant by crystallographic data [V_m(Si)], are magnified in the right half of the figure.

Table 3. Values of constants from the h-block [5] (cf. Table [7] in review [10]); u_r is the relative standard uncertainty.

Quantity	Symbol	Value and unit	u_r
Planck constant	h	$6.626\,068\,96(33)\times10^{-34}$ J s	5.0×10^{-8}
Elementary charge	e	$1.602\,176\,487(40)\times10^{-19}$ C	2.5×10^{-8}
Avogadro constant	N_A	$6.022\,141\,79(30)\times10^{23}$ mol^{-1}	5.0×10^{-8}
Faraday constant	$F=N_Ae$	$96\,485.3399(24)$ C mol^{-1}	2.5×10^{-8}
Electron charge to mass quotient	$-e/m_e$	$-1.758\,820\,150(44)\times10^{11}$ C kg^{-1}	2.5×10^{-8}
Electron gyromagnetic ratio	$\gamma_e=2\lvert\mu_e\rvert/\hbar$	$1.760\,859\,770(44)\times10^{11}$ s^{-1} T^{-1}	2.5×10^{-8}
Electron mass	m_e	$9.109\,382\,15(45)\times10^{-31}$ kg $0.510\,998\,910(13)$ MeV/c^2	5.0×10^{-8} 2.5×10^{-8}
Proton mass	m_p	$1.672\,621\,637(83)\times10^{-27}$ kg $938.272\,013(23)$ MeV/c^2	5.0×10^{-8} 2.5×10^{-8}
Bohr magneton	$\mu_B=e\hbar/2m_e$	$927.400\,915(23)\times10^{26}$ J T^{-1}	2.5×10^{-8}
Nuclear magneton	$\mu_N=e\hbar/2m_p$	$5.050\,783\,24(13)\times10^{-27}$ J T^{-1}	2.5×10^{-8}
Josephson constant	$K_J=2e/h$	$483\,597.891(12)\times10^{9}$ Hz V^{-1}	2.5×10^{-8}

Table 4. Recommended values of independent constants [5] (cf. Table 8 in review [10]); u_r is the relative standard uncertainty.

Quantity	Symbol	Value and unit	u_r
Newtonian constant of gravitation	G	$6.674\,28(67)\times10^{-11}$ m^3 s^{-2} kg^{-1}	1.0×10^{-4}
Boltzmann constant	k	$1.380\,6504(24)\times10^{-23}$ J K^{-1}	1.7×10^{-6}
Molar gas constant	$R=N_Ak$	$8.314\,472(15)$ J K^{-1} mol^{-1}	1.7×10^{-6}

This problem still requires resolution, and this demands new independent experiments which are now being conducted in different countries.

7. Independent constants

There are several physical constant that have no effect on the processing of other data or whose effect is negligible. Some of these constants are listed in Table 4.

The situation with the fundamental physical constant k differs substantially from that with G (both are accumulated in Table 4). The Boltzmann constant k and the molar gas constant R were measured with the accuracy mentioned in Table 4 relatively long ago, and in the course of almost two decades this accuracy has not increased. Figure 3 illustrates the original results used in the 2006 adjustment. The only difference with the previous adjustments (1998 and 2002) is that recently new results (true, not very reliable ones) from NIST and PTB (Die Physikalisch-Technische Bundesanstalt, Braunschweig, Germany) emerged, results that are not important in and of themselves but are an indication of possible progress in the near future.

As for the gravitational constant G, here the main obstacle is the substantial scatter in the data. Although G is one of the

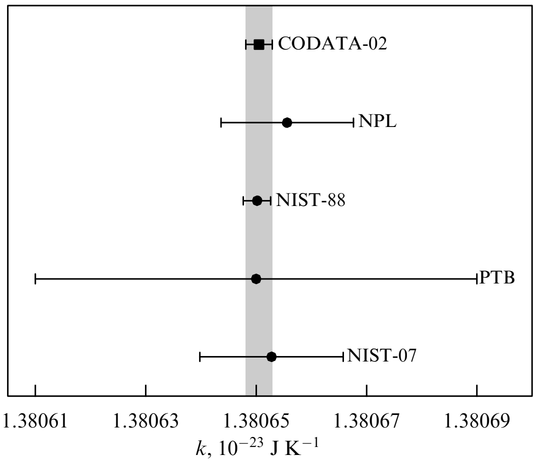

Figure 3. Determining the Boltzmann constant k in the 2006 adjustment [5]. The vertical band corresponds to the recommended value.

most fundamental quantities in modern physics, its exact value plays no significant role, with the result that all the experiments concerning G are far removed from the problems of fundamental physics.

Indeed, the fundamental nature of this constant stems from the fact that it together with the Planck constant h and the speed of light c determine the characteristic Planck scale, but this is only a scale, and exact values of the constants are not needed here. The theory of general relativity can be verified with a high accuracy, which unquestionably is very important both theoretically and practically. One such experiment is the verification of the universality of free fall. This, strictly speaking, does not require knowing the acceleration of free fall; what is more important is knowing the gradients of the acceleration of free fall. One can also study the movement of the Moon about the Earth or the planets around the Sun (the reader will recall that it was the observation of the position of Mercury's perihelion that served as one of the practical justifications for general relativity). But the respective calculations need the product of G and a certain 'large mass' (the mass of the Sun or one of the planets) and the ratio of the Sun's mass to that of planets. It goes without saying that such products and ratios are known with much higher accuracy than that of G.

Measurements of G are performed in specially designed experiments, which, on the one hand, involve the use of classical macroscopic objects but, on the other hand, require measuring the magnitudes of very small effects. Such experiments are necessarily extremely complicated and are characterized by the presence of multiple systematic uncertainties.

The spread of the data in Fig. 4, which presents particular results of G measurements, shows that these small effects are difficult to take into account. Figure 4 demonstrates the results of the last four adjustments (the recommended value of 1986 [2] is marked CODATA-86 in the left diagram). The main changes here amount to the following. The 1986 result was fairly accurate, but in 1998 the uncertainty increased because of a serious contradiction between the data on which the 1986 recommendation was based and the PTB data. In 2002, after a thorough analysis [4] of the data, it was decided that the PTB data would be excluded from processing, with the result that the uncertainty again became smaller. As before, today the uncertainty is determined by the scatter in the data and is much larger than the uncertainty of some particular values. The difference between data processing in 2002 and in 2006 is not that any absolutely new results were obtained but that the analysis of data whose preliminary results were published by the end of 2002 was completed.

It appears that the uncertainty estimate made in Ref. [5] is somewhat conservative, but this result has no effect on the qualitative nature of the problem. Unfortunately, the impossibility of reliably estimating all the systematic errors leads to a substantial scatter in the data and to contradictions in the results. And this remains the main problem in measuring the gravitational constant G.

8. Conclusion

At the end of this brief review of the new data and the new results of the 2006 adjustment, let us compare them with earlier results. The trend of an increasing announced accuracy is illustrated in Fig. 5 for the entire period during which the CODATA Task Group on Fundamental Constants operated, while the values of the most important physical constants for the last three adjustments [3 – 5] are summarized in Table 5.

Figure 5 shows that in some cases the uncertainty decreases rather than increases. This is due either to the appearance of new data that contradict the existing results or to the discovery of systematic errors that were not accounted for earlier. The shift of some values of physical constants from adjustment to adjustment can, at least

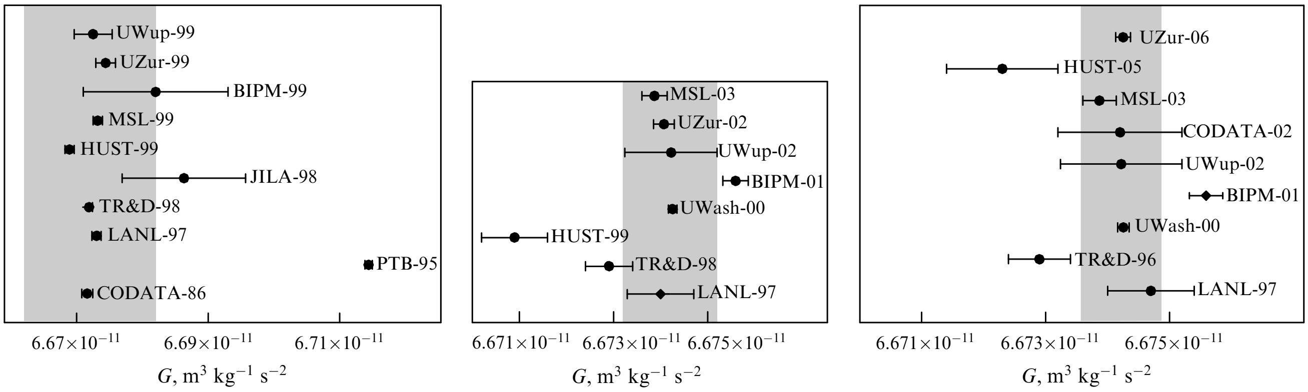

Figure 4. The results of measurements of the gravitational constant G incorporated into the 1998 adjustment [3] (left), the 2002 adjustment [4] (center), and the 2006 adjustment [5] (right). The vertical bands correspond to the recommended values from the respective adjustments.

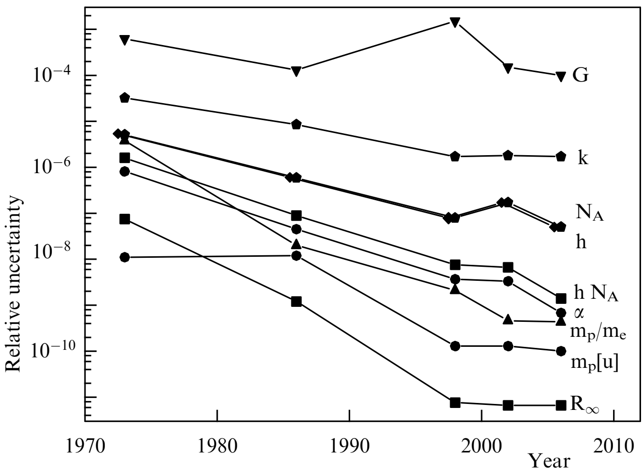

Figure 5. Uncertainty in determining the values of fundamental physical constants in CODATA adjustments [1 – 5].

theoretically, take us outside the error bars in their determination. Luckily, this is not the case with the constants in Table 5. Such problems primarily stem from the fact that obtaining results with a higher accuracy often leads, from the practical angle, to intrusion into an entirely new area, since the effects that were considered unimportant become at a certain instant of time extremely important. And the possibility of an error increases substantially.

Strictly speaking, the goal of an adjustment of values of constants is, primarily, to expose such situations by establishing the contradictions in the data pertaining to different quantities. Although tables of recommended values of fundamental constants are used more often that other results of adjustments [1 – 5], they are not the most important part of such work. Much more important, from the scientific angle, is the analysis of data (e.g., see the reviews [10, 11]). The chief result of such an analysis is that the data on the whole match each other, thus indicating that our understanding of nature is correct.

There is no reason to expect that 'understanding nature' refers only to fundamental laws. Any theory is, in a certain sense, only an approximation of reality, and we should not underestimate the role of approximations in fundamental physics. Often in each specific case we more or less understand which approximation is used, but this is not always true. Whether the approximations should match on the whole is not a trivial question, and we all recall examples from physics at the beginning of the 20th century. At the time there existed several reasonable theories that successfully described some facts, but some of these theories carried approximations whose nature was unclear in those days. Contradictions among approximations led to contradictions among theories. It was unclear how to combine the successful theory of mechanical motion with the no less successful electromagnetic theory: first, what was one to do with the relativity principle, Newtonian mechanics, and, say, the description of interaction between point charges; second, it was unclear how atoms bound, it appeared, by electromagnetic forces could be bound by such forces since electrostatic forces do not ensure a stable equilibrium, while any accelerated movement of charges is sure to lead to the emission of radiation. What resulted from all this was the realization that classical Newtonian mechanics is a theory that completely ignores relativistic and quantum effects, and its use cannot be justified in describing electrical phenomena and processes that take part over atomic distances.

From the pragmatic viewpoint, the problem was that a theory correctly substantiated by experiments was used outside the realm of its admissible applicability. There is always this risk when the area of research is extended to new ranges of energy, temperature, etc. or when the accuracy of measurements or calculations increases substantially. Hence, the adjustment of values of physical constants, a process that uses highly accurate data from different areas of physics, is a highly important instrument in verifying the self-consistency of adopted approximations.

Going back to the topic of adjusting results, I would like to note that agreement of data on the whole means not only that we have a correct (and clear) understanding of the main laws of nature but also that we are using the data correctly, which refers, explicitly or implicitly, to formulated approximations and well-developed and effective methods, including their practical implementation in the form of highly accurate

Table 5. Progress in determining the fundamental physical constants in the 1998 – 2006 adjustments [3 – 5].

Constant (unit of measure)	Recommended value		
	1998 [3]	2002 [4]	2006 [5]
R_∞ [m^{-1}]	10 973 731.568 549(83)	10 973 731.568 525(73)	10 973 731.568 527(73)
m_p [u]	1.007 276 466 88(13)	1.007 276 466 88(13)	1.007 276 466 77(10)
m_p/m_e	1 836.152 667 5(39)	1 836.152 672 61(85)	1 836.152 672 47(80)
α^{-1}	137.035 999 76(50)	137.035 999 11(46)	137.035 999 68(9)
hN_A [J s mol^{-1}]	$3.990\,312\,689(30) \times 10^{-10}$	$3.990\,312\,716(27) \times 10^{-10}$	$3.990\,312\,682\,1\,(57) \times 10^{-10}$
h [J s]	$6.626\,068\,76(52) \times 10^{-34}$	$6.626\,069\,3(11) \times 10^{-34}$	$6.626\,068\,96(33) \times 10^{-34}$
N_A [mol^{-1}]	$6.022\,141\,99(47) \times 10^{23}$	$6.022\,141\,5(10) \times 10^{23}$	$6.022\,141\,79(30) \times 10^{23}$
e [C]	$1.602\,176\,462(63) \times 10^{-19}$	$1.602\,176\,53(14) \times 10^{-19}$	$1.602\,176\,487(40) \times 10^{-19}$
k [J K^{-1}]	$1.380\,650\,3(24) \times 10^{-23}$	$1.380\,650\,5(24) \times 10^{-23}$	$1.380\,650\,4(24) \times 10^{-23}$
G [$m^3\,kg^{-1}s^{-2}$]	$6.673(10) \times 10^{-11}$	$6.674\,2(10) \times 10^{-11}$	$6.674\,28(67) \times 10^{-11}$

devices and, in particular, standards. These standards form the basis for the metrological support of various areas of science and technology.

The author is a member of the CODATA Task Group on Fundamental Constants and the current chairman of a similar Russian group. This paper is a review of the data related to the last adjustment of values of fundamental physical constants [5] conducted by the Task Group. While the recommended values resulted from the work of the entire group, the various comments express the viewpoint of the author and do not necessarily coincide with the viewpoint of the Task Group as a whole. The author is grateful to all his colleagues in the international and Russian task groups for the useful discussions.

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